Optics and Quantum Electronics

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Research Areas and Projects

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Publications, Presentations, Thesis and Books
Ultrashort Pulse Laser Technology
Long-Term Stable Coherent Superposition of Broadband Mode-Locked Lasers

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Coherent superposition of multiple mode-locked lasers has been recognized as one of the most promising techniques to generate well-isolated, highly-stable single-cycle optical pulses beyond the bandwidth limitations of gain media and laser mirrors. To synthesize single-cycle optical pulses, we have worked on the synthesis of optical combs spanning from the visible to the infrared range from mode-locked Ti:sapphire and Cr:forsterite lasers.

As one step closer toward the single-cycle pulse synthesis, we present the generation of a long-term stable phase-coherent spectrum spanning from 600 nm to 1500 nm by synchronizing Ti:sapphire and Cr:forsterite lasers with residual timing and phase rms-jitters of 380 as and 480 as, respectively.

Figure 1 shows the schematic of the synchronization set-up. Ultrabroadband Ti:sapphire (600-1200nm) and Cr:forsterite (1100-1500nm) lasers are combined at a broadband 50:50 beam splitter [1] (BS1 in Fig. 1). For timing synchronization, a balanced cross-correlator [2] is used. Once tight timing synchronization is obtained, heterodyne beat signals between the two lasers in the overlapped spectral range (centered at 1120 nm) is obtained. This beat signal is locked to a local oscillator (f_LO in Fig. 1) by modulating the pump power of the Ti:sapphire laser with an AOM.

Figure 1: Schematic outline of the synchronization set-up. AOM, acousto-optic modulator; APD, Avalanche photodiode; BPF, band-pass filter; Cr:fo, Cr:forsterite laser oscillator; GD, group delay
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element; GDD, group delay dispersion; EOM, electro-optic modulator; LF, loop filter; PD, digital phase detector; SFG, sum frequency generation; Ti:sa, Ti:sapphire laser oscillator.

To improve the long-term stability and reduce the residual phase jitter, a noise eater and an orthogonal controller are installed. The noise eater is based on an intensity regulating feedback loop with a Pockels cell in the 1064nm pump beam. With the noise eater, the low frequency noise of Cr:forsterite laser is greatly reduced. Extending the bandwidth of noise eater is in progress by using a resonantly-damped Pockels cell. The orthogonal controller reduces the influence of pump power change to the timing lock. The signal driving the fast PZT is subtracted in part from the signal driving the AOM to minimize the cross-talk between the timing lock and the phase lock. In this way, more than 10 dB reduction of cross-talk is obtained.

Figure 2: (a) Sub-fs timing synchronization over 12 hours. (b) Long-term sub-fs phase synchronization result. The residual phase jitter is 480 as (1 mHz-1 MHz). The bottom trace shows the pump power change when the phase is locked.

Figure 2(a) shows the out-of-loop cross-correlation trace over 12 hours when the two lasers are timing synchronized with a balanced cross-correlator. The measured residual timing jitter is 380 as ± 130 as from 0.02 mHz to 2.3 MHz bandwidth. The timing jitter is limited by the amplitude noise of the lasers. Figure 2(b) shows the output from the digital phase detector when the difference in carrier-envelope offset frequency is locked to a 3 MHz local oscillator over 1000 seconds. The in-loop integrated rms phase noise is 0.26π radians measured from 1 mHz to 1 MHz. This is equivalent to 480 as rms phase jitter at 1120 nm. The bottom trace shows the pump power change over the same time frame. To the best of our knowledge, this is the first time to obtain a long-term phase coherent spectrum over 1.5 octaves by locking two independent lasers. The next step is locking the difference in carrier-envelope offset frequency to DC. For this, we will use a combination of offset locking and balanced homodyne detection. The offset locking will result in wider locking range by use of a digital phase detector. Additional balanced homodyne detection will remove the slow drift and enable long-term drift-free operation.

In summary, we have presented a phase-coherent ultrabroadband optical spectrum ranging from the visible to the infrared by drift-free timing and phase synchronization of mode-locked Ti:sapphire and Cr:forsterite lasers. Long-term sub-fs rms timing and phase jitters between the two lasers of 380 as and 480 as are demonstrated. It is expected that further noise reduction and optimization of orthogonal control enable phase jitter much less than 2π. This will opens up the possibility to generate single-cycle pulses at 1 μm from a long-term stable setup. More detailed technical information on this pulse synthesis system can be found in Ref. [3].
References:


Broadband Optical Parametric Chirped Pulse Amplification at 2.0 \( \mu \)m

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In recent years, research in high-power ultrafast optics has called for intense, few-cycle pulsed light sources that work beyond the limitations of traditional optical amplifiers in gain bandwidth and wavelength selection. Among such research is the generation of soft X-rays by means of high-harmonic generation (HHG) with long-wavelength driver pulses. Driving light pulses in the mid-infrared with intensities of \( 10^{14} \text{ W/cm}^2 \) and greater are necessary, with stabilized carrier-envelope (CE) phase and durations approaching a single optical cycle. Laser amplifiers cannot produce such light pulses directly.

To drive HHG experiments, we have constructed an intense CE-phase-stabilized two-cycle 2-\( \mu \)m pulse source by means of optical parametric chirped-pulse amplification (OPCPA). OPCPA employs chirped-pulse amplification, by which pulses may be amplified to high energies without nonlinear phase distortion, while using an optical parametric amplifier (OPA) instead of a laser gain medium. The OPCPA allows broadband amplification at high gain, and at wavelengths unavailable from laser gain media [1].

Our OPCPA design consists of two OPA stages that employ collinear degenerate difference frequency generation (DFG), allowing a total gain of \( 10^7 \), a gain bandwidth spanning almost a half-octave, and minimal amplification of spontaneous parametric fluorescence. The setup is shown in Fig. 1. The system is driven by an octave spanning Ti:sapphire laser [2]. We used the broadband output of the laser to directly generate phase stable pulses by DFG in a MgO:PPLN crystal with a poling period of 13.1 \( \mu \)m. This process generates broadband 2-\( \mu \)m seed pulses. After the DFG stage, the 1030 nm fundamental spectrum is preamplified in a fiber amplifier to seed a Nd:YLF regenerative amplifier that provides the pump pulses for the subsequent OPCPA stages. The seed pulses are stretched in a block of silicon to about 20-ps length and preamplified in OPA1. After the first stage, when enough signal amplification has occurred, an infrared DAZZLER is used for pulse shaping and higher order dispersion compensation. Then the pulses are amplified to the >0.1mJ level in a second OPCPA stage (OPA2) and compressed in a suprasil (FS) block.

![Fig. 1. Schematic of the optical setup for generating CE-phase-stable, 14fs, 0.1mJ laser pulses.](image-url)

Infrared pulses (1.6-2.4\( \mu \)m), obtained by difference-frequency mixing of octave-spanning Ti:sapphire pulses in a MgO:PPLN crystal, are amplified from 4pJ in two OPA stages to 0.1mJ. Synchronization of the 30ps Nd:YLF regenerative amplifier is accomplished by seeding with 1047nm light from the laser oscillator pre-amplified in a Yb-doped fiber amplifier. The stretcher-compressor unit can be implemented using bulk suprasil300 and silicon blocks and an IR DAZZLER.
The 2μm seed pulses generated by DFG of the Ti:Sapphire oscillator are shown in Fig. 2. The pulse energy is in the few pJ range and the spectrum corresponds to a ~14fs, two-cycle pulse. Since the infrared light at 2μm is created by difference-frequency generation, the seed pulses for the OPCPA automatically possess a stable CE phase [3].

Fig. 2: (a) Measured DFG spectrum obtained by difference-frequency mixing of octave-spanning Ti:sapphire pulses in a MgO:PPLN crystal. (b) Electric field versus time calculated from the spectrum under the assumption of a flat spectral phase. This electric field corresponds to a DFG pulse duration of ~14 fs or approximately two optical cycles at 2μm assuming perfect dispersion compensation.

To ensure efficient energy transfer from the Nd:YLF pump pulses to the signal (i.e., seed) pulses, the temporal durations of the signal and pump pulses must be matched. For 30-ps pump pulses and 14-fs signal pulses, this corresponds to a stretching factor of ~2000. We have designed an ultracompact stretcher-compressor unit employing a 30mm silicon block, a programmable acousto-optic dispersive filter (DAZZLER from Fastlite) based on a 45mm TeO2 crystal, and a Brewster-cut 150 mm suprasil300 glass block for compression. As the DFG pulse energy is in the few pJ range, we first stretch the pulses almost lossless in silicon in front of the first OPA stage. Placing the DAZZLER, which has a diffraction efficiency of only ~10%, in between the first and second OPA stages has the advantage to reduce problems arising from amplified spontaneous emission (ASE) in the first OPA stage due to the low seed pulse energy.

The broadband amplified spectrum of the 2-μm pulses directly after OPA1 is shown in Fig. 3. The average power of the 1-kHz amplified pulse train measures >20 times that of the 80-MHz seed pulse train. Since only one in 80,000 seed pulses is amplified, this demonstrates a gain of 1.6 x 10^5 for each amplified pulse. The spectral bandwidth can support a two-cycle pulse at 2 μm after compression, ample power is available for saturation of parametric gain in the second OPCPA stage, allowing 10% conversion of pump light to 2-μm light and high pulse-to-pulse power stability. Finally, the low superfluorescence (ASE) will allow >10^3 contrast between the 2-μm pulse and the ASE pulse after the compression stage.
Fig. 3: Measured OPCPA spectrum after OPA1 obtained by parametric amplification of chirped DFG pulses (black; see Fig. 2). For comparison, the DFG seed pulse spectrum, multiplied along the y-axis by a factor of 20 (red), and the spectrum of the ASE generated when no seed pulses are present (blue).

References:


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Generation of High Repetition Rate Femtosecond Pulse Trains with an External High Finesse Fabry-Perot Cavity

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Ultrashort pulse generators producing femtosecond pulse trains with pulse durations in the 100 fs range in the optical communications wavelengths range at high repetition rates (≥ 1 GHz) are in high demand for numerous applications such as femtosecond laser frequency comb generation for frequency metrology, arbitrary optical waveform generation, timing and frequency distribution via optical fiber links, and high speed optical sampling. The recently reported GHz-Cr4+:YAG laser [1], is one possible candidate for such applications, but low gain and material reproducibility of this laser material are challenging. Actively mode-locked lasers with intra cavity Fabry-Perot (FP) filters or passively mode locked laser using saturable absorbers can produce pulse trains with repetition rates well over 1 GHz [2-4], but subsequent pulse compression is needed to reach a pulse duration in the range of 100 fs. This pulse compression may lead to undesired pulse pedestals or enhanced phase fluctuations which may negatively impact or even prohibit the intended applications. In this paper, we demonstrate repetition rate multiplication to the GHz range, by locking a 200 MHz fundamentally mode-locked ErFL to an external FP-cavity with a finesse of 2100. Since the FP cavity is used as a simple external filter element without support of intra cavity appropriate side mode suppression. A 130 fs pulse train at a repetition rate of 1 GHz centered at 1560 nm with a fundamental mode suppression of 50 dB is generated.

![Experiment setup](image)

Fig. (a) Experiment setup. (λ/4: quarter waveplate; λ/2: half waveplate; SMF: single mode fiber; M1: front FP mirror; M2: output FP mirror; other abbreviations are mentioned in text) Fig (b) RF spectra analyzer scans of the pulse train from the output of the external FP cavities, detected with a 10 GHz photodetector. Fig. (c) Optical spectral analyzer scans of the pulse train before (dashed) and after (solid) the FP cavity.

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The experimental setup is shown in Fig. (a) fundamentally passively mode-locked ErFL in a sigma cavity configuration was constructed to generate 110 fs pulses at a repetition rate of 200 MHz. The configuration of the laser is similar to [5] with some slight variations. The output of the laser is coupled and mode-matched into a free space Fabry-Perot cavity using an aspherical lens. The Hänisch-Couillaud locking scheme [6] is used to lock the mode comb of the laser to the transmission maxima of the external FP cavity by controlling the Piezo-mounted mirror on the sigma arm of the ErFL cavity. Detailed performance comparisons were carried out between a low finesse FP cavity (reflectance: M1=98.00%, M2=99.85%, Brewster plate loss=2%) and a high finesse cavity (reflectance: M1=M2=99.85% with negligible Brewster plate loss). The finesse of the low finesse cavity is 156, and the high finesse cavity is 2100. For the case of the high finesse, cavity, both mirrors M1 and M2 are dispersion flattened around 1550 nm.

For both cases, the RF spectrum of the output of the FP cavity is measured with a 10 GHz bandwidth photodetector. Fig (b) show that for a finesse of 2100, more than 50 dB fundamental mode suppression in the RF domain is achieved, corresponding to a 56 dB fundamental mode suppression in the optical domain. The fundamental mode suppression achieved for both cases agrees well with the suppression ratio calculated from the finesse of the FP cavities. Fig. (c) shows the optical spectra of the pulse train before and after the FP external cavity for the high finesse case. The 3 dB bandwidths of the spectrum before and after the FP cavity are 23.1 nm and 19.6 nm, respectively, corresponding to transform limited pulse durations of 110 fs and 130 fs. Since the FP-cavity mirrors are dispersion flattened, the reduction in the pulse spectrum width is mainly due to the carrier envelope frequency offset of the mode-locked comb of the pulse train generated from the ErFL. This is verified by varying the pump power of the laser to maximize the output spectrum width [7].

In conclusion, the generation of 130 fs pulse trains centered at 1560 nm with a repetition rate of 1 GHz is reported from a passively mode-locked ErFL by locking to an external high finesse FP cavity. Suppression of the fundamental laser modes by 56 dB is achieved.

References:


Two-dimensional spectral shearing (2DSI) for ultrashort pulse characterization

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As few-cycle pulses have become common, spectral shearing interferometry (SPIDER [1]) has become a proven method for measuring the spectral phase of such pulses [1-3]. We have recently developed a two-dimensional spectral shearing (2DSI) technique [4, 5] which, in contrast to standard SPIDER, requires only the non-critical calibration of the shear frequency and does not perturb the pulse before up-conversion. Rather than encode phase as a sensitively calibrated fringe in the spectral domain, this method robustly encodes phase along a separate dimension. This allows for measurement at the sampling limit of the spectrometer, as we do not need to oversample the spectrum to resolve the fringe found in standard SPIDER. This advantage, along with the use of monochromatic frequency upconversion typical of all spectral shearing methods, enables measurements over extremely large bandwidths, potentially exceeding an octave.

In our scheme, the pulse under test is up-converted with two chirped pulse copies. The two chirped quasi-CW signals are created in an interferometer and mixed with the short pulse in a Type-II crystal (see Fig. 1). The two up-converted copies are sheared spectrally, but are collinear and temporally identical (they essentially form a single pulse). The delay of one of the chirped pulses is scanned over a few optical cycles by vibrating the corresponding mirror in the interferometer. Since the chirped pulses are essentially monochromatic over the time scale of the short pulse, this is equivalent to scanning the zeroth-order phase of one of the pulse copies. The spectrum of the output pulse is recorded as a function of this phase delay, yielding a 2-D intensity spectrum that is given by

\[
I(\omega, \tau_\phi) = 2A(\omega)A(\omega - \Omega)\cos[\phi(\omega) - \phi(\omega - \Omega)] + \text{D.C.}
\]

where \(\tau_\phi\) and \(\omega_{\text{CW}}\) are the delay and local frequency, respectively, of the quasi-CW signal being scanned, \(A(\omega)\) is the magnitude of the up-converted pulse spectrum, and \(\phi(\omega)\) is the spectral phase. The under-bracketed term is the first-order finite difference of the spectral group delay multiplied by the shear frequency.
A simple two-dimensional raster plot of the raw spectra (see Fig. 2) reveals the shifted pulse spectrum along the $\lambda$-axis, with fringes along the $\tau_\phi$-axis that are shifted by an amount proportional to the group delay at the corresponding wavelength. The user can thus immediately ascertain the salient properties of the complex spectrum simply by looking at the raw output of the measurement: each spectral component is vertically shifted in proportion to its actual shift in time. Precise quantitative determination of the fringe phase (and thereby group delay spectrum) can be directly obtained from the output with FFTs taken along the phase axis, with no iterative processing or filtering required.

The only calibration needed is for the shear, $\Omega$. This calibration can be done very accurately and easily by measuring the pulse before and after transmission through a known dispersive element. Multiple shears can be used to measure a given pulse as a self-consistent verification that no spurious absolute phase errors have occurred. This ability also allows for a wide range of pulse widths to be measured by the same setup.

It is not necessary to know the length or rate of the scan, so long as it is relatively linear over the measurement and long enough to determine a phase. Only the relative phase of the fringes matters in (1) and thus the technique is robust to detector noise and scan variations. This fact also greatly simplifies the implementation and analysis of 2DSI.

To gauge the relative accuracy of the method, we measured a few-cycle (~5 fs FWHM) pulse from a prismless Ti:sa laser. We then introduced a 1 mm fused silica plate and measured the
dispersed pulse. Raw output of the scans is shown in Fig. 2. The resulting group delay, obtained by directly subtracting the computed group delays from two measurements, matches the theoretical value well (Fig. 3). The difference curve is smooth despite significant group delay ripple in the individual pulses (caused by the chirped mirrors in the laser) evidenced in Fig. 2. The fused silica plate was used to calibrate the shear for this experiment, and any errors that were constant between the two measurements will cancel out. This does not, therefore, constitute conclusive proof that the method does not have absolute systematic errors. However, this relative measurement does suggest that the method is robust to noise (considering the reconstruction is good even where the spectrum is very weak) and capable of high precision measurement over large bandwidths. The extent to which our assumptions about the simplicity of the calibration are true will be determined in further experiments.

In summary, 2DSI does not require dispersive splitting of the measured pulse, characteristic of SPIDER, nor the associated highly sensitive calibration of pulse delay. This, together with the significant relaxation on spectrometer resolution, renders 2DSI extremely well suited for the measurement of wide-bandwidth pulses, including those with potentially complicated spectral phase.

In addition to the ongoing characterization work mentioned above, we are developing an extension of the method, 4DSI, which should be capable of measuring the full spatio-temporal profile of a pulse, even including pulse front tilt in any axis.

References:

A Preconditioned Newton-Krylov Method for Computing Stationary Pulse Solutions of Mode-locked Lasers

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The effective numerical solution of the steady state solution to a mode-locked laser is essential to the design, optimization, and study of such lasers [1], as well as coherent pulse addition in passive cavities. The standard method for tackling such problems is to simply simulate the operation of the cavity in question, generally with a split-step Fourier method, until convergence is reached at some precision [2]. While this has the advantage of demonstrating self-starting and solution stability, simulation is rather poor when viewed as a numerical algorithm, exhibiting slow linear convergence. For example, a solid-state laser operating in the dispersion-managed soliton regime can take many tens of thousand round trips to converge to within one part in 10⁴. This is especially true of cavities with relatively weak nonlinearity and loss (i.e. high Q resonators).

In contrast, our algorithm converges quadratically to the stable solution, requiring the evaluation of only tens of round trips to converge to within numerical precision, typically two to three orders of magnitude faster than with simulation. This speed up is achieved by directly solving the periodic boundary value problem for the nonlinear cavity using a Newton-Raphson method. At each step we use a matrix-implicit, preconditioned Krylov subspace solver to compute the approximate solution. This means we never explicitly compute the Jacobian of our cavity, but rather send a short series of trial perturbations through the cavity to compute a very good approximation to the solution of the linearized sub-problem. The preconditioning is critical to both the quadratic convergence of the algorithm, as well as its efficiency in terms of round-trip evaluations. Our method enables many new opportunities for design and analysis of mode-locked lasers, such as putting the laser model inside an optimization loop.

In our method, the cavity is simply treated as an arbitrary n-dimensional discrete nonlinear function \( g(u) \). Internally, it can be modeled in any way that is convenient, and it is not actually necessary for the vector \( u \) to correspond to direct physical quantities. In the case we consider here, a dispersion-managed soliton laser, the elements of \( u \) are the Fourier coefficients of the field. We seek an “eigenvector” \( u \) and “eigenvalue” \( e^{i\phi} \) such that \( g(u) = e^{i\phi} u \). We solve this by casting it as the multidimensional root-finding problem

\[
f(u) = e^{i\phi(u)} g(u) - u = 0,
\]

where \( \phi(u) \) is defined so as to set the phase of the first element of \( e^{i\phi(u)} g(u) \) to zero. While this is consistent with solving the original problem, it is not necessarily optimal for convergence and was purely chosen for simplicity. It has been found to empirically work quite well, however.

Given a guess \( u_i \), we perform a standard Newton iteration by linearizing (1) around \( u_i \) and solving for \( u_{i+1} \). However, there are several problems with doing so directly. First, if we were to compute the full Jacobian \( J \) numerically, it would require \( n \) evaluations of the round trip model \( g \), largely negating the efficacy of the algorithm. Second, it turns out that, in general, the Jacobian is badly conditioned and has a non-sparse eigenspectrum. Thus, direct solution methods will be numerically unstable, and iterative solution methods will converge slowly.

To address this, we precondition with a diagonal matrix \( B = (D_g(u) - I)^{\frac{1}{2}} \), where \( D_g(u) \) contains the sum of all diagonal terms in the model. For example, if \( u \) represents Fourier
coefficients of our cavity field, then $D$ will contain the gain and loss spectra, as well as dispersion phases. The better it estimates the actual Jacobian, the quicker the linear subproblems will converge. Thus, it pays to choose a basis where $J_g$ is as diagonal as possible. In the case of our dispersion-managed soliton laser, the Fourier domain is optimal.

The linear subproblem $B(J_g - I)\Delta u_k = Bf(u_k)$ generally becomes better conditioned by roughly an order of magnitude, and perhaps most importantly, it greatly simplifies the eigenspectrum of the system, allowing each subproblem to converge in only a few round trips. To solve the linear subsystem, we use a generalized minimal residual method (GMRES), a conjugate gradient-like method that can handle asymmetric systems [8]. A common feature of Krylov subspace solvers is that they only need information about how the matrix in question operates on a series of vectors. Thus, we never need to explicitly compute the Jacobian, but simply approximate its action on a set of trial vectors (perturbation directions) using first-order finite differences.

**Figure 1**: Log-log convergence plot of our direct method (left) compared to standard simulation (right) as a function of roundtrip evaluation. The same noise initial conditions were used for both.

We tested our algorithm on a dispersion-managed soliton laser model producing roughly 100 fs pulses, shown schematically in Fig. 2, below. This example was chosen due to the relatively slow evolution. Starting from noise, our method needed nine Newton steps to converge to an absolute error of 10^{-8}, with each step taking 6 GMRES iterations (7 round trip evaluations). Thus, a total of only 64 cavity round trip evaluations were needed. In comparison, over 70,000 round trips were required to converge to the same accuracy by simply simulating the laser dynamics (see Fig. 1).

**Figure 2**: A schematic of the laser cavity used as our model problem. SA: saturable absorption; GVD: group velocity dispersion; SPM: self-phase modulation.

There are several interesting avenues to pursue with this method. One is the optimization of laser components (such as dispersion compensating mirrors) by directly minimizing the simulated pulse width. In addition, there are many theoretical studies which are enabled by the ability to rapidly compute a series of perturbations, such as an exploration of the relation between pulse energy and carrier envelope phase slip. Finally, the use of reduced basis sets (i.e. parameter vectors $u$ which are much smaller in dimension than the underlying simulation) could allow for significant further speed gains with little sacrifice in accuracy. We
hope this could allow the algorithm to be eventually applied towards a full spatio-temporal model of a laser cavity, facilitating the quantitative study of Kerr lens mode locking.

References:
Multiple Pass Cavity Lasers

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Project Staff
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Direct writing of waveguide devices using femtosecond laser pulses is a powerful and versatile technique for fabricating photonic devices. It enables the fabrication of three-dimensional structures and has the potential for high-density integrated photonic circuits, thus providing enhanced functionality not possible in planar geometries. In contrast to the conventional semiconductor-based fabrication process, the micromachining process is a single step process, allowing for rapid construction of a variety of devices. Since the first demonstration for modifying refractive indices in glass materials, various structures have been fabricated via direct writing using femtosecond lasers. They include a wide variety of planar devices such as several types of couplers, interferometers, and active waveguides but also three-dimensional structures, such as optical splitters [8], interconnects, wavelength-division multiplexing couplers, and directional couplers [4].

Because waveguide properties such as mode size and index of refraction are sensitive to both the exposure power and scanning speed, it is important to explore the threshold for high-speed femtosecond laser waveguide fabrication. To this end, it is essential to develop specialized writing sources for meeting the needs of the experiment. Our group has developed a novel compact Kerr-lens mode-locked femtosecond Ti: Sapphire laser based on a novel multiple pass cavity (MPC), which was used to fabricate all devices in this study. The MPC laser generates 45 fs duration pulses with 150 nJ of energy per pulse [2]. The extended cavity reduces the laser repetition rate from about 100 MHz to 5.85 MHz, scaling the output pulse energy accordingly. In contrast to amplified femtosecond systems, the MPC laser has a repetition rate high enough to produce an accumulated heating effect which enables device fabrication approximately three orders of magnitude faster than possible using amplified systems. Moreover, MHz-range repetition rate lasers are advantageous for fabricating waveguide devices since the photomodification is caused mainly by thermal diffusion, resulting in symmetric waveguide cross-sections, while kHz repetition rate lasers can cause elliptical or non-symmetric cross-sections due to nonlinear absorption and plasma. Finally, the relatively high energy generated by the MPC laser system enables material processing to be performed with fewer constraints on the numerical aperture, giving greater flexibility and versatility to the writing process. Fig. 1 shows the layout of the MPC Ti:Sapphire laser [4].

Figure 1. Schematic layout of MPC Ti:Sapphire laser [4].

After optimizing mode-locked operation, the beam from the output coupler of the laser source is focused using a high NA objective, often using immersion oil, on a substrate mounted to a
translation stage. Fig. 2 shows a diagram of the fabrication setup. The substrate was translated in a direction orthogonal to that of the propagating beam using a high-precision floating 3 axis stage (Aerotech) controlled using CNC code (G code). The output from the MPC Ti:Sapphire oscillator is attenuated so the exposure at the sample is around 125 mW, then focused with an oil-immersion lens w/ 1.25 NA onto the substrate. The scan speed is set at around 12 mm/s.

**Figure 2** Waveguide fabrication setup [1]

References


Couplers and Mach-Zehnder Interferometers

Sponsors
National Science Foundation – ECS-0501478, BES-0522845

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1.1. Symmetric couplers

To build more complex photonic structures, it is important to fabricate reliable couplers and interferometric devices. A number of groups have performed existing work on couplers and Mach-Zehnder interferometers including couplers in the telecom range [6] and tunable Mach-Zehnder interleavers [7]. Our objectives were to show improved fabrication results and to make comprehensive spectral characterization of these devices. In addition, one can use the sensitivity of the Mach-Zehnder device to characterize important waveguide properties such as the propagation constant. We characterize the spectral features of directional couplers and unbalanced Mach-Zehnder interferometers written in Corning Eagle 2000 glass using the above-mentioned MPC Ti:Sapphire laser. Samples are scanned transverse to the laser beam at a speed of 12mm/s at a power of 125 mW on the sample. Fig. 3 (a) shows the schematic of a symmetric directional coupler, the separation between waveguides in the interaction region is 5um. The interaction length, labeled “Lint” is varied from 0 to 14 mm.

![Schematic of symmetric directional coupler](image)

Figure 3. (a) Schematic configuration of a symmetric directional coupler, and (b) Spectral characteristics measured for a coupler with 1mm and 14mm interaction lengths.

To characterize the directional coupler, light from a continuous wave tunable laser source from 1500 to 1600 nm was coupled into the waveguide using single mode fiber. Fig 3 (b) shows the spectral characteristics of thru and cross port coupling ratios for 1mm and 14 mm interaction lengths, respectively. The thru and cross port powers vary sinusoidally as
expected for long interaction lengths, while the coupling behavior is relatively flat for 1mm Lint. The variability in spectral characteristics means shorter interaction lengths can be chosen to give wavelength independent behavior when desired, and longer interaction lengths can be used to tailor the wavelength characteristics.

Couplers optimized for 3 dB coupling and relative wavelength independence were used to build an unbalanced Mach-Zehnder Interferometer. Fig. 4 shows the geometrical layout of the Mach-Zehnder Interferometer structure. It consists of two asymmetric couplers connected using straight waveguides. The difference in path length between the two arms was varied by changing the vertical dimension of the S bends in one arm (D). The total arm lengths can also be changed by varying the straight waveguide region L.

![Figure 4. Schematic diagram of the Mach-Zehnder interferometer. Couplers are optimized for 3dB coupling and relative wavelength independence. The path length unbalance is varied by changing the vertical dimension of the S bend D.](image)

Fig. 5 (a) and (b) show the spectral characteristics of Mach-Zehnders with different path length differences dL. The output power is measured at the thru port and normalized with respect to losses in the straight waveguide. The spectral characteristics show the expected change in spectral period with change in path length difference. The oscillations have high extinction ratios but do not reach 1 at their maxima because normalization with respect to the straight waveguide does not take into account other losses. The wavelength dependence loss here is conjectured to be from a wavelength-dependent bending loss. Using this set of measurements, an estimate for the propagation constant inside the waveguide can be made.

![Figure 5. Spectral characteristics of Mach-Zehnder interferometers with varying unbalances dL from 17.8um to 100.6 um. Power is measured at the thru port and normalized with respect to losses in the straight waveguide.](image)
References


Bragg Gratings and Long-Period Gratings

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Project Staff
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1. Waveguide Bragg Gratings

Since the first demonstration a decade ago [1], a variety of devices have been fabricated inside transparent materials using near-infrared femtosecond laser pulses. This technique has many advantages, including rapid prototyping and three-dimensional (3D) structure fabrication. By fabricating devices with different functions together in a single substrate, high-density integrated optical circuits can be realized. As one of the core elements, gratings have been actively fabricated via direct writing with femtosecond pulses. While most of them were limited to free-space diffraction gratings or fiber Bragg gratings, recently several experiments on Bragg grating fabrication inside bulk materials have been reported [2, 3]. However, these studies all used Ti:Sapphire amplifiers, and no oscillator-based demonstration has been reported. It has been well known that kHz amplifiers usually generate elliptical-shaped waveguide cross-sections, but MHz oscillators can induce circularly symmetric waveguide cross sections resulting from an accumulated heating effect. In this report, we describe fabrication of submicron-period Bragg gratings inside waveguides in glass substrates using a 5.85-MHz Ti:Sapphire laser oscillator. The relative polarization insensitivity of these devices suggests they have circularly symmetric cross sections in contrast to devices written using amplified systems.

Since Bragg gratings typically have a period which is one-half of the operating wavelength and must account for the index of refraction of the glass, gratings with ~500-nm periods are required for the optical communication band. This submicron resolution has been difficult to achieve using micromachining with infrared femtosecond pulses, because of the diffraction limit. One way to address this problem is to create higher-order resonances via strong index modulation, where the grating period is not required to be shorter than a micron. However, using femtosecond direct-writing where nonlinear processes modify the refractive index, it is possible to find an optimum writing power where nonlinear processes occur only at the submicron-sized central region of the focused beam. Using this technique, it is possible to direct write first-order Bragg gratings without any phase masks or interference techniques.

Figure 1. Phase contrast microscope images for Bragg gratings with periods of (a) 4.5 μm and (b) 780 nm, fabricated in 5 μm wide waveguides.
Waveguides were fabricated in soda-lime glass substrates (Corning 0215) by focusing ~50 fs pulses emitting from a 5.85-MHz repetition rate, multi-pass-cavity, Kerr-lens mode-locked Ti:S laser using a 1.25-NA, 100x immersion objective lens, as reported in [4]. The glass substrate was translated by a three-axis, air-bearing stage (Aerotech). A pulse energy of ~22 nJ and a scan speed of 10 mm/s were used. After a waveguide was fabricated, the stage was translated a second time along the same path to write a Bragg grating pattern. For grating fabrication, an acousto-optic modulator was inserted to periodically modulate the writing beam amplitude, while the pulse energy and scanning speed were reduced to ~12 nJ and 0.1~0.5 mm/s, respectively. Since the first-order Bragg condition is written as

\[
\lambda_B = 2n_{\text{eff}}\Lambda,
\]

(1)

where the Bragg grating wavelength, \(\lambda_B\), represents the free space center wavelength that will be back-reflected, \(n_{\text{eff}}\) is the effective refractive index of the waveguide, and \(\Lambda\) is the grating period, by changing the writing speed and the modulation frequency a different grating period can be obtained. Figures 1(a) and (b) show phase contrast microscope images for Bragg gratings with periods of 4.5 \(\mu\)m and 780 nm, respectively. Periodic patterns can be clearly observed along the center of ~5 \(\mu\)m wide waveguides. Bragg grating periods of ~500 nm were too small to be observed on phase contrast microscopy. For this study, ~40 mm long gratings were made inside 75 mm long waveguides.

![Figure 1](image1.png)

Figure 1. (a) Transmission spectra of the gratings with periods of 1536.1, 1556.2, 1576.4, and 1598.2 nm and (b) Transmission and reflection spectra of the grating with 17dB transmission and 45% reflection.

To characterize the gratings, a continuous-wave laser, tunable from 1500 nm to 1600 nm (Santec), was split into two arms, with 20% used as a reference and 80% coupled into the waveguide through a circulator. The coupled output power normalized to the reference power was measured as a function of wavelength for each waveguide. The transmission of the grating device was then normalized to the transmission of a waveguide without a grating. The reflection was measured through the third port of the circulator and normalized by the 100% reflection case. Fig. 2(a) shows transmission spectra of the gratings with periods of 1536.1, 1556.2, 1576.4, and 1598.2 nm, which were fabricated with different combinations of the scan speed and modulation frequency. The resulting resonance wavelength was linearly related with the grating period and \(n_{\text{eff}}\) was estimated to be ~1.498, according to Eq. (1). Fig. 2(b) shows the strength of a typical grating. At the resonance, the transmission was reduced by 17dB and the reflection peak was 45% compared to 100% back reflection. Note that the grating was uniform enough to have a reflection bandwidth of 80 pm.

In summary, we demonstrate, for the first time to our knowledge, the realization of submicron-period waveguide Bragg gratings via direct writing using a near-infrared femtosecond laser oscillator. This result suggests that submicron grating devices with a wide range of periods can be fabricated.
2. Long-Period Gratings

In this section, we report, for the first time to our knowledge, microbend gratings fabricated inside glass substrates via direct writing with near-infrared femtosecond laser pulses.

A critical period exists for microbend gratings, where the spatial bend frequency is matched with the mode spacing, which maximizes the coupling from guided modes to radiation modes and, hence, transmission loss. Conventionally, the microbend has been implemented by sandwiching a fiber between two plates with periodic grooves. By changing the distance between the two plates, the degree of bending varies, enabling applications for sensing various physical parameters, such as displacement, pressure, temperature, acceleration, etc. At the critical period, the sensitivity is known to be the highest [5]. Recently, long-period gratings with periodic tapers were reported [6]. In our study, long-period gratings with periodic microbends were implemented via femtosecond direct writing. This method enables us to investigate physics underlying microbend gratings. Furthermore, by choosing materials with physical or chemical properties better than glasses, we may be able to realize sensor applications.

The experiment setup identical to the previous section was used for microbend fabrication. A pulse energy of ~24 nJ and a scan speed of 2 mm/s to 15 mm/s were used. Gratings consisted of a series of S-bends with two mutually symmetric S-bends determining the grating period. The grating pattern can be made either horizontally or vertically, depending on its application, which was possible due to the ability to fabrication in 3 dimensions using femtosecond direct writing. Fig. 3(a) shows a phase contrast microscope close-up of a horizontally fabricated grating with a period of 200 μm and a displacement (D) of 4 μm. The scan speed was 3 mm/s.

![Phases image](image)

**Figure 3.** (a) Phase contrast microscope image of a microbend grating with a period of 200 μm and a displacement of 4 μm, (b) Transmitted power at 1600 nm as a function of microbend period for different displacements.

The characterization setup is identical to that of the previous section, except for the absence of the circulator and the use of a multimode fiber at the waveguide end. In the first set of experiments, the transmitted power was measured as a function of grating period, with the displacement varying from 1 μm to 10 μm, as shown in Fig. 3(b). 10-cycle gratings were made with 3 mm/s writing speed. This result indicates that the critical period remains same at 2.4 mm for all displacements, the sensitivity of the loss to the displacement is maximum at the critical period, and loss saturation occurs for higher displacements, all of which are consistent with fiber-based microbends [5].

In the second set of experiments, a variation of the critical period was observed when the refractive index of the waveguide was changed by adjusting the writing speed. Under the Wentzel-Kramers-Brillouin (WKB) approximation, the critical period of the multimode microbend can be written as
where $n_{\text{clad}}$ is the cladding refractive index, $a$ is the waveguide radius, and $\Delta n$ is the refractive index difference in the waveguide [5]. In our experiment, Eq. (2) cannot be applied directly because the number of modes cannot be assumed to be very large since waveguides are small, the exact waveguide size is difficult to determine on phase contrast microscopy, and changing writing speeds changes the waveguide size as well as the index difference. Fig. 4(a) shows the transmitted power as a function of grating period for different writing speeds. The critical period increases as the writing speed increases up to 5 mm/s, indicating that the writing speed had a larger effect on the index difference than the waveguide size. However, for faster speeds, the critical period is not significantly changed, possibly due to the decrease of the number of guided modes. The power level at the critical period decreases as the speed increases up to 5 mm/s but increases again for faster speeds, as shown in Fig. 4(b), which is consistent with the shift of the critical period. The full-width at half maximum (FWHM) of the dip is also shown in Fig. 4(b) as a function of speed. The FWHM monotonically increases with speed, indicating that it may have a stronger correlation with writing speed.

In summary, we implemented, for the first time to our knowledge, microbend gratings inside glass substrates via direct writing with near-infrared femtosecond pulses. We observed the phenomena similar to fiber-based microbends, in spite of many different features, such as lack of cladding and stresses, core size, and so on.

References

Diode Pumped Cr:LiCAF Laser

Sponsors
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any applications in ultrafast spectroscopy, biomedical imaging, and high harmonic generation require low-cost, high-performance femtosecond lasers. Typically, the most expensive component of a state-of-the-art femtosecond system is the pump laser, whose cost is proportional to its output power. In the case of a standard femtosecond Ti:sapphire laser, for
example, the green pump laser may cost in the 50-100k$ range. One approach for lowering
the cost of femtosecond lasers is to use gain media which enables direct diode pumping. A
number of Cr$^{3+}$-doped Colquirite gain media such as Cr$^{3+}$:LiSAF, Cr$^{3+}$:LiSGaF, and
Cr$^{3+}$:LiCAF have broad absorption bands in the red spectral region, overlapping with the
emission lines of high-brightness, low-cost laser diodes [1]. These gain media further exhibit
high quantum efficiency and tunability in the 700-1000 nm wavelength range, enabling the
generation of ultrashort pulses with duration of the order of 10 fs.

Previously our group demonstrated femtosecond ultrashort pulse generation with a diode-
pumped Cr:LiCAF laser [2]. Using two 500 mW pump diodes as a pump source, we obtained
as high as 150 mW of output power during continuous wave (cw) operation. In mode-locked
regime, we were able to demonstrate 10 fs pulses with an average output power of 40 mW,
using soft-aperture KLM. In the current project, as an alternative to our earlier work where we
used Kerr-lens mode-locking to initiate fs pulses, we are using saturable Bragg reflectors
(SBRs) to initiate mode-locking. Advantages of using SBRs instead of Kerr-lens mode locking
include self-starting mode-locked operation, immunity to environmental fluctuations and
reduced cavity alignment requirements. In particular, for the case where multimode and
asymmetric diodes are sued for pumping, SBR mode-locking is easier and more convenient
than soft-aperture KLM mode-locking.

Figure 1 shows the schematic of the diode pumped Cr:LiCAF laser setup. Four diodes each
producing 1 W of pump power around 665 nm were used for pumping. As shown in Fig. 1, to
combine the pump diodes, we applied polarization coupling. This is possible, since
absorption and emission cross sections of the Cr:LiCAF system do not vary significantly with
polarization, and reflection loss of the TE polarized light from the Cr:LiCAF surface is low due
to the low refractive index. Figure 2 (a) shows the measured efficiency curve for cw
operation. With the availability of high power diodes, obtained cw powers increased to 520
mW level. To our knowledge, this is the highest cw output power obtained with diode pumped
Cr:LiCAF laser system [3]. Here, we should note that one disadvantage of Cr:LiCAF medium
is it has strong upconversion, which causes excessive heating of the crystal at high pump
intensities. In our case, pumping from both sides was crucial in obtaining high output power,
since this allows more homogeneous distribution of the pump power inside the gain medium
and reduces thermal effects.

In initial mode locking experiments we used a regular SBR with ∼50 nm reflectivity bandwidth
around 800 nm. The SBR consisted of twenty layers of AlAs and Al$^{0.17}$Ga$^{0.83}$As stacks for high
reflectivity and five 6 nm-thick GaAs quantum wells for saturable absorption action. The
modulation depth and nonsaturable loss of the SBR were ∼3% and >1%, respectively. In
mode locked regime, pulses with ∼100 fs duration and 300 mW of average power could be
obtained at a repetition rate of 160 MHz (corresponding pulse energy is about 2 nJ). To our
knowledge, this is the highest average mode-locked power obtained with the Cr:LiCAF
system. As an example, Fig. 2 (b) shows the obtained mode locked spectra, centered around 805 nm. As a demonstration of the advantage of using SBRs, mode locking was self starting and stable.

![Graph](image1)

![Graph](image2)

**Figure 2.** (a) Cw efficiency curve for the Cr:LiCAF laser (b) Spectrum of the mode locked laser.

As the last step of this project, future work will focus on reducing the pulsewidths down to ~10-20 fs level. Reducing the pulsewidths to this level, require using oxidized SBRs with ~200 nm reflectivity bandwidth around 800 nm.

### References


Lasing and Modelocking of a Novel Erbium-doped Bismuth Oxide Glass Waveguide Laser

Sponsors
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The development of novel broadband light sources at 1.5 μm is strongly motivated by the widespread application of WDM technology and is key to expanding the usable bandwidth of optical transmission systems. In addition, in combination with external supercontinuum generation, these sources have the potential to be compact, stable, high-bandwidth optical oscillators, with applications in optical metrology, ultra-wideband optical communications, sub-diffraction-limit imaging, and optical arbitrary waveform generation.

Rare-earth doped glass amplifiers are particularly promising. Thulium-doped glass amplifiers provide gain in the 1480-1510 nm wavelength range. Erbium-doped tellurite glass have a gain bandwidth of 70 nm centered around 1530 nm that covers the conventional gain bandwidth of silica-based erbium-doped glasses as well as somewhat longer wavelengths. The widest emission band from erbium-doped glasses in the 1.5 μm wavelength range have been reported in a Bi₂O₃-B₂O₃-SiO₂ system [1], making it an attractive alternative and a strong candidate for use in a modelocked laser. In addition to the broad bandwidth, the erbium doping can be much higher in a bismuth-oxide glass host than in conventional silica, offering the possibility of a significant reduction in the device length needed for laser gain. This makes the material attractive for short-cavity high-repetition-rate systems.

Both cw signal amplification [2] and picosecond pulse amplification [3] over the wavelength range 1520-1600 nm using a bismuth oxide-based erbium-doped fiber amplifier have been demonstrated. In addition, wavelength-tunable passive modelocking from 1570 nm to 1600 nm was observed with a bismuth oxide-based erbium-doped fiber laser [4]. We look to extend these results to the waveguide form of the erbium-doped bismuth-oxide glass, demonstrating cw lasing and modelocking in a Bi-ED waveguide laser.

Our collaborators at the Asahi Glass Company (Japan) prepared Er-doped bismuth-oxide glass films by RF magnetron sputtering under Ar/O₂ atmosphere. The host glass contains Bi₂O₃, SiO₂, and Ga₂O₃. The Er concentrations were varied from 6250 to 37500 ppm in weight. Numerical aperture and Δ at 1304 nm were 0.32 and 1.5%, respectively. Substrates used were soda lime silicate glass, the thermal expansion coefficient of which is nearly the same as those of the core and cladding films. To fabricate these waveguides, photolithography and dry etching techniques were used. Samples came in the form of chips of 2 cm and 6 cm in length, with several waveguides of height 3.5 μm and widths ranging from 3-7 μm written on each chip.

The first step was to demonstrate cw lasing for this waveguide laser. The initial setup we used is shown below in Figure 1(a). Pump light at 980 nm is coupled into the waveguide with a tapered lensed fiber mounted on an XYZ stage. This same lensed fiber is used to couple 1530 nm light in and out of the waveguide. The design parameters of the lensed fiber were chosen so as to best optimize both the pump coupling into the waveguide and the coupling of the 1530 nm laser light in and out. Pictures of the lensed fiber mount and the waveguide being pumped are shown in Figure 2. Feedback is provided by high reflector and output coupler mirrors on opposite ends of the cavity. Initially, we chose to butt couple a cleaved SM fiber to couple light in and out of the waveguide facet opposite the pump input.
index-matching fluid to fill the gap between facet and cleaved fiber, we briefly observed cw lasing in this configuration. However, this setup was difficult to align and unstable, and was not conducive to testing different waveguides on the sample chip. The index-matching fluid, once set, was challenging to remove, and, as a result, had the potential to damage the waveguide facet. To overcome this hazard, we modified the setup to Figure 1(b), replacing the butt-coupled SMF with another tapered lensed fiber, chosen to optimize 1530 nm light coupling. This setup proved more robust and made possible the testing of multiple waveguides on the sample chip. With maximum pumping at 500 mW, output cw powers up to 6 mW at 1535 nm were observed. More extensive data collection is now underway to characterize the cw lasing characteristics of the waveguide laser. We believe we are the first to observe cw lasing of these erbium-doped bismuth-oxide waveguides.

![Diagram](image)

**Figure 1.** (a) Bismuth oxide-based erbium-doped waveguide laser setup for cw lasing demonstration. (b) Modified cw setup with lensed fibers on both ends of the waveguide.

In addition to the cw lasing demonstration, we also configured the setup for modelocked operation with a saturable Bragg reflector (SBR). The setup is shown below in Figure 3. At
this point, we had also replaced the high reflector mirror on one end of the laser cavity with a mirror coating on one waveguide facet that would serve as the output coupler. The coating was designed to pass 980 nm pump light with >95% transmission and reflect 99% of the 1510–1580 nm light. By adding the coating, we have significantly shortened the cavity, paving the way to high repetition operation of the waveguide laser.

Figure 2. (a) Mounting of the input tapered lensed fiber and waveguide structure. (b) Bismuth oxide-based erbium-doped waveguide being pumped at 980 nm through the lensed fiber.

Figure 3. Bismuth oxide-based erbium-doped waveguide laser setup for modelocking demonstration. (Inset) Sample output spectrum of laser.

We are currently working towards stabilizing and more extensively characterizing the modelocking of these waveguide lasers. A sample output spectrum is shown in the inset of Figure 3. Once operational, we plan to test a number of SBR structures, both old and new, in this setup, and investigated more thoroughly laser operation in different operating regimes.

References:


Femtosecond Frequency Combs and Phase Control

Octave Spanning 1GHz Ti:sapphire Oscillator For HeNe-CH4 based Frequency Combs and Clocks

Sponsors
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High repetition rate, octave spanning Ti:sapphire oscillators have numerous applications in time resolved and frequency domain spectroscopy, frequency metrology and optical arbitrary waveform generation. As compared to lower repetition rate fiber and other solid state lasers no additional external broadening is necessary and the large mode separation enables easier access of the comb lines with more power per mode.

We demonstrate here a greatly improved octave spanning 1GHz Ti:sapphire laser [1] using the most broadband double-chirped mirror pairs, optimized Kerr-Lens modelocking (KLM) and an optimized output coupler. As a result the laser generates, at 9W of pump power, 0.6W-1W of output power with an output spectrum of more than one octave as measured on a linear scale, see Figure 1a. The spectrum corresponds to a Fourier limited pulse of 3.5fs duration. Second harmonic generation with this output in 1mm BBO directly generates 1f-2f beatnotes for carrier-envelop phase stabilization with >55dB signal-to-noise (SNR) in 100kHz bandwidth, Figure 1b top trace, and by difference frequency generation (DFG) in a 5mm long PPLN radiation at 3.39μm is generated. The 3.39μm radiation is strong enough to result in a beatnote with a single frequency HeNe reference laser of 30dB, Figure 1b bottom trace. This laser serves as the clockwork of a HeNe CH4-based molecular clock [2] with a measured Allan variance approaching 10^{-14} in 100s and as an absolute femtosecond laser frequency comb for an optical arbitrary waveform generator, see Fig. 2.

Fig. 1: (a) Output spectrum of the 1GHz Ti:Sapphire laser on a logarithmic(top) and linear(bottom) scale; (b) 1f-2f beatnote (top) and 3.39μm beatnote with HeNe reference laser (bottom).
The laser is a standard KLM four mirror Ti:sapphire ring laser with a 1GHz repetition rate. The mirrors are double-chirped mirror pairs (DCMPs) and provide precise dispersion compensation together with two thin pieces of BaF\(_2\), a plate and wedge, both inserted at Brewster’s angle. Output coupling is achieved by coating one side of the BaF\(_2\) wedge with a coating designed to give 4% output coupling in the center of the spectrum increasing to >50% output coupling above 1050nm and below 650nm. With 9W of pump power, 600mW of output power with a FWHM spectrum of >200nm is achieved, Fig. 1. With the same output coupler coating on a fused silica spectrum more than 1W output power is extracted with slightly reduced spectral wings. We attribute the increased output power and reduced spectral wings to the higher optical quality of the fused silica wedge and the increased 3\(^{rd}\) order dispersion of the fused silica wedge, respectively. The laser is nearly self-starting, requiring only slight movement of the focusing mirrors. Once mode-locked the laser is very robust and operates over many hours without extensive shielding against vibrations. Further, the laser exhibits a wavelength dependent mode structure with shorter wavelengths appearing in a ring around the power carrying middle wavelengths of the output spectrum. Longer wavelengths appear only as horizontally transverse higher order modes. It is believed that this wavelength dependent mode structure will provide further insight into the spatio-temporal behavior of the KLM process.

**Fig.2**. Schematic representation of the 1GHz Ti:Sapphire based optical clock and frequency comb system. LF, Loop Filter; DCM, Double chirped dispersion compensating mirrors; PBS, Polarizing beam splitter; AOM, Acousto-Optic modulator; PZT, Piezo electric transducer; PPLN, Periodically poled lithium niobate; LBO, Lithium triborate.

The stability of the optical clock and frequency comb system is derived from the stability of the CH\(_4\) stabilized HeNe laser as well as the locking arrangement. By making the repetition rate lock in the optical domain, we are able to take advantage of a division ratio of nearly 10\(^5\) to increase the stability of the pulse repetition rate as detected on a photodiode. In addition, by making the phase lock between the HeNe reference laser and the Ti:Sapphire laser via an offset lock arrangement we are able to further reduce the introduction of noise from the
stabilization process. The stability of the clock is currently under investigation by comparing it with a Hydrogen-Maser.

References:
Sub-2-Cycle Carrier-Envelope Phase Controlled Ti:sapphire Oscillator

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Phase-stabilized sub-2-cycle pulses are generated from a compact prismless octave-spanning laser without extracavity nonlinear optical processes distorting the generated pulse. The necessary 1f-2f signal components generated intracavity are separately coupled out through cavity mirrors and generate a 50-dB carrier-envelope beat note.

For the first time a phase-stabilized sub-2-cycle pulse is directly generated from a prismless octave-spanning laser without the need for subsequent nonlinear interaction of the emitted laser pulse for phase stabilization purposes. Newly designed double-chirped mirrors allow for a compact and efficient implementation of 1f-2f interferometry to detect and control the carrier-envelope phase with minimum impact on the quality of the generated sub-two-cycle pulses.

The laser (Fig. 1a) is a standard Kerr-lens modelocked four-mirror ring design [1] with a 500 MHz repetition rate and a 2-mm-thick Brewster-cut Ti:sapphire crystal (X) placed between two 5-cm radius mirrors (M1,M2). All mirrors (M1-M4) are novel double-chirped mirror pairs (Fig. 1b) designed to transmit 50% of the intracavity spectrum around the 1f and 2f components (at 1160 nm and 580 nm, respectively), while providing precise dispersion compensation and a smooth spectral phase for the spectrum comprised between these two frequencies [2]. Fine tuning of intracavity dispersion is achieved through a BaF2 wedge (W) combined with a fused-silica wedge (OC) that also carries the broadband output-coupler coating designed for 2% reflectivity in the center of the spectrum and >50% reflectivity above 1050 nm and below 650 nm. The 1f and 2f components are efficiently output coupled in a collimated beam through mirror M3. This mirror is coated on a thin (1-mm) fused silica substrate to minimize the dispersive delay between the two frequencies. The CE phase is detected with an improved 1f-to-2f interferometer (dashed box in Fig. 1a) comprising an all-reflective delay line of double-chirped mirrors (M5-M8) for temporal overlapping of the 1f and 2f components [3] before focusing in a 2-mm BBO crystal cut for SHG at 1160 nm.

Fig. 1: (a) Octave-spanning phase-stabilized sub-two-cycle laser. AOM, acousto-optic modulator; LO, local oscillator; OC, broadband output coupler on fused-silica wedge; W, BaF2 wedge; BBO, 2-mm-thick BBO crystal; PBS, polarizing beamsplitter; APD, avalanche photodiode. (b) Reflectivity and combined group delay of the novel double-chirped mirror pair.
Modelocking is self-starting and unidirectional, and the laser generates 0.35W-0.65W (depending on intracavity dispersion) when pumped with 6.5W from a DPSS laser, with an output spectrum of more than one octave as measured on a linear scale (see spectra in Fig. 2b). The oscillations in the spectrum from 700-1000 nm exactly match the residual oscillations in the measured GDD of the double-chirped mirror pair, which are due to manufacturing tolerances and can be corrected in subsequent coating runs. Second-harmonic generation in the BBO crystal generates 1f-2f beatnotes with ~50 dB SNR measured in a 100 kHz bandwidth directly from the APD output. The CE frequency was locked to a microwave synthesizer at 31 MHz or to a sub-multiple of the lasers repetition rate. By interchanging mirrors M3 and M4 (see Fig. 1a), the main output coupling can be made to occur before transmission of the 1f-2f components, which results in the larger output spectrum also shown in Fig. 2b (dotted line), although at the expense of a relatively weaker 1f-2f beatnote with ~40 dB SNR. To confirm the generation of sub-2-cycle pulses, the pulses were characterized using both broadband SHG interferometric autocorrelation and two-dimensional spectral interferometry (2DSI) [4] which resulted in the trace of Fig. 2a; the retrieved spectral phase is shown in Fig. 2b. The measured and retrieved IAC traces (Fig. 2c) show a very good agreement, and the retrieved sub-two-cycle pulse (inset of Fig. 2c) has a FHWM duration of 4.9 fs FWHM.

Fig. 2: (a) Raw 2DSI interferogram. (b) Measured output spectra for two different laser configurations - optimized for maximum spectral coverage (dotted line) and optimized for maximum CE beat signal (solid-line) - and spectral phase retrieved from 2DSI. The spectra are octave-spanning on a linear scale. (c) Measured and retrieved interferometric autocorrelations of the generated sub-2-cycle pulses for the CE beat optimized configuration (inset shows the retrieved pulse intensity).

In conclusion, sub-2-cycle phase controlled pulses are generated directly from an octave spanning Ti:sapphire laser by filtering out the 1f-to-2f spectral components generated inside the laser cavity using novel double-chirped mirror pairs. No external nonlinear processes acting and distorting the main output pulse are necessary for carrier-envelope phase stabilization of the laser output.

References:
Long-Term Stable Microwave Signal Extraction from Mode-Locked Lasers

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Mode-locked lasers show a great potential to generate ultralow-jitter microwave signals encoded in its pulse repetition frequency [1]. However, it is a highly nontrivial task to transfer the low noise properties of the pulse train in the optical domain to the electronic domain, and extract a drift-free, ultralow-jitter microwave signal with a power level sufficient for the intended application from an optical pulse train. Direct photodetection, the most commonly used technique for microwave signal extraction from pulse trains, suffers from excess phase noise [2]. The intensity noise and power drifts of optical pulse trains as well as temperature variations in the diode can be converted into a significant amount of excess timing jitter and drifts, and degrade the long-term stability of the extracted microwave signals. Although the short-term jitter can be suppressed down to the 1 fs level [3], the slow phase drift of extracted microwave signals is still the major limitation, for example, 56 fs (3.5 mrad at 10 GHz) drift over 100 seconds caused by 0.3 % amplitude fluctuation as shown in Ref. [4]. To circumvent the amplitude-to-phase conversion and to ensure long-term stable microwave signal extraction directly at the microwave power level needed for subsequent experiments, a balanced optical-microwave phase detector was recently proposed and demonstrated [5]. It is based on the precise phase detection in the optical domain using a differentially-biased Sagnac fiber loop and synchronous detection. Because the phase error between the optical pulse train and the microwave signal is detected by electro-optic sampling in the optical domain, it has a potential to be more robust against power and thermal drifts. In this report, we present out-of-loop characterization results using two balanced optical-microwave phase detectors.

Figure 1: Experimental setup for long-term out-of-loop relative timing jitter measurement between two microwave signals locked to a mode-locked laser. DBM: double-balanced mixer, LPF: low-pass filter, PLL: phase-locked loop, VCO: voltage-controlled oscillator.

Figure 1 shows the schematic of the experimental setup for out-of-loop relative timing jitter measurements between the two 10.225 GHz microwave signals locked to a free-running 44.26 MHz, 1550 nm stretched-pulse Er-doped fiber mode-locked laser. Two nearly identical optoelectronic PLLs based on balanced optical-microwave phase detectors were built with
10.225 GHz (the 231st harmonic of the fundamental repetition rate, \( N = 231 \)) VCOs (PSI DRO-10.225). From each VCO, +10 dBm output power at 10.225 GHz can be extracted for external measurements. To evaluate the out-of-loop relative timing jitter between the two extracted microwave signals, the outputs from the locked VCOs are mixed in quadrature in the out-of-loop phase noise characterization setup. Note that only the out-of-loop phase noise characterization setup is actively temperature-stabilized to enable a long-term measurement, while both PLLs are not temperature-stabilized or otherwise shielded against environmental perturbations.

![Image](image.png)

**Figure 2:** (a) Long-term background timing drift measurement of the characterization setup. Although the temperature is actively stabilized within 0.41 °C (maximum-minimum) over 10 hours, at certain time frames, up to 41 fs (in 1 hour) and 48 fs (in 4 hours) timing drifts are observed. (b) Long-term out-of-loop drift measurement between two locked VCOs shows that the maximum timing deviation is within 48 fs over one hour. The data was taken at every 5 seconds.

Even though the temperature of the characterization setup is actively stabilized within 0.4 °C (±0.07 °C rms) over 10 hours, at certain time frames, up to 41 fs (in 1 hour) and 48 fs (in 4 hours) timing drifts are observed, as shown in Fig. 2(a). The measured timing drift and the temperature are not clearly correlated, and the exact reasons for this rather abrupt drift are currently not fully understood. Path length variations in the microwave cables and connectors that have not been stabilized might be a major cause for this abrupt and large phase fluctuations (note that a 50 fs drift corresponds to a path length change of only 15 μm). This drift in the characterization setup sets the limitation of the long-term drift measurement.

Figure 2(b) shows the result for long-term timing drift measurements between the two 10.225 GHz microwave signals when both VCOs are locked. The output voltage from the characterization setup was recorded every 5 seconds over a time span of one hour. The relative timing between the two microwave signals shows a maximum deviation of 48 fs over one hour. This corresponds to 3 mrad phase stability at the 10.225 GHz carrier frequency. As shown in Fig. 2(a), the characterization setup itself may contribute up to >40 fs drift. Therefore, the long-term timing drift measurement result in Fig. 2(b) is currently limited by the characterization setup itself. To overcome the limitations in the long-term drift measurement, we are currently working on an all optical characterization setup.

In summary, we have demonstrated, for the first time to the best of our knowledge, long-term stable (<3 mrad over 1 hour) microwave signal extraction from a mode-locked laser using balanced optical-microwave phase detectors at the frequency of 10.225 GHz and the power level of +10 dBm. This excellent long-term phase stability is achieved by electro-optic sampling of the microwave signal with the optical pulse train in a Sagnac-loop interferometer.

**References:**

Generation of Supercontinuum at High Repetition Rates

Sponsors
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The development of stable optical frequency combs based on mode-locked lasers has been rapid over the past decade [1-4]. These stable combs have proven useful in a number of applications, most notably in frequency metrology [2], where the comb is locked to a stable frequency reference (such as an atomic transition), and thus serves as an ultra-precise frequency “ruler”.

Another application of stable frequency combs is in optical arbitrary waveform generation (OAWG). In this application, each frequency component’s amplitude and phase is independently controlled, and the resulting frequency components superposed. In this way, the Fourier construction of an arbitrary optical waveform is accomplished.

In order to generate stable frequency combs, two properties of the comb must be controlled. First, the spacing of the comb’s frequencies must be stabilized. This corresponds to stabilizing the laser’s repetition rate, and can be achieved using a number of locking techniques [5, 6]. Second, the carrier-envelope offset (CEO) frequency, f_{ceo}, must be locked. In the frequency domain, f_{ceo} quantifies the shift of the frequency comb from zero frequency. In the time domain, f_{ceo} corresponds to a change in the delay between the carrier and the pulse envelope (i.e. the carrier-envelope phase) from pulse to pulse, and results from a difference in the group and phase velocities.

One technique for locking the carrier-envelope phase involves generating an octave-spanning comb from the laser source, and then frequency doubling the low-frequency portion of the comb to overlap with the high-frequency portion. The resulting high frequency combs are then beat on a detector, which produces their mixing products. These mixing products include the difference frequencies, the smallest of which is equal to f_{ceo}, which is filtered out and used for feedback stabilization [1]. The following equation describes the difference frequency that is created:

\[ f_{ceo} = \left( 2f_{ceo} + Nf_{rep} \right) - \left( f_{ceo} + 2Nf_{rep} \right) \]

Our work seeks to develop stabilized frequency comb sources for OAWG in the 1550 nm wavelength range using mode-locked fiber lasers. Because the spectra from such lasers are generally not octave-spanning, the output of these lasers must be spectrally broadened using nonlinearity. It is convenient to use nonlinear fibers to generate the required octave-spanning supercontinuum spectra, which may then be used to stabilize the mode-locked fiber laser frequency comb [3, 4].

At increasingly high repetition rates, more average power is needed to achieve the pulse energies required for the generation of octave-spanning supercontinuum. As such, this work includes a significant effort to develop high-power amplifiers for sub-100 fs pulses. The most recent system to be used is shown in Figure 1. A soliton fiber laser’s output (100 fs, up to 5 mW) is anomalously chirped with approximately 2 m of SMF-28e fiber, and then coupled into a fiber amplifier designed for ultrafast pulse amplification. This amplifier is a multiple-pump, single stage design.
Note that the signal path of this amplifier is primarily made of normal GVD fiber. As a result, the majority of the spectral generation in the amplifier comes from self-phase modulation, which leads to pulses with a linear, compressible chirp. Short lengths of anomalous GVD fiber at the output ports results in more nonlinearity and contributes further to pulse shortening.

The amplified pulses from both the free-space and fiber output ports are nearly transform-limited, depending on the input power and chirp. Internal waveplates control the polarization at the input of the amplifier, allowing one to control the distribution of output power at the output ports. This polarization control also affects the quality of the output pulse shape. The free-space port allows coupling into various HNLFs using lenses, and the fiber port allows the generation of supercontinuum in an all-fiber setup.

The maximum average power obtainable with the system is 320 mW. However, at this power the background power is significant. At powers of approximately 200 mW, the background power is reduced, without any significant change in pulse duration. Based on our observations, the additional power at 320 mW is mostly contained in the background, and does not improve the spectral generation. Figure 2 shows a second-harmonic generation autocorrelation measurement of the amplifier output pulses from the free-space port, when optimized for pulse shape quality.
These pulses were coupled, using the fiber output port, into 65 cm of Furukawa polarization maintaining HNLF ($\beta'' = -0.9$ ps$^2$/km, $\eta = 23$ W$^{-1}$km$^{-1}$). A length of 11 cm of SMF-28e is spliced to the input end of the HNLF, and approximately 1 m of SMF-28e is spliced to the output end of the HNLF. Figure 3 shows the laser spectrum and the resulting supercontinuum that is achieved.
This work will continue to refine the amplifier design and increase the amplified power. Improvements will include increasing the pump power, using dual-wavelength pumping, and moving to a polarization-maintaining design to eliminate polarization mode-dispersion (PMD) caused by the isolators and to eliminate unwanted nonlinear polarization rotation (NPR).

References:


Development of High Repetition Rate Fiber Lasers for Optical Arbitrary Waveform Generation

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Optical arbitrary waveform generation (OAWG) seeks to completely control the time-domain electric field. In the frequency domain, this means complete control of the amplitude and phase of the spectrum. One approach to achieving complete control of the spectrum is to use a periodic signal, such as that generated by a mode-locked laser. In this case, the corresponding spectral modes can be spatially separated by an arrayed waveguide-grating (AWG) and then independently modulated in both amplitude and phase to produce the arbitrary (and periodic) time-domain waveform.

The need to spatially separate the frequency components places restrictions on the source. As the laser repetition rate (i.e. the mode spacing) decreases, the spectral resolution of the AWG must increase, leading to larger AWGs, more strict tolerances on waveguide path lengths, and the need for more waveguides for a given spectral bandwidth. Current AWG technology requires the repetition rate of the source to be greater than 1 GHz.

Generally, two approaches to achieving high repetition rates are being pursued. First, the physical size of the cavity can be reduced. The intracavity pulse traverses the cavity more quickly, which reduces the temporal spacing between pulses in the output pulse train. However, reducing the cavity size causes energy to leak out of the cavity more quickly. For a given pump power, this means that the steady-state intracavity power will decrease as the cavity is reduced in size. At some point, the intracavity power will not be enough to saturate the saturable absorber mechanism, and the laser will not mode-lock.
Figure 1 illustrates the system design. The laser is in a sigma configuration, so that a reflection point exists to allow for feedback control of the repetition rate. Saturable absorption is provided by a saturable Bragg reflector (SBR). The only fiber in the cavity is the erbium gain fiber with anomalous group velocity dispersion (GVD); the soliton effects of the fiber should ensure that the intracavity pulses will be near transform-limited at the saturable absorber, and thus saturation of the SBR will be maximized. With optimization, a fundamental repetition rate of 1 GHz should be achievable.

![Figure 1. Short cavity mode-locked fiber laser approach.](image)

The second approach is to operate the laser with multiple, equally-spaced intracavity pulses; this is known as harmonic mode-locking. This approach is challenging in light of the fact that OAWG systems require that the repetition rate and carrier-envelope phase slip to be stabilized. In a harmonically mode-locked laser, the carrier-envelope phase of each intracavity pulse is independent, which means that the output pulse train will not have a well-defined, constant carrier-envelope phase slip from pulse to pulse.

The second approach is shown in Figure 2. The system consists of a soliton fiber laser, again in a sigma configuration. An intracavity filter, such as a Fabry-Perot interferometer (FPI), with a resonance frequency equal to a multiple of the repetition rate of the laser, correlates the intracavity pulses, leading to a constant carrier-envelope phase slip from pulse to pulse. The FPI also provides a sorting mechanism to space the pulses equally. The saturable absorber mechanism is nonlinear polarization rotation (NPR). This system should be scaleable up to 2 GHz with current pump technology.
Figure 2. Harmonically mode-locked fiber laser approach.
Ultrafast Phenomena and Quantum Electronics

Multimode regimes in quantum cascade lasers.

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A theoretical and experimental study of multimode operation regimes in quantum cascade lasers (QCLs) has been carried out. It is shown that the fast gain recovery of QCLs promotes two multimode regimes in QCLs: One is spatial hole burning (SHB), and the other one is related to the Risken-Nummedal-Graham-Haken (RNGH) instability predicted in the sixties. A model based on Maxwell-Block Equations has been developed, that can account for coherent phenomena, a saturable absorber and SHB. A wide variety of experimental data on multimode regimes is presented. Lasers with narrow active region and/or with metal coating on the sides tend to develop a splitting in the spectrum, roughly equal to twice the Rabi frequency. It is proposed that this behavior stems from the presence of a saturable absorber, which can result from a Kerr lensing effect in the cavity. Lasers with a wide active region, which have weaker saturable absorber, do not exhibit a Rabi splitting, and their multimode regime is governed by SHB. There are many physical mechanisms which can drive a laser from a single-mode to a multi-mode regime. Common examples are spatial and spectral hole burning (SHB), saturable absorption, and self-phase modulation [1]. Multimode dynamics in QCLs is different from that of more common lasers. This is mainly due to the unusually fast gain recovery of QCLs, which occurs on a picosecond scale.

We have identified two mechanisms that play a key role in the multimode dynamics of QCLs: A coherent multimode instability and spatial hole burning. The coherent multimode instability is related to the so-called Risken-Nummedal-Graham-Haken (RNGH) instability [1,2]. The latter was theoretically predicted as early as in 1968: the CW solution loses its stability when the pumping level exceeds the lasing threshold by typically 9-10 times. Its observation remains controversial. In our experiments, the multimode instability occurs at much lower pumping rates than 9-10 times above threshold. However, we have shown that the presence of a saturable absorber, provided e.g. by a Kerr-lensing mechanism lowers the threshold for the instability considerably. A typical signature of this type of mechanism is a splitting in the laser spectrum of the order of the Rabi frequency. The second mechanism is spatial hole burning.

The lasers studied can be divided into two categories. In the first category, the sidewalls of the laser ridge are covered by a lossy metal contact, which acts as a Kerr-lens type saturable absorber [1]; the latter is weaker in the second category, as the gold contacts and the waveguide core are separated by a thick insulating InP layer. The above differences are clearly visible in Fig. 1.a & b. The optical spectra measured in continuous mode with devices belonging to each of the two categories show obvious signs of instability, as illustrated in Fig. 1.c & d. In type 1 devices (Fig. 1.c), the spectra are single mode and become clearly multimode with two pronounced sidebands separated around the cw solution by the Rabi frequency. This is a typical signature of the RNGH instability. In type 2 devices (Fig. 1.d), the envelope of the spectra show continuous multiple peaks, whose separation is independent of the pumping level.

We have developed a model of the instability using the Maxwell-Bloch equations. Both a saturable absorber and spatial-hole burning were incorporated into the calculations. When a
saturable absorber is present, the spectra obtained numerically show clearly the growth of mode sidebands around the original CW frequency separated by the Rabi frequency, and thus have the same characteristic as the type 1 spectra, (Fig. 1.e). Without the saturable absorber the splitting of the spectrum is not observed (Fig. 1.f). When spatial hole burning is dominant, the simulated spectra show the growth of the instability at very low pump ratios above the lasing threshold, as well as multiple peaks with pumping-independent separation, in good agreement with the experimental data.

In summary, we have observed wideband multimode operation in QCLs with spectral signatures that can be traced back to spatial-hole burning and the RNGH instability. Furthermore it will be shown in detail that the characteristics of the measured spectra are in good agreement with spectra computed from a model based on the Maxwell-Bloch equations.

Fig. 1. a SEM image of type 1 laser. b. SEM image of type 2 laser. c. Spectra of type 1 laser. d. spectra of type 2 laser. e. Simulated spectrum with a saturable absorber. f. Simulated spectrum without a saturable absorber.
Compact Background-Free Balanced Optical Cross-Correlator

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Balanced cross correlation was previously implemented for optical pulses with different center wavelengths [1]. Using group delay dispersion (GDD) to vary the group delay between two pulses of different center frequency, this balanced cross-correlator was used to lock two independent mode-locked lasers with different optical spectra within 300 as residual timing jitter. Recently, it has also been shown that this method enables long-term (greater than 12 hours) sub-fs timing synchronization [2]. However, this method is limited to the case of optical pulses with different center wavelengths, because the delay between the two pulses was generated by the GDD. It is not applicable to the case when the two optical pulses have the same center wavelength.

In this case and in general, one can use fast photodiodes followed by a microwave mixer to extract the timing information, but the resolution and stability of this method are very limited due to the limited time resolution and drifts of microwave mixers. No pure electronic method has achieved long-term stable sub-100 fs resolution in the timing detection between two optical pulses.

Here we propose and demonstrate methods for an extremely precise detection of the timing error between two ultrashort laser pulses with fs and possibly sub-fs resolution using only a single nonlinear crystal. By use of a balanced detection scheme, this method is insensitive to the amplitude noise from the laser sources, and is able to extract only the timing error in a long-term stable way. The ingredients include (a) generation of a group delay difference between two orthogonally polarized pulses; and (b) generation of the second-harmonic or sum-frequency component by a type-II phase-matched nonlinear crystal. In both cases, the detected signal is background free, i.e., if the pulses do not overlap in time, the detector signal is vanishing. In particular, using the group delay from the polarization difference enables the implementation of balanced cross-correlation in the same wavelength range, which has not been achieved so far. The group delay and SHG/SFG functions can also be combined in a single nonlinear crystal. This feature allows self-aligned operation as well as integration on an optoelectronic chip. Amongst many applications, this cross-correlator applies (a) to laser-laser synchronization, (b) to timing link stabilization, (c) to phase noise measurements of free-running mode-locked lasers, and (d) to an optical timing detector in general.
Figure 1: Operation of a compact background-free balanced cross-correlator based on a type-II phase matched single periodically-poled crystal. SHG: second-harmonic generation.

Figure 1 shows the operation of the single-crystal balanced cross-correlator. The input pulses are transmitted through a first dichroic beamsplitter which transmits the input pulses but reflects the SHG of the input pulses. The pulses are focused into a type-II phase-matched PPKTP crystal. The use of a PPKTP crystal is especially advantageous because of the extended phase-matching bandwidth of 100 nm centered at 1550 nm [3]. For input pulses with 200-fs pulsewidth and 77-pJ pulse energy at 1550 nm, the optimum conversion efficiency of PPKTP is calculated as $\eta_{\text{opt,PPKTP}} = 8 \times 10^{-3}$ [4]. The measured efficiency with a 5-mm long PPKTP crystal with a poling period of 46.2 $\mu$m is $\eta = 60 \mu W / 15 m W = 4 \times 10^{-3}$, which shows a fairly good agreement with the optimum theoretical efficiency. The generated SHG component is transmitted through the second dichroic mirror and detected by photodiode 1 in the balanced detector. The remaining fundamental input pulses are reflected from the dichroic mirror and again focused into the PPKTP crystal. The SHG component generated by the back-reflected pulses is separated by the dichroic beamsplitter and detected by photodiode 2 in the balanced detector. At the balanced detector output, a signal proportional to the relative position between the two input pulses is extracted.

Figure 2(a) shows the measured autocorrelation trace of a 77 pJ, 200-fs pulse at 1550 nm using a balanced cross-correlator with a 5-mm long PPKTP crystal (poling period = 46.2 $\mu$m). By use of $\sim$10 mW input power level, it could easily saturate photodetector at the maximum overlap region. Figure 2(b) shows the photo of the constructed balanced cross-correlator. It could fit 7" by 3" footprint, and can be made in a more compact size by further careful engineering.
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Figure 2: (a) Autocorrelation trace of the balanced cross-correlator. (b) Photo of the balanced cross-correlator.

As will be shown in the “Timing Stabilized Fiber Link for Large-Scale Timing Distribution” section of this progress report, by use of this compact background-free balanced cross-correlator, we could stabilize a 300 meter long fiber link with long-term sub-10 fs accuracy for the first time.

References:


Physics and Technology of Ultrafast X-ray Sources

Timing Stabilized Fiber Links for Large-Scale Timing Distribution

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Precise optical timing distribution to remote locations is important for large-scale facilities requiring high-precision synchronization, for example, seeded x-ray free electron lasers [1] and phased-array antennas [2]. It is also crucial for the optical time/frequency standard distribution over long distances [3]. Acoustic noise and thermal drifts introduced to the fiber involved in the distribution must be cancelled by a proper feedback loop. So far, electronic techniques based on high-speed photodetectors and microwave mixers are used to stabilize fiber links on a rather short-term time scale. The limited timing resolution as well as thermal drifts of microwave components makes it difficult to stabilize links better than 100 fs in a long-term stable way.

To overcome these limitations set by the performance of microwave components and techniques, it is highly desirable to use optical cross-correlation techniques for high-resolution and drift-free detection of timing errors between two optical pulses. As shown in the “Compact Background-Free Balanced Cross-Correlator” section of this report, we have demonstrated a balanced cross-correlator that can be used for the timing link stabilization purpose. Figure 1 shows the schematic for a 310-meter timing stabilized link using the single-crystal balanced cross-correlator.

Figure 1: Schematic of the timing stabilized fiber link.
A 194-MHz soliton Er-doped fiber laser is used as the optical pulse source. The output power is 40 mW and the pulsewidth is 200 fs. Part of the input pulse train is tapped off by a polarizing beamsplitter cube (PBC 1 in Fig. 1) to the out-of-loop characterization setup. The other part of the light is transmitted through a 310-meter long dispersion-compensated fiber link containing a piezo-stretcher. The fiber link is comprised of ~40 meter of dispersion-compensating fiber (DCF) ($D_2 \approx -114.3$ ps/km/nm) and ~270 meter of SMF-28 fiber ($D_2 \approx +17$ ps/km/nm). Half of the link-transmitted pulses are back-reflected by a 50:50 Faraday rotating mirror (FRM) at the end of the fiber link. With the FRM, the polarization state of the returning pulse is orthogonal to that of the input pulse, which enables 100% transmission through PBC 2 (in Fig. 1). Due to the coupling loss to the collimator, the splicing loss between DCF and SMF-28 fiber and the insertion loss inside the FRM, the loss is more than 10 dB for the reflected pulses compared to the input pulses. To compensate those losses in the transmission, we used an Er-doped fiber amplifier (EDFA) at the end of the fiber link. The reflected pulse (measured pulsewidth \(\sim 420\) fs) is combined with the fresh pulse directly from the laser at the polarizing beamsplitter cube (PBC 2 in Fig. 1). The combined pulses are applied to the balanced cross-correlator (balanced cross-correlator 1 in Fig. 1). The error signal generated from the balanced cross-correlator is regulated by a loop filter and applied to the piezo-stretcher in the link via a high-voltage piezo driver. This closes the timing stabilization loop. When it is locked, the timing fluctuation introduced to the fiber link is compensated by the counteraction of the piezo stretcher. To evaluate the out-of-loop performances, a second balanced cross-correlator (balanced cross-correlator 2 in Fig. 1) is used to compare the transmitted pulses through the 310-meter link with fresh pulses directly from the mode-locked laser.

![Figure 2](image)

**Figure 2:** Long-term out-of-loop cross correlator trace of the 310-meter long stabilized fiber link.

Figure 2 shows the long-term out-of-loop timing jitter trace over 100 seconds measured with an oscilloscope. The rms-value of this measurement confirms the stabilization to a precision of 9.7-fs. The jitter analysis was mainly limited by the limited signal-to-noise ratio of the detection. With a higher optical power level and/or lower losses in the fiber link as well as a lower noise balanced photodetectors, it is clearly possible to improve the locking performance as well as the measurement resolution. The bottom trace of Figure 2 shows the displacement of the piezo stretcher in the fiber link during the same time frame. The fiber link used in this experiment is not temperature, vibration, nor airflow stabilized, and the locking is broken purely by the limited displacement range of the piezo stretcher we used (~700 \(\mu\)m, corresponding to \(2\times10^{-6}\) length fluctuation of the whole fiber link). With additional manual adjustment of the translation stage, we could keep the lock for more than one hour. To the best of our knowledge, this result is the first long-term 10-fs level stabilization of a fiber link. It also indicates that adding a motorized translation stage and polarization control at the end of the fiber will enable to maintain this level of accuracy in synchronization as long as desired.
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The goal of this program is to leverage the low jitter properties of mode-locked lasers to achieve an electronic-photonic integrated circuit (EPIC) that facilitates high speed analog-to-digital conversion (ADC) beyond the bottleneck set by electronic jitter. Several photonic ADC techniques have been investigated in recent years [1,2]. The photonic ADC architecture pursued here in the form of an EPIC is known as time-interleaved optical sampling using wavelength-division multiplexing (WDM) [2] techniques. The envisioned sampling system is shown in Figure 1. A chirped optical clock signal from a mode-locked laser is channelized in time using precisely-tuned WDM filters to create time-interleaved optical sampling signals, each

![Figure 1: Schematic layout of EPIC for high-speed ADC.](image-url)
operating at the rate of the mode-locked laser. The total sampling rate is then the optical clock rate times the number of WDM channels. However, in order to realize the high resolution, the sampling times of the interleaved channels must be uniform, the converter gains from each channel must be closely matched, and the sample memory effects must be minimal. These characteristics require monitoring and tight feedback control of the WDM filters. A signal recovery algorithm has been developed that enables reconstruction of the actual RF-signal in the presence of small but characterizable errors in filter spacing and unequal converter gain. The ADC chip requires the development of a number of devices: Thermally tunable WDM filter banks with large FSR, wideband optical modulators, Ge-photodetectors, and low jitter femtosecond lasers, potentially also integrated. These devices are pursued in a close collaboration between research groups at MIT Campus and MIT Lincoln Laboratory in various technologies. All these devices and techniques must be integrated on a CMOS compatible technology platform. As an example the proposed ADC chip requires filters with large free spectral range (FSR) and low loss. These two key requirements call for microring filters fabricated in a high-index contrast (HIC) material system.

The microring resonator filter designs used for fabrication of the filter banks presented here are based on the design described in [3]. By utilizing this design with the HIC materials of silicon-rich silicon nitride (n =2.2 @ 1550 nm) forming the core, and silicon dioxide (n =1.455 @ 1550nm) or air cladding a very wide FSR of 20 nm is realized. The filter design was fine tuned to achieve the objective of a 3 dB bandwidth of 25 GHz and less than 30 dB adjacent channel crosstalk for 80 GHz spaced channels. A 20 channel dual filter bank was fabricated (Figure 2).

![Figure 2: Twenty channel dual filter bank fabricated in SiN.](image)

Direct-write scanning electron beam lithography (SEBL) was used due to its combination of high resolution and high level of dimensional control. The basic fabrication process used is similar to that described in [4]. Controlling the resonant frequency of HIC microring resonator filters requires an extremely high level of dimensional control. Fine tuning of filters to an exact frequency grid with heaters is in progress.

Description of the other devices necessary for the EPIC ADC-chip, such as low jitter femtosecond lasers, high-speed silicon modulators and Ge-photodetectors can be found in various summaries of the participating groups throughout this progress report.

References:


Chapter 31. Optics and Quantum Electronics

Silicon Electro-Optic Modulator

Sponsors
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Project Staff
Fuwan Gan, Dr. Gui-Rong (Rona) Zhou, Dr. Steven Spector, Robert Schulein and Dr. Ted Lyszczarz (MIT-Lincoln Laboratory) and Professor Franz X. Kärtner

CMOS-compatible high speed silicon modulators play important roles in developing electronic-photonic integrated circuits (EPIC’s) such as high speed A/D converters [1]. The free-carrier plasma effect in silicon has proven to be an efficient means to achieve electro-optical modulation [2]-[4]. Among the recent work on silicon modulators, the reverse-biased pn junction in a Mach-Zehnder interferometer configuration [3] and a forward biased p-i-n in a resonant ring structure [4] are the two most appealing devices. The reverse-biased pn-junction structure [3] has achieved a 20GHz of modulation bandwidth by employing a traveling wave electrode design but still suffered from a relatively low sensitivity with a $V_{π}$L~5.0V.cm which are apparently too large for EPIC applications. The forward biased p-i-n ring modulator [4] has demonstrated a 12.5Gb/s modulation by engineering the NRZ driving signal with a pre-emphasis technique. However, its high contact resistance (7.7kΩ) has greatly limited its sensitivity and hence a ~2V of DC bias is still required. In this project, we investigate high-speed silicon electro-optic modulators under both forward and reverse-bias operations aiming at compact size, high sensitivity while increasing the modulation bandwidth.

A schematic layout of the modulator and the SEM image of the fabricated devices have been presented elsewhere in our previous work [5]-[7]. Here, we employ a Mach-Zehnder arrangement but in a push-pull RF driving mode. The light intensity is modulated by the phase shifts induced in each arm by carrier injection (under forward biased regime) and carrier depletion (under reverse-biased regime). The fabricated waveguide dimensions are wxh=520nmx220nm. Aluminum is used as electrical contact on top of the highly doped contact regions to minimize the contact resistance. The intrinsic region of the modulator is lightly n-doped to be around $10^{17}$/cm$^3$, so it can also be used in reverse-biased regime by modulating the width of the depletion region, sweeping the carriers in and out of the waveguide. The waveguide sidewalls are moderately doped to $10^{18}$ to reduce resistance and optical loss. A high doping of $10^{21}$/cm$^3$ is employed at both contact regions to reduce contact resistance. This has proven to be very effective as the measured I-V characteristics match with the numerical simulations very well as shown in Fig. 1(a). Due to the increased sensitivity provided with reduced contact resistance, a 4% modulation trace is obtained at 20GHz as shown in Fig. 2(a). Only 63mW of input power are required for obtaining this trace.

![Fig. 1](image1.png)

**Fig. 1.** (a) I-V characteristics from simulation and measurement after an improved contact is employed. (b) 4% Modulation trace at 20 GHz.
The measured frequency response of the fabricated silicon Mach-Zehnder modulator with a 0.5mm long phase shifter region is plotted in Fig.2 (a). At low frequencies, the forward biased device is very sensitive, which requires only 1mW of RF power and 10-20mW of DC power to operate the device. The device shows a roll-off at around 100MHz. However, due to its high sensitivity, only 100mW of RF power is required for achieving a modulation depth of 25%. This modulation depth and drive power are appropriate for the A/D converter being developed [1][5]. The bandwidth of the forward biased modulator can be extended by employing a high-pass pre-compensation filter in the electronic drive circuit. The filter is a 1.1kΩ of series resistor in parallel with its small intrinsic capacitor. It is shown in Fig. 2(a) that the response of the modulator with the filter is nearly flat until 5GHz. The plots have been normalized to be 0dB at the lowest frequency. Alternatively, we have also demonstrated that a forward-biased modulator with carrier lifetime shortening by silicon ion implantation technique can achieve a >1GHz modulation bandwidth [5].

To investigate differences between operation mechanisms, the amplitude of the electrical to optical frequency response S21 of the fabricated Mach-Zehnder modulator with 0.5 mm long p’in’-sections are measured and shown in Fig. 2(b) under both forward and reverse bias operations. Similar to Fig. 2(a), the forward biased operation has shown high sensitivity in response to the modulation signal which accords with our previous measurement on V_{πL} of only 0.02V.cm [5],[6]. The reverse-biased devices show a much flatter response until ~10GHz but with reduced sensitivity as opposed to its forward biased counterpart. This detailed comparison will allow us to come up with optimum designs with balanced performance on speed and sensitivity.

![Fig. 2](attachment:fig2.png)

**Fig. 2** (a). Measured frequency response of a Silicon Mach Zehnder modulator (a) with 0.5mm long phase shifter with and without pre-compensation filter. (b) of 0.5mm long phase shifter under forward bias and 0.5mm and 1mm long phase shifters under reverse bias;

**References:**


Chapter 31. Optics and Quantum Electronics


1GHz Q-switched mode-locked erbium-doped waveguide laser

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An optical gain medium sandwiched between two highly reflecting mirrors can be pumped to produce laser radiation with continuous output. Inserting in addition a saturable absorber between the two mirrors can transform the continuous wave output into a very short repetitive pulse train with pulse widths less than hundred femtoseconds and a repetition rate equal to the roundtrip time of the cavity. Such lasers have been built using bulk laser optics. Such laser systems typically cost several ten thousand to hundred thousand dollars depending on the parameter range. In this project, we aim towards a monolithically integrated femtosecond laser on a silicon chip that later can even be integrated with other optic, optoelectronic and electronic devices.

As an intermediate step, we demonstrate that an erbium-doped waveguide on silicon wafer attached with a discrete III-V semiconductor saturable absorber can produce a pulse train at a repetition rate of up to 1GHz. Fig. 1 illustrates the waveguide chip fabricated by Inplane Photonics. The chip has four identical sets of waveguides (one set boxed yellow) and each set includes waveguides with three different lengths, 1cm, 5cm and 10cm. For each waveguide, the left side is open, while the right side has an integrated output coupler. The output coupler is based on a loop mirror structure with coupling ratio of 50%, which can be lowered up to about 5% depending on applications. The 980nm pump beam is coupled to the waveguide through a dedicated input port from the right side of the chip. The pump and output ports are permanently coupled to a pair of fibers to simplify the experiment.

![Fig. 1: Left: picture of waveguide chip coupled with a pair of fibers. Right: schematic of waveguide chip. Waveguides with three different lengths are included. Fabricated by Inplane Photonics, Inc.](image-url)
The experimental setup and schematic are shown in Fig. 2. The left side surface of the waveguide chip touches a III-V saturable absorber fabricated in Leslie Kolodziejski’s group. The maximum modulation depth of the absorber is 18% and its recovery time is 43ps. Current silicon germanium (Si/Ge) saturable absorbers [1] have a modulation depth less than 0.5%, which is not enough to start modelocking or Q-switching. Development of a Si/Ge saturable absorber with a few percent of modulation is in progress. The waveguide chip sits on a vacuum chuck and the air suction at the bottom holds the chip, leaving the freedom of rotational movement. In this way, the chip can self-align to the absorber over the waveguide plane. As a result, a very efficient butt-coupling becomes possible by only trying several vertical tilts of the absorber.

![Fig.2. Picture and schematic (side view) of the mode-locked waveguide laser with the SBR attached.](image)

Fig. 3 shows the measured optical and RF spectrum of the laser. The optical spectrum ranges from 1558nm to 1559nm. The RF spectrum confirms that the absorber can start a train of modelocked pulses at a 920MHz repetition rate. However, the pulse train is not yet steady, since the higher harmonics of the repetition rate decay rapidly and broad sidebands in the RF spectrum indicate additional Q-switching.

![Fig.3. Measurement data from the mode-locked waveguide laser setup (SBR attached). (a) Optical spectrum and (b) RF spectrum with a close-up in the inset.](image)

The measured RF spectrum resembles those of Q-switched mode-locked lasers, where pulses are modulated by at a slower time scale. Unbalance between the time scale of gain saturation and absorber bleaching can cause the Q-switching or the periodic fluctuation in pulse amplitude. There are several ways to suppress the Q-switching such as gain control, intracavity loss modulation or inverse saturable absorption. The method pursed here is to
Chapter 31. Optics and Quantum Electronics

provide inverse saturable absorption by bringing the laser into the soliton mode-locking regime and creating additional gain filtering loss proportional to the pulse energy. [2] In order that a laser operates in the soliton mode-locking regime, it is important to achieve a net negative dispersion in the cavity. Different schemes to achieve net negative dispersion are currently evaluated.

References

Transparent wavelength switching of resonant filters

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In this work [5], a general approach was proposed and experimentally demonstrated for the tuning of a microphotonic resonant circuit response from one resonant wavelength band to another in a manner that is fully transparent to signals lying at all other wavelengths. This means that no substantial attenuation or dispersion is seen in the rest of the spectrum before, during and after tuning. The new class of switchable resonant structures based on this approach enabled the first demonstration of fully hitless tunable filters, reported here, based on silicon microring resonators. Hitless tuning [1,2] is a prerequisite for reconfigurable optical add-drop multiplexers (R-OADMs). It requires that channel add-drop filters switch from one target wavelength to another without causing any bit errors in other wavelength channels. Hitless tuning of microring resonators has been claimed [3] but not achieved because suppression of the phase response was ignored, whereas it is critical for tuning without introducing signal degradation and bit errors. Hence, the cavity detuning approach [3] is not

Figure 1. Fully (amplitude- and phase-) transparent tuning of a filter based on a Si-core microring resonator: (a) top-view optical micrograph shows waveguides and tuning/switching Ti heaters; (b)-(c) hitless tuning in action: drop- and through-port responses as the filter is disabled at a 1546nm wavelength channel, tuned by two channel spacings to a 1550nm channel, and re-enabled. This device has 40 GHz bandwidth, <2 dB drop loss, >35 dB thru extinction, 16nm FSR.
The proposed hitless disabling of filters is based on interferometric input couplers that provide a controllable waveguide-resonator coupling coefficient, and operating so that switching takes resonances into an undercoupled (minimum-phase) regime of operation. The latter condition entails necessarily providing a sufficient loading mechanism for the resonant modes other than the input coupling. A practical design of the simplest case of such a hitless filter is shown in Fig. 1a, where a Mach-Zehnder (MZ) input coupler has an arm length difference $\Delta L = 2\pi R$ (any integer multiple thereof), with $R$ the ring radius.

When this concept is applied to higher-order resonator designs required for telecom-grade filters, a second MZ coupler is required to suppress all resonances of the multiple-cavity system at once (Fig. 2a). The second MZ coupler acts as a controllable loss mechanism to a second cavity. This permits strong line-broadening of the supermodes to increase suppression in the off-state. In Fig. 2(b,c), in the on-state, the input coupler is enabled and the loss coupler is disabled, providing the simulated bandpass response. The situation is reversed in the off state where the loss coupler is enabled, providing >30dB drop rejection, and nearly dispersionless (<0.3 ps/nm) through-port transmission. These simple structures sufficiently suppress the through-port amplitude and phase of a resonant add-drop filter to permit wavelength tuning with no effect on other channels. To demonstrate hitless switching and tuning in silicon microring resonators, a 40GHz, single-ring hitless demonstrator filter (Fig. 1a) was designed, as well as a hitless-switchable version of a fourth-order, telecom-grade filter (Fig. 2a). A novel silicon waveguide design with ~600x100nm cross-section was chosen, that is optimized for thermal tuning and tolerant to dimensional error and sidewall roughness [4]. Titanium heaters (Figs. 1a) were designed, using heat flow simulations, to raise the microring core temperature to ~250°C, permitting tuning a full FSR (16 nm) using ~40 mW per ring. The devices were fabricated on a Unibond silicon-on-insulator (SOI) wafer with 3 $\mu$m buried oxide undercladding and a 220 nm silicon layer, thinned to 106 nm. The waveguides were defined by e-beam lithography using 60-nm-thick hydrogen silsesquioxane (HSQ) as e-beam resist and mask for reactive-ion etching in pure HBr. 100-nm-thick Ti heaters were formed on top of an HSQ overcladding by aligned contact photolithography, e-beam evaporation and liftoff.

In Figs. 1(b,c), the fabricated single-ring hitless filter (Fig. 1a) is shown performing a hitless tuning operation. By first actuating the MZ coupler heater, the filter is turned off and the drop-port resonance is extinguished by 25dB, while the initial through port extinction of >35dB is replaced by a flat spectrum with no signature of a resonance. By next actuating both heaters, the filter (in the off state) is tuned to align with another channel. Releasing the coupler heater power (Fig. 1c, legend) returns the filter to operation at the new wavelength. The key aspect
of this operation is that the switching action suppresses both the amplitude and phase response in the through port, in contrast to previously used cavity detuning approaches where a dispersive "all-pass" response remains at all times. This is the first demonstration of truly hitless tuning in micro photonics.

For dense WDM applications, high-order transparently switchable filters are required. As a stepping stone to fully transparent (hitless) Si R-OADMs, we also reported the first fully tunable 4th-order silicon filter meeting typical telecom requirements (shown in Fig. 2c). Further integration with MZ couplers according to Fig. 2a yields a fully transparent, telecom-grade Si R-OADM filter. Characterization of such a fabricated filter is under way. The new class of transparently wavelength switchable resonators proposed and demonstrated here is ideally suited to enable the first truly hitless R-OADMs — an important advance for dynamically reconfigurable networks — using device technology unique to micro photonics and not achievable using bulk optics (non-integrated) structures.

References
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Fiber to Chip Couplers

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The coupling of light between submicron-size high-index contrast waveguides and transmission fibers is one of important problems on the way to practical application of silicon microphotonics devices. Existing approaches to this problem include horizontal couplers based on inverse tapers [1,2] and vertical couplers based on gratings [3,4]. Some of the horizontal couplers reported previously are quite efficient and claim 0.5-1dB coupling loss; however they work only for coupling from special small-core fibers (mode field diameter ~ 4μm). In this work, we propose an efficient horizontal coupler which couples light between standard single mode fibers (mode field diameter ~ 10μm) and silicon waveguides, achieving about three orders of magnitude mode area reduction with low coupling loss and small footprint [5]. In addition to eliminating the need for specialty high-index contrast fibers, this coupler also has reduced sensitivity to fiber misalignment.

The proposed coupler is based on two-stage adiabatic field evolution and is illustrated in Fig. 1 [5]. The light is first coupled into a waveguide of approximately the same dimensions as the fiber. The polymer is chosen as the material for this waveguide because of fabrication considerations. At the first stage of the coupler, a rib is introduced into the rectangular waveguide and the rib width is adiabatically narrowed until most of the field is “squeezed” into the lower part of the waveguide. At this point the rib can be terminated with very little power loss. As a result, at stage I the light is transferred from a large into a smaller polymer waveguide. At the stage II, the field is transferred into a high-index contrast (Si) waveguide by using an inverse taper [1,2]. In the beginning of the inverse taper Si waveguide is very narrow so the fundamental mode is not confined to the Si core and matches well the mode of the polymer guide. The silicon waveguide is then adiabatically widened until the fundamental mode of the structure becomes well-confined in the silicon core. The mode field evolution in both stages is illustrated in Fig. 1.

The coupler parameters to be optimized include dimensions of the polymer waveguide at the beginning of stage I, dimensions of the polymer waveguide at stage II, and taper shapes for both stages. For our specific simulations, we assumed that the polymer is cyclotene (n=1.53) and the output Si waveguide cross-section is 400x250nm.

The dimensions of the input polymer waveguide are chosen to maximize overlap with the fiber mode. For coupling to SMF-28 fiber with mode field diameter of about 10μm, choosing polymer waveguide with width 12μm and height 11μm was found to give the coupling loss of 0.28dB. Note that the waveguide with such dimensions is multi-mode; this should not lead to multi-mode interference effects.

Figure 1. A schematic of the two-stage coupler and mode evolution along tapered rib waveguide (stage I) and inverse taper (stage II).
as long as the waveguide cross-section is changed gradually enough along the taper and the coupler does not have much surface roughness and slanted sidewalls introduced in fabrication.

The dimensions of the polymer waveguide at stage II are more difficult to optimize. It turns out that its height is an important factor determining the overall efficiency of the coupler. If the stage II waveguide is too tall, the length of stage II for efficient mode conversion becomes too large. For example, if the height is 11μm (i.e. if the first stage is absent), the required taper length becomes on the order of several centimeters, which is too much for practical applications. This is the reason why inverse tapers alone without the first stage cannot be used to couple light from standard single-mode fibers into a high-index contrast waveguide. On the other hand, as the polymer height at stage II is decreased, the first stage must become longer because it must reduce the vertical mode size by a larger fraction. Therefore, an optimal value of the stage II polymer height exists; for our coupler parameters it was found to be around 3.5-4.5μm.

The simplest choice of taper shape is linear; in this case, the overall length of two stages of 1.2mm allow to achieve 0.2dB mode conversion loss. The taper length can be considerably decreased by optimizing its shape. The shapes of both stages synthesized using the approach described in [6] are shown in Fig. 2. The mode conversion loss in each stage versus its length is shown in Fig. 3 for linear tapers and tapers with optimized shape. The taper shape optimization allows to decrease the total coupler length to 500μm (335μm stage I + 165μm stage II) giving only 0.2dB mode conversion loss. The total simulated coupler loss is thus 0.5dB.

The taper parameters given above were obtained by optimizing it for TE mode only. The taper shapes found for TE mode are not automatically the best ones for TM mode. Therefore, if efficient operation is required for both polarizations, the coupler length must be increased; in our case 800μm coupler gives about 0.8dB loss for TM mode.

References

Figure 2. Optimized taper shapes for stage I (top) and II (bottom).

Figure 3. Mode conversion loss vs. length stage I (top) and II (bottom) for linear and optimized taper shapes.
Fabrication of Fiber to Chip Couplers

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Fiber to high index contrast waveguide couplers are essential for overall efficiency of integrated photonic devices. We have developed ideas to improve the coupler design. These techniques include using an optimization algorithm for designing adiabatic tapers and thinning of the waveguide over-cladding in the taper.

The side view of the proposed coupler is shown in Fig. 1. Light from a high numerical aperture fiber is coupled to the fundamental mode of the rectangular polymer waveguide. Then, the polymer waveguide mode is adiabatically converted into a submicron silicon nitride waveguide mode.

![Fig. 1. Side view of the fiber to on-chip SiN waveguide coupler.](image)

To fabricate the coupler, it is first necessary to create silicon nitride waveguides with our proposed adiabatic taper design. The fabrication process we employ for the silicon nitride waveguide and the tapered structure is based on a previously proposed method [1].

In addition, we plan to implement electrical filters for controlling the integrated photonic devices and we need to isolate the metal heaters from the optical mode to avoid light absorption. Therefore, an insulator with low optical absorption and good stability at high temperatures is needed between the waveguides and heaters. Thus, hydrogen silsesquioxane (HSQ) is used as an inexpensive and reliable insulator with an excellent gap filling property [2].

After spinning and annealing HSQ, we should thin it down in the coupler region, otherwise HSQ, with its lower refractive index than that of the polymer, will serve as an optical isolator between the polymer and SiN waveguide, and thus prevent efficient coupling. For thinning down the HSQ layer, different etching processes were tested, and reactive ion etching process with CF4 is chosen.

Bisbenzocyclobutane (BCB) polymer, also called cyclotene, is used for coupler overcladding due to its good transparency at wavelengths above 400 nm [3]. The maximum achievable thickness of cyclotene 3022-35 is 2.2 um, while we need 4.3 um thick waveguide. Thus cyclotene must be coated and annealed in two steps. The first step includes spinning cyclotene and putting the sample on a 90 C heater immediately after the spinning process for 5 minutes to have a stable film on the sample. The sample is then put in an oven with 90 C for 30 minutes, then the temperature is increased to 150 C, and after 30 minutes the temperature is increased to 240 C, and the sample is soaked for 40 more minutes. After the
sample naturally cools down in the oven and reaches 150 °C, it can be taken out. This process (softcure) makes the cyclotene layer to be 80% polymerized. A second layer of cyclotene is then coated onto the sample. The same steps are repeated, but instead of 240 °C in the last step the temperature should go to 250 °C, and the sample should be soaked in this temperature for one hour. The second process (hardcure) makes cyclotene to be 95% polymerized.

In order to etch the dry-etch cyclotene we need hard mask since the selectivity of photo-resist and cyclotene is 1:1, and by using photo resist vertical walls cannot be obtained. A 500 nm oxide mask is deposited on cyclotene, and a lithography step is done on the sample using 1 um of OCG-835 as photo resist. After exposing, developing and post-baking the sample, oxide mask is etched using RIE with CHF3. Then cyclotene is etched in RIE chamber using 33% of CF4 and 66% of oxygen. Near to the end of cyclotene etching, the CF4 percentage is reduced for having lower etch rate, and avoid reaching the underlying HSQ surface. The SEM of the final fabricated structure is shown in Fig.2. The loss of the couplers has not been measured yet, however the preliminary test shows that there is light at the output of the couplers with different designs.

![Figure 2](image)

*Figure 2. SEM of Cyclotene waveguide on top of HSQ, and SiN waveguide. Oxide hard mask is on top.*

References:


Super-Collimation in a 2D Rod-Based Photonic Crystal

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Photonic crystals (PhCs) are engineered structures with peculiar dispersion characteristics that can be used to control light at very small scales[1-9]. A recent effect observed in such structures is the propagation of optical beams without diffraction, referred to as super-collimation (or self-collimation)[2-6, 8, 9]. This is a linear effect and is a natural result of unique dispersive properties of PhCs. Centimeter-scale super-collimation in a large-area 2D photonic crystal of air-holes has been reported[6, 8]. The inverse structure, a PhC of rods in air, presents a higher fabrication challenge. In addition, such a configuration exhibits super-collimation for TM-like radiation, which makes the out-of-plane radiation much weaker (compared to the inverse structure) and harder to detect and characterize. We have recently fabricated and observed super-collimation in a 2D PhC of silicon rods in air, for the first time, to the best of our knowledge[10].

![Figure 1](image-url)

**Figure 1**: 2D Photonic crystal of silicon rods in air: (a-b) scanning electron micrographs (SEMs) of the fabricated large-area structure; (c) equifrequency contours of the PhC, showing flat regions in the Γ-M direction for wavelengths around 1550nm.

The 2D PhC was patterned with square lattice of silicon rods in air – Figure 1(a-b). The structure was fabricated on a silicon-on-insulator (SOI) wafer with a 700nm-thick silicon layer over a 3μm-thick oxide layer, using interference lithography and reactive ion etching[11]. The lattice constant is \( a = 437.5\)nm and the rod radius is \( r = 125\)nm, resulting in a super-collimation wavelength around 1550nm for TM radiation (electric field perpendicular to the 2D plane), in the lowest energy band. From the SEMs, it is observed that the rods are actually tapered, which presents some deviation from the ideal case of perfectly cylinder rods. The projected band structure is shown in Figure 1(c). Around \( \lambda = 1550\)nm, the computed equifrequency contours are flat in the Γ-M direction and show little spatial dispersion in the transverse wavevector, leading to super-collimation.

Interference lithography enables the fabrication of centimeter-scale samples, and the size of the tested PhCs varied from 2mm to 7mm – Figure 2(a). Light from a tunable laser source is coupled into the PhC sample through a high NA single-mode (SM) lensed fiber with a spot...
size of 1.5μm full-width at half-maximum (FWHM) and a working distance of about 8μm. The light scattered out of the plane is then detected with an infrared (IR) camera, as illustrated in Figure 2(b).

![Figure 2: Experimental details: (a) photograph of a centimeter-scale-sized PhC sample on the mounting holder; (b-c) schematic and photograph of the experimental measurement apparatus.](image)

The experimentally observed wavelength for super-collimation was around 1530nm, and for different wavelengths the beam exhibits diffraction-like behavior. This is explained by the curvature of the equifrequency contours. Figure 3 shows IR images of the wavelength dependence of the propagating beam inside the PhC. No accurate loss measurements were performed over the sample, but the bright out-of-plane scattering is indication of large loss. The images shown are about 125μm-long, but the effect was observed over ~0.5mm. A rough loss estimation return values of ~20dB/mm.

![Figure 3: IR images showing the wavelength dependence of the propagating beam inside the 2D PhC. Super-collimation is observed around λ = 1530nm, and the beam diffracts as the wavelength increases.](image)
The discrepancy between the measured and simulated super-collimation wavelength is about 1%. The large value estimated for the loss is mainly due to short scale disorder, such as fabrication roughness. In addition to optical interconnects[8], super-collimation can be used to develop optofluidic technology[12].

References:


Thermo-Optic Tuning of High-Order Silicon Microring Resonator Add-Drop Filters for DWDM Applications

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Reconfigurable optical add-drop multiplexers (R-OADM) for optical networks combine integrated add-drop filters with efficient low power tuning and transparent switching. Telecom-grade add-drop filters require large free spectral range (FSR), wide tunability, large throughput-port extinction and low drop loss [1]. Previous work has been reported in wide thermal tuning and high-order microring filters [2-5], but not meeting the required telecom characteristics.

We have recently demonstrated the largest reported full-FSR thermal tuning on silicon microring resonators with 16nm FSR [6], and reported the first high-order silicon microring resonator with telecom specifications and suited for dense wavelength-division multiplexed (DWDM) applications [7].

Figure 1: Cross-section of the filter, showing a Si ring and bus waveguide. The device was fabricated on a SOI wafer.

Figure 2: Drop-port transmission spectra of a silicon single microring resonator, for different tuning powers. A 20nm tuning is achieved with a power of about 44mW.

Figure 1 illustrates the different material layers for the fabricated devices. A silicon-on-insulator (SOI) wafer with a 3μm oxide layer and an initial 220nm silicon layer was thinned down to about 100nm, where the waveguide structures were defined by e-beam lithography and reactive ion etching. The over cladding was formed by a 1μm layer of hydrogen silsesquioxane (HSQ) and the titanium heaters were defined on top of the HSQ by contact photolithography. An additional 100-nm-thick oxide layer was sputtered on top of the heaters to reduce heater oxidation at high operating temperatures (~500°C).

The waveguide dimensions (600×100nm for the ring waveguides and 500×100nm for the bus waveguides) were optimized for thermal tuning and reduced sidewall roughness sensitivity.
The microrings have a 7μm radius and were designed to have a FSR of 16nm. The heater design maximizes the tuning range and allows tuning over the whole FSR (16nm). The titanium layer used to form the heaters was placed far enough from the waveguides to avoid significant optical loss. The individual Si microrings showed quality factors (Q) of ~250k and ~130k, without and with the Ti heaters, respectively. These values translate to propagation losses of about 2-2.5 dB/cm and 4.5 dB/cm.

The single microring filter tuning response is presented in Figure 2. The drop-port transmission spectra show tuning over 20nm, for a heater power of 44mW, which is equivalent to an average tuning efficiency of ~17μW/GHz. Over the first 10nm, the average tuning efficiency is about 28μW/GHz. This wide tuning range is the largest reported for a single microring in silicon. The measured time response shows rise times of 7μs and fall times of 14μs [6], suitable for R-OADM applications. The 16nm wide tuning range of these filters can be combined with a FSR doubling scheme to allow operation over the entire C-band [9].

Single microrings can be combined to form high-order filters suitable for telecom applications. A fourth-order series coupled design [10] (Figure 3(a)) was used to fabricate the first tunable high-order add-drop filter based on silicon microring resonators [7]. The filter was designed to have a 40GHz flat and low loss drop-port channel, with through-port extinction over 24dB and over 30dB extinction at the adjacent channel (100GHz, for the ITU WDM grid). Figure 3(b) is an optical micrograph of the fabricated fourth-order filter, showing the microrings laid out in a folded and compact configuration, the bus waveguides, and the titanium heaters.

The tuning results of the fourth-order filter are shown in Figure 4. Each microring has an independent heater and can be fine tuned to correctly align the four microrings. The drop-port loss is about 1dB, and the FSR is about 16nm. As seen, the power needed to fully tune each ring over the whole FSR is less than 50mW. The through-port extinction is ~20dB, and the 100GHz extinction is >30dB. A multi-stage design of such fourth-order filter will provide the through-port extinction needed to comply with telecom specifications [11].
Figure 4: Tuning results (drop- and through-ports) for the first fabricated fourth-order tunable silicon microring add-drop filter: (a) tuning over 6 channels (600GHz), showing good match with designed filter; (b) 16nm FSR of the filter, spanning 20 100GHZ-channels.

References:

Ultrafast Carrier Dynamic Study of Ion-implanted Silicon and Silicon-Germanium Devices

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Teraflop processing has become a reality as a result of rapid growth in CMOS technology and advanced parallel computing architectures. However, full exploitation of the features of such a system remains under utilized due to the limitation in the performance of ADC circuits. This limitation is mainly due to the electronic clocking-circuits jitter, which may be in the excess of 0.25ps. However, one of the attractive features of femtosecond mode-locked lasers is the low jitter (<10fs) pulse-train produced by such lasers. Such a pulse-train, when used as the clock signal in analog-to-digital conversion (ADC) applications, can enable sampling rates in the GHz range [1]. Electronic photonic integrated circuits (EPIC) based on CMOS technology may enable high speed and high resolution analog-to-digital converters. To determine the speed limitation of such ADC devices, the ultrafast carrier dynamics of their constituent elements such as silicon-based optical modulators and high speed photodetectors are studied.

The proposed optoelectronic ADC-chip, shown in Figure 1, utilizes CMOS technology and makes the fabrication of this system compatible with Si technology for on chip integration. However, to implement the high speed modulator needed to accommodate the high data rates of communication systems, materials and structures that are both process-compatible with silicon technology and have carrier recovery times in the order of a few picoseconds must be utilized. One of the natural options is bulk silicon, but it has recovery times on the order of several nanoseconds. This is too long for GHz modulation rates, hence other options must be sought. By ion implantation and introduction of defect states, the carrier recovery time of bulk silicon can be reduced significantly [2]. To measure carrier recovery times of ion-implanted Si a two-color cross-polarized pump probe experiment, as shown in Figure 2 is utilized.
Chapter 31. Optics and Quantum Electronics

Our experimental setup utilizes two different pulsed optical sources, a Ti:Sapphire laser and an optical parametric oscillator (OPO). The output of the Ti:Sapphire laser is fixed at 810nm and the pulses are 80fs in duration. This laser is used as the pump for the OPO, the output wavelength of which is tunable between 1470nm and 1600nm with 150fs long pulses. The repetition rate of both lasers is 82 MHz. The pump signal is taken from the output of the Ti:Sapphire laser, and it’s chopped either using a mechanical chopper or an AOM. The probe signal is taken from the output of the OPO. The two beams are overlapped on the sample; and, since the probe beam is incident upon the sample at a slightly different angle than the pump, its reflection also traverses a different path from that of the pump beam. The reflected beam is collected and is incident upon a detector circuit whose output is detected using a lock-in amplifier tuned to the chopping frequency. The delay stage consists of a mechanical translation stage which provides a variable delay between the pump and the probe pulses. The results are plotted as the normalized magnitude of the probe.

Figure 1: High resolution, high speed optical sampling chip.

Figure 2. Two-color pump probe setup. Pump= 800nm, and Probe=1540nm.
Figure 3. Carrier dynamics of Si sample with $10^{14}/\text{cm}^2$ ion implantation.

Figure 4. Carrier dynamics of Si sample with $10^{15}/\text{cm}^2$ ion implantation.

beam modulation versus the delay. Two different ion-implanted silicon structures were fabricated at MIT Lincoln Laboratory. One of the structures consisted of Si with $10^{14}/\text{cm}^2$ ion implantation while the other consisted of Si with $10^{15}/\text{cm}^2$ ion implantation. Both of these samples were measured at various different fluences using the two-color pump probe set up, and the results are shown in Figures 3 and 4. Recovery times of the two different samples were measured to be 650fs and 450fs, respectively. This shows that the greater level of ion bombardment results in faster recovery times. Further studies of recovery times versus implantation density and annealing procedures are planned.
Silicon Germanium Saturable Absorbers

The integration of a femtosecond-pulse laser on a chip with processing compatible with silicon technology would be very attractive because it would lower the cost and size of these devices. An SBR based on Si/Ge and SiO₂ was recently built and its performance in mode-locking an Er-Yb:glass laser was demonstrated [4]. At MIT, in collaboration with Professor Kimerling’s group, Si/Ge-SBRs were fabricated as shown in Figure 5.

A pump-probe experiment was performed at 1540 nm wavelength with 150fs pulses using the degenerate cross-polarized pump-probe. The sample exhibited 0.8% modulation depth with a subpicosecond carrier recovery time limited by the pulse width of the OPO. This SBR was used to mode-lock a laser with 220fs pulse width with 169MHz repetition rate. Additional SBRs with various modulation depths are being prepared for use at higher repetition rates.

References:
Chapter 31. Optics and Quantum Electronics

Frequency Swept Lasers and Fourier Domain Mode Locking (FDML)

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1. Frequency-Swept Lasers and Fourier Domain Mode Locking (FDML)

Femtosecond lasers have found numerous applications as high performance light sources for biomedical imaging. Besides the use of their high pulse powers for non-linear imaging, their broad spectrum and short coherence length served as enabling tools for ultrahigh resolution optical coherence tomography (OCT - see the chapter dealing with Laser Medicine and Biomedical Imaging) [1-3]. Recently, efforts have been made to apply narrowband, rapidly frequency-tunable lasers for OCT imaging to achieve higher acquisition speeds and greater imaging sensitivity [4-14]. This concept is called “swept source / Fourier domain OCT,” or sometimes “optical frequency domain imaging (OFDI).” The measurement concept is similar to optical frequency domain reflectometry (OFDR), although the requirements for the laser are more demanding for OCT applications. The concept of swept source / Fourier domain OCT imaging and the experimental imaging setup are described in the Laser Medicine and Biomedical Imaging chapter in detail. In this section, we will discuss progress in laser development for swept source / Fourier domain OCT.

1.1 Conventional Frequency-Swept Lasers

Since early in the history of laser development, many different concepts and designs of narrowband tunable or swept laser sources were investigated for numerous applications. However, none of these designs could provide sufficient performance to meet the demands for swept source / Fourier domain OCT. To be suitable for OCT imaging, the laser must operate within the “therapeutic window” where tissue absorption and scattering are low. For imaging epithelial tissues, a 1300 nm center wavelength is preferred for improved depth penetration. For ophthalmic imaging, a 1060 nm center wavelength is preferred to minimize losses from water absorption in the vitreous fluid. The imaging speed, axial resolution, and imaging depth of OCT systems are determined by the sweep rate, tuning range, and instantaneous linewidth of the laser, respectively. Therefore a tuning range of > 100 nm, an instantaneous linewidth of < 0.1 nm, and a sweep rate of 50,000 – 500,000 sweeps/sec (50 – 500 kHz) are simultaneously desired [15]. The resulting optical frequency sweep speeds are up to 10^{16} Hz/s, and the required average output power is > 10 mW.

Frequency-swept lasers incorporate a tunable intracavity wavelength-selective filter element in order to produce an output that varies in wavelength over time. In a conventional swept laser, the maximum sweep rate is usually limited by the time required for lasing to build up from the amplified stimulated emission (ASE) background of the gain medium. This time depends on the filter function, the ASE intensity, the saturation power, the laser gain, and the cavity roundtrip time. A conventional swept laser is restricted by two speed limits: the saturation limit, and the single roundtrip limit.
The saturation limit represents the maximum sweep rate that still allows for full build-up of lasing from the ASE background. When the intracavity filter is tuned in wavelength, the ASE background is amplified up to the saturation power limit of the gain medium, provided that the time the filter transmits a given wavelength is sufficiently long for this build up. The saturation limit gives the approximate maximum sweep rate above which a decrease in output power will occur. For sweep rates higher than the saturation limit, the output power will decrease until the sweep rate reaches the single roundtrip limit. At this second limit, the light on average makes only one pass from the gain medium to the filter before being coupled out of the cavity. At this point, the filter is tuned so rapidly that during the next roundtrip it blocks the propagating wavelength. At the single roundtrip limit, the output light shows characteristics spectrally filtered ASE that is only amplified by a single pass through the gain medium.

Figure 1.1 shows a plot of output power versus sweep rate for a conventional swept laser built in our lab. An external booster can be used to boost output power outside of the cavity. The region that begins at 10 kHz and ends at ~25 kHz defines the saturation limit and the single roundtrip limit. Note that output power begins to fall at the saturation limit, and that operation is not possible beyond the single roundtrip limit. Sophisticated optical frequency shifting spectrometers, multi-detector balancing setups, or optoelectronic self referencing must be applied to reduce the problems with standard tunable lasers at higher sweep rates [16, 17]. Still, since imaging speeds of several hundred thousand axial lines per second are required for three-dimensional OCT imaging (3D-OCT), conventional swept lasers cannot provide adequate performance for this application.

1.2 Fourier Domain Mode Locking (FDML)

Fourier Domain Mode Locking (FDML) is a new swept laser technique that overcomes limitations in the maximum speed rate while simultaneously providing a broad tuning range, narrow instantaneous linewidth, and high output power. FDML lasers generate very low-noise frequency sweeps, equivalent to train of highly chirped laser pulses [18-21]. Figure 1.2 (left) shows a schematic representation of the FDML concept compared to a conventional swept laser. In the conventional laser, light from a broadband gain medium is spectrally filtered by a narrowband optical bandpass filter within the cavity and fed back to the gain medium. Only
longitudinal modes with frequencies that are transmitted through the filter can lase at one point in time. When the passband of the filter is tuned during a sweep, lasing collapses and must build up from ASE at each new position of the filter. This significantly limits the performance and imposes a trade-off between sweep rate, instantaneous linewidth, tuning range, and output power [15].

In FDML lasers, as shown in Figure 1.2 (right), a dispersion managed delay line is incorporated into the cavity and the filter is tuned synchronously to the cavity round-trip time (or a harmonic of the round-trip time). This results in a quasi-stationary mode of operation. Light from one sweep propagates through the cavity and returns to the filter at the exact time when the transmission window of the filter is tuned to the position. Therefore, light from the previous round-trip is coupled back to the gain medium and lasing does not have to build up again from ASE. In other words, an entire frequency sweep is optically stored within the dispersion managed delay line in the laser cavity. Under ideal operation, sequential frequency sweeps have the same phase evolution and are mutually coherent. The filter dissipates almost no energy since the backcoupled light contains only frequencies that are matched to the transmission window of the filter at each moment. In the frequency domain, this requires destructive interference of all longitudinal modes that are not transmitted through the narrowband filter at a given time. Thus, the phases of the longitudinal modes must be locked. Standard mode-locked lasers have longitudinal modes locked with constant phase, which corresponds to the generation of a train of short pulses at a repetition rate equal to the cavity round-trip time. Fourier domain mode-locked lasers have modes locked with a different phase relationship. The laser output is not a train of short pulses; instead, it is a train of frequency sweeps or highly chirped, very long pulses. The tunable narrowband filtering is equivalent to an infinite number of narrowband amplitude modulators that are slightly out of phase. Fourier domain mode locking is performed by periodic spectral modulation, rather than amplitude modulation. This can be viewed as the Fourier domain analog of mode locking for short-pulse generation.

Figure 1.2. The concepts of conventional wavelength-swept lasers (left) and FDML lasers (right). In FDML, all modes are active within the cavity simultaneously, and quasi-stationary operation is achieved.

Figure 1.3 shows a schematic diagram of an FDML laser. The laser uses a fiber ring geometry with a semiconductor optical amplifier (SOA) as the gain medium and a fiber Fabry-Perot filter (FFP-TF) as the tunable, narrowband optical bandpass filter. Depending on the birefringence properties of the fiber ring, the SOA can be polarized (low cavity birefringence) or polarization-insensitive (high cavity birefringence). The FFP-TF is selected to have a free spectral range greater than the desired tuning range. The FFP-TF is driven with a sinusoidal waveform created by a high-precision digital function generator. The waveform is amplified by an electric power amplifier for driving the low-impedance capacitive load of the lead zirconate titanate (PZT) FFP-TF actuator. The optical isolators eliminate extraneous intracavity reflections and ensure unidirectional lasing of the ring cavity. A fiber splitter acts as the output.
coupler, with the coupling ratio controlling the tradeoff between output power and tuning range. For OCT imaging, the laser output can be further amplified with a second SOA. The length of the dispersion-managed delay varies based on the desired sweep rate. For a 21 kHz drive frequency the delay should be 9.8 km, whereas for a 185 kHz drive frequency the delay should be only 1.1 km. Since the drive signal is sinusoidal, two wavelength sweeps are produced during each drive period as the FFP-TF is moved forward and backward. Therefore the effective sweep rate is twice the drive frequency.

\[ n \cdot \tau_{\text{sweep}} = \frac{l_{\text{cavity}}}{c} \]

**Figure 1.3.** Schematic of an FDML laser. FFP-TF: fiber Fabry-Perot tunable filter.

### 1.3 Performance of FDML Lasers

Figure 1.4 shows the transient intensity profiles of a typical FDML laser operating at 1310 nm for forward (shorter to longer wavelengths) and backward (longer to shorter wavelengths) sweeps at different effective sweep rates. The data is shown for the direct laser output without post-amplification in order to ensure that the transient intensity profiles are not obscured or shaped by saturation effects [15]. The physical cavity length was 7 km, which corresponds to a 10-km optical path length. In contrast to other high-speed, frequency-swept lasers, in FDML lasers, the forward and backward frequency sweeps have the same intensity profile and the same maximum power for a wide range of sweep rates.

**Figure 1.4.** Transient intensity profiles of an FDML laser operating at 58 – 290 kHz. The profiles remain unchanged as the sweep rate is scaled up, unlike conventional wavelength-swept lasers that degrade with increasing sweep rate.

Figure 1.4 shows that the shape and amplitude of the transient intensity profile remain consistent as the sweep rate is increased. The maximum sweep rate is limited only by the mechanical response of the FFP-TF. This enables extremely high-speed OCT imaging, as discussed in the Laser Medicine and Biomedical Imaging chapter in detail. Figure 1.5 shows
the time-averaged spectral output of the FDML laser. Again, the spectral shape of the output remains consistent as the sweep rate is increased.

**Figure 1.5.** Average integrated output spectrum of an FDML laser operating at sweep rates of 58, 116, 232, and 290 kHz. The laser spectrum remains constant as the sweep rate is scaled up.

FDML lasers provide improved stability compared to conventional wavelength-swept lasers, resulting in a narrower instantaneous linewidth and larger ranging depth. Top: time-lapse view of interference fringes from a Mach-Zehnder interferometer acquired with an FDML (left) and conventional swept laser (right). Bottom: OCT point spread functions versus ranging depth for an FDML (left) and conventional swept laser (right).

**Figure 1.6.** FDML lasers provide improved stability compared to conventional wavelength-swept lasers, resulting in a narrower instantaneous linewidth and larger ranging depth. Top: time-lapse view of interference fringes from a Mach-Zehnder interferometer acquired with an FDML (left) and conventional swept laser (right). Bottom: OCT point spread functions versus ranging depth for an FDML (left) and conventional swept laser (right).

Since FDML lasers operate in a quasi-stationary regime, they are inherently less noisy than conventional swept lasers. This is illustrated in Figure 1.6. Figure 1.6 (top) shows the RF
interference fringes produced by an asymmetric Michelson interferometer when an FDML and a standard swept laser are used as the light source. The mutually-coherent sweeps in the FDML laser provide superior phase stability, which is discussed in more detail in section 3 below. Due to the narrow instantaneous linewidth of the FDML laser, the OCT point spread functions shown in Figure 1.6 (bottom) roll off more slowly than the conventional swept laser case. Imaging depths of up to 7 mm are possible using FDML lasers, whereas a considerable drop in sensitivity is observed over only 3 mm with the conventional swept laser. From the roll off of the point spread functions, a linewidth of 0.06 nm can be calculated for the FDML laser. This is much narrower than the filter bandwidth of 0.25 nm, and underlines the fact that in FDML the instantaneous linewidth is decoupled from the filter width. Much broader spectral filters can therefore be applied, reducing component costs and losses in the cavity.

2. Buffered FDML for Ultrahigh-Speed Operation

Despite the fact that both forward and backward sweep directions have approximately the same transient power characteristics in FDML lasers, as the effective sweep rate is increased beyond 300 kHz the two sweep directions begin to exhibit different noise characteristics. Additionally, for OCT imaging applications it is desirable to produce unidirectional sweeps in order to reduce signal processing requirements. With bidirectional sweeping, for example, every second interference fringe must be reversed prior to Fourier transformation and image formation. Finally, it is not technically straightforward to achieve extremely high sweep rates (> 400 kHz) simply by driving the FFP-TF at higher speeds due to the mechanical properties of the filter. An architecture called “buffered FDML” addresses these issues, enabling ultrahigh-speed sweeping and unidirectional operation.

Figure 1.7 (left) shows the setup of a typical FDML laser. The fiber cavity is 2 km long and the filter is driven with a sinusoidal waveform at 185 kHz. At these high speeds, it is necessary to select a drive frequency close to a mechanical resonance of the FFP-TF. At frequencies slightly off resonance, the filter response decreases significantly and it is difficult to drive the filter over a range sufficient to support a wide tuning range. Here, an FFP-TF specially designed with a high-frequency resonance was used in order to achieve the increased sweep rate. Because two optical frequency sweeps are generated for each period of the sinusoidal drive wave (bidirectional sweeping), the resulting effective sweep rate is 370 kHz. Average output powers of up to 36 mW can be achieved, with total tuning ranges of up to 100 nm and instantaneous linewidths of approximately <0.1 nm, at a center wavelength of 1300 nm. The transient intensity profiles are shown in Figure 1.7 (right). In the center of the plot, one forward sweep (-1.5 to 1.2 μs) and one backward sweep (1.2 to 3.9 μs) can be seen.

![Figure 1.7. Schematic (left) and transient intensity profiles (right) for an FDML laser operating at a sweep rate of 370 kHz.](image-url)
Figure 1.8 (left) shows the measured dynamic range of an OCT imaging system incorporating a standard FDML laser operating at an effective sweep rate of 370 kHz. The dynamic range is the ratio between the peak value of the OCT point spread function and the system noise floor when the sample arm of the Michelson interferometer is not blocked. Dynamic range gives a relative value for the ratio between the smallest and largest reflections detectable simultaneously within a single axial scan. Note that at these extremely high sweep rates, the dynamic range of the forward sweep degrades much faster than the backward sweep. Since the effect is independent of the cavity power level, and FDML laser output power is not dependant on the sweep direction, non-linear optical frequency shifting does not seem to be a dominant effect here [15, 19]. Different relaxation dynamics in the SOA can be expected depending on which electronic states are depleted first. The effect on the signal noise would be more pronounced at higher sweep speeds and larger depths, as the fringe signal period approaches the carrier relaxation time.

![Figure 1.8](image)

**Figure 1.8.** Dynamic range versus imaging depth for an FDML laser (left) and a buffered FDML laser (right). The forward sweep in the FDML laser has increased noise compared to the backward sweep, so dynamic range degrades more quickly. In a buffered FDML laser, the forward sweep is eliminated and the backward sweep is replicated, eliminating the dynamic range degradation problem.

Buffered FDML lasers use a cavity design that optically replicates the low-noise backward sweep and removes the undesired forward sweep by using a combination of time multiplexing and gain modulation. This concept is illustrated in Figure 1.9. In Figure 1.9 (left) the interference fringes produced by an asymmetric Michelson interferometer are shown, with the desired backward sweep circled in green and the undesired forward sweep crossed out in red. The buffered FDML cavity is shown in Figure 1.9 (right). Two output couplers are placed at evenly-spaced locations within the cavity. Each output coupler extracts an optical copy of the propagating sweep, with the second coupler extracting a copy that is time-delay by exactly one half of the cavity round-trip time. During the time normally occupied by the forward sweep, the intracavity SOA is modulated off. The two copies of the remaining backward sweep are combined outside of the cavity using a 50/50 fiber splitter and boosted by an external SOA. The result is a series of unidirectional, low-noise wavelength sweeps generated at twice the FFP-TF drive frequency, a record 370 kHz[19]. The dynamic range versus imaging depth of a buffered FDML laser is shown in Figure 1.8 (right).

As previously mentioned, it is difficult to drive the FFP-TF at arbitrarily high frequencies due to a decrease in the mechanical response of the filter. Buffered FDML technology can be applied to multiply the effective sweep by adding additional output couplers and overdriving the FFP-TF near a mechanical resonance. Near a mechanical resonant frequency, the FFP-TF undergoes a large physical translation for a relatively small amplitude drive signal. At these resonant points, the FFP-TF can be swept over a range larger than the desired total
tuning range. This compresses the wavelength sweep into a smaller time window, allowing additional time-delayed copies to be extracted from the cavity. For every additional copy extracted, the effective sweep rate is further multiplied. Using four output couplers and a drive frequency of 185 kHz, for example, would give an effective sweep rate of 740 kHz. Another benefit of this approach is an improvement in sweep linearity. As the portion of the sinusoidal drive signal occupied by the sweep decreases, the wavelength versus time evolution of the sweep becomes more linear. This reduces the signal processing requirements for OCT due to nonlinear optical frequency evolution. In the future, higher-order buffering concepts will be explored to further increase the sweep rate and sweep linearity of FDML lasers.

![Figure 1.9](image)

Figure 1.9. Buffered FDML lasers provide unidirectional sweeps at multiples of the cavity’s fundamental frequency. Left: concept of buffered FDML with a two-tap cavity. The desired backward sweep is replicated, and the cavity SOA is turned off during the forward sweep. Right: Schematic of a buffered FDML cavity. SOA: semiconductor optical amplifier. ISO: optical isolator. FFP-TF: fiber Fabry-Perot tunable filter

3. FDML Operation with a Dispersive Cavity

FDML lasers have been proven to provide unparalleled performance for OCT imaging at center wavelengths near 1310 nm. This wavelength region is ideal for imaging in highly-scattering biological tissues or material samples. However, the region around 1310 nm is not suitable for imaging samples rich in water such as the human eye due to high absorption. Ophthalmic imaging is the most developed and widespread application of OCT, and is also an application where sample motion is a significant limitation to image quality. Therefore an FDML laser that enables ultrahigh-speed imaging of water-rich samples is highly desirable.

There are two wavelength regions in the near infrared (NIR) where water absorption is manageable. The first extends from ~700 – 900 nm and the second from ~1020 – 1120 nm [22]. To construct an FDML laser at either of these two wavelengths, however, requires that the effects of cavity dispersion be carefully considered. Earlier FDML designs operated near 1310 nm, which is the zero-dispersion point of conventional SMF-28 optical fiber, thereby precluding the need for specific attention to dispersion issues. Our group has recently developed a basic theory and set of design rules for FDML operation in dispersive wavelength regions, and has constructed an FDML laser at 1070 nm to enable ultrahigh-speed ophthalmic OCT imaging at a record 236,000 axial lines per second [20].

A dispersive FDML cavity can be understood by defining several criteria necessary for FDML operation. The first FDML criterion is given by the need to maintain synchronization between the intracavity tunable filter and the propagating light. This synchronization criterion is given by:

$$f_{\text{drive}} = c/(n \cdot L_{\text{fiber}})$$

(1)
Here \( f_{\text{drive}} \) is the filter drive frequency, \( l_{\text{fiber}} \) is the fiber length, \( c \) is the speed of light, and \( n \) is the refractive index of the fiber. For an operating wavelength of 1070 nm, however, the linear dispersion in the optical fiber is not negligible. The time delay mismatch per roundtrip, \( \Delta \tau_{\text{mismatch}} \), between the longest wavelength and the shortest wavelength in the laser spectrum is given by:

\[
\Delta \tau_{\text{mismatch}} = l_{\text{fiber}} \cdot d \cdot \Delta \lambda_{\text{tuning range}} \tag{2}
\]

Here \( d \) is the chromatic dispersion coefficient of the fiber, and \( \Delta \lambda_{\text{tuning range}} \) is the total tuning range of the laser. For FDML operation, the time mismatch must be smaller than the time duration \( \tau_{\text{gate}} \), during which the bandpass filter transmits a single wavelength [21].

With the filter bandwidth \( \Delta \lambda \) and a factor \( \eta \approx 1/\pi \) accounting for the higher sweep speed in a bidirectional, sinusoidal, non-linear sweep [15], the gate time \( \tau_{\text{gate}} \) can be calculated as:

\[
\tau_{\text{gate}} = \frac{\eta \cdot \Delta \lambda}{f_{\text{drive}} \cdot \Delta \lambda_{\text{tuning range}}} \tag{3}
\]

Since the filter must be open at least as long as the mismatch between propagating wavelengths during one cavity round-trip, we also require that \( \tau_{\text{mismatch}} \leq \tau_{\text{gate}} \). The time gate criterion is therefore given as:

\[
l_{\text{fiber}} \cdot d \cdot \Delta \lambda_{\text{tuning range}} \leq \frac{\eta \cdot \Delta \lambda}{f_{\text{drive}} \cdot \Delta \lambda_{\text{tuning range}}} \tag{4}
\]

Equation (4) can be solved for the filter bandwidth \( \Delta \lambda \) as:

\[
\Delta \lambda \geq \frac{c \cdot \Delta \lambda_{\text{tuning range}}^2 \cdot d}{\eta \cdot n} \tag{5}
\]

Equation (5) provides several interesting insights for FDML operation within a dispersive cavity. First, it is remarkable that to first approximation the minimum filter bandwidth required for synchronization is independent of the cavity length. A longer cavity causes more dispersion and leads to a larger temporal asynchronization between the different wavelengths in the sweep. However, the gating time \( \tau_{\text{gate}} \) of the filter also increases proportionally to cavity length, which largely compensates for this effect. Second, the tuning range occurs as a quadratic factor in equation (5). This implies a large effect on the filter bandwidth requirements when a larger tuning range is desired. It is important to emphasize that only synchronization for two optical roundtrips was assumed in this analysis. For quasi-stationary operation, more roundtrips and a longer effective cavity photon lifetime are desired, which is provided by increasing the optical filter width.

To validate the theory developed above, our group constructed an FDML laser for operation at a center wavelength of 1070 nm as shown in Figure 1.10 (left). This represents an "external buffered" configuration, providing unidirectional sweeping at twice the filter drive frequency. The buffering concept is similar to the one described in section 2 [19], however here the additional optical delay is outside the laser cavity. The cavity consists of 1.7 km of Corning HI-1060 fiber, which is single mode at a wavelength of 1050 nm. An effective sweep rate of 236 kHz was achieved with a total tuning range of ~63 nm, as shown in Figure 1.10 (right). This tuning range supports an axial resolution of 11 \( \mu \)m in tissue for ophthalmic OCT imaging, as discussed in the chapter on Laser Medicine and Biomedical Imaging.

FDML laser performance was characterized using three FFP-TF filters with different bandwidths, in order to validate the theory developed above. With a dispersion value of \( d = 40 \) ps/nm/km for HI-1060 fiber, the refractive index \( n = 1.46 \), and a desired tuning range of 80 nm, equation (5) gives a minimum filter bandwidth of 0.16 nm for FDML operation. Filters with bandwidths of ~0.08, ~0.15, and ~0.3 nm were tested and the OCT point spread functions were measured as a function of imaging depth to assess resolution and system sensitivity, as shown in Figure 1.11. The FDML lasers incorporating 0.08 and 0.15 nm filters show
comparable sensitivity roll off at short delays, whereas the 0.3 nm filter has a more rapid roll off due to a wider instantaneous linewidth. At longer delays the 0.15 nm filter provides slightly enhanced performance compared to the 0.08 nm filter, possibly due to increased losses after one round trip in the case of the 0.08 nm filter. These observations support the theory developed in our group, and verify that an optimal filter width of ~0.16 nm is required for operation at sweep rates of 236 kHz.

Figure 1.10. Left: schematic for a 1070 nm FDML laser with external buffering operating at a sweep rate of 236 kHz. Right: average integrated output spectrum. A total sweep range of 63 nm is achieved, supporting an OCT imaging resolution of 11 μm in the eye.

Figure 1.11. OCT point spread functions for various imaging depths, obtained using an FDML laser at 1070 nm with three different tunable filter widths (0.08, 0.15, and 0.3 nm). As filter width increases, a larger tuning range is possible but the instantaneous linewidth is increased and imaging range decreases.

The 1070 nm FDML laser was subsequently used for in vivo imaging of the human retina at a record 236,000 axial lines per second, enabling high quality 3D imaging with significantly reduced motion artifacts. This application is discussed more in the chapter dealing with Laser Medicine and Biomedical Imaging. In general, the availability of FDML lasers at new center wavelengths will expand the range of applications for the technology, enabling more research areas to benefit from the improved performance of FDML compared to conventional swept lasers.

4. Enhanced Phase Stability in FDML Lasers

FDML lasers have been demonstrated to provide an exceptional combination of sweep rate, tuning range, output power, and narrow instantaneous linewidth. This makes them excellent
sources for high-speed OCT imaging, where the amplitude and frequency of interference fringes generated by a Michelson interferometer can be used to generate 3D maps of a sample’s microstructural architecture. With a laser that is highly phase-stable, however, it is possible to analyze the phase of the OCT interference fringes in order to detect picometer-scale surface displacements [23]. This technique is often referred to as OCT phase microscopy, or more generally, phase sensitive OCT. Phase-based techniques provide a complementary contrast mechanism to standard OCT analysis. Recently, our group has demonstrated that the quasi-stationary operating regime of FDML lasers makes them very well suited for phase-sensitive OCT imaging [18]. FDML lasers can detect surface features as small as 39 pm, comparable to the best OCT phase microscopes previously demonstrated, but at speeds up to an order of magnitude faster.

The phase of the interference signal generated during OCT imaging is analyzed by Fourier transforming the fringes and then evaluating the phase, as opposed to the amplitude, as a function of sample depth. This phase information can be exploited in two ways. Differential phase information measured at multiple time points can be used for Doppler flow imaging [24], while absolute phase information measured at multiple spatial locations can be used for OCT phase microscopy [23]. In both cases, small changes in the phase of the interference signal can be correlated to small, sub-resolution changes in the location of backscattering or backreflecting surfaces within the sample. These changes are not detectable using conventional OCT analysis since the phase information is discarded during image formation. Phase sensitive OCT imaging requires a light source with extremely high phase stability, since phase jitter in the laser can easily drown out the phase changes associated with displacements of the sample. Simultaneously, high-speed imaging is desirable in order to minimize parasitic sample motion and maximize the range of displacements.

FDML lasers operate in a quasi-stationary regime where each wavelength in the sweep has many characteristics of a narrowband continuous-wave laser. Our group demonstrated that FDML lasers achieve very high levels of phase stability by measuring the phase noise of a series of conventional swept lasers, standard FDML lasers, and buffered FDML lasers. Figure 1.12 shows the setup used for making phase sensitive OCT measurements. 95% of the laser power enters a common path Michelson interferometer. Here, the front surface of a thin glass cover slip provides the reference reflection for the interferometer instead of a separate reference arm. A common path setup is advantageous for phase-based measurements since it eliminates phase noise arising from the different paths traveled by the sample and reference light in a typical Michelson interferometer. A sample, such as a biological tissue or photonic device, can be placed on the back surface of the coverslip.

Five percent of the laser power is directed to a second common path interferometer, which is used to calibrate out the slow phase drift of the FDML laser. This calibration is required since the phase noise of FDML lasers consists of a low amplitude white Gaussian component and a larger amplitude slow “drift” component. The slow component typically has a period of several milliseconds and is likely caused by thermal or mechanical drift in the FFP-TF. Calibration of this drift is performed by low-pass filtering the calibration signal and subtracting it from the sample signal. The sample and calibration channels are simultaneously recorded by a high-speed data acquisition system. A computer is used for resampling the interference fringes onto a uniform optical frequency spacing, Fourier transformation, phase extraction, and calibration.

The sensitivity of the system to surface displacement (displacement sensitivity) was measured by recording the phase at the back surface of a 210 μm cover slip relative to the front surface. Phase information was obtained by Fourier transforming the interference fringes, isolating the back surface reflection, and finding the angle of its complex-valued peak. Buffered FDML lasers with sweep rates of 42, 117, and 370 kHz were constructed by varying the fiber length within the laser cavity. A non-buffered FDML laser operating at 42 kHz and a conventional swept laser [15] operating at 2 kHz were also tested. All lasers had a similar tuning range (~110 nm) and average output power (~11 mW) at a center wavelength of 1285 nm. The same FFP-TF and semiconductor optical amplifiers were used in all of the lasers.

Optical path displacement $\Delta z$ can be calculated from the measured phase $\Delta \phi$ using the relationship $\Delta z = \lambda_c \Delta \phi / (4 \pi n)$, where $\lambda_c$ is the center wavelength and $n$ is the sample refractive index [25]. The standard deviation of $\Delta z$ over several hundred measurements gives the system displacement sensitivity. Differential displacement sensitivities were calculated by subtracting the measured phase of consecutive axial scans $\Delta \phi - \Delta \phi'$. This measurement gives an indication of how well FDML lasers will perform for Doppler OCT imaging. Finally, the theoretical signal to noise ratio (SNR) limited displacement sensitivity for each laser was calculated using $\Delta z_{\text{lim}} = \left( \frac{\lambda_c}{4 \pi n} \right) \text{SNR}^{-1/2}$, where SNR is measured at the back surface reflection of the cover slip[25]. The SNR-limited displacement sensitivity is a theoretical limit and can be used to judge the level of excess phase noise in a laser. The SNR ranged from 62 – 77 dB for the lasers tested, and is calculated as the peak reflection intensity divided by the noise floor present within the same measurement.

Figure 1.13 shows the displacement sensitivity measurements for a conventional swept laser operating at 2 kHz (2,000 sweeps per second) and buffered FDML lasers operating at 42, 117, and 370 kHz. The buffered FDML lasers provide 2.2 – 5.8x better displacement sensitivity while operating at speeds that are 31 – 185x faster. Detailed results of these measurements are shown in the Table 1.1, column 2. All FDML lasers provide improved displacement sensitivities (DS in Table 1.1) compared to the conventional swept laser, even though the FDML sources operate at much higher sweep speeds. Comparing the non-buffered FDML laser at 42 kHz to the buffered FDML laser at 42 kHz, buffered FDML provides an additional 1.8x improvement in displacement sensitivity because the buffered FDML laser produces alternating sweeps, in groups of two, that are virtual optical copies of each other [19]. Since no filtering or amplification occurs between the two output couplers, the sweeps have increased phase correlation compared to non-buffered FDML lasers. As the sweep rates of the buffered FDML lasers are increased, displacement sensitivity degrades moderately from 39 pm at 42 kHz to 102 pm at 370 kHz. This compares favorably with previously reported displacement sensitivities of 25 pm at 29 kHz for spectrometer-based systems [26] and 475 pm at 16 kHz for conventional swept lasers [27]. For surface profilometry applications, where displacements of a single surface are measured, a buffered FDML laser could measure a continuous range between the displacement sensitivity (39 – 102 pm) and the laser coherence length (> 4 mm), over ~8 orders of magnitude.
Figure 1.13. Phase noise displayed as optical path displacement error for a conventional swept laser source operating at a sweep rate of 2 kHz (top left), and buffered FDML lasers operating at 42 kHz (top right), 117 kHz (bottom left) and 370 kHz (bottom right). FDML provides increased displacement sensitivity at much higher sweep speeds.

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>DS [pm]</th>
<th>SNR Limit [pm]</th>
<th>DDS [pm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional swept laser @ 2 kHz</td>
<td>226</td>
<td>9</td>
<td>361</td>
</tr>
<tr>
<td>FDML @ 42 kHz</td>
<td>71</td>
<td>26</td>
<td>115</td>
</tr>
<tr>
<td>Buffered FDML @ 42 kHz</td>
<td>39</td>
<td>22</td>
<td>43</td>
</tr>
<tr>
<td>Buffered FDML @ 117 kHz</td>
<td>52</td>
<td>38</td>
<td>56</td>
</tr>
<tr>
<td>Buffered FDML @ 370 kHz</td>
<td>102</td>
<td>50</td>
<td>119</td>
</tr>
</tbody>
</table>

Table 1.1. Displacement sensitivity (DS), signal-to-noise ratio (SNR) limited displacement sensitivity, and differential displacement sensitivity (DDS) for a conventional swept laser, a non-buffered FDML laser, and three different buffered FDML lasers. Buffered FDML lasers provide displacement sensitivities that are comparable to spectrometer-based OCT systems, but at speeds 1.5 – 12x higher.

Table 1.1, column 3 shows the SNR-limited displacement sensitivities calculated for each laser. Buffered FDML lasers come within 1.4 – 2.0x of the SNR limit, compared 25x for the conventional swept source. This further highlights the enhanced phase stability of FDML lasers. Table 1.1, column 4 shows the measured differential displacement sensitivity for each laser. This shows the minimum displacement that can be measured between two consecutive axial scans by subtracting their phases. The performance of the conventional swept laser and non-buffered FDML laser degrade by a factor of $\sqrt{2}$ compared to their respective single-measurement displacement sensitivity values. This is expected since the phase noise of these lasers is mainly additive white noise. For the buffered FDML lasers, however, the differential and single-measurement values are very similar. This enhancement is also the result of the multiple optical copies of the wavelength sweeps produced by buffered FDML lasers, and could significantly improve Doppler OCT measurements in the future. Further improvements may also be possible by adding additional output couplers to extract larger numbers of highly phase correlated sweeps.

The buffered FDML laser operating at 117 kHz was used to demonstrate high-sensitivity high-speed OCT phase microscopy for two different applications: the detection of nanometer-
scale time-varying surface waves; and the detection of nanometer-scale spatially-varying surface features. For the first application, a gold mirror was mounted to a PZT transducer. The phase was measured at one point on the mirror as the PZT was actuated over +/- 3 nm at a rate of 5 kHz. As shown in Figure 1.14 (left), the FDML laser and phase-sensitive OCT detection system were capable of clearly resolving this small, rapid surface motion. The slowly varying offset in the measured position is motion of the mirror mount relative to the reference surface.

For the second application, a glass coverslip was placed in the sample arm. The phase of the back surface relative to the front surface was measured at each point in a 1000 x 1000 μm square region and displayed as an optical path difference in a false color image. The results of this 3D OCT phase microscopy experiment are shown in Figure 1.14 (right). Exceptionally low phase noise is evident in the resulting image. Nanometer-scale surface defects and grooves are visible in this sample that is nominally “flat”, and nonlinear variations in sample thickness (+/- 2 nm) or refractive index (+/- 1.4 x 10^{-5}) can be visualized. The 3D dataset consists of 230 x 230 axial scans and was acquired in only 0.45 s. This demonstrates that buffered FDML lasers can perform 3D OCT phase microscopy with nanometer sensitivities at speeds significantly higher than other technologies.

In general, buffered FDML technology provides an exception combination of high phase stability and high sweep rates. This makes FDML lasers a good choice for phase-sensitive measurements, including OCT phase microscopy, Doppler flow imaging, and phase-based surface profilometry. Future improvements and new buffering concepts may further improve the displacement sensitivity and sweep rate, increasing the phase dynamic range and opening new areas of investigation.

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Optical Coherence Tomography for Nondestructive 3D Evaluation

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Optical coherence tomography (OCT) is a cross-sectional imaging modality that creates 2D and 3D maps of architectural morphology by interferometrically measuring the echo time delays of light. OCT is conceptually similar to ultrasound imaging, except the spatial resolution of OCT is typically 3 – 30 μm and the penetration depth is 1 – 3 mm. OCT technology is described extensively in the chapter dealing with Laser Medicine and Biomedical Imaging. OCT has historically found the most widespread use in medical fields such as ophthalmology, cardiology, gastroenterology, gynecology, and urology. More recently, our group has investigated new applications for OCT in nondestructive material evaluation. By combining high-speed Fourier Domain Mode Locked (FDML) lasers with advanced OCT data acquisition and image processing techniques, we have performed 3D analyses of historical works of art from the Harvard University Art Museums and optical materials from the Lawrence Livermore National Laboratory. OCT is well-suited for samples where a 3D microstructural analysis is required but removal of material is problematic or impossible.

1. OCT for Studies in Art Conservation

The field of art conservation science is primarily focused on preserving, restoring, and understanding the creation of historical works of art. Therefore art conservation relies on a thorough understanding of the materials and techniques used to create artwork. A great deal of this understanding can be obtained by studying the microstructural properties of the artwork, such as the thickness of various layers of paint or glaze. Traditionally, such studies have been carried out by removing small pieces of material from the edges of specimens. However a nondestructive technique for assessing microstructure is clearly more desirable due to the historic and monetary value of many works of art. Optical methods are attractive for their ability to perform high resolution, non-contact imaging using incident power levels low enough to avoid damaging the sample. Previously, techniques such as holography, speckle pattern interferometry, and optical coherence tomography (OCT) have been applied to the study of artwork [1-4].

Amongst the optical imaging techniques, OCT is especially well-suited for art conservation science since it can characterize the 3D layered structures common to many forms of art. OCT instruments utilize low-power near infrared (IR) radiation (typically 700 – 1400 nm) that can penetrate up to several millimeters of common material such as varnish, glaze, and paint. The working distance of OCT instruments can be set to several centimeters, enabling non-contact imaging and preventing mechanical damage to the sample. Finally, the axial resolution of OCT instruments can be < 5 μm, which is sufficient for analyzing thin layers of material often present in works of art. With the advent of Fourier domain OCT techniques[5-7] and corresponding increases in imaging speed, three-dimensional OCT (3D-OCT) data can now be acquired at up to 75,000 axial lines/sec using spectral / Fourier domain OCT [8] and
up to 370,000 axial lines/sec using swept source / Fourier domain OCT with Fourier domain mode locked (FDML) lasers [9]. This high-speed 3D imaging technology allows large regions of a particular piece to be fully analyzed in seconds.

Other groups have previously demonstrated the application of OCT for some aspects of art conservation. These areas include the including analysis of archaic jade objects [10], glaze layers on porcelain and faience ceramics [4], the degradation of parchment [11], and the layered structure of paintings and varnishes [12-17]. OCT has also been shown to correlate well with conventional stratigraphy of paintings, where samples are physically removed and analyzed using light microscopy [13, 14]. OCT can be used to visualize deeply situated layers such as underdrawings, depending on the transparency of the overlying material [15]. An analysis of canvas deformation was also previously demonstrated in order to understand the influence of environmental conditions on the painting degradation [15, 18].

Our group has applied high-speed 3D-OCT imaging to investigate a previously unexplored area of art conservation science; the analysis of small tool marks such as those used to create gold punchwork. On the gilded surfaces of panel paintings from the early Italian Renaissance, halos and garments were often adorned with impressions of punches in various shapes. The historical development of the punch technique, its spread from Italy to Bohemia and France, the manufacture of tools, the relevance of punch marks for problems of attribution, and questions regarding artists and their workshops sharing or handing down tools have all been important research areas. Perhaps most importantly, gold punch decorations can be used to link a particular painting to potential creators, since the motif punches or formalized clusters of punches are uniquely characteristic of specific workshops [19, 20].

3D structural information of punch marks is particularly difficult to obtain when paint, discolored varnish, or other material is deposited on top of the tool mark. Most studies in this field have been based on visual examination, hand sketches, or conventional photography and therefore often fail to observe fine details of the punch marks. Marks made with the same tool can be misidentified as being made with different tools, or vice versa. Therefore a 3D microscopic imaging technique such as 3D-OCT is potentially valuable for analyzing punches, where microscopic defects in the marks could serve as “fingerprint” characteristics of a specific punch tool.

Our group studied gold punchwork in several paintings using 3D-OCT imaging. Here, we describe the results obtained from “Marriage of the Virgin,” produced by the Master of the Orcagnesque Misericordia (active between 1375 – 1400). The 3D-OCT data was compared to high-resolution digital photographs acquired with a state-of-the-art digital camera. Although the OCT and photography systems provided similar transverse resolution (15 – 20 μm), 3D-OCT was able to detect micron-scale features in the punchwork that could not be detected using photography. This was especially evident in “Marriage of the Virgin”, where an aged varnish layer obscures the gold layer. These features can conceivably be used to identify other paintings made using the same punch tools.

“Marriage of the Virgin” is a painting on a wooden support. This piece contains a large amount of gold punchwork detailing as well as an aged varnish surface layer that makes visual inspection of the punch details difficult. Figure 1.1(A) shows a standard-resolution photograph of the painting, which is 37.4 x 23.0 cm (X x Y) in dimension. The red boxes indicate two regions of the painting that contain gold punchwork detailing. Figure 1.1(B,C) show enlarged views of the regions of interest. The yellow arrows indicate three specific circular punches that were analyzed using 3D-OCT and high resolution color photography.

3D-OCT data sets of the gold punches were acquired using a swept source / Fourier domain OCT imaging system. This technology is described in the chapter dealing with Laser Medicine and Biomedical Imaging. A buffered FDML laser was used as the light source,
providing unidirectional wavelength sweeps at 42,000 sweeps/sec (42 kHz). The laser tuned over a range of 118 nm at a center wavelength of 1287 nm, providing an axial image resolution of 9.3 $\mu$m in air or ~6 $\mu$m in material such as paint or varnish. Although FDML lasers with sweep rates up to 370 khz have been demonstrated [9], the data acquisition system used for this study is not compatible with operation at such speeds. Each 3D dataset consisted of 512 x 512 x 512 pixels (X x Y x Z), spanned a region of 4 x 4 x 3 mm, and was acquired in ~6 sec.

Figure 1.1. “Marriage of the Virgin”, 1375 – 1400. A. Photograph of the painting with regions of interest indicated by red boxes. Painting dimensions are 37.4 x 23.0 cm. B. Enlarged view of the first region of interest, showing the location of the first gold punch. C. Enlarged view of the second region of interest, showing the locations of the second and third gold punches.

Figure 1.2(A) shows a synthetic en face OCT image of the first circular punch. This image was formed by axially summing each line in the volumetric data set over the entire depth range of the volume, similarly to what is done in ophthalmic 3D-OCT imaging for en face visualization of the retina [21] The outline of the large circular punch and surrounding small punches is clearly visible in the OCT image. Since a 3D dataset is acquired, cross-sectional images can also be generated with exact registration to the en face surface view. The red and blue dashed lines indicate the locations of the cross-sectional images shown in Figure 1.2(B) and Figure 1.2(C). The cross-sectional images reveal a 50 – 220 $\mu$m thick varnish layer, indicated by the white arrows, uniformly deposited on top of the gold layer. The punch depth can be quantitatively measured as 100 – 120 $\mu$m.

Figure 1.2. OCT images of the first gold punch in “Marriage of the Virgin.” A. En face image formed by summed voxel projection, where every line in the 3D dataset is axially summed over the entire depth range. Red and blue lines indicate the locations
3D-OCT imaging also enables the application of arbitrary cut planes, which in this case can be used to visualize the gold layer separately from the varnish layer. This concept is illustrated in Figure 1.3. The dashed line in Figure 1.3(A) indicates the orientation of a cut plane parallel to the surface of the painting. The cut plane can be translated perpendicularly to the surface, as indicated by the red arrows, and an OCT image can be extracted at each location. Figure 1.3(B) shows the OCT image extracted when the cut plane is positioned inside the varnish layer. Note the lack of detail and diffuse scattering produced by the varnish. Figure 1.3(C) shows the OCT image extracted when the cut plane is positioned inside the gold layer. Compared to the en face image formed by axial summation in Figure 1.2(A), the image in Figure 1.3(C) shows significantly more detail since the confounding effects of the varnish layer have been removed.

Figure 1.3. A. YZ cross-sectional image of the first gold punch. Dashed line shows the orientation of an image plane parallel to the surface of the painting. The plane can be translated perpendicularly to the surface. B. Single-slice en face image obtained by positioning the plane in the varnish layer. C. Single-slice en face image obtained by positioning the plane in the middle of the gold layer. More detail is apparent when the gold layer is analyzed separately from the varnish layer.

To evaluate the potential for 3D-OCT to identify punches created with the same tool, two additional regions on the same painting were imaged and compared with high-resolution color photographs. OCT images of the gold layer were extracted for each punch using arbitrary cut planes as described above. Figure 1.4(A-C) shows the OCT images corresponding to the 1st, 2nd, and 3rd punches, respectively. Several characteristic “fingerprint” features are visible in each punch, including a small ridge at 10 o’clock and a widened depression at 1 o’clock, as indicated by the red arrows. These features are nearly identical in each punch and most likely represent imperfections in the tool used to create the punches. Therefore these characteristic features as seen with 3D-OCT could possibly be used to identify other works of art produced using the same tool. Figure 1.4(D-F) shows high resolution color photographs of the same three punches as Figure 1.4(A-C). The varnish layer heavily obscures the fine details of each punch, making it impossible to detect the characteristic features visible in the OCT images. Surface scratches in the gold and discoloration in the materials further add to the difficulty in analyzing the punches. In this
example, 3D-OCT is much better suited for characterizing the punches than high resolution photography.

Compared to high resolution digital photography, 3D-OCT is more suitable for the analysis of gold punchwork. 3D-OT is capable of quantitative measurements of punch depth, and can also identify unique features of the 3D punch profile not visible with high resolution photography. These “fingerprint” features corresponding to imperfections in the tool used to create the punches were visualized in an original 14th century panel painting, and the 3D-OCT data could conceivably be used to identify other works created using the same tools. In the future, we will study multiple works containing gold punches attributed to the same artist, and will attempt to determine whether or not the same tools were used to create each work. We will also study known and suspected forgeries, and attempt to verify that different gold punch tools were used to create the forgeries than the authentic works. In general, 3D-OCT will improve the understanding of historical art work by enabling 3D microstructural examination without the need to remove material.

Figure 1.4. A-C. En face OCT images of the first, second, and third gold punches in “Marriage of the Virgin”, obtained by positioning a cut plane in the middle of the gold layer. Red arrows indicate unique identifying features, suggesting that the same tool was used to create all three punches. D-F. High resolution color photographs of the same three punches. Identifying features are not visible with photography due to the lack of depth selectivity and the presence of the surface varnish layer.

2. OCT for the Evaluation of Optical Materials

In high-energy optics, repeated exposure to intense optical beams can lead to structural damage in lenses and other components. When damage is detected early, before catastrophic failure, the defects can often be repaired using thermal ablation or annealing techniques. The optical components can be inspected using conventional light microscopy, but this requires removing each component from what are typically very complex experimental setups, performing the inspection, replacing the components, and realigning the system. A more suitable approach would be to quickly analyze the optics in situ, removing the requirement for time-consuming microscopic inspections.
In collaboration with researchers at Lawrence Livermore National Lab, our group has investigated the use of high-speed 3D-OCT to detect microstructural defects in high-power optical components. These components are exposed to high intensity pulsed laser beams with energy densities of 20 – 30 J/cm² and pulse durations of 3 – 7 ns. The components can develop defects on the exposed surfaces or within the bulk of the material. 3D-OCT can be used either to closely examine the microstructural properties of a known defect, or to quickly screen a large optic for any signs of damage. For this study, a swept source / Fourier domain OCT imaging system identical to the one described in Section 1 was used. Two groups of representative samples were analyzed. The first sample was a piece of standard optical glass that contained a series of surface defects. The second group of samples consisted of several pieces of KDP crystal that contained damage in the bulk of the material.

The optical glass was analyzed and 3D-OCT was assessed for its ability to characterize the microstructural details of surface damage. Figure 1.5 shows 3D visualizations of one characteristic surface damage feature. The acquisition of the entire 3D data set of a 1.5 mm x 1 mm x 5 mm volume enables visualizations in the form of projection views in three orthogonal directions, as shown in Figure 1.5(A). 3D volume rendered images of the damage can also be generated as shown in Figure 1.5(B,C). The data set was acquired by imaging through the back surface of the glass at 29,000 axial lines per second (29 kHz). The 1024 x 512 x 200 pixel volumetric data set was acquired in ~3.5 seconds. The axial resolution in the material was about 10 μm, and the transverse resolution about 30 μm. With 3D-OCT imaging speeds of up to 370 kHz made possible by FDML laser technology, a large optic with a 5 cm diameter could be fully analyzed at high resolution in ~6 minutes without removing the optic from its setup. The current system was limited in speed only by data acquisition electronics, which will significantly improve over the coming 1-2 years.

**Figure 1.5.** Volumetric images of surface damage in optical glass formed by high-intensity laser radiation. A. Projection of the volumetric data onto three orthogonal planes. B. Projections (grayscale) with a volume rendering (orange) superimposed. C. Volume rendering only.

A larger survey scan of the optical glass was also performed in order to assess the ability of 3D-OCT to quickly locate surface damage sites. Figure 1.6 shows a single frame from this survey scan. The frame is 4.5 mm in length and ~2 mm in depth, consisting of 4096 x 1024 pixels, and was acquired in 0.14 seconds. Six damage zones are clearly visible. The insets show light microscopy images of the same damage sites for comparison. 3D-OCT can provide comparable quality images but is much easier to perform in situ.
The second set of samples consisted of KDP glass with bulk damage to the volume of the material. Figure 1.7 illustrates the manner in which the optical damage was created in the KDP, and the orientation of the OCT imaging beam. The damage was written in a series of stripes within the KDP by exposing the material to a focused, high-intensity pulsed laser. Figure 1.8 shows an en face reconstruction of a KDP sample exposed to 7 ns pulses with pulse intensities of 28 J/cm$^2$. The samples show some surface damage even though the beam was focused inside the KDP. The surface damage appears as circular spots approximately 33 μm in diameter. Figure 1.9 shows a cross-sectional image through one of the damaged regions. Subsurface bulk damage is visible approximately 80 μm beneath the surface. This demonstrates that 3D-OCT is also capable of locating small, subsurface bulk damage in materials exposed to high power optical pulses.

Figure 1.7. Schematic showing the orientation of optical damage zones written into a KDP crystal using a high intensity laser beam. The orientation of the OCT imaging beam is also shown.
In the future, a system will be developed for imaging high-power laser optics \textit{in situ}. This will require long working length objectives and a mechanism capable of scanning the OCT beam over large areas. High-speed FDML lasers will be incorporated to enable comprehensive sample analysis in time scales of several minutes. This 3D-OCT technology will decrease experimental downtime in high-energy optical setups and prevent expensive components from degrading to the point where they cannot be readily repaired.

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