Advanced Technologies for Optical Frequency Control and Optical Clocks

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Outline

Few-cycle laser development
- Ti:sapphire, Cr:forsterite, Cr:YAG
- Phase sensitive nonlinear optics
- Attosecond-precision laser synchronization

Optical frequency metrology with ultracold hydrogen
- Hydrogen spectroscopy and frequency referencing
- Locking of femtosecond laser comb to single frequency cw laser

Nonlinear optical techniques for comb technology
- Efficient SHG and DFG with chirped-grating PPLN
- 3-to-1 self phase-locked optical frequency divider
- DFG for comb locking to methane-stabilized HeNe laser

Ultra-broadband mirrors and saturable absorbers for few-cycle lasers
- Novel wide-area GaAlAs oxidized mirrors
- Saturable Bragg reflectors for few-cycle lasers

Cylindrical photonic bandgap fibers
- Novel microstructured fiber for nonlinear optics
- Broadband dispersion characteristics of bandgap fibers

Ultra-low-jitter modelocked diode laser
- Locking to visible wavelength reference
5-fs Ti:sapphire Laser

- double-chirped mirrors
- enhanced SPM
- octave-spanning spectrum
- dispersion-managed modelocking
Chirped and Double-Chirped Mirrors

Bragg-Mirror:

\[ \text{TiO}_2 / \text{SiO}_2 \]

\[ \text{SiO}_2 - \text{Substrate} \]

\[ \lambda_B/4 \text{- Layers} \]

Chirped Mirror:

Bragg-Wavelength \( \lambda_B \) Chirped

\[ \text{SiO}_2 - \text{Substrate} \]

\[ \lambda_2 > \lambda_1 \]

Negative Dispersion:

\[ \lambda_1 \]

\[ \lambda_2 \]

\[ \text{SiO}_2 - \text{Substrate} \]

\[ \text{SiO}_2 - \text{Substrate} \]

\[ \text{Air} \]

Double-Chirped Mirror:

Bragg-Wavelength and Coupling Chirped

\[ d_h \leq \lambda_B/4 \]

\[ \text{SiO}_2 - \text{Substrate} \]

\[ \text{AR-Coating} \]

\[ \text{Air} \]

“Impedance” - Matching

\[ \text{Air} \]

\[ \text{SiO}_2 - \text{Substrate} \]

\[ \text{TiO}_2 / \text{SiO}_2 \]

\[ \lambda_B/4 \text{- Layers} \]

\[ \text{SiO}_2 - \text{Substrate} \]

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\[ \lambda_2 > \lambda_1 \]
DCM-Pairs Covering One Octave

Designed

Measured

Fabricated by Tschudi Group, Darmstadt

MURI - Technology for Optical Frequency Control and Optical Clocks
5-fs Pulse Characterization

- Nonlinear autocorrelation
- Spectrum
- Recovered amplitude and phase
Pulse-to-Pulse Phase Slip in a Modelocked Laser

\[ V_{\text{GROUP}} \neq V_{\text{PHASE}} \]

Modelocked laser

\[ \Delta \phi \]

\[ 2n_0 L/c \]
Phase-Dependent 2\textsuperscript{nd} Harmonic

\textbullet \text{ rf tones reveal } \frac{\partial \phi}{\partial t}

RF spectral power density [dB]

RF Frequency [MHz]

Laser \quad 5 \text{ fs pulse} \quad \rightarrow \quad \text{SHG} \quad \text{Pol.} \quad \text{Filter} \quad \text{PMT}

1160 \text{ nm} \\
+580 \text{ nm} \\
580 \text{ nm}

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Stopping the Optical Phase Slip

\[ mT_{\text{opt}} = T_{\text{rf}} \]

The optical frequency is locked to an exact multiple of the rf rep rate!
Locking an octave by SHG: \[ 2f_1 = f_2 = f_1 + \frac{mc}{2n_gL} \Rightarrow f_1 = \frac{mc}{2n_gL} \]
Second Harmonic Generation with Octave-Spanning Spectrum

=> Interference between fundamental and 2nd harmonic
Continuum Generation with Microstructured Fiber

Strong guiding shifts the zero-dispersion wavelength to the near visible

Spectrum resulting when 80fs pulses from a Ti:sapphire oscillator are focused into a holey fiber

J. Ranka et al.

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14 fs Cr:forsterite Laser

- All solid state
- 1.3 µm wavelengths

Recent result: SBR stabilized

Chuboda et.al.

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20-fs Cr\textsuperscript{4+}:YAG Laser

Nd:YVO\textsubscript{4} Laser – 1064nm

f = 10 cm

DCM

SBR

2-cm Cr\textsuperscript{4+}:YAG

OC

\begin{itemize}
  \item SBR Reflectivity
  \item Wavelength (\textmu m)
  \item Autocorrelation
  \item 20 fs FWHM
\end{itemize}

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Overlapping Femtosecond Laser Spectra

Ti:Sapphire, Cr:Forsterite and Cr:YAG
A Compact Prismless Ti:sapphire Laser

Octave-spanning spectrum

Future:
- Even more compact
- Scaling to higher repetition rates
- >500 MHz, ring laser

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Overlapping Femtosecond Laser Spectra

- Compact, prismless octave spanning Ti:sapphire laser
- Stabilized Cr:forsterite laser
- Laser synchronization 300 asec timing-jitter
- Opportunities: extended frequency comb: 600–1600 nm and/or single-cycle pulse generation
The residual out-of-loop timing jitter measured from 10mHz to 2.3 MHz is 300 as (a tenth of an optical cycle)

Output spectrum: 650-1450nm
Optical Frequency Metrology with Ultracold Hydrogen

OVERALL GOAL
To pursue ultraprecise spectroscopy of ultracold atomic hydrogen for:

SCIENCE
• Resolve discrepancies in the theory of quantum electrodynamics
• Better values for fundamental constants
• Test theories of atomic interactions and atomic structure

TECHNOLOGY
• Explore the possibilities for an atomic hydrogen optical clock
• Develop and apply techniques for measuring the frequencies of optical transitions
• Stimulate the development and application of optical frequency combs

IMMEDIATE GOAL
Measure absolute frequencies of transitions such as 2S → 10S (2-photon, 730 nm)
using atomic hydrogen as an optical frequency standard
Spectroscopy with a Hydrogen Optical Clock

Lock to 1S-2S (243 nm)

- Excite 1S→2S transition (known to about 1 part in $10^{14}$.)
- Lock 486 nm laser to 1S→2S
- Excite two-photon transition such as 2S→10S
- Measure excitation frequencies with an optical frequency comb, referenced to the 486 nm laser, i.e. referenced to hydrogen
Nonlinear Optical Techniques for Comb Technology

Ultra-broadband SHG with zero group velocity mismatch
• 70 nm bandwidth for 1580 nm → 790 nm in PPKTP

Difference-frequency generation of 3.39 μm
• locking Ti:sapphire laser comb to CH-stabilized HeNe laser
• collaboration between MIT and JILA

3-to-1 frequency divider
• self-phase-locked optical parametric oscillator with cascaded nonlinear interactions in PPLN
• provides phase-locked markers at 532, 798, and 1596 nm
Difference Frequency Generation of 3.39 \( \mu \text{m} \)

- Ti:S fs pulses
- Servo to lock comb spacing to He-Ne
- PPLN difference-frequency generator
- cw 3.39 \( \mu \text{m} \) output
- Phase-locked
- CH-stabilized He-Ne @ 3.39 \( \mu \text{m} \)

N pairs of modes yield \( N^2 \) enhancement
\( N \sim 15,000 \)

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Self-Phase-Locked OPO Yields 3:2:1 Frequency Markers

- **Pump**: 532 nm
- **Signal**: 798 nm
- **Idler**: 1596 nm

**OPO grating**
**SHG grating**

**Self-phase locking** ($\Delta \omega = 0$)

**PZT**
Ultra-Broadband Saturable Absorber Mirrors

GOALS

• High index-contrast oxidized mirrors for broadband low dispersion
• In-based absorber optimized for wavelength – integrated on mirror
• Large area for low power density
• Stable, durable structures

PROGRESS

• Integrated broadband SBRs for Cr:YAG and Cr:forsterite lasers
• Dramatic improvement in layer stability with AlGaAs/Al$_x$O$_y$ structures
• Wide area oxidization (>500\,\mu m diameter)

GOALS

GaAs/Al$_x$O$_y$ Mirror

<table>
<thead>
<tr>
<th>delaminated interface</th>
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</thead>
<tbody>
<tr>
<td>GaAs</td>
</tr>
<tr>
<td>Al$_x$O$_y$</td>
</tr>
<tr>
<td>GaAs substrate</td>
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</tbody>
</table>

PROGRESS

AlGaAs/Al$_x$O$_y$ Mirror

<table>
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<tr>
<td>Al$<em>{0.3}$Ga$</em>{0.7}$As</td>
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</table>
Issues Affecting the Distributed Bragg Reflector

Oxidation of AlGaAs Layers

- Edges of mesa less oxidized than at center
- Mirror bandwidth a function of position

GaAs/InGaAs

$\text{Al}_x\text{O}_y$

$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$

GaAs substrate

99μm from mesa edge

13μm from mesa edge

R946, 5 hr, 415 C
Oxidized 11/13/2002

R946, 5 hr, 415 C
Oxidized 11/13/2002

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Issues Affecting Saturable Absorber

Sensitivity to Oxidation Time

Sensitivity to Oxidation Temperature

Sensitivity to Growth Temperature

Center = ~3mm from wafer edge

Center = ~11.4mm from wafer edge

Center = ~18.4mm from wafer edge

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OmniGuide Mirror Fibers

primary gap centered around 1.5 µm
Bandgap Fiber with and without Defect

Regular OmniGuide structure

Modified (defect) structure

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Mirror-guide Dispersion Characteristics

Bandgap fiber

Fiber with cavity mode

Dispersion $D$ (ps/nm-km)

Vacuum wavelength ($\mu$m)

Metallic

LH

1.55 $\mu$m

ZD

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Modelocked External External Cavity Diode Laser

- 500 \( \mu \text{m} \) gain section
- 50 \( \mu \text{m} \) saturable absorber section
- \( \lambda = 1547\text{nm} \), \( f = 9.35 \text{ GHz} \)
- BPF = 0.7 nm : \( \tau = 6.7 \text{ ps} \)
- BPF = 5 nm : \( \tau = 3 \text{ ps} \)

NEC external cavity MLLD

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Residual Phase Noise Measurement

- Vector signal analyzer for low frequency offsets (1-10 MHz)
- RF spectrum analyzer for high frequency offsets (10 MHz – 4.5 GHz)

(RF analyzer after mixer has higher sensitivity than for direct detection.)
Single-Sideband Phase Noise - Results

- Hybrid MLLD, 9GHz, 6.7 ps, Poseiden SBO
- Vector signal analyzer (0 – 10 MHz)
- RF spectrum analyzer (10 MHz – 4.5 GHz)

![Graph showing phase noise data for spectrum and vector signal analyzers.]

Integrated timing jitter from 10 Hz to 4.5 GHz = 86 fs

1kHz – 10MHz : 40 fs

154 fs including all noise spurs
SBO jitter = 5.6 fs (10 Hz to 10 MHz)
Synchronization of Modelocked Diode Laser to Visible Standard

MIT-JILA collaboration

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Timing Jitter Spectral Density of Stabilized MLLD

20 fs jitter (1Hz – 10 MHz)
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