It is a pleasure to welcome The International Symposium on Ultrafast Photonic Technologies (ISUPT) to MIT. The ISUPT was created to promote collaboration among researchers from Europe, the United Kingdom, the United States and Japan working on ultrafast photonic technologies for high-speed signal processing, precision metrology and next generation photonic networks with channel speeds of greater than 100Gb/s. The 1st ISUPT was held in Chiba, Japan in 2003 and the 2nd in St. Andrews, Scotland in 2005. This 3rd ISUPT again brings together leaders in ultrafast photonics from these different international communities to describe the latest advances in ultrafast photonics, discuss potential applications and consider future directions for research and development. The 2-day program features 19 invited speakers and 7 distinguished invited session chairs. This Proceedings includes bios of all invitees as well as abstracts and slides for the talks.

We are very grateful to the NICT, AIST and RIEC of Japan and to RLE and CIPS at MIT for their sponsorship and support of the Symposium, and we hope that you enjoy it.

Local Organizing Committee
James Fujimoto
Scott Hamilton
Erich Ippen
Franz Kärtner
## MONDAY, AUGUST 20, 2007 | STATA CENTER 32-123

### Session I: Ultrahigh-speed Transmission Systems

**Chair:** Teruo Sakurai, AIST

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<td>Masataka Nakazawa, Tohoku University</td>
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<td>9:30am</td>
<td>Reinhold Ludwig, Heinrich Hertz Institute</td>
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### Session II: Network Applications of Ultra-highspeed Systems

**Chair:** Chris Cole, Finisar

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### Session III: Ultrafast Technologies for Networks

**Chair:** Yuichi Matsushima, NICT

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<td>Naoya Wada, NICT</td>
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### Session IV: Ultrashort-Pulse Fiber Lasers

**Chair:** Matthew Grein, MIT Lincoln Laboratory

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<td>9:00am: Andrew Weiner, Purdue University</td>
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<td>10:00am: Shigeki Watanabe, Fujitsu Laboratories</td>
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Session I

Ultrahigh-speed Transmission Systems

Session Chair

Teruo Sakurai

Invited Senior Research Scientist
National Institute of Advanced Industrial Science and Technology
Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
Tel:+81-29-861-5080(ext35620) Fax:+81-29-861-5627
Email: teruo-sakurai@aist.go.jp

Teruo Sakurai was born in Kyoto, Japan in 1943. He received the B.S., M.S., and PhD degrees in physics from Kyoto University, in 1966, 1968 and 1973, respectively. He joined Fujitsu Laboratories Ltd. in 1971, where he studied ion implantation in semiconductors as well as ion channeling. In 1980, his research field was transferred to optical semiconductor devices; light emitters and detectors, integrated optoelectronic circuits. In 1996, he moved to The Femtosecond Technology Research Association (FESTA) where he was engaged in research of ultrahigh-speed optical devices and metrology using femtosecond X-ray pulses. Since April, 2005, he has been working at National Institute of Advanced Industrial Science and Technology (AIST).
New Frontiers in Optical Communication: Ultrahigh-speed Transmission and Coherent Transmission

Masataka Nakazawa

Research Institute of Electrical Communication
Tohoku University
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Tel: 81-22-217-5522, Fax: 81-22-217-5523, <nakazawa@riec.tohoku.ac.jp>
http://www.nakazawa.riec.tohoku.ac.jp

Abstract

There are two emerging technologies in recent optical transmission. One is ultrahigh-speed OTDM transmission with advanced modulation formats. The other is coherent optical transmission using an optical phase of the laser beam. As for the high-speed transmission technology, I describe 160 Gbit/s over 1,000 km distortion-free transmission using a time-domain optical Fourier transformation. For the coherent transmission technology, I describe a QAM transmission using a frequency-stabilized fiber laser at 1.55 m. The laser was frequency-stabilized to one of absorption lines of C2H2 molecules. A 1 Gsymbol/s coherent 64 QAM transmission with a spectral efficiency of 8 bit/s/Hz has been successfully achieved with the use of a 150 km-long optical PLL circuit.

After receiving his Ph.D. from the Tokyo Institute of Technology in 1980, Dr. Nakazawa joined the Electrical Communication Laboratory of Nippon Telegraph & Telephone Public Corporation. He was a visiting scientist at MIT from 1984 to 1985. From 1989 he led the High-speed Optical Transmission Research Group, and he became the first Distinguished Technical Member of NTT Laboratories in 1994 and the first NTT R&D Fellow in 1999. He was appointed a professor at the Research Institute of Electrical Communication of Tohoku University in 2001. His current interests are ultrahigh-speed optical transmission, coherent transmission, EDFAs, fiber devices, and lasers. Dr. Nakazawa is a Fellow of the IEEE, OSA, NTT and the IEICE. Recently, he served as the president of Electronics Society of the IEICE. He has published 360 papers and holds more than 100 patents. He has received many awards including the D. E. Noble Award 2002, the R. W. Wood prize 2005, and was a Thomson Scientific Laureate in 2006.
New Frontiers in Optical Communication: Ultrahigh-speed Transmission and Coherent Transmission

Masataka Nakazawa
Research Institute of Electrical Communication
Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai-shi, 980-8577 Japan

Outline

(1) Introduction

(2) Ultrahigh-speed OTDM transmission using time-domain optical Fourier transformation (OFT)
   • 160 Gbit/s-1,000 km DPSK-OFT transmission
   • All-optical FT using parabolic pulse train

(3) Highly spectral-efficient QAM coherent transmission using optical phase-locked loop (OPPL)
   • 1 Gsymbol/s, 64 coherent QAM optical transmission over 150 km with a spectral efficiency of 8 bit/s/Hz

(4) Summary

Optical communication trends

M-PSK, QAM
Coherent transmission with frequency-stabilized lasers

High-speed transmission
OTDM/OTFC
Driving force for high-speed optical networking

Spectrally efficient transmission
DWDM/FDM
Driving force for ultra-efficient large capacity FTTH

Conventional optical transmission
Waveform disturbed. The transmitted spectrum may vary

Compensation of individual waveform distortion in time domain

Distortion-free transmission with optical Fourier transformation (OFT)
The spectral shape must be maintained

Simultaneous elimination of all linear distortions (including time-varying perturbations)

How to realize OFT

1. The transmitted pulse is linearly chirped in the form
   \[ s_{in}(t) = \exp\left(\frac{-t^2}{\Delta \tau^2}\right) \] (\( \Delta \tau \) is the chirp rate)

2. When \( D = 0 \), the output \( \psi(t) \) is written in the following form
   \[ \psi(t) = \int_{-\infty}^{\infty} \exp\left(\frac{-\omega^2}{2 \Delta \nu^2}\right) \left(\hat{f}(\omega) \exp\left(\frac{-i \omega^2 \Delta \tau^2}{2 \Delta \nu^2}\right)\right) \frac{d \omega}{2 \pi} \]

3. When \( D = \Delta \nu \), the output \( \psi(t) \) is expressed as
   \[ \psi(t) = \int_{-\infty}^{\infty} \exp\left(\frac{-i \omega^2 \Delta \tau^2}{2 \Delta \nu^2}\right) \hat{f}(\omega) \frac{d \omega}{2 \pi} \]

4. The output waveform is proportional to the input spectrum \( \hat{f}(\omega) \).

160 Gbit/s-1,000 km OTDM DPSK transmission using time-domain OFT

160 Gbit/s transmitter
975 km transmission line
EDFA
Demodulated OOK signal after demultiplexed to 40 Gbit/s

Outline

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4. The output waveform is proportional to the input spectrum \( \hat{f}(\omega) \).
Features of QAM format:
- Two carriers with the same frequency are amplitude-modulated independently.
- The phase of the two carriers is 90 deg. shifted each other.
- 2^n QAM processes N bits in a single channel, so it has N times spectral efficiency compared with OOK.

Advantages of QAM optical transmission:
- Drawbacks of QAM wireless or metallic cable transmission:
  - Fading noise caused by obstacles
  - Narrow bandwidth transmission
- Optical fiber transmission:
  - Advantages of QAM optical transmission:
    - No fading noise in optical fibers
    - Broad bandwidth transmission

Quadrature Amplitude Modulation (QAM) format

Table: Eb/N0 at BER = 10^-4 is shown assuming synchronous detection.

\begin{align*}
\text{Eb/N0} (\text{dB}) & \quad \text{C/W (bit/s/Hz)} \\
16 \quad & \quad 1.6 \\
64 \quad & \quad 1.2 \\
256 \quad & \quad 0.8 \\
1024 \quad & \quad 0.4 \\
4096 \quad & \quad -0.4 \\
16384 \quad & \quad -0.8 \\
\end{align*}
Two emerging optical transmission technologies were described.

(1) Ultrahigh-speed OTDM transmission
   - 160 Gbit/s-1,000 km transmission was successfully achieved by combing DPSK and time-domain OFT.
   - All-optical time-domain FT was demonstrated by using XPM with a dark parabolic pulse. Distortion due to third-order dispersion was successfully eliminated.

(2) Coherent QAM transmission
   - We have successfully transmitted a polarization-multiplexed 1 Gsymbol/s, 64 QAM (12 Gbit/s) coherent optical signal over 150 km within an optical bandwidth of 1.5 GHz using a Nyquist filter.
   - Thus, a spectral efficiency of 8 bit/s/Hz has been achieved in a single channel.

Experimental result for polarization-multiplexed 1 Gsymbol/s, 64 QAM (12 Gbit/s) transmission over 150 km

Conclusion
Single Channel Transmission beyond 1 Tbit/s: Technology and Challenges

Reinhold Ludwig

Fraunhofer Institute for Telecommunications
Heinrich-Hertz-Institut, Einsteinufer 37, 10587 Berlin, Germany
phone: +49-30-31002-446, fax: +49-30-31002-241, email: ludwig@hhi.de

Abstract

The global traffic growth in 2005 was 115%. This growth will saturate the existing network capacity in only a few years (2008-2010). In 10 years even the very challenging capacity of 100 Tbit/s per fiber pair will not be sufficient to handle the projected IP traffic. To reach a capacity of 100 Tbit/s per fiber pair an optimized mixture of wavelength division multiplexing (WDM) and time division-multiplexing (TDM) has to be used. The ultimate limits of OTDM transmission technology are not given by the terminal equipment but by the transmission properties of the fiber link including all repeater or amplifier stages. With higher TDM bit rate data transmission in fiber is stronger affected by chromatic dispersion (CD), polarization-mode dispersion (PMD), fiber non-linearity, and the limited bandwidth of repeaters or amplifiers in the transmission link.

We combined DQPSK with OTDM-multiplexing technology and polarization-division multiplexing to generate a record single channel data rate of 2.56 Tbit/s. The 2.56 Tbit/s DQPSK data signal was transmitted over 160 km dispersion managed fiber (DMF).

In our presentation signal generation using advanced modulation formats, transmission over appropriate fiber spans and ultrafast demultiplexing will be discussed.

Reinhold Ludwig was born in 1952 in Lahnstein, GERMANY. He received the Ing.grad. degree from the Fachhochschule Kobenz in 1974 and the Dipl.-Ing. and Dr.-Ing. degrees from the Technical University Berlin in 1985 and 1993. In 1985 he joined the Heinrich Hertz Institute (HHI) Berlin, where he is involved in research on photonic components and systems. He worked as a visiting scientist at Nippon Telephone &Telegraph Co.(NTT), Japan in 1991 and at Bell Labs, USA in 1993. Since 1985 he authored and coauthored more than 300 scientific papers and holds several patents.

In 1996 he founded the first HHI spin-off company, LKF Advanced Optics GmbH, and served as CEO until the merger of LKF and u2t Innovative Optoelectronic Components GmbH in 2001. In 1999 his group received the Philip-Morris-Science Award and he was nominated for the Innovation Award of the German Bundespraesident.
Single Channel Transmission beyond 1Tbit/s
Technology and Challenges

R. Ludwig, C. Schubert
C. Schmidt-Langhorst
B. Hüttl, H.G. Weber

Optical Time Division Multiplexing (OTDM)

Base rate (40 Gb/s)
2560 Gb/s
40 Gb/s

40 GHz
pe-optical pulse

Fiber link ~ 500 km

640 Gbit/s: OTDM, single polarization
1280 Gbit/s: 640 Gbaud OTDM + DQPSK modulation format
2560 Gbit/s: 640 Gbaud OTDM + DQPSK + alternating polarization multiplexing

Pulse width needed for 640 Gbaud

Frequency domain

Time domain

Goal:
- 0.4 ps sech² Pulses
- low jitter
- low RIN
- no pedestal
- transform limited
- low linewidth
- high extinction ratio
- long term stability

Ultra Short Pulse Generation Scheme


Pulse source

S.C. Zeller et al, ECOC, Stockholm (S), 2004, Th 3.4.3

- fundamental mode-locking
- phase stable
- jitter 40 fs
- extinction ratio > 30dB
- 10 dBm output power
- low RIN
- ~ 10 GHz rep. rate
**Transmitter**

| 640 Gbaud transmitter | 40 Gbaud Transmitter | 80-8 640 Gbaud | Multiplexer |

- Pulse compressor contains 1 km fiber → phase drift
- Clock recovery required to synchronize pulses and modulation

DQPSK: Mach-Zehnder Modulator operating in push-pull mode
- Linear phase modulator

**Transmitter Summary**

| 40 Gbaud transmitter | OTDM-MUX |

**Fiber Link**

- Additional RIN small
- Output pulse width 0.4 ps after compensation
- Time bandwidth product: 0.6

| OTDM-MUX |

**Pulse Cleaning**

- >40 dB pedestal suppression
- Additional RIN small
- Additional jitter small
- 640 Gbaud transmitter 640 Gbaud receiver
- Pulse source

**2.56 Tbit/s Transmitter (for Lab system)**

- For real system: 64 modulators!
**640 → 40 Gbaud Demultiplexer**

- **Clock recovery**: EAM-based, operation supported by MUX asymmetry
- **Optical gate**: NOLM based on HNLF
- **Demultiplexing does not disturb DPSK signal**!

**Demux data (40 Gbaud)**

**640 Gbaud optical data**

**Results for 2.56 Tb/s over 160 km**

- Symbol rate: 640 Gbaud in One Polarization Single Wavelength
- PolMux and DQPSK: 2.56 Tb/s data signal
- BER back to back: error free (10^-9) detection reached
- BER after 160 km fiber link: error rate well below FEC Limit

**Conclusion**

- **Challenges of 1Tb/s and beyond**
  - Higher stability and availability
  - Overcoming fiber span limitations
  - Loss / bandwidth limitation
  - Small dispersion tolerances
  - PMD
- **2015 we need 50Tb/s per fiber pair**
  - Optical networking with appropriate combination of ETDM, OTDM, WDM

**Summary**

- Available pulse sources do not fulfill requirements for 640 Gbaud
  - Pulse compression scheme using:
    - Mode locked solid state laser
    - Pulse compressor
    - Pulse cleaner
    - Clock recovery for modulation
  - 0.4 ps pedestal free pulses achieved
- 2.56 Tb/s DQPSK data signal transmitted over 160km DMF
- HNLF- NOLM Demultiplexer with 1.8ps switching window:
  - Error free back to back
  - Below FEC threshold after 160km DMF
- Limitations due to:
  - EDFA bandwidth
  - DMF dispersion slope
  - PMD
High Speed Transmission Technologies for 100Gbit/s-class Systems

Itsuro Morita

KDDI R&D Laboratories
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Tel: +81 49 278 7865, Fax: +81 79 278 7821, <morita@kddilabs.jp>

Abstract

The demand for high speed optical transmission systems is increasing. However, the realization of single-channel 100Gbit/s-class high speed transmission has many technical challenges due to, for instance, a high sensitivity towards inter-symbol interference (ISI). In this paper, two approaches for 100Gbit/s-class high speed transmission are discussed. One is the approach using a compensator for polarization mode dispersion (PMD), which is one of the most severe impairments in high speed transmission. By utilizing Return-to-Zero differential phase shift keyed (RZ-DPSK) signals and a polarizer-based PMD compensator, 8 x 160 Gbit/s WDM field transmission over 200 km has been achieved. Another approach is to use multi-level signal, which can reduce the symbol rate in high speed transmission. With differential quadrature phase shift keyed (DQPSK) signal, 100Gbit/s transmission has been successfully demonstrated without optical time-division-multiplexing (OTDM).

Itsuro Morita received the B.E., M.E. and Dr. Eng. degrees in electronics engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1990, 1992 and 2005, respectively. He joined Kokusai Denshin Denwa (KDD) Company Ltd. (currently KDDI Corporation), Tokyo, Japan in 1992 and since 1994 he has been working at their Research and Development Laboratories. He has been engaged in research on long-distance and high-speed optical communication systems. In 1998, he was on leave at Stanford University, CA.
High Speed Transmission Technologies for 100Gbit/s-class Systems

Itsuro Morita
morita@kddilabs.jp
KDDI R&D Laboratories

Limitations in Higher Speed Transmission

- Larger impairment
  - Higher required OSNR
  - Lower tolerance
    - Chromatic Dispersion
    - Polarization Mode Dispersion
    - Fiber nonlinearity
  - ...
- BW Limitation in optical/electrical components

160Gbit/s Field Transmission Experiments with PMD Compensator

100Gbit/s Transmission Experiments with Multi-level Signal

PMD Characteristics

- 200km transmission line
- Measured by JME method for 10 hours with 90 seconds interval

PMD Characteristics of Spooled Fiber

- Spooled Fiber
- Installed Fiber

JGNII Optical Testbed segment B

Including aerial cable route
Total length: 200 km

JGNII Optical test bed is operated by NICT from April, 2004. The test bed includes aerial cable routes in Spans 2 and 3.
**Comparison of PMD Characteristics**

- 200km transmission line
- Measured by JME method for 6 hours with 10 minute interval

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Spooled Fiber</th>
<th>Field Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>1535 1540 1545 1550 1555 1560 1565</td>
<td>Mean DGD: 1.3 [ps]</td>
<td>Mean DGD: 1.3 [ps]</td>
</tr>
</tbody>
</table>

- 1.0 ps

**Transmission Performance**

- 8 x 160 Gbit/s WDM transmission over 200km

- Q-factor [dB]

- OSNR [dB/0.1nm]

- In-band FEC limit = 13.3 dB

- Corrected BER = 1E-13

- 1E-13

**DQPSK**

- Differential Quadrature Phase Shift Keying

- Higher symbol rate

- Narrower spectrum width

- Higher tolerance towards CD & PMD

- Required BW in Tx & Rx is halved

- 2 bit/symbol

- 3.2 psps

**KDDI & R&D Laboratories Inc. National Institute of Information and Communications Technology Sumitomo Osaka Cement Co.**

- 100Gbit/s transmission with DQPSK

- Optical spectra for 42.7Gbit/s signal

- Frequency (50GHz/div)
**Tx & Rx Configuration for 100Gbit/s DQPSK**

**Experimental Setup**

**Optical Spectrum and Waveforms**

**Performance Comparison – NRZ vs. RZ –**

**Summary**
Chris Cole received a B.S. in Aeronautics and Astronautics, and B.S. and M.S. degrees in Electrical Engineering from the Massachusetts Institute of Technology. As a staff member at Hughes Aircraft Company (now Boeing SDC,) he contributed to multiple imaging and communication satellite programs. While at M.I.T. Lincoln Laboratory, he worked on an EHF spread spectrum communication satellite payload. He then consulted on voice band communication product designs for Texas Instruments DSP Group and Silicon Systems Inc. (now Teridian.) After joining the Acuson Corporation (now Siemens Ultrasound,) Chris contributed to the system architecture, signal processing algorithms, and circuit designs for the Sequoia coherent imaging ultrasound platform, for radiology and cardiology applications. There, he managed the Hardware and Software Development Groups. Subsequently, as a Principal Consultant with the Parallax Group, he carried out signal processing analysis and product definition for several imaging and communication products.

Chris is currently a Director at Finisar Corporation, (which acquired his previous company; Big Bear Networks,) where he manages the design, integration and deployment of 40Gb/s and 100Gb/s LAN and WAN optical communication Transceivers. He is a Senior Member of the IEEE.
Future Networked Broadcasting System with Ultrahigh-speed Optical Transmission Technologies

Yoshihiro Fujita

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Tokyo 157-8510 , Japan
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Abstract

NHK demonstrated its 4000 line television system, SuperHiVision, for the first time in the world wide NAB show at Las Vegas last year and announced its development plan to broadcast it for the next generation television. Since then a number broadcasters around the world have begun to take a serious look at future TVs - the systems which will be the successors of today's HDTV. Studio broadcasting networks handling SuperHiVision signals require more than the channel speed greater than 50 Gb/s. They raise many questions how program production be made, and which network technologies applicable? Examples of these challenges are presented, including, uncompressed SHV signal material transmission system. The discussion will be focused on how will SuperHiVision push the ultrafast photonic technologies as an application driver.

Yoshihiro Fujita received the B.S.E.E. degree and the Ph.D. degrees from University of Tokyo, Japan, in 1976 and 1998, respectively, all in electrical engineering. Since 1976 he has been with the Japan Broadcasting Corporation (NHK) Tokyo Japan, where he has been engaged in the advanced broadcasting system research. He is currently the deputy director-general of NHK science and technical research laboratories. He and his co-workers are responsible for a number ultra HDTV system research and are also developing new broadcasting services based on the convergence technologies of telecommunication and broadcasting. He is the chairman of digital broadcasting R&D standardization group at ARIB (Association of Radio Industries and Businesses). ARIB was chartered by the Minister of Posts and Telecommunications as a public service corporation. He is a member of the IEEE and a member of the ITEJ (Institute of Television Engineers Japan).
Future networked broadcasting systems with ultra high-speed optical transmission technologies

Yoshihiro Fujita
Science & Technical Research Laboratories
NHK (Japan Broadcasting Corporation)

Changes of TV Screen in Japan

Future of Television Broadcasting

Ultra HDTV Demonstration at Major Shows

Result of Subjective Assessment Test-Visual Angle

Visual Angle and Sensation of Reality
Parameters of Ultra HDTV

Ultra HDTV
- 7,680 pixels
- 4,320 pixels
- Ultra HDTV
- HDTV
- Standard TV
- 1,920 pixels
- 1080 pixels
- 720 pixels
- 480 pixels
- Viewing angle: 30 deg., 100 deg., 3 H
- Scores of Subjective assessment: 1.5, 1, 0.5, 0
- H: picture height
- 0.75 H
- 1 H
- 1.5 H
- View angle (degree)
- Evaluated score of reality
- Evaluation scale: 40, 60, 80, 100

Standardization at ITU-R

- LSI: Large Scale Digital Imagery
- Expanded LSI
- EHS1: Extremely High-Resolution Imagery
- Evaluated score of reality: 3.0840 x 1089
- Recommendation ITU-R BT. 1560
- Recommendation ITU-R BT. 1561
- Recommendation ITU-R BT. 1562
- Recommendation ITU-R BT. 1563
- Recommendation ITU-R BT. 1564
- Recommendation ITU-R BT. 1565

Video format of Ultra HDTV

<table>
<thead>
<tr>
<th>Video Format</th>
<th>Information Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920 x 1080 (HDTV)</td>
<td>HD-SDI 1.5G bps</td>
</tr>
<tr>
<td>7680 x 4320 (Ultra HDTV)</td>
<td>Dual G Spec. 24G bps*1</td>
</tr>
<tr>
<td>1920 x 1080 (HDTV)</td>
<td>Full G Spec. 48G bps*1</td>
</tr>
<tr>
<td>7680 x 4320 (Ultra HDTV)</td>
<td>Full G 12bit Spec. 72G bps*1</td>
</tr>
</tbody>
</table>

*1 not yet standardized

Information Bit Rate of Ultra HDTV

Applications of Ultra HDTV

- Large displays for immersive feeling
- Large screen displays with wide visual angle of 180 degrees will provide immersive feeling.
- Direct view displays without constraints of viewing distance
- Displays for graphics, documents, electronic magazines, and so on.
- Flexible displays will provide a new application of Ultra HDTV in various scenes.
- Analytics
- Video archiving of various arts and architecturals, museum application, and medical application
- Multi-functional display
- Pseudo-sensing on the wall, electronic shopping terminal, and so on
- 3D televisions
- Components for Ultra HDTV will be a key component for 3DTV without glasses.
- Studio equipment for HD TV production
- Ultra HDTV images can be used as materials for HD TV production by cutting out the necessary part

Schedule for Ultra HDTV research and Development

- Ultra HDTV is a driving force for future electronics and information industries
Required speed and throughput of studio network

<table>
<thead>
<tr>
<th>Studio</th>
<th>Image Source</th>
<th>Number of Studio</th>
<th>128~512</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Image Source</td>
<td>4~12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required Speed</td>
<td>160Gbps~</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required Throughput</td>
<td>160Tbps~</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Image Source</th>
<th>Non-compressed</th>
<th>SDTV</th>
<th>HDTV</th>
<th>Ultra HDTV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Bit rate</td>
<td>270Mbps</td>
<td>1.5Gbps</td>
<td>24/48/72G bps</td>
<td></td>
</tr>
</tbody>
</table>

Live relay experiment

Advanced Ultra HDTV transmission system

Conclusion

- HDTV is the best quality TV achievable using the given state of the art.
- Ultra HDTV may be called HDTV in ten to twenty years.
- Recent data survey shows Web traffic, in particular video & audio streaming overtakes Pier-to-Pier as the largest percentage of bandwidth on network.
- Ultra HDTV is an application driver for Ultrafast photonic technologies.
Multi-Terabit/s Network Sustaining FTTHs

Kazuo Hagimoto

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http://www.ntt.co.jp/mirai/

Abstract

Broadband access services, especially FTTH are penetrating into residential areas in Japan. Around 30 million broadband users enjoy image distribution or exchanging services as well as Web applications. Therefore, their traffic is also growing at exchange points. Photonic network which has huge transmission capability and reconfigurable flexibility plays important role in commercial networks. High-end users always welcome higher interfaces such as 10GbE and 100GbE in the future. New transport technologies for 10GbE and 100GE are discussed in this talk.

Kazuo Hagimoto was born in Aichi, Japan. He received the B.S. and M.S. degrees in physical electronics engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1978 and 1980, respectively. In 1980, he joined the NTT Electrical Communications Laboratories, Yokosuka, Japan, where he has lead research and development on high-speed optical communications systems including 10G and 40G fiber amplifier repeatered systems. After a senior manager of Operation Support Systems group of Network business unit of NTT Communications, he is now an executive manager of NTT Network Innovation Laboratories. His current research interests include very large capacity optical network systems and media networking technologies utilizing these systems.
Introduction

Penetration of Photonic Network
- Long distance: exceed 1Tb/s using fiber amplifiers
- OXC are operating in National testbeds
- Metro: ROADM is commercial,
- Access: PON and Digital Radio on Fiber

NGN
- ROADM and FTTH continuously sustain NGN infrastructure
- We have to prepare for aged society, digital divide and heating environment.

Lightwave has to learn Microwave more,
- Challenge to the limitation of transmission capability
- Transmission and multiplexing technology

Broadband users in Japan

Future PON System perspective

IEEE announced IEEE802.3av (10G-EPON) will released by 2009.3.
- PON system speed enhancement trend teaches us the future PON system target.

Progress on photonic network systems

Reconfigurable Add/Drop Multiplexer
To keep the same S/N for repeater spacing of 100km, more bitrate needs more power.

Averaged launched optical power (mW)

0.1 1 10 100 1000

Bit rate (Gbit/s)

F-10G F-2.5G F-1.6G F-400M

F-10G, F-2.5G, F-1.6G

OSNR of distributed and lumped amplifier systems

Assumption:
- Fiber loss: 0.25 dB/km
- EDFA spacing: 100 km
- EDFA NF: 7 dB
- Raman gain: 10 dB
- Launched power: 0 dBm

Ideal transmission line

System Transmission Capability

10G × 80ch × 500km Raman repeater system

Modulation spectrum profile in 40-Gbit/s capacity

Simple conversion of optical modulation spectra is feasible in TDM data signal

RZ, NRZ, RZ-DQPSK, CSRZ-DPSK

Modulation Band vs Spectral Width of Light Sources

Reduction of Spectral Width

R&D Target

Impairment Mitigation

SBS-limit

FP-LD, DFB-LD

EDFA

EDF

Distributed Amp

Lumped Amp

Dangerous Level

OTDR, WDM-120G

F-10G, F-2.5G, F-1.6G

NTT communications has installed commercial 40G based WDM systems. The main features are real systems. Total capacity reaches 1.6Tbit/s and

Transmitted OSNR: 60 dB

Transmission distance [km]

OSNR [dB]

0 50 100 150 200 250 300 350 400

Intensity (dB)

Frequency (GHz)

100 GHz

Intensity (dB)

Frequency (GHz)

Calculation

Calculation

100 GHz

RZ-DQPSK, CSRZ-DPSK

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**Transport of 100GbE**

### ETDM 100 Gb/s experiment

<table>
<thead>
<tr>
<th>Conference</th>
<th>Total capacity</th>
<th>distance</th>
<th>Line Rate</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucent</td>
<td>100 Gb/s</td>
<td>1.8 km</td>
<td>107 Gb/s</td>
<td>NRZ-OOK</td>
</tr>
<tr>
<td>Lucent</td>
<td>1 Tbps</td>
<td>390/1000 km</td>
<td>107 Gb/s</td>
<td>NRZ-OOK</td>
</tr>
<tr>
<td>Siemens</td>
<td>100 Gb/s</td>
<td>480 km</td>
<td>107 Gb/s</td>
<td>NRZ-OOK</td>
</tr>
<tr>
<td>Cisco</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Next generation systems enable 100GbE transport with existing facilities.**

**Ultra broadband amplifiers**

**14Tb/s transmission experiment**

- LD1
- LD68
- LD67
- 1550.12 nm
- 1601.45 nm
- 10 ps
- 1540 1560 1580 1600 1620
- Optical Power (10 dB/div)
- Wavelength (nm)
- Received optical Spectra

**Challenge to OFDM for 100GbE transport**

- 22 subcarriers convey 110 Gb/s over 80 km SMF without any equalizer by T. Kobayashi et al., OECC2007 PD, Yokohama

**Broadband Network Technology Trend**

- FTTH users really enjoy image archiving services such as U-Tube, IP-TV etc.
- Photonic networks provide huge flexibility to optical path Networks such as On-demand bandwidth or \( \lambda \).
- A series of Ethernet Service are widely supported by mass and business users in Japan. UNI such as GbE, 10G, 40G/100G Ether will be able to transport by Multi-Terabit networks.
- We are learning wireless tech more, and Fiber will vacuum air as well as digital.

**Challenge to more than 10Tb/s**

- 3 Bands
- Multi-level coding
- Our target 100GbE transport
- X denotes total capacity in Tb/s

**Line rate of optical channel (Gb/s)**

- 20.4-Tb/s (204 x 111 Gb/s) Transmission over 240 km using Bandwidth-Maximized Hybrid Raman/EDFAs by H. Masuda et al, OFC07 PD

**Output of the 3rd Span Fiber**

**Input of the 3rd Span Fiber**

**Summary**

- Next generation systems enable 100GbE transport with existing facilities.
- Ultra broadband amplifiers
Session III

Ultrafast Technologies for Networks

Session Chair

Yuichi Matsushima

Vice President
National Institute of Information and Communications Technology
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Yuichi Matsushima was born in Osaka, Japan in 1948. He received the B. Eng., M. Eng., and D. Eng degree in electrical engineering from Waseda University, Tokyo, in 1972, 1974, and 1978, respectively. After joining KDD R&D Laboratories, Tokyo, in 1978, he has worked in the research field of semiconductor optical devices, long distance optical fiber transmission systems, and photonic networking technologies. At 2001 he was named Executive Vice President of KDDI R&D Laboratories. In 2003 he moved in to the Communication Research Laboratory (at present, National Institute of Information and Communications Technology: NICT) as Executive Director of Information and Network Systems Department. From April 2006, he has been Vice President of NICT. Dr. Matsushima was awarded by Science and Technology Agency Award, the IEE Electronics Letters Premium and the Achievement Award of the IEICE. He is a member of IEEE (SM), IEICE (Fellow) and JSAP.
Ultrafast Optical Satellite Networks

Scott A. Hamilton

MIT Lincoln Laboratory
Optical Communications Technology
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Abstract

Free-space optical communication imposes unique challenges for optical networks including size/weight/power limitations, long propagation latency, and pointing- or atmospheric-induced fades. In this talk, we will discuss free-space satellite networks and >100-Gb/s line-rate time-domain packet-routers enabled by ultrafast all-optical logic gates and switches.

Scott A. Hamilton studied electrical engineering and received the B.S. degree with high honors from the University of California, Davis in 1993. He continued on as a graduate student at UC Davis and earned the M.S. and Ph.D. degrees in electrical engineering in 1996 and 1999 where his research was focused on developing wideband high-linearity polymer modulators for RF-photonic links. From 1989 to 1998, he worked for the Aircraft Systems Engineering Branch at the Naval Air Warfare Center in China Lake, CA. In 2000, Scott joined the Optical Communications Technology Group at MIT Lincoln Laboratory where he is conducting research on ultrafast all-optical packet routing and free-space laser communication. In 2005, he was promoted to assistant group leader and his research interests include high-sensitivity lasercom, high-speed short-pulse communication systems, ultrafast optical signal processing, nonlinear optics, and integrated microphotonics. Scott is an associate editor for the IEEE Journal of Quantum Electronics, the chair of the Optical Fiber Communication conference (OFC) fibers and optical propagation effects subcommittee, a member of the Conference on Lasers and Electro-Optics (CLEO) lightwave networks subcommittee, and a member of the IEEE Electron Devices Society (EDS) optoelectronic devices subcommittee. Scott is also a member of the Optical Society of America and IEEE Lasers and Electro-Optics Society (LEOS).
Optical Satellite Networks and Ultrafast Technologies
Scott A. Hamilton and Bryan S. Robinson
Optical Communications Technology
MIT Lincoln Laboratory
20 August 2007

Acknowledgments:

This work was sponsored by the Air Force Research Laboratory (AFRL) under Air Force contract #FA8721-05-C-0002. Opinions, interpretations, recommendations, and conclusions are those of the author and are not necessarily endorsed by the United States Government.

Outline

• Satellite Networks
• Broadcast-and-Select Receiver
• Time-Domain Packet Router

Satellite Orbits

• Geosynchronous Orbit (GEO)
  - Altitude ~35,768 km
  - Large antenna/power
  - 250-280 ms round-trip time
  - High deployment cost
  - Fixed position for Earth observer
  - Large coverage footprint
  - 3-satellite global network

• Low-Earth Orbit (LEO)
  - Altitude ~200-3,000 km
  - Small antenna/power
  - 20-25 ms round-trip time
  - ~100-minute orbit
  - Fast satellite tracking required
  - Doppler shift
  - Small coverage footprint
  - >60-satellite global network
  - High spectral efficiency

“Bent-Pipe” Satellite Networks

Satellites limited to relay functionality
  - Inefficient resource utilization
  - Long latency

“Intelligent” Satellite Networks

Satellite packet routing functionality requires
  - Satellite crosslinks
  - Packet processing
### Commercial Satellite Networks

<table>
<thead>
<tr>
<th></th>
<th>Iridium</th>
<th>Celestri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constellation</td>
<td>LEO</td>
<td>LEO</td>
</tr>
<tr>
<td>Altitude</td>
<td>780 km, 1,400 km</td>
<td></td>
</tr>
<tr>
<td># Satellites</td>
<td>66</td>
<td>63</td>
</tr>
<tr>
<td># Orbits</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Network Config</td>
<td>2π</td>
<td>2π</td>
</tr>
<tr>
<td>Intra-orbit ISL</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inter-orbit ISL</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total # ISLs</td>
<td>121</td>
<td>189</td>
</tr>
<tr>
<td>ISL rate</td>
<td>25 Mb/s</td>
<td>4.5 Gb/s</td>
</tr>
<tr>
<td>Service</td>
<td>Telephony</td>
<td>Broadband</td>
</tr>
</tbody>
</table>

### Future Satellite Optical Network Backbone

- **Ring Network Architecture**
  - Simple Network management
  - Straightforward quality of service provision
  - Network resource utilization capacity limited

- Broadcast-and-select protocol provides packet processing functionality

### Wavelength-Routing Interconnectivity

- **Wavelength Routing Goal**
  - Provide full network connectivity via WDM ISLs
  - Remove switching electronics
  - Size, weight, and power savings

- **Celestri Example**
  - ISL wavelength count excessive
  - Wavelength conversion does not provide significant reduction

### Broadcast-and-Select Receiver Node

- **Phaselocked Optical Clock**
- **NAND**
- **Address Compare**
- **Pulse Generator**
- **User Data**

### Packet-Processing Interconnectivity

- **On-Board Processing (OBP) Goal**
  - Provide packet routing at each satellite node
  - Assumption (e.g., Internet)
    - 25% of uplink capacity is long-distance traffic

- **Celestri Example**
  - 25-56% OBP capacity required for transit traffic
  - Electronic packet routers are not designed for low size, weight, and power

- **Should optical logic be considered for OBP in satellite networks?**

### 112.5 Gbit/s Header Processing

- **OTDM Network Receiver Address Comparison**
- **Broadcast and Select OTDM Network**

- **Scalable address space**
  - PMM address format yields XOR functionality

- **Low Switching Energy**
  - Control 19 fJ
  - Signal 1 fJ

- **Extinction ratio 6.4 dB**
Next-Generation Satellite Optical Network Backbone

- Mesh Network Architecture
  - More efficient use of communication resources
  - More robust network with multiple communication paths
  - Complex network management
  - Packet routing functionality required

Spatial Switching Fabric

- Advantages:
  - Transparent switch matrix
    - Data format flexibility – NRZ, RZOOK, DPSK, QPSK
    - Data rate independent
    - Client protocol agility
    - Nonblocking
  - Ultrafast header processing
    - Reduced buffer depths, reduced latency
    - Straightforward header processing

- Disadvantages:
  - Significant insertion loss
  - Batcher scales as $N(\log_2 N)^2$
  - Limited port count
  - $8 \times 8$ SOA (K. Hamamoto, Elect. Lett., 1992)
  - Developing technology

Virtual Network Topology

- Fixed Virtual Topology
  - Simplified routing table
  - Virtual node spatial location fixed
  - State information passed between satellites as physical topology changes

2 x 2 Unit-Cell Header Processing

- All-optical header processing at each 2 x 2 unit cell can be achieved with low optical logic density!

Ultrafast Time-Domain Packet Router

- Optical Packet Forwarding
  - Transparent switching matrix for advanced modulation formats
  - Ultrafast optical logic header processing
  - Fewer ports – simpler management
  - Reduced size, weight, and power

- Electronic Virtual Node Routing
  - Recalculate switching matrix only when satellite moves between virtual nodes
  - Known satellite orbital information used for virtual node handover

Summary

- High-performance future satellite data networks will require optical crosslinks and on-board packet processing
  - All-optical logic may provide ultrafast operation speeds and size, weight, and power savings compared to electronic options
- OTDM-based broadcast-and-select protocols may be applicable to free-space ring networks
- Ultrafast time-domain packet processing combined with virtual-node routing can be used to implement a broadband satellite mesh network:
  - Ultrafast channel rates
    - Fewer ports – reduced size, complexity
    - Fewer wavelengths – reduced laser count, simplified network management
  - Ultrafast header processing
    - Reduced buffer depths, reduced latency
  - Fixed virtual network topology
    - Simplified routing tables
Ultrafast Optical Technologies for Optical CDMA and Network Security

Paul Prucnal

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Princeton University
Princeton, NJ 08544
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Abstract

Optical code-division multiple access (CDMA) provides congestion-free transmission of multiple simultaneous users, with variable bit rates and qualities of service (QoS). The soft-blocking properties of optical CDMA can be used to mediate congestion and allow graceful scaling of the size of networks. The orthogonality properties of the OCDMA codes, independent of code length or weight, can be used to flexibly and dynamically assign bandwidth and QoS to different priority traffic. Optical CDMA can also be used to provide privacy for the physical layer of the network. Several demonstrations of physical level privacy using optical CDMA based on ultra-fast optical technologies will be presented. Applications to access and sensor networks will be discussed.

Professor Paul Prucnal received his A.B. from Bowdoin College, and the M.S., M.Phil. and Ph. D. from Columbia University. He joined Columbia’s faculty of Electrical Engineering in 1979 where he was a member of the Columbia Radiation Laboratory, and in 1988 joined Princeton University as Professor of Electrical Engineering, and founding Director of Princeton’s Center for Photonics and Optoelectronic Materials. Professor Prucnal has authored or co-authored some 250 journal articles/book chapters and holds 17 U.S. patents. He is editor of the book, Optical Code Division Multiple Access: Fundamentals and Applications (Taylor and Francis, 2006). Professor Prucnal is a Fellow of the Institute of Electrical and Electronics Engineers and the Optical Society of America, and is a member of Phi Beta Kappa,Eta Kappa and Sigma Xi. He has been honored with Princeton’s Engineering Council Award for Excellence in Teaching in 2004 and 2006, the Graduate Mentoring Award in Engineering in 2005, and the Gold Medal from the Faculty of Mathematics, Physics and Informatics at the Comenius University in 2006.
Ultrafast technologies for optical CDMA and network security

Professor Paul Prucnal
Recent students: Camille Bres, Darren Rand, Varghese Baby
Current: Yue-Kai Huang, Bernard Wu, Konstantin Kravstov,
Yanhua Deng, Zhenxing Wang

Center for Networks Research & Applications
Department of Electrical Engineering
PRINCETON UNIVERSITY

MIT Ultrafast Photonics Symposium
August 20, 2007

Ultrafast technologies for optical CDMA and network security

Incoherent OCDMA schemes
- Second dimension adds more scalability
- Shorter codes and better correlation properties than temporal 1D OCDMA
- No statistics on autocorrelation
- Bounded crosscorrelation

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Multiple access interference
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Optical multiaccess in passive optical networks
- TDM based approaches require “ranging” for global synchronization.
- WDM lacks scalability, fine granularity and capability for QoS provisioning.
- OCDMA is asynchronous, scalable, and provides variable QoS and bit-rate.

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Incoherent 2D OCDMA
- Asynchronous and scalable
- Reconfigurable multiaccess
- Can use off-the-shelf technology
- Bandwidth on demand - “Soft blocking”
- No “busy signal” Adding users gracefully degrades BER
- Flexible bandwidth & QoS provisioning
  - Using “wavelength-hopping time-spreading” codes permits multi-rate & multi-BER
  - Larger code-weight improves BER, while increasing multiaccess interference (MAI)

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Time gating with the TOAD
- “Terahertz optical asymmetric demultiplexer”
  - The new and cw data pulses go through the SOA before and after the fast nonlinearity in the SOA
  - “Ultrafast” switching speed, ~1Tb/s
  - Low switching energy, < 100 fJ
  - Low crossstalk and polarization sensitivity
  - Integrated on InGaAsP

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- “Ultrafast” switching speed, ~1Tb/s
- Low switching energy, < 100 fJ
- Low crossstalk and polarization sensitivity
- Integrated on InGaAsP

OCDMA Decoder

Input to TOAD with MAI

2ps TOAD gating window

Remove MAI with the TOAD

Experimental setup

Error-free operation to $10^{-11}$ measured with 8 users (no FEC)

Passive code converter for code re-use

OCDMA add/drop multiplexer for rings

Tunable variable weight encoder: variable QoS

Experimental Results: 8 users, 5 Gbps

Tunable variable weight encoder for code re-use

Provide differentiated QoS in heterogeneous networks

Can be achieved in physical layer using coding

Variable code weight properties of 2D OCDMA codes

Use optical delay lines and time gating

Remove $\lambda$s on the fly

Bres et al., to appear in Optics Communications

Bres et al. "All-Optical OCDMA Code-Drop Unit for Transparent Ring Networks," IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 17, NO. 5, MAY 2005

Bres et al., presented at LEOS Summer Topical 2005

Bres et al., PTL, 18(7) April 2006

Stealth communications under the noise floor
Simulations of coherent optical transmission with spreading

Effect of stealth channel on BER of public channel

Sending the key on a stealth channel

Optical data encryption with integrated coders

Conclusion
Ultra-fast Optical Packet Switching Node Technologies for Future Photonic Networks

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http://www2.nict.go.jp/w/w112/index.html

Abstract

In order to build a network capable of handling the tremendous amount of traffic in the future, it will be necessary to improve the node throughput, as well as the link capacity. While the link capacity can be easily increased by bundling optical fibers, the electronic processing in current node systems may limit the achievable increase in node throughput. In new-generation optical networks, high scalability and fine granularity will be essential, in addition to increased network capacity. Although IP/GMPLS/WDM technology will enable transmission of huge capacities of data with fine granularity, its slower electronic processing, such as memory access for header analysis at IP routers, will be a bottleneck in the network. To avoid such bottlenecks in commercial high-end IP routers, electronic parallel processing technologies are often used. However, such large-scale parallel processing leads to serious power consumption problems. Recently, despite the relative immaturity of optical technologies, many optical packet switching (OPS) systems have been developed to exploit the merits of OPS systems, such as high capacity, ultra-high-speed hopping, and fine physical-granularity. We propose and experimentally demonstrate recent optical code-label processing technologies and their applications in OPS networks.

Dr. Wada received the B.E., M.E., and Dr. Eng. degrees in electronics from Hokkaido University, Sapporo, Japan, in 1991, 1993, and 1996, respectively. In 1996, he joined the Communications Research Laboratory (CRL), Ministry of Posts and Telecommunications, Tokyo, Japan. He is currently a project reader of Photonic Node Project and research manager of the Photonic Network Group. His current research interests are in the area of photonic networks such as OPS network, optical processing, and optical code-division multiple access (OCDMA) system. Dr. Wada received the 1999 Young Engineer Award from the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, and the 2005 Young Researcher Award from the Ministry of Education, Culture, Sports, Science and Technology. He is a member of IEEE Comsoc, IEEE LEOS, the IEICE, the Japan Society of Applied Physics (JSAP), and the Optical Society of Japan (OSJ).
Ultra-fast Optical Packet Switching Node Technologies for Future Photonic Networks

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Outline

Three different approaches for OPS node system (in NICT)

- Opto-electronics (Opt. < Elect.)
  - Merits: Reliability, Many function
  - Demerits: Serial / parallel conversion, Electrical parallel processing

- Quasi-all-optical (Opt. > Elect.)
  - Merits: Wideband switching, Ultra-fast processing
  - Demerits: Buffer, Scalability

- Other approach (SFQ logic)
  - Merits: High-speed, Low power consumption
  - Demerits: Lack of high speed interface

AKARI project
http://www2.nict.go.jp/w/w111/index_e.html

Talk of today

AKARI project

Functions of OPS

Functional partitioning and operation order in a optical packet switch system

Ingress node
- Switching
- Label processing
- Buffering

OPS node
- Optical packet transmitter
- Optical label processor
- Optical switch
- Optical buffer

Egress node
- Optical packet receiver
- Restructuring
- Sending

OTDM based 160Gbps/port OPS prototype

Architecture
- Optical packet switch with output optical buffer

Input ports
- 2

Output ports
- 1 (in experiment)

Maximum data rate
- 160 Gbit/s (correspond to OC-3072)

Packets rate
- 1.9 million packets / s / port

Label recognition method
- Optical matched filtering using PLC based correlator with 16-chip BPSK codes (25 Gchip/s : 40 ps)

OTDM based ultra-high speed OPS network
• Tx.: Electro-absorption modulators (EAM) with distributed feedback (DFB) lasers

• The receiver consists of high-speed uni-traveling-carrier PD and a low jitter gated voltage controlled oscillator with digital ring PLL.

• A transient response of EDFA distorts the waveform of short-term optical packet.
• Many EDFAs are used in systems and networks. The cumulative transient response effect is very big.
• We developed a new EDFA which adopted EDF with enhanced active erbium area and successfully suppressed the transient response.

Multiple optical label processing
• We first introduce 200 Gchip/s multiple optical code (OC) encoder/decoder with an arrayed waveguide configuration.
• It can generate and recognize simultaneously sixteen different 16-chip optical phase shift keying codes with low latency.
• The processing rate is 13 Gpacket/s.

Stack of processing devices

(a) Encoding
(b) Decoding

Auto correlation
Cross correlation

Burst mode EDFA

• A transient response of EDFA distorts the waveform of short-term optical packet.
• Many EDFAs are used in systems and networks. The cumulative transient response effect is very big.
• We developed a new EDFA which adopted EDF with enhanced active erbium area and successfully suppressed the transient response.

Commercially available one
Developed EDFAs
Experimental Results 2

**Ingress node**
- Network Analyzer
- Core node
- Optical Packet

**Core node**
- Label processing
- Switch
- Controller

**Switch**
- OPS system
- (DA IP: 192.168.0.2)

**HDTV Monitor**
- 3D-HDTV Input System
- 3D-HDTV camera
- UDP/IP/Ethernet protocol

**Eye of Recovered payload by Packet Rx.**
- Time (20ps/div)
- Power (a.u.)

**Recovered clock by Packet Rx.**
- Time (200ps/div)
- Power (a.u.)

**Frame loss rate**
- Transmitted rate (bps)

**Acknowledgment**
A part of this work has been done in collaboration with NTT Electronics, Yokogawa Electric, Fujitsu, Anritsu, and Amonics.

We would like to thank H. Furukawa, T. Miyazaki, H. Harai, Y. Awaji, X. Wang, N. Kataoka, S. Shinada, Y. Tomiyama, T. Hanyu, H. Sumimoto, and T. Makino of Photonic network group in NICT for their collaboration in experiments.

We would like to extend my thanks to G. Cincotti of University Roma Tre and K. Kitayama of Osaka University for their valuable discussions and collaboration in all-optical label processing.
Session IV

Ultrashort-Pulse Fiber Lasers

Session Chair

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Matthew E. Grein received the B.S. degree (summa cum laude) in electrical engineering from Texas A&M University in 1993 and the M.S. and PhD degrees in the same field from the Massachusetts Institute of Technology (MIT), Cambridge, in the Ultrafast Optics and Quantum Electronics Group in 1997 and 2002. After completing a postdoc at MIT, he joined MIT Lincoln Laboratory in 2003 as a staff scientist in the Optical Communications Technology Group. His research interests include ultrafast fiber and semiconductor lasers, laser noise, and photon-counting optical receivers.
Recent Progress in High Power Short Pulse Fiber Laser Technology

David Richardson

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Abstract

Over recent years the powers that can be achieved from fiber lasers have grown rapidly due to parallel advances in high power diodes, diode-to-fiber coupling schemes and doped fiber design and fabrication. Whilst the headline results have generally related to the possibilities of scaling continuous-wave fiber lasers, with 2.5kW now possible from an effectively single-mode core, advances in many aspects of pulsed laser performance have been just as spectacular. Using the fiber MOPA approach it is now possible to realise fs and ps pulsed fiber systems operating at the multi-100W level with pulse energies that are rapidly approaching the 1 mJ level. In the nanosecond regime multi-100W systems have also been achieved with single mode pulse energies as high as 10mJ, and by relaxing the mode quality pulse energies approaching 100mJ are now possible. Within this talk I shall review the state-of-the-art in the pulsed fiber laser systems, describe some of the issues limiting further power and energy scaling, describe various applications now being targeted, and speculate as to likely future developments.

David J. Richardson holds a personal Chair in Photonics at the University of Southampton and is Deputy Director of the Optoelectronics Research Centre (ORC) where he is responsible for Optical Fiber Device and Systems research. His current research interests include amongst others: microstructured fibers, high-power fiber lasers, short pulse lasers, optical fiber communications, and nonlinear fiber optics. He has published more than 600 conference and journal papers in his time at the ORC, and produced over 20 patents. He is a frequent invited speaker at the leading international optics conferences in the optical communications, laser and nonlinear optics fields and is an active member of both the national and international optics communities. Prof. Richardson, a founder of SPI Lasers Ltd., was made a Fellow of the Optical Society of America in 2005.
Recent Progress in High Power Short Pulse Fiber Laser Technology

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Ultra-high powers from fibres

Wavelength ~ 1.1 µm

2.5 kW YDFL / MOPA (IPG, 2005)

20 W x 36 976 nm LDs in total
20 W x 36 976 nm LDs in total
20 W x 36 976 nm LDs in total

• Not really laser, but low-gain MOPA (7 dB)
• Total pumping 144 x 975 nm LDs with 20 W of power into 100 mm pigtail
• Further power scaling possible

*“2 kW CW ytterbium fiber laser with record diffraction-limited brightness” V. Gapontsev et al. CLEO-E 2005, C-J-1-750*

High-power fiber MOPAs
Beyond raw power

High control
High gain
High power

• Fibers provide high gain, high power, broad bandwidth and ready cascability
• Precision provided by (low power) seed oscillator
• Combination allows projection of seed properties to ultra high power levels

Challenge is to maintain seed fidelity in presence of noise, gain dynamics, nonlinearity, dispersion, birefringence etc..

Cladding Pumped Fibre Devices

Advanced amplifier designs for high power applications

Rare-earth-doped core converts multimode pump energy to high brightness, diffraction-limited, signal beam
Operating regimes of fibre based ultrashort pulse sources

- Chirped pulse amplification
- Parabolic pulse amplification
- Direct amplification
- Basic Oscillator

Pulse on demand

Q-switching

MOPA systems

1mJ

1 µJ

1nJ

10pJ

120W Q-switched YDFL (ns)

8.4 mJ @ 0.5 kHz
0.6 mJ @ 200 kHz (120 W)
500 ns pulses at 1060 nm
Reasonable mode quality $M^2 = 4$

- Highest energy
- Highest power

Operating regimes of fibre based ultrashort pulse sources

Our vision - the perfect light source

- Nonlinear wavelength conversion
- Materials processing
- Chemical reaction
- Detection, imaging

Process monitoring

- Learning loop counteracts degradation through nonlinear effects
- The powers required to drive industrial processes are becoming available in MOPA configurations
- Flexibility, rapid control, near-linearity of fiber MOPAs greatly enhances scope for adaptive control
- The technology now available for this powerful concept (?)

Adaptive pulse shape control

- Control of current to seed diode to define shape of pulse at system output
- Optimisation algorithm to optimise pulse shape for industrial process e.g. cutting

Record average power for short pulsed fiber system

- Average power= 321 W
- 74% pump conversion
- Repetition rate=1 GHz
- Pulse duration= 20 ps
- Bandwidth=0.5nm (broadened by SPM)
- Peak power =13 kW (Energy ~260nJ)
- $M^2=2.4$

• Learning loop counteracts degradation through nonlinear effects
• The powers required to drive industrial processes are becoming available in MOPA configurations
• Flexibility, rapid control, near-linearity of fiber MOPAs greatly enhances scope for adaptive control
• The technology now available for this powerful concept (?)

321W Gain Switched Oscillator and Fiber Amplifier

- Average power= 321 W
- 74% pump conversion
- Repetition rate=1 GHz
- Pulse duration= 20 ps
- Bandwidth=0.5nm (broadened by SPM)
- Peak power =13 kW (Energy ~260nJ)
- $M^2=2.4$

Record average power for short pulsed fiber system

- Control of current to seed diode to define shape of pulse at system output
- Optimisation algorithm to optimise pulse shape for industrial process e.g. cutting

Collaboration SPI Laser/Cambridge University

DTI project MAGIC

Parabolic pulse amplification (fs)

- Broad gain bandwidth of Yb allows amplification of ultrashort (~100fs) pulses
- Parabolic pulse formation exploits nonlinear and gain characteristics of fiber to produce high power linearly chirped pulses that can be readily compressed to ultrashort pulse durations
- Cladding pumping allows scaling to high average powers/high pulse repetition frequencies
- Wide range of applications including imaging and materials processing

>5MW peak power ~100fs pulses at 25W average power levels


VECSEL-fiber MOPA

- VECSEL: ~10mW, 1040nm, 500 fs pulses at 1.1 GHz
- Parabolic evolution in amplifier
- 53 W average power
- After compression: 110 fs, TBW ~0.47

Unabsorbed pump

YDF

Pump LD

λ

/2

Pump LD

λ

/2

Compression

Output

Unabsorbed pump

YDF

1X or 2X

Mode-locked VECSEL

Dupriez et al., OE, 14(21), 2006 (Collaboration with UOS Physics)

Fiber Based CPA

- ~100-fold average power increase relative to conventional fs laser systems
- mJ pulse energies/GW peak powers in reach
- Higher material processing speeds/efficient conversion to UV/IR

H. Fei et al. CLEO 2007 (Collaboration with LLNL)

Second harmonic generation

- Pulsed LD, 80 ps, 80 MHz
- λ/2

80 W at 530 nm

Conversion efficiency over 60%
Target 80%

Can one imagine a more versatile photon-engine?

Q-switch fiber laser pumped OPO

- 50ns frequency doubled, Q-switch pump pulses
- 10 MicroJoule threshold, 40% efficiency
- Tuning of idler/signal in range 1-4.5 microns demonstrated

Core pumped system using just 300 mw pump power

P. Britton et al., OL, 23, 1998

Summary

- Fiber lasers now capable of kW scale average power operation with 10kW level in sight.
- Operation in new wavelength ranges continuously improving with new fiber designs and types.
- Improvements in mode management offer new LMA fibers with reduced nonlinearity, opening route to higher peak powers and pulse energies for pulsed systems.
- MOPA concept truly enabling, allowing amplification of seed laser properties to ultrahigh average power levels.
- In pulsed regime high rep-rate, high average power systems favoured.
- Various nonlinear frequency conversion options allow projection of source properties to new wavelength ranges from X-ray to THz regime.

Can one imagine a more versatile photon-engine?
Broadband Femtosecond Fiber Lasers and Applications: 
From Bioimaging via Precision Metrology 
to Ultrafast Single Photonics

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Abstract

Femtosecond Er:fiber lasers are promising candidates for a widespread use of compact, stable and robust sources of ultrashort pulsed radiation in the future. We present a systems concept where the power of a mode-locked Er:oscillator is increased up to 500 mW by one or multiple parallel amplifiers shortening pulse durations below 60 fs. Due to their emission wavelength of 1550 nm, a large variety of nonlinear fiber optic components is available for frequency conversion via third-order processes. A combination of numerical simulations and precise characterization of fiber dispersion and input pulse characteristics has allowed us to generate tailored supercontinua with emission peaks tunable between 970 nm and 2.4 μm. Compression down to 13 fs has been demonstrated. Highly efficient frequency doubling results in a low-noise femtosecond pulse train that is tunable from blue to red with average powers up to 10 mW. These sources are suitable for a broad variety of applications. Examples from the following fields will be presented: linear and nonlinear confocal microscopy in life sciences, frequency combs for precision metrology, ultrafast time and frequency resolved measurements on single-electron systems, as well as generation of phase-stable mid-infrared and terahertz pulses.

Alfred Leitenstorfer holds the Chair of Modern Optics and Quantum Electronics at the Department of Physics of the University of Konstanz and is Head of the Center for Applied Photonics. His current research interests focus on ultrafast quantum physics with compound photonic nanostructures, nonlinear dynamics of elementary excitations studied with phase-locked pulses, as well as femtosecond and terahertz technologies. His group has generated innovative results in various fields of ultrafast science. Examples range from the femtosecond buildup of quasiparticles and quantum phase transitions via fiber laser based frequency combs to electro-optic sampling techniques of electric field transients with record-breaking bandwidths beyond 100 THz.
Broadband Femtosecond Fiber Lasers and Applications from Bioimaging via Precision Metrology to Ultrafast Single Photonics

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University of Konstanz
Germany

fs-Er:Fiber Systems: General Setup

Er:fiber ring oscillator
• similar to the systems described in

Nonlinear Er:fiber amplifier
• single pass gain by factor 100
• standard fiber as pulse stretcher to set correct pre-chirp
• simultaneous amplification, nonlinear broadening and recompression in Er:fiber

Variable Si prism sequence
• adjustment of spectral phase of output pulses


Spectral Broadening in Nonlinear Amplifier

seed spectrum
amplified output for various lengths l of the stretcher

Fourier transform assuming flat phase:
minimum pulse duration \( \tau_p = 85 \text{ fs} \)

Nonlinear Er:Amplifier Output

• temporal and spectral pulse analysis in amplitude and phase via second harmonic FROG

• 1.55 µm system parameters after recompression:
  – repetition rate: 100 MHz
  – average power available per amplifier branch: up to 400 mW

Continuum Generation in Bulk Fiber

\( \tau_p = 57 \text{ fs} \)
\( P = 300 \text{ mW} \)
\( f_{\text{rep}} = 100 \text{ MHz} \)

polarization maintaining dispersion-shifted germanosilicate fiber
\( d = 3.7 \mu \text{m}, l = 7 \text{ cm} \)

Tunability of Nonlinear Fiber Output

emission maxima tunable via pre-chirp

Simulation of Nonlinear Mixing in Fiber

Compression of High-Frequency Part

Efficient Broad- to Narrowband Conversion via Combined SHG and SFM in PPLN

Tunable High-Brightness VIS-Pulses

Total Tunability Range Covered

Application 1: Optical Frequency Divider + Transfer Oscillator – Example from PTB


also:
• SHG to 780 nm: 120 mW, 140 fs
• THG to 520 nm: 55 mW, 285 fs
• FHG to 390 nm: 6 mW


Result of Stability Transfer and Comb Test via Yb⁺ Standard

source: H. Schnatz, Physikalisch-Technische Bundesanstalt, to be published

Application 2: Femtosecond Spectroscopy and Control of Mesoscopic Systems

- highly sensitive, low-temperature transient transmission setup
- based on turn-key two-color version of visible fs-Er:fiber laser

Towards Ultrafast Excitation and Readout of Single Electrons with Single Photons

- microresonators with CdSe/ZnS quantum dot in spacer layer
- coupling of femtosecond pump and probe pulses into resonant cavity modes enhances electron-light interaction by factor of \( Q = 10^3 \ldots 10^4 \)

Application 3: Confocal Microscopy

Femtosecond Two-Photon Excitation in the Near Infrared for Deep Tissue Imaging

- sample: nerve cells in organotypic tissue from hippocampal region of mouse brain
- resolution: 300 nm in layer 100 µm below surface
- project: correlation of spine shape and number with brain functions like learning and memorizing

in collaboration with A. Jeromin, Center for Learning & Memory, University of Texas, Austin, USA

Local Damage and Repair of DNA via Ultrafast Three Photon Absorption

- femtosecond laser writing of sub-micron DNA damage within nucleus of human cancer cell
- time resolved monitoring of migration of various repair enzymes to damage site

in collaboration with H. Nägeli, Institute for Pharmacology and Toxicology, University of Zurich, Switzerland
Ultrafast Yb-Fiber-Laser Systems for Passive Cavity Enhancement

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Abstract

A promising concept to achieve high peak intensities at high repetition rates is the coherent addition of femtosecond pulses produced by mode-locked lasers inside passive high-finesse cavities. This concept enables the access to high field phenomena using relatively compact and inexpensive laser sources with the additional benefit of access to the frequency comb structure of the mode-locked laser. It will be shown that fiber laser systems provide an excellent match to the pump-source requirements for passive coherent addition due to their power scalability via the technologies of cladding pumping and chirped pulse amplification, good spatial mode quality and long-term uninterrupted operation. In initial experiments, which were performed jointly between IMRA and the University of Colorado, we achieved 230 MW peak power (3 kW average power) at 136 MHz pulse repetition rate using a 13W average power, 136MHz, 75fs fiber laser system. The peak intensity of $3 \times 10^{14}$ W/cm² was sufficient to ionize noble gases and to generate high harmonic radiation.

Ingmar Hartl received the Ph.D. degree in physics from the University of Munich, Germany in 1999. After a postdoctoral fellowship at MIT, Cambridge, MA, he joined 3D Systems, Valencia, CA. as Senior Research Scientist. Currently a Senior Research Scientist at IMRA America, Inc., his research interests include femtosecond fiber laser and fiber amplifier technology, ultrafast and nonlinear optics and optical phase control. His recent efforts focused on low noise fiber laser frequency combs and the coherent addition of femtosecond pulses.
Ultrafast Yb-Fiber-Laser Systems for Passive Cavity Enhancement

I. Hartl, A. Marcinkevicius and M. E. Fermann
IMRA America, Inc., Ann Arbor, MI
T. R. Schibli, D. C. Yost, D. D. Hudson and J. Ye
JILA, NIST and CU, Boulder, CO

Outline

• Introduction
• Laser system
• Enhancement cavity
• Noble gas plasma

High repetition rate, high intensity lasers

- Cavity dumped oscillator
- Long cavity oscillator
- Chirped pulse oscillator
- Coherent pulse addition via enhancement cavity
  - Full oscillator repetition rate (~ 100 MHz)
  - Highly reduced averaging time in experiments
  - Frequency comb structure available

Cavity enhancement: Mode-locked

\[ T_n = \frac{4T}{n^2} = \frac{4T}{(\frac{f_{rep}}{f_{fs}})^2} \]

Coherent addition of laser pulses

- Ti:sapphire oscillator
  - Limited in average power
- Fiber CPA system
  - Power scalable!
- Cladding pumping
- Large mode areas
- Low heat removal problems
Coherent addition of laser pulses

- Ti:sapphire oscillator
  - limited in average power
- Fiber CPA system
  - power scalable!

- Enhancement cavity required:
  - high damage threshold
  - low dispersion
  - high reflectivity mirror coating
  - ≈ 20nm bandwidth

80 fs @ 1060 nm
50 fs @ 800 nm

Compact, passively modelocked in-line Yb similariton oscillator

FBG period distribution

Dispersion

FBG temperature tuning provides nearly orthogonal control of repetition rate and CEO phase slip

42nm FWHM
136MHz
>100mW

Noise Issues

Intracavity noise: Broadens comb line
  - Cavity length (fixed point ~ 0)
  - Pump fluctuations (fixed point ~ comb center)

Extracavity noise: Reduces comb visibility
  - Continuum noise, amplifier ASE

Feedback: intracavity noise is reduced

High power & coherent?

Locking electronics

13W Yb: fiber laser

10MHz

0.6MHz DDS

96%
F-to-2f Interferometer

1.5W, 120fs (previous version of laser system)

Enhancement cavity

Laser system: 13 W, 136 MHz
rHR=99.988%
rOC=99.4%
F≈1000

Focus: 150 μm²

Plasma generation in noble gases at 136 MHz pulse repetition rate

Intensity [W/cm²]

750m Torr

Average power [kW]

First evidence of VUV radiation

Detected high harmonic light two orders of magnitude above background (Lock-In detection)

Summary

Fiber CPA system:
 Average power: 13.5 W
 Pulse duration: 75 fs
 Pulse repetition rate: 136 MHz
 Beam profile (M²): ~1.2
 Full phase control (fRep & fCEO)

Cavity enhanced CPA system:
 Average power: 3000 W
 Peak power: 230 MW
 Peak intensity: 3·10¹⁴ W/cm²
 Pulse duration: 95 fs
 Pulse repetition rate: 136 MHz

Outlook:
• Higher laser power → 100W possible
• High field physics at 136 MHz repetition rate
  - VUV spectroscopy
  - molecular imaging


Challenge:
• High harmonic output coupling
• Occasional mirror damage
Session V

Ultrafast Optical Signal Processing

Session Chair

Naoto Kobayashi

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Naoto Kobayashi was born in Chiba, Japan in 1950. He received the B.S. degree in Physics in 1973, the M.S. degree in Nuclear Engineering in 1975, and Ph.D. degree in 1978 all from Kyoto University. In 1978, he joined the Electrotechnical Laboratory (ETL), Japan. He was engaged in research on quantum beam material interaction, ion implantation and modification of semiconductors, wide bandgap semiconductor materials and so on. He worked also for the national project of 'Advanced Material-Processing and Machining System (1986-1994)'. From 1998 through 2001 he worked as the Director of Quantum Radiation Division of ETL for quantum beam frontier technologies. In 2001, he was appointed as the Director of Photonics Research Institute of the National Institute of Advanced Industrial Science and Technology (AIST) which was reorganized into an Incorporated Administrative Agency. He worked as the supervisor of the national project of 'Femtosecond Technology (1995-2005)'. Since 2003, he has been Vice President of AIST.
Wavelength-Parallel Pulse Generation and Equalization Technologies

Andrew M. Weiner

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Abstract

Fourier-domain optical signal processing offers great flexibility for manipulation of ultrashort pulses, with a number of applications to ultrahigh-speed communications. In this talk I will review the use of Fourier pulse shaping technology for frequency-programmable chromatic dispersion compensation of sub-ps pulses and for all-order polarization-mode dispersion (PMD) compensation and emulation. Both chromatic dispersion and PMD are critical issues that must be overcome to scale lightwave communications into the sub-ps regime. I will also discuss our recent work on short pulse generation by line-by-line pulse shaping of phase modulated continuous-wave laser sources.

Andrew M. Weiner is the Scifres Distinguished Professor of Electrical and Computer Engineering at Purdue University. Prior to his current position, he was Member of Technical Staff and later Manager of Ultrafast Optics and Optical Signal Processing Research at Bellcore. His research focuses on ultrafast optics signal processing and applications to high-speed optical communications and ultrawideband wireless. He is especially well known for his pioneering work in the field of femtosecond pulse shaping. Prof. Weiner is a Fellow both of the Optical Society of America and of the Institute of Electrical and Electronics Engineers and has won numerous awards for his research. He has published six book chapters and approximately 200 journal articles, is author of over 300 conference papers, and is holder of 9 U.S. patents. Prof. Weiner has served as Co-Chair of the Conference on Lasers and Electro-optics and the International Conference on Ultrafast Phenomena and as associate editor of several journals. He has also served as Secretary/Treasurer of IEEE LEOS and as a Vice-President of the International Commission on Optics (ICO).
Wavelength-Parallel Pulse Generation and Equalization Technologies

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• Femtosecond pulse shaping: a core technology
• Optical equalizer technologies
  - Chromatic dispersion compensation
  - Femtosecond pulses
  - WDM (10 Gb/s)
  - Polarization-mode dispersion (PMD) compensation (& monitoring)
• Spectral line-by-line pulse shaping and waveform generation

Femtosecond Pulse Shaping

- Fourier synthesis via parallel spatial/spectral modulation
- Diverse applications: fiber communications, coherent quantum control, few cycle optical pulse compression, nonlinear microscopy, RF photonics …
- Liquid crystal modulator (LCM) arrays:
  - Typically 128 pixels (up to 640), millisecond response
  - Functionalities: phase-only, independent phase and intensity, polarization

Reflective Pulse Shaper

• Reduced size & component count
• Insertion loss as low as ~4 dB (including circulator!)

Programmable Fiber Dispersion Compensation

- Coarse dispersion compensation using matched lengths of SMF and DCF
- Fine-tuning and higher-order dispersion compensation using a pulse shaper as a programmable spectral phase equalizer
- Similar ideas apply to dispersion compensation in femtosecond amplifiers and few-cycle pulse generation

Higher-Order Phase Equalization Using LCM

• No remaining distortion!

460 fs transmission over 50 km SMF

• 5 ns after SMF
• 13.9 ps after DCF
• 470 fs after quadratic/cubic phase equalization

Commercial DCF module with spectral phase equalizer

Essentially distortionless
Virtually Imaged Phased Array (VIPA)

Extending Pulse Shaping/Processing to Individual WDM Channels

- Offers high spectral resolution, as in a Fabry-Perot
- But acts as a spectral disperser, with large spectral dispersion arising from multiple beam interference in "side-entrance" etalon geometry

Why?

\[ \frac{\partial \tau}{\partial x} \approx k \frac{\partial \theta}{\partial \omega} \]

Bor et al., Opt. Commun. 59, 229 (1985)

8-Channel Hyperfine Demux

(-700 MHz inewidth, ~3 GHz channel spacing, 50 GHz FSR)

Tunable Dispersion Compensation for 10 Gb/s Lightwave Systems

Fixed dispersion compensation

Tunable dispersion compensation

Programmable Hyperfine Resolution VIPA Pulse Shaper

Tunable Dispersion Compensation: 10 Gb/s over 240 km Fiber

Polarization Mode Dispersion (PMD)

A complicated vector distortion:

- Frequency-dependent polarization scrambling
- Frequency- and polarization-dependent delays

All-Order PMD Compensator: First Demonstration!
Fast Wavelength Parallel Polarization Sensor

Application to PMD sensing and compensation

- 1D configuration: <250 channels @ 0.4 nm (50 GHz) channel spacing, <1 ms read-out time, < 5° polarization error
- High resolution 2D configuration: <1000 channels @ 2.5 GHz channel spacing (>20 dB crosstalk), 5 ms read-out time (potential)

First in class performance, in terms of speed and wavelength parallelism

Sensing in the Lab and in the Field with AT&T

AT&T laboratory test-bed: PMD stress testing of 1600 km commercial (Nortel) WDM system

Seek to identify correlation between string length and system impairment -spectral polarimetry as a tool for optical performance monitoring

State-of-polarization strings (10 GHz bandwidth)

Stability Issues of Mode-Locked Laser

Fluctuations of Comb-Offset Frequency $\delta$

- Spectral lines fluctuate
- Comb-offset frequency $\delta$ fluctuates
- Phase between pulses $\Phi$ fluctuates
- Overlapped regime fluctuates

- Stabilized frequency comb is required for line-by-line pulse shaping
- Self-referenced high-rep-rate mode-locked lasers have not been available

Complex Optical Arbitrary Waveform Generation

- Linear plus cubic phase examples
- Measurement and calculation agree closely: high fidelity waveforms!

Spectral phase function
All-Optical Sampling for High Resolution
Optical Waveform Analysis

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Abstract

Techniques to analyze optical waveforms with high resolution are discussed. Emphasis is on all-optical sampling that offers high resolution with excellent sensitivity.

Peter Andrekson received his Ph.D. from Chalmers University of Technology, Sweden in 1988. After three years with AT&T Bell Laboratories, Murray Hill, N.J. he returned in 1992 to Chalmers where he is a full professor of Photonics. He was Director of Research at CENiX Inc. in Allentown, PA, during 2000 – 2003 and with the newly established Center for Optical Technologies at Lehigh University, Bethlehem, PA, during 2003 – 2004. His research interests include nearly all aspects of high speed and high capacity fiber communications such as optical amplifiers, nonlinear pulse propagation, all-optical functionalities, and very high speed transmission. Andrekson is a Fellow of the Optical Society of America and of the IEEE, and is serving on several technical program committees (e.g. ECOC and OFC). He is an associate editor for IEEE Photonics Technology Letters and has served as an expert for the evaluation of the Nobel Prize in Physics in 1996 and 2007.
All-Optical Sampling for High Resolution Optical Waveform Analysis

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What matters when measuring optical waveforms?

- Temporal resolution and impulse response
- Timing jitter - < 5% of resolution
- Sensitivity (signal peak power) to reach certain SNR
- Linearity (especially for analog signals, but also multi-bit/symbol data)
- Polarization independence (e.g. for PMD impaired signals)
- Optical bandwidth
- Dynamic range / effective # of bits (e.g. for add-drop multiplexing)

Some key considerations

- Needed time resolution:
  - Electronic solutions (< 100 GHz) or all-optical solutions (~ THz)
- Waveform averaging:
  - Improves sensitivity but unacceptable for eye diagrams/statistics
- Intensity waveform or full vector analysis:
  - e.g. for constellation diagrams
- Repetitive waveforms or unique events / data bursts:
  - Real-time (ideally Nyquist-limited) or equivalent-time sampling

Tools for high speed optical pulse and waveform monitoring

- Autocorrelation
  - < 1 ps resolution, no trigger needed
  - no patterns, symmetric waveform, a priori knowledge of shape
- Streak camera
  - ~ 2 ps resolution, short data patterns possible, no eye-diagrams
- High speed detector & electronic sampling
  - 5-10 ps resolution, ‘ringing’ due to impedance mismatch, etc
- All-optical sampling
  - < 1 ps resolution, sensitive, no ‘ringing’, ...

High speed sampling of optical signals

Electronic sampling:
- Need fast photo diode and fast electronics
- Impedance mismatch is a concern
- Electrically sampled waveform is affected by receiver

Optical sampling:
- No need for fast photo diode or fast electronics
- Can use APD for sensitivity improvement
- Optically sampled waveform gives true shape

Measured 40 Gb/s waveform
Optical sampling gate designs

Switching by rapid change of:
- Optical phase
- Frequency
- Polarization

Sampling gate

Gating principle

- Sum frequency generation in $\gamma^{(3)}$ materials (e.g., short nonlinear crystal, few mm)
- Nonlinear refraction in $\gamma^{(2)}$ materials (e.g., high-$\gamma$ optical fibers, 100 m)
- Parametric amplification, cross-phase modulation, Kerr switch

Cascaded $\gamma^{(2)}$ nonlinearity devices:
- Frequency doubling and difference frequency generation mimicking $\gamma^{(2)}$ in fibers

SOA in different configurations

- Two-photon absorption
- Coherent mixing on photo-diode (linear)
- Stimulated Raman scattering

Trade-offs

Material choice
- Interaction length
- Sampling power

Example:
- Efficiency/sensitivity improves with increasing interaction length
- Resolution and optical bandwidth degrades with increasing interaction length

Software-synchronized sampling – Why and how?

- No clock-recovery circuit required
- Bit-rate independent & modulation format flexible
- Reduced sampling system complexity
- High sampling rate – minimizes drift concern
- The samples are (Fourier) analyzed and time stamped
- Both eye diagrams and patterns

Software-synchronized sampling – How?

- Generated idler wave is filtered out
- All-fiber-spliced compact and robust
- Software-based synchronization → No trigger needed

Polarization-independent sampling

- Add DGD-element before gate
- Align sampling pulses at 45° to PSP → "two samplers in one fiber"
- Low BW detector averages power resulting in polarization independence

- 7% residual polarization dependence
- No resolution impairment

Optical signal bandwidth

- Optical bandwidth well over 100 nm is achievable
- 3 nm sampling pulse source wavelength tolerance
Pulse width limitation
Efficiency $= P_{out}/P_{in}$
- Gate width compression
- Ex. Sampling pulse width $T_{samp} = 1.3$ ps

Walk-off limitation
$\Delta T = \sqrt{T_{samp}^2 - T_{sps}^2}$
$= \sqrt{2.95^2 - 2.35^2} \approx 0.9$ ps

With $S = 0.02$ ps/nm/km and $L = 10$ m
100 nm BW with 1 ps resolution

Sensitivity ↔ time resolution trade-off

<table>
<thead>
<tr>
<th>Resolution</th>
<th>PIN</th>
<th>APD (M=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ps</td>
<td>-9 dBm</td>
<td>-11 dBm</td>
</tr>
<tr>
<td>8 ps</td>
<td>-12 dBm</td>
<td>-18 dBm</td>
</tr>
<tr>
<td>18 ps</td>
<td>-15 dBm</td>
<td>-22 dBm</td>
</tr>
</tbody>
</table>

Sensitivity definition:
- Signal power needed for 20 dB SNR
- $S \approx 0.05$ ps/nm/km

Optical signal transmission
Oscillations in pulse tail caused by pulse propagation in optical fiber link

Conclusions
- Next generation optical communication system need high performance optical waveform measurement tools.
- All-optical sampling provides a versatile solution:
  - High resolution without ringing
  - High sensitivity for statistical analysis
  - Scalable to higher resolution and to other wavelength ranges
  - Compatible with advanced phase encoded signals
  - Compatible with very high sampling rates
Ultrahigh-speed Optical Signal Processing for Future Optical Transmission and Photonic Networks

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Abstract

Ultrahigh-speed optical signal processing is an essential technology for future photonic networks. Fully transparent features in both the time and wavelength domain will be required for optical signal processors. A fiber-based optical processor is a promising candidate because it can provide an ultra-broad conversion band and ultra-high speed operation at over Tbit/s. By using nonlinear optical fibers, examples of ultrahigh-speed processing technologies are demonstrated including optical regeneration and optical parametrically amplified fiber switch. Issues of systems/devices technologies and steps for further improvements will be discussed.

Shigeki Watanabe is Research Fellow for advanced phonic technologies at Fujitsu Laboratories and is responsible for optical innovations using advanced photonic devices and systems technologies. His research includes optical signal processing, ultrahigh-speed photonics and novel applications of nano-optical devices. Since 2001 he has been promoting collaboration research on ultrahigh-speed optical signal processing between Fujitsu Laboratories and FhG Heinrich Hertz Institute. In 2005 he served as a guest professor at COM center in Technical University of Denmark. Dr. Watanabe is a member of IEEE, OSA and IEICE. He received the Commendation by the Minister of Education, Culture, Sports, Science and Technology 2003 in Japan.
Ultrahigh-speed Optical Signal Processing for Future Optical Transmission and Photonic Networks

August 21, 2007
Shigeki Watanabe
Fujitsu Laboratories Ltd.

Outline
- Photonic network and optical processing
- Optical signal processing using nonlinear fibers
- Ultra-high speed systems demonstration
  - Optical regeneration
  - Optical parametrically amplified fiber switch, etc.
- Issues and future perspective
- Summary

Technologies for Future Photonic Network
- Optical routing/processing
- Efficient communication
- Core node
- WDM/TDM
- Multi-level (m-PSK, QAM, ...)
- Optical packets
- Compensation, DSP
- Quantum communication
- Optical regeneration
- Optical parametrically amplified fiber switch, etc.

Application of High-speed Optical Switches
- Optical DEMUX
  - Requirements:
    - High-speed optical switch
    - Retiming for channel selection
  - λ-conversion
    - High-broadband nonlinearity
    - High efficiency
  - Packet SW
    - High-speed optical switch
    - Optical buffer
    - Packet recognition
  - Optical 2R/3R
    - High-speed and transparent
    - Broadband reshaping
    - Retiming and data synchronization (3R)

Prerequisites for Optical Signal Processors
- Functions
  - Optical switching (Optical DEMUX/sampling, λ-conversion, packet SW, - - -)
  - Optical 2R/3R regeneration
  - Optical pulse generation, optical-comb generation
  - Optical monitoring
- Features
  - Transparency
  - Ultra-high speed and ultra broadband
  - Bit-rate free, modulation format free, waveform independent, etc.
  - Multi-channel/multi-level processing
  - Low loss, flexible input power,
  - Low noise and small distortion
- Issues
  - Low power consumption
  - Nonlinearity increase
  - Polarization independence
  - Matching to transmission fibers

χ(^3)-Nonlinear Effects in Fiber
- Self-phase modulation (SPM)
  - Higher nonlinearity
  - Trade-off between BW and OSNR
- Cross-phase modulation (XPM)
  - Higher nonlinearity
  - Efficiency limit by walk-off
  - Polarization dependence
- Four-wave mixing (FWM)
  - Higher nonlinearity
  - Efficiency limit by phase matching
  - Efficiency limit by walk-off
  - Polarization dependence
### 640 → 40 Gbaud Demultiplexer

- **640 Gbaud transmitter**
  - 40 Gb/s Transmitter
  - 640 → 40 Gb/s Multiplexer
- **Fiber Link**
  - WDM-Laser
  - Fiber Laser
  - HiBi PBS
- **640 → 40 Gbaud OTDM DEMUX**
  - PMF (λS)
  - Time (ps)
  - Output signal

### Optical Regeneration

- **Schematic**
  - Pulse shaper
  - Optical gate
- **Function**
  - Signal pulse (s)
  - Optical gate (Kerr-switch)
  - Jitter reduction by pulse shaping
  - Polarizer by fiber Kerr-switch
- **Requirements**
  - Noise suppression
  - Jitter suppression
  - Reshaping
  - Ratemming
- **Motivations**
  - Breaking down the system limit; increase in transmission distance and span length.
  - Mitigation of system tolerances; that of power, dispersion, nonlinearity, etc.
  - Increase in the flexibility of the system and network.
  - Cost effectiveness
  - Low power consumption

### 160 Gb/s Optical 3R-Regenerator

- **Configuration**
  - Optical 3R-regenerator
- **Pulse shaper**
  - (Ref. T. Ohashi et al., IEEE PTL, 2000)
- **Optical gate (Kerr-switch)**
  - Jitter reduction by pulse shaping
  - Optical gating by fiber Kerr-switch
- **Setup**
  - Transmitter 640 Gb/s
  - Receiver 640 Gb/s

### 160 Gb/s Optical 3R-Transmission

- **BER characteristics**
  - Improvement by 3R

### Optical Parametrically Amplified Fiber Switch

- **Schematic**
  - OPA
  - Nonlinear fiber
- **Function**
  - Output signal
  - Control pulse (E0)
  - Polarizer
  - Switched out from the polarizer
- **Features**
  - High optical SN
  - Ultra-high-speed (≥7 Ts/s) ultra broadband over the full C/L-band
  - Wavelength preserved switching

### Ultrahigh-speed Optical DEMUX by Fiber Switch

- **Setup**
  - Optical fiber SW
  - Signal: Eo
  - Polarizer
- **Switching characteristics**
  - Pulse width
  - 160 GHz 1.6 ps
  - 220 GHz 0.75 ps
  - 1050 GHz 3.8 ps
- **BER characteristics**
  - Bit error rate (BER)
Amplitude Noise Suppression by Fiber Switch

Configuration

- Amplitude noise suppression by gain saturation of optical parametric amplification (OPA)
- Suppression of system deterioration due to AM/PM noise conversion in PSK transmission

Features

- Ultra-high speed and ultra-broadband reshaping
- Format free operation: OOK, PSK, - - -
- Wavelength preserving
- Lower level suppression by the polarizer

Noise Suppression of 160-Gb/s DPSK Signal

Features

- Optical modulation by XPM
- Optical phase shift induced by XPM in a nonlinear fiber
- Ultra-high-speed optical PSK/QPSK modulation controlled by OOK data pulse

Application to format conversion

All-optical Phase Modulation

- Optical modulation by XPM
  - Optical phase shift induced by XPM in a nonlinear fiber
  - Ultra-high-speed optical PSK/QPSK modulation controlled by OOK data pulse

For Further Improvement

- Increase in nonlinearity
  - Kerr phase shift: \( \phi_{NL} \propto \gamma P \)
  - to achieve \( \phi_{NL} \sim 1 \),
  - \( \gamma > 100 \) W\(^{-1}\) km\(^{-1} \) (for \( P \sim 100 \) mW, \( L \sim 100 \) m)

- Increase in bandwidth
  - Fine control of dispersion is required for BW > 100 nm
  - to achieve phase matching, small walk-off
  - \( \Delta \lambda < 0.1 \) nm, third-fourth-order dispersion control

Nano-Optical Devices

- Photonic crystal fiber (PCF)
  - Ultra high speed
  - > 10–100 times larger than HNLF
- Nonlinear quantum-dot
  - Dense integration
  - Strong nonlinearity
  - Ultra high speed
- Silicon photonics
  - Applicable to
  - Highly-integrated signal processor
  - Optical switches
  - WDM processing, etc.

Summary

- Ultra-highspeed optical signal processing is a key technology for realizing flexible, cost-effective photonic network with low power consumption.
- Nonlinear fibers are practical candidates of the material for transparent optical signal processors.
- Systematic applications using optical fiber switches were demonstrated;
  - Optical 2R/3R regeneration
  - Optical parametrically amplified fiber switch, etc.
- Further improvements in performance and feasibility are required for both devices and systems.
- Ultra-highly nonlinear fibers, nano-optical devices, Si-photonic devices could be breakthrough for optical signal processing in future photonic network.
Session VI

All-Optical Switching

Session Chair

Boris Stefanov

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Boris Stefanov received a B.S. degree in Physics in 1992 from Sofia University, Bulgaria, and a Ph.D. in Chemical Physics in 1996 from Florida State University. In 1996, he joined the Photonic Materials Research Department at Bell Laboratories in Murray Hill, NJ where he studied the optical properties of SiO₂-GeO₂ fibers and semiconductor surfaces.

In 1998 he moved to the Optical Networking Group of Lucent Technologies, where as a systems engineer and systems architect and was involved in the technology transfer and productization of MEMS optical switching technology from Bell Labs and the introduction of the first commercial optical cross-connect system. In 2000 Boris joined his colleagues, B. Dave and R. Simprini to found Alphion Corporation, a start-up company chartered to develop all-optical switching and transport technologies where he has had responsibility for a variety of areas including technology development, operations, and marketing as Director of Product Development, Operations, and Product Strategy. In 2006, he was appointed Alphion Vice President for Product Development. Boris has authored 15 Patents in the area of optical switching, signal processing, and communications and many scientific articles in peer-reviewed publications.
All-Optical Packet Switching at Ultra-high Bit-Rates

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Abstract

All-optical packet switching at ultra-high bit-rates is discussed. In particular, we focus on integrated devices that are required to make switching decisions in the optical domain. In particular, we focus on monolithically and hybrid integrated all-optical flip-flops and ultra-fast semiconductor based wavelength converters. The operation principles are explained and implementations are given. Finally, a 160 Gb/s all-optical packet switching experiment over 110 km of field installed optical fiber is described.

Harm Dorren received his M.Sc. degree in theoretical physics in 1991 and the Ph.D. degree in 1995, both from Utrecht University, Utrecht, the Netherlands. After postdoctoral positions he joined Eindhoven University of Technology, Eindhoven, The Netherlands in 1996 where he presently serves as the scientific director of the COBRA Research Institute. In 2002 he was also a visiting researcher at the National Institute of Industrial Science and Technology (AIST) in Tsukuba in Japan. His research interests include optical packet switching, digital optical signal processing and ultrafast photonics. Dr. Dorren (co-)authored over 250 journal papers and conference proceedings and currently serves as an associate editor for the IEEE Journal of Quantum Electronics.
Integrated devices for all-optical packet switching

Harmen J.S. Dorren

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Outline

• Background/motivation
• Wavelength conversion
• Optical flip-flop memories
• Packet switching at ultra-high bitrates
• Optical buffering
• Conclusions

Exponential traffic growth

Traffic increase in Amsterdam Internet Exchange (factor 2.5/18 months)

Commercial Packet Routers

• Up to 92 Tbit/s
• Optical inputs but electronic switching
• Each linecard at 40 Gbit/s
• Up to 80 shelves
• Very large power consumption: 10 nJ per bit = 10^5 x bit energy

This system is too small for Amsterdam in 2015


The dream: Integrated photonic packet switched cross connects

Monolithically integrated circuit switch cross-connect: Meint Smit's group (2000)

Early implementation 1 x 2 photonic packet switch

Hill et al, Elec. Let. 37, 774-775 (2001)
Wavelength conversion based on cross-gain modulation

Operation principle

BER performance

Monolithically integrated 80 Gb/s wavelength converter
**Optical flip-flops/Operation principle**

- Symmetric configuration that acts as a master-slave system
- Optically set and reset
- Different implementations possible (Lasers, MZIs, polarization switches)
- Early implementations in fiber

\[ \text{Laser 1} \quad \text{Laser 2} \]

\[ \text{Symmetric configuration that acts as a master-slave system} \]

**Optical flip-flops/Operation principle**

**Experimental set-up**

**Conclusions**

- Overview of photonic packet switching research at COBRA, Eindhoven University of Technology is given
- Large progress in high-speed optical switching and wavelength conversion
- Monolithically integrated photonic memories have been realized and have been used in high-speed photonic packet switch experiments
Ultrafast All-Optical Switches Using Intersubband Transitions in Quantum Wells

Hiroshi Ishikawa

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Abstract

We report a new all-optical phase modulation phenomenon in InGaAs/AlAs/AlAsSb quantum well intersubband transition (ISBT) switch. The TE probe light, which is not absorbed by ISBT, is deeply phase modulated by TM pumping light. This new phenomenon can be explained by plasma dispersion effect associated with carrier redistribution among subbands, whereby band nonparabolicity plays a crucial role. Using this effect we have demonstrated a wavelength conversion of picosecond pulses with 10Gb/s repetition, and a demultiplication operation of 160Gb/s signal to 10Gb/s. The newly found phase modulation effect enables us to realize low-insertion-loss ultrafast all-optical signal processing devices.

Hiroshi ISHIKAWA is a Director of Ultrafast Photonic Devices Laboratory in National Institute of Advanced Industrial and Science and Technology (AIST). He previously was in Fujitsu Labs Ltd. At Fujitsu Labs he worked for the development of optical semiconductor devices such as lasers and nonlinear optical devices. After joining AIST in 2004, he is responsible for developing ultrafast all-optical switching devices for ultrafast optical communication systems. He and his coworkers are working for CdS/ZnSe/BeTe and InGaAs/AlAs/AlAsSb based intersubband transition all-optical switches, and photonic crystal based all-optical optical functional devices. The most important objective now is to establish technologies for 160Gb/s OTDM systems. This includes the hybrid integration of ultrafast optical devices and Si-wire waveguides. He is a Fellow of IEEE, and member of Physical Society of Japan, Japan Society of Applied Physics, and The Institute of Electronics, Information and Communication Engineers (IEICE).
Ultrafast All-Optical Switches Using Intersubband Transitions in Quantum Wells

H. Ishikawa

National Institute of Advanced Industrial Science and Technology (AIST)

Quantum wells for intersubband transition (ISBT) switch

<table>
<thead>
<tr>
<th>Material system</th>
<th>Well depth (eV)</th>
<th>Recovery time (fs)</th>
<th>Research group</th>
</tr>
</thead>
<tbody>
<tr>
<td>(GaN)/AIN</td>
<td>1.7-2.0</td>
<td>&lt; 200</td>
<td>Toshiba, University of Tokyo, Lucent</td>
</tr>
<tr>
<td>(InGaAs)/AlAs/AlAsSb</td>
<td>1.6</td>
<td>600fs-1ps</td>
<td>AIST</td>
</tr>
<tr>
<td>(CdS)/ZnSe/BeTe</td>
<td>3.1</td>
<td>&lt; 500fs</td>
<td>AIST</td>
</tr>
</tbody>
</table>

- Deep potential well is needed for 1.55μm transition.
- T1 and T2 depend on effective mass, LO-phonon energy, and dielectric constant. GaN system is the fastest.
- Larger energy is needed for faster response.

Saturation characteristics and time response

Operating principle of intersubband transition (ISBT) all-optical switch

\[
P_s = \frac{c n g J^2}{2 \mu T_1 T_2}
\]

\[ \mu : \text{dipole moment} \\
T_1 : \text{energy relaxation time} \\
T_2 : \text{dephasing time} \]

Small T1 and T2 value enables very fast switching

InGaAs/AlAs/AlAsSb ISBT switch

- Length: 380 μm
- Mesa width: 1 μm
- Waveguide is 6 degree tilted
- AR coating on both facet
- Design for larger effective refractive index
- Employment of SCH structure

New cross-phase modulation effect in InGaAs/AlAs/AlAsSb ISBT switch

- Phase modulation on TE light by TM pump light
- No phase modulation by TE light
- No phase modulation in CdS/ZnSe/BeTe ISBT switch

Measurement of phase shift (2)

Phase shift as a function of pump energy

\[ \tau = 1.88\text{rad} \]

\[ L = 240\mu m \]

\[ \Gamma = 0.3 \]

\[ \Delta n = \frac{\Delta \phi L}{2 \pi L \Gamma} = 6.4 \times 10^{-3} \]

Mechanisms of refractive index modulation

Absorption saturation for TM mode does not cause the refractive index change for TE mode. (Kramers-Kronig relation)

Why?

New mechanism
Plasma dispersion effect, associated with carrier redistribution among subbands, where band non-parabolicity plays a crucial role.


Quantum well model and mechanism of refractive index change

Due to different effective mass at each subband, there arises refractive index by TM pumping.

Calculation of electron density by rate equation

Refractive index change by plasma dispersion

This occurs due to the small effective mass and band nonparabolicity.

Positive refractive index change of the order of 10^{-3} can be explained.

Calculation of electron density by rate equation

Why only in InGaAs/AlAs/AlAsSb quantum well?

InGaAs/AlAs/AlAsSb system

\[ \lambda_p = 12.5\mu m \] (6 x 10^{19}cm^{-3})

\[ m^* = 0.035m_0(1+1.2E) \]

CdS/ZnSe/BeTe system

\[ \lambda_p = 29\mu m \] (6 x 10^{19}cm^{-3})

\[ m^* = 0.20m_0(1+0.4E) \]

Small effective mass and large nonparabolicity in InGaAs system causes the all-optical phase modulation.
Advantageous features of this phase modulation effect

- Phase shift occurs in loss-less TE probe signal
- There is no TPA for TE mode originating from the cross term with TM pump pulse
- Ultrafast response (order of 1ps)

Low-insertion-loss ultrafast devices with lower-switching energy can be realized.

Wavelength conversion of 10Gb/s pulses with picosecond width

- $L_{TE} = 3.72 \text{ dB}$
- $L_{TM} = 26.5 \text{ dB}$

Application to signal processing

- OOK to PSK conversion
- OOK to DPSK conversion

Summary

- A new ultrafast all-optical phase modulation effect was found in InGaAs/AlAs/AlAsSb ISBT switch.
- Mechanism of the phase modulation was made clear.
- Error-free wavelength conversion for 10-Gbps signal with 2.6ps pulse width was demonstrated.

This new phase modulation effect is highly promising for ultrafast devices.
Session VII

Femtosecond Pulse Generation and Control

Session Chair

Jinendra K. Ranka

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Jinendra Ranka was born in New York in 1969. He received a B.S. degree in Electrical Engineering in 1991 from the California Institute of Technology and a Ph.D. in Applied Physics in 1997 from Cornell University. In 1997, he joined the Lucent Technologies’ Bell Laboratory where he was engaged in research on nonlinear effects in optical fibers. From 2000 through 2003 he worked at Sycamore Networks in the areas of system engineering and optical-amplifier design. In 2003, he joined the Quantum Electronics group at MIT Lincoln Laboratory where he is currently a member of the Technical Staff.
Femtosecond Technologies for Optical Clocks and Arbitrary Optical Waveforms

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Abstract

Femtosecond lasers have led to a revolution in frequency metrology over the last decade and bear the potential for arbitrary optical waveform generation. The progress made in high repetition rate laser sources as an oscillator technology for optical clocks and arbitrary optical waveform generation covering the wavelength range from 600nm-2μm is discussed. These are in particular carrier-envelope phase stabilized octave spanning Ti:sapphire lasers with repetition rates from 100MHz to 1GHz, which can be carrier-envelope phase stabilized without external continuum generation. The 1GHz repetition rate laser is used to demonstrate a methane-stabilized HeNe-laser-based compact optical clock. Also high repetition rate 1.5μm fiber based sources, 200MHz fundamentally mode-locked and 1GHz with repetition rate multiplication, are demonstrated. Continuum generation with these lasers covers the 1-2μm and permits carrier-envelope phase locking.

Franz X. Kärtner received his Diploma and Ph.D. degrees in Electrical Engineering from Technische Universität München, Germany in 1986 and 1989, respectively. From 1991-93 he was a Feodor-Lynen Fellow of the Alexander of the Humboldt Foundation at Massachusetts Institute of Technology (MIT). From 1993-1997 he was a research scientist at the Swiss Federal Institute of Technology (ETH) where he received his Habilitation degree in Experimental Physics in 1997. After a visiting professorship at MIT in 1998 he joined the Electrical Engineering Department at Universität Karlsruhe (TH), Germany and headed the High Frequency and Quantum Electronics Laboratory. In 2001, he returned to MIT where he is currently a Full Professor in the Department of Electrical Engineering and Computer Science. His research interests include classical and quantum noise in electronic and optical devices; femtosecond lasers and their applications in frequency metrology, femtosecond precision timing distribution and the study of ultrafast phenomena; high-index contrast micro-photonic devices and their use in high speed signal processing and optical communications. He is a member of the German Scholarship Foundation, the German Physical Society, the IEEE and the OSA.
Femtosecond Technologies for Optical Clocks and Optical Arbitrary Waveforms

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Outline

I. Femtosecond Laser Frequency Combs
II. Octave Spanning Ti:sapphire Lasers
III. Scaling to High Repetition Rates
IV. Methan-Stabilized HeNe Optical Clock
V. High Repetition Rate Fiber Lasers
VI. Conclusions

Femtosecond Laser Pulse Train

Laser

$\phi_1 = 0 \quad \phi_2 = \frac{2 \pi}{f_R}$

Here:

$f_{CE} = \frac{f_0}{5}$

$\phi_{CE} = \frac{2 \pi}{f_R}$

Optical Clock

$\phi_1 = 0 \quad \phi_2 = 0 \quad \phi_3 = 0 \quad \phi_4 = 0 \quad \phi_5 = 0 \quad \phi_6 = 0$

Optical Ref.

$(n/m) f_0 = m f_R$

DCM-Pairs Spanning One Octave

Reflectivity

Group Delay (fs)

Wavelength, nm

Phase Controlled Ti:sapphire Laser (200 MHz)

Carrier-Envelope Phase Noise

power spectral density (PSD) of carrier-envelope phase fluctuations

integrated carrier-envelope phase error $\phi_{CE}$

$\sqrt{\phi_{CE}^2} = 0.1 \text{ rad}$
$2.5 \text{ mHz} \text{ to } 10 \text{ MHz}$
$< 45 \text{ as carrier-envelope timing jitter (in loop)}$

5fs Pulses Directly From Ti:sapphire Lasers


1 GHz Ti:sapphire Laser

$\pi$-controller

$1.02 \pi = \phi_{CE}$

$\phi_{CE} < 45 \text{ as carrier-envelope timing jitter (in loop)}$

Pump Laser

30mm DCM (typ. 2)

8cm

15cm


Spectrum

Output power: 0.6-1W

> Octave with Fourier limit: 3.5fs

Beat Notes

1f-2f beat: 55dB

DFG-HeNe beat: 30dB

100 kHz Bandwidth


First Allan Deviation Measurements

Limiting by CH$_4$-HeNe-Amplifier Lock

Ron Walsworth, CFA Harvard

Spectral and Temporal Characteristics

- 167fs pulses with 2.8 THz spectral width
- Very low intensity noise


Repetition Rate Multiplication to 1GHz

Conclusions

- Ti:sapphire lasers today are truly octave spanning
- 1f-2f carrier-envelope phase locking is directly possible with minimum carrier-envelope phase jitter (50 as).
- Sub-2 cycle optical pulses directly from the laser (compressed to 3.7fs by U. Morgner, Universität Hannover)
- CH$_4$-stabilized HeNe-Clock with final stability 10$^{-14}$@1sec
- Octave spanning Ti:sapphire laser workhorses:
  - Frequency metrology and Attosecond physics,
  - High repetition rate compact Er-fiber laser technology: Arbitrary Optical Waveform Generation (AOWG) and High-Speed Sampling (EPIC)
Carrier Envelope Phase Detection by Quantum Interference Control in Semiconductors

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Abstract

The ability to detect the carrier-envelope phase evolution of the pulse train emitted by a mode-locked laser has led to the field of femtosecond combs. Typically, the carrier-envelope phase is detected using a nonlinear optical interferometer that compares the output of the laser two its second harmonic. In a similar fashion, quantum interference between one- and two-photon absorption is sensitive to the carrier-envelope phase. Results demonstrating this method of detecting the carrier envelope phase will be presented. Quantum interference detection of the carrier envelope phase has also been used to stabilize the comb spectrum from a mode-locked Ti:sapphire laser, which in turn was used to measure optical frequencies.
Carrier Envelope Phase Detection by Quantum Interference Control in Semiconductors

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Time Domain ↔ Frequency Domain

Time Domain

Frequency Domain

F.T.

Frequency modes of the fs pulse are offset from $f_n = 0$ by $f_0$

Derivation:

Implementation of self-referencing

Quantum Interference Control (QIC) of injected photocurrents

Quantum Interference Control (QIC) of Injected Photocurrents

First observed in GaAs by van Driel and Sipe (U. Toronto)

Sensitive to $\Phi_{CE}$ if $\nu$ and $2\nu$ pulses are derived from a single octave spanning pulse

How can we measure the offset frequency?
Self-referencing:

- Compare the comb to its second harmonic

Fundamental Spectrum

Second Harmonic Spectrum

For the nearest comb lines $m = 2n$, then heterodyne beat frequency is $2(nf_r + f_0) - (2nf_r + f_0) = f_0$

Requires an "octave" of bandwidth

Injected photocurrent:

$J \propto 2E_0^2E_\nu \sin(\Delta \phi)$

$\Delta \phi = 2\phi_\nu - \phi_{2\nu}$

Interference between 1-photon and 2-photon absorption

Quantum Interference Control of Injected Photocurrents

First observed in GaAs by van Driel and Sipe (U. Toronto)

- Using SHG to generate $2\nu$ pulse from $\nu$ pulse

Sensitive to $\Phi_{CE}$ if $\nu$ and $2\nu$ pulses are derived from a single octave spanning pulse
### QIC Detection of \( \Phi_{CE} \)

**Injected photocurrent:**

\[
J \propto 2 E_v^2 E_{2\nu} \sin(\phi_{2\nu})
\]

**Conduction band**

**Valence band**

**QIC experimental setup**

Lock to finite \( f_0 \) to facilitate detection

Use MS fiber in first demonstration to increase optical power at \( \nu \) and \( 2\nu \)

Spectrum Analyzer

**QIC results**

Signal \( \sim 1 \) mV (measured by lockin)

**Power dependence of QIC signal**

\[
J \propto 2 E_v^2 E_{2\nu} \sin(\Delta \phi)
\]

- Verification of origin of signal
- Vary \( \nu \) and \( 2\nu \) intensities independently
- Expected result:
  \( S_{QIC} \sim I_\nu \)
  \( S_{QIC} \sim \sqrt{I_{2\nu}} \)
- Data agrees very well

**QIC experimental setup: static \( \phi_{CE} \) shifts**

Lock to finite \( f_0 \) to facilitate detection

Use MS fiber in first demonstration to increase optical power at \( \nu \) and \( 2\nu \)
Measurement of static shifts with QIC

- Measure phase fluctuations directly
  - Slight correlation with amplitude fluctuations
  - Likely due to M.S. fiber
- Impose static shifts by varying propagation distance through glass plate
  - Actually in locking arm, serve adjusts laser
- Good agreement with estimate from dispersion
  - Deviation at large angle due to misalignment

Amplitude to Phase Conversion

- Amplitude to phase noise conversion is a concern in optical detection
- Explicitly vary amplitude of light as a function of time
  - After M.S. Fiber
  - Monitor amplitude and phase of QIC signal
- Correlation coefficient: $R = -0.02515$
  - Negligible conversion of amplitude to phase modulation

Stabilization of Laser using QIC

- Optimized preamplifier: transimpedance matched to QIC device
  - 30 dB SNR in 10 kHz
  - Electrical bandwidth ~ 500 kHz
- Tracking oscillator to improve signal-to-noise ratio

QIC locking of $f_0$

- Locking stability comparable to standard v-to-2v interferometer
  - Similar phase noise spectrum
  - RMS phase jitter ~0.13 rad at 0.1 sec

Population QIC

- Control of total excited state population possible in medium with broken inversion symmetry
  - "Population" QIC
  - Possible in (111) oriented GaAs
    - demonstrated with optical readout (jump probe)
    - [M. Fraser and H. M. van Driel, Phys. Rev. B 68, 085308 (2003)]
  - Modulation of a few percent obtained
- Electrical readout needed for practical use
  - "Two-pulse" demonstration

Summary

- Demonstrated quantum interference control of injected photo-currents based on carrier-envelope phase
- Characterized electrical properties of sample
  - Design custom transimpedance amplifier
- Demonstrated that QIC can be used to stabilize laser
  - Comparable to "traditional" v-to-2v optical interferometer
- Demonstrated electrical detection of population QIC

Further Reading

Dispersion Micromanagement in Holey Fibers: Advances and Applications in Femtosecond Technology

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Abstract

Dispersion management is commonly employed on a terrestrial scale (km) in lightwave networks to counteract effects of dispersion in communications systems. Inside ultrafast lasers, dispersion management is used to control pulse dynamics on a meter scale. We discuss experiments in which the dispersion of an optical fiber is managed on a microscopic scale (100 microns or less), with corresponding strong effects on the nonlinear propagation of femtosecond optical pulses [1]. We describe a microfabrication technique that allows us to produce uniform or programmed tapered holey, photonic crystal or doped optical fibers with desired dispersion profiles, and give examples of applications of these unique scalable broadband low-noise optical sources in various technology areas.

Wayne H. Knox is Professor of Optics and Director of The Institute of Optics at the University of Rochester. His research includes femtosecond microfabrication, tapered photonic crystal dispersion micromanagement devices, and novel applications of femtosecond technology. He and his co-workers are responsible for a number of innovations in femtosecond technology and applications including: scalable Ytterbium femtosecond fiber laser systems, low-noise continuum generation using nonlinear tapered fiber devices, semiconductor modelocking devices, applications in biomedical imaging and precision frequency measurement.

Dispersion Micromanagement in Holey Fibers: Advances and Applications in Femtosecond Technology

Wayne Knox
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Why should we care about noise in continuum sources?

- A limitation in Optical Coherence Tomography, where source can give < 1 micron coherence length... (Fujimoto et al.)
- A limitation in precision frequency metrology... (Cundiff et al.)
- A limitation in telecommunications for WDM sources... (WHK or CX, et al.)

As much as 20 dB excess noise has been reported


Dudley et. al OPEX 21 October 2002 / Vol. 10, No. 21 / OPTICS EXPRESS 1215

Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm

J. Dudley, K. Ruotsi, D. V. Whittaker, and Andrew J. Stair
MRL Laboratories Laser Technologies, 58 Stevenson Avenue, Murray Hill, New Jersey 07974


Input: Ti:Sapphire 100fs laser, 885nm

Loss: 2.3dB
2D-800nm

396 mw

Looks nice – but complex and noisy light.
If the continuum $\lambda$ component is produced by a random process, the fringe contrast between one pulse and the next one in the train will be low, and the RF spectrum will be noisy at that wavelength. If it is produced by a deterministic process, fringes will be sharp and RF spectrum will be low-noise.

Spectral coherence of continuum depends strongly on input wavelength.

Optimizing dispersion profile along axis may be the key to generating low-noise continuum.

Why Micro-Manage Dispersion?
- Because we can!
- Because at high intensities, the nonlinear phase in only 1 mm propagation length with a 2.5 micron core size is $\pi/4$!!
- Should be very important with very short pulses like <10 fs …

We fabricated a parabolically tapered holey fiber 1 cm long from: Blaze NL 3.3 -880

Tunability of AS feature by varying taper diameter
Noise Comparisons of Different Continuum Generation Techniques

![Graph showing noise comparisons](image)

Broadband Noise Comparison Results

![Graph showing broadband noise comparison results](image)

Three regimes of dispersion management

- **No dispersion micro-management**
  - narrow AS feature, narrowband phase-matching

- **“Slow” dispersion micro-management (5-10 mm)**
  - broader AS features, broader phase-matching, but retains high coherence and low noise

- **“Rapid” dispersion micro-management (<1 mm)**
  - can we generate broader AS features “sub-continuum” yet retain full coherence and low noise?
  
  *(note a holy grail here........)*

Applications for Continuum sources

- Multispectral imaging
- Spectroscopy
- Optical Coherence Tomography
- Precision frequency measurement
- Generation of CEP-locked light
- Telecommunications - sources

![Graph showing applications for continuum sources](image)