AFRL-SR-AR-TR-02-0174

Error Rate Measurement Instrumentation For Multiwavelength Optical Switching

F49620-00-1-0223

David J. Blumenthal
University of California

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Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia

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REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0074

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE 7-30-2001	3. REPORT TYPE AND DA Final

4. TITLE AND SUBTITLE
Error Rate Measurement Instrumentation for Multiwavelength Optical Switching

5. FUNDING NUMBERS
F49620-00-1-0223

6. AUTHORS
Professor Daniel J. Blumenthal

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering, Engineering I, University of California, Santa Barbara, California 93106-9560

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release - distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The equipment purchased under this DURIP grant is designed to generate high-speed data for optical communications and network experiments. The ability to generate data using this type of instrument is essential to measure the performance of devices and systems and understand what the limitations are. This work resulted in 20 publications, which are listed at the end of this report. Four areas of research were positively impacted by the acquisition of this equipment: (i) all-optical label swapping, (ii) all-optical wavelength conversion, (iii) all-optical serial to parallel conversion and (iv) high-speed wavelength switching. These areas are critical to the future of military and commercial communications infrastructure and the results from this work have laid fundamental groundwork that will shape future optical network technologies and architectures.

14. SUBJECT TERMS
Optical communications, optical networks, wavelength division multiplexing, fiber optic nonlinearities

15. NUMBER OF PAGES
12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-1
298-102

02-28-02 P

Final Technical Report
Research Agreement No. F49620-00-1-0223

Daniel J. Blumenthal
University of California
Santa Barbara, CA 93106
Tel: 805-893-4168
Fax: 805-893-5705
Email: danb@ece.ucsb.edu

1 Executive Summary

The equipment purchased under this DURIP grant is designed to generate high-speed data for optical communications and network experiments. The ability to generate data using this type of instrument is essential to measure the performance of devices and systems and understand what the limitations are. This work resulted in 20 publications, which are listed at the end of this report. Four areas of research were positively impacted by the acquisition of this equipment: (i) all-optical label swapping, (ii) all-optical wavelength conversion, (iii) all-optical serial to parallel conversion and (iv) high-speed wavelength switching. These areas are critical to the future of military and commercial communications infrastructure and the results from this work have laid fundamental groundwork that will shape future optical network technologies and architectures.

The personnel that were supported on the projects related to this DURIP award includes

Olga Lavrova: Ph.D. student, graduated 2001

Lavanya Rau: Ph.D. student, 4th year

Bengt-Erik Olsson: Post Doctoral Fellow, now at Optillion, Sweden

Milan Masanovic: Ph.D. student, 3rd year

Giammarco Rossi: Post Doctoral Fellow, now at Agilent Technologies, Italy

Tim Dimmick: Visiting research scientist, now at Optimum Corporation

Roopesh Doshi: Ph.D. student, 3rd year

Ramesh Rajaduray: Ph.D. student 2nd year

Mads Nielsen: Master's student, completing Ph.D. at Technical University of Denmark

Peter Ohlen: Master's student, now at Optillion, Sweden

Olivier Jerphenon: Master's student, now at Calient Networks

2 Purchased Equipment

The following equipment was purchased in conjunction with industrial matching funds in the form of discounts greater than the standard educational discounts.

Vendor/ (Qnty) Description	Cost
Anritsu MP1763B 12.5 Gbps Pulse Pattern Generator	**$132,592.50**
Anritsu MP1763B-Opt. 01 12.5 GHz Synthesizer	**$21,510.00**

2.1 Changes to Original Equipment List

The original proposal listed a receiver/error-detector and we decided it was more critical at the onset of our research projects to utilize the companion equipment, a pattern generator/transmitter that operates at 12.5 Gbps and that the receiver would be purchased at a later time.

3 Summary of Research Projects for Which Equipment was Used

The acquired equipment was used for the following research projects:

- ***All-optical label swapping at 40 Gbps:*** DURIP equipment was used to generate optical packets at 10 Gbps which were optically multiplexed up to 40 Gbps.
- ***40 Gbps all-optical wavelength conversion using cross-phase modulation in a nonlinear fiber:*** DURIP equipment was used to generate 10 Gbps data for optical multiplexed 40 Gbps data stream that served as input to converter.
- ***40 Gbps optical WDM to OTDM conversion using optical fiber nonlinearities:*** DURIP equipment was used to generate 10 Gbps data for optical multiplexed 40 Gbps data stream that served as input to converter.
- ***High-***Speed Wavelength Switching: The DURIP equipment was used to generate a 10 Gbps data stream to demonstrate wavelength conversion in a fast tunable semiconductor laser.

3.1 All-Optical Label Swapping

All-Optical Label Swapping (AOLS) is a promising new approach to routing packets in optics. Individual IP packets or groups of packets are encapsulated with an optical label as they enter the optical network as shown in Figure 1. The difference between the optical label and the IP packet header is that the optical label is erased and rewritten at each photonic packet switch while the IP packet header is kept intact with the payload through the optical network. Routers only need to look at the smaller label and figure out which output port to send the packet to, which wavelength to convert to the new label.

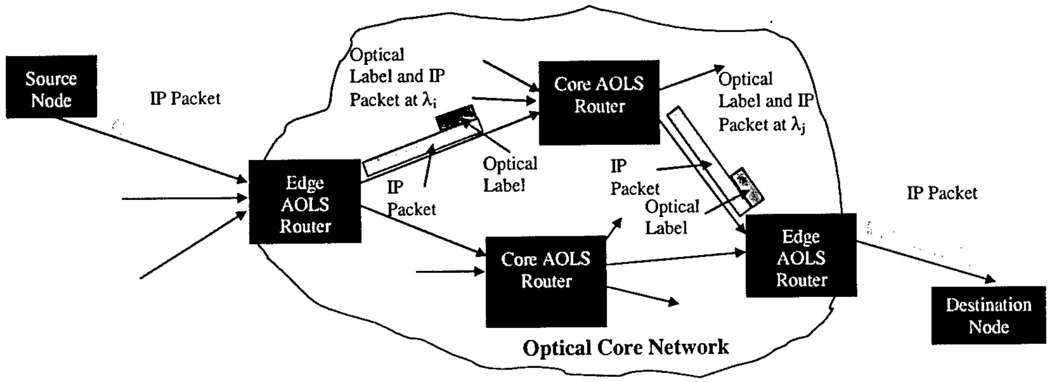


Figure 1 Optical label switched network approach.

A practical approach is to switch the packet optically but use electronics to make the routing decisions. An AOLS subsystem is shown in Figure 2 with separate photonic switching and routing control planes. A small percentage of light is removed at the switch input and the packet label is recovered to compute how to set the switching elements and a new label. The label data rate is independent of the payload bit rate and is chosen at a rate compatible with burst mode electronics. These label-processing circuits operate at a bit-rate that is independent of the payload bit-rate. For example both 40 Gbit/sec and 10 Gbit/sec packets can be routed using 2.5 Gbit/sec headers and electronic circuits.

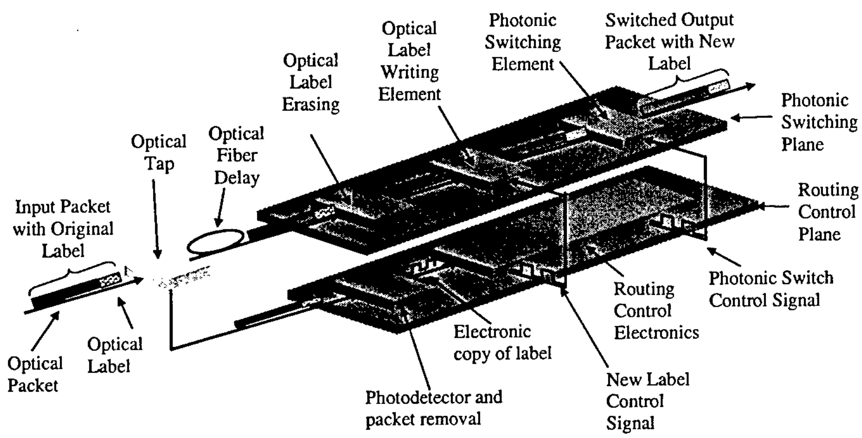
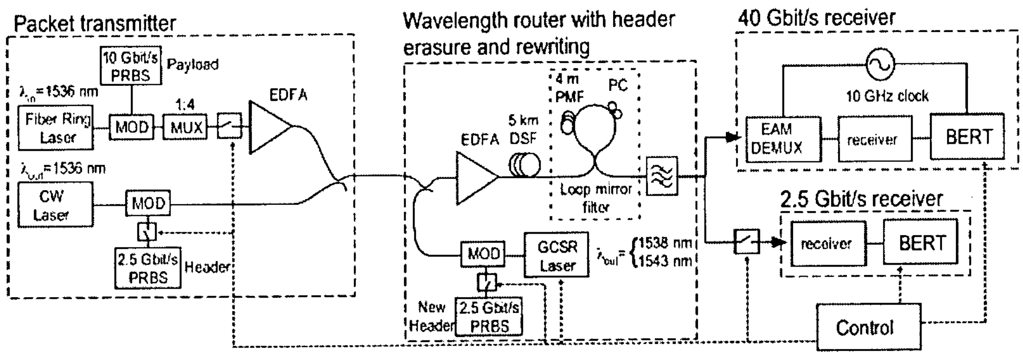


Figure 2 Optical label swapping module

To demonstrate AOLS at high bit-rates we replaced headers on 40 Gbit/s packets using a XPM fiber wavelength converter. The 40 Gbit/s payload was in RZ format and an attached time domain label was encoded using NRZ at 2.5 Gbit/s. Figure 3 shows the experimental set-up. The packet generator consisted of an actively mode-locked fiber ring laser generating 10 ps at 1536 nm followed by a LiNbO3 modulator encoding 10 Gbit/s data. The 10 Gbit/s data were injected into a passive 10 to 40 Gbit/s multiplexer and an acousto-optical modulator (AOM) gated out a 2.5 μs payload that was combined with a 2.5 Gbit/s 500 ns long header. The header was aligned in front of the payload with 100 ns guard band determined by the 100 ns rise time in the AOM. The packets were then injected into the wavelength converter that consisted of an erbium-doped fiber amplifier (EDFA) followed by 5 km dispersion-shifted fiber (DSF) with a zero-dispersion wavelength of 1542 nm. A grating coupled sampled rear reflector (GCSR) laser that could be tuned to either 1538 or 1543 nm within 5 ns, determined the new wavelength. The GCSR laser was also used to encode the new 2.5 Gbit/s header before entering the wavelength converter. After the DSF, a loop mirror filter was used to suppress the original CW light. The separation between the notches was 1 nm and the suppression was better than 27 dB. A second filter was used to select one of the two sidebands and to suppress the original data.



- 2.5 s 40 Gbit/s payload
- 500 ns 2.5 Gbit/s header
- 100 ns guard time due to 100 ns rise time in AOM

- Fast tunable laser (5 ns)
- New header modulated on input signal to WC
- > 10 nm bandwidth in WC

- Burst-mode bit-error rate measurements by gating BERT
- AOM in 2.5 Gbit/s receiver to reject payload
- 15 ps switch window in EAM

Figure 3 Experimental setup of 40 Gbps all-optical label swapping experiment using a fiber XPM wavelength converter.

3.2 40 Gbps Optical Wavelength Conversion using Cross-Phase Modulation in an Optical Fiber

All-optical wavelength conversion will play an important role in future ultra high-speed networks due to the significant increase in flexibility and potentially reduction in need for optical buffers. In this research we have demonstrated a wavelength conversion technique using XPM in a dispersion shifted fiber followed by an optical notch filter is demonstrated. The principle of operation is as follows: the incoming data is combined with a continuous wave (CW) signal and sent through an optical fiber, then the original data imposes a phase modulation onto the CW light using XPM. This phase modulation generates optical sidebands on the CW signal, which can be converted to amplitude modulation by suppressing the original CW carrier using an optical notch filter. 40 Gbit/s wavelength conversion was demonstrated and the method will most likely be scalable to operation at several hundreds of Gbit/s.

Figure 4 shows the experimental set-up of the wavelength converter. The data pulses were generated with an actively mode-locked 10 GHz fiber ring laser giving 10 ps pulses with a time-bandwidth product (TBP) of 0.46 at 1536 nm. 10 Gbit/s PRBS data (2^{31}-1) was subsequently encoded and a 40 Gbit/s data stream was obtained by passively multiplexing 4·10 Gbit/s data streams together. The 40 Gbit/s data was combined with CW light from a tunable external cavity laser and amplified before injected into a 10 km

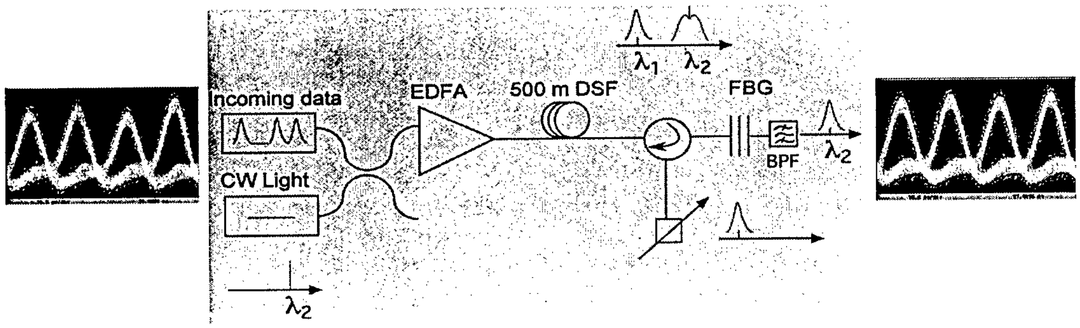


Figure 4   Experimental set-up of the XPM wavelength converter

3.3 Pulse Width Restoration of PMD Distortion

With the advent of optical communication systems using return to zero (RZ) data format operating at very high bit-rates, i.e. 40 Gbit/s and beyond, there will be a need for technologies to combat transmission effects that give rise to pulse broadening that can not easily be compensated for. Such effects are for example polarization mode dispersion (PMD) and higher order chromatic dispersion. We demonstrated for the first time that PMD distorted pulse restoration can be achieved using self-phase modulation (SPM) in dispersion-shifted fiber with subsequent optical band-pass filtering. This technique has previously been demonstrated to improve the extinction ratio of RZ-data. The basic idea is to broaden the spectrum using SPM in optical fiber and then slice the spectrum with an optical band-pass filter that will determine the output pulse width, in the same way as in a super continuum source. In principle the output pulse width should be independent of the input pulse width as long as the SPM broadened spectrum is broad enough. In the case of signal degradation due to PMD, the effective pulse width will vary over time, due to variation in signal polarization state relative to the principal states of polarization (PSP) in the system, as well as variation in the total differential group delay (DGD), and also the PSPs of the system. In this work, a pulse width restorer is demonstrated to restore 40 Gbit/s data that suffers from pulse broadening due to PMD.

To demonstrate restoration from PMD distortion, an experiment was constructed as depicted in Figure 5. 10 Gbit/s data was encoded on 8 ps pulses from an actively mode-locked fiber ring laser at a wavelength of 1547 nm. The 10 Gbit/s data was then passively time multiplexed to 40 Gbit/s using a split, delay, and interleave type of multiplexer based on 50/50 fiber couplers and variable optical delay lines. A polarizer was placed at the output of the multiplexer to ensure equal state of polarization of the 40 Gbit/s data stream. This is important since otherwise each channel will be impaired differently by the PMD. The 40 Gbit/s data was sent through a PMD emulator consisting of 12 sections of birefringent fiber spliced with random angels giving a differential group delay of 10 ps at 1547 nm. A polarization controller was used at the input of the PMD emulator to adjust the input polarization state to equally excite the principal states of polarization in the emulator. In this way the PMD emulator causes maximum distortion of the data. The distorted data was then set through a pulse width restorer as described above. An EDFA with 1W average output power was used and 850m of DSF needed to achieve sufficient SPM broadening of the 40 Gbit/s data. A 0.7nm optical band pass filter was used to slice the SPM broadened spectrum to restore the pulse width. The restored data was then sent through another PMD emulator consisting of 8 sections of birefringent fiber spliced with random angles, giving a differential group delay of 6 ps at 1547nm. The receiver contained a phase-locked loop based clock recovery circuit utilizing an electro-absorption modulator to recover a 10 GHz clock from the 40 Gbit/s data. This allowed stable visualization of the PMD distorted data on a sampling oscilloscope.

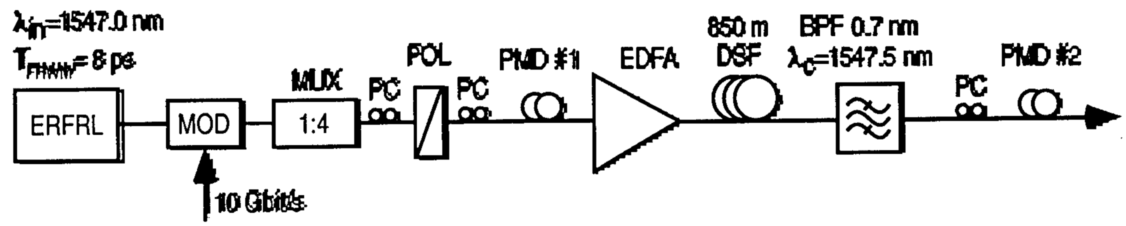


Figure 5 Experimental setup for restoration of PMD distortion using XPM in optical fibers.

Figure 6a shows the input 40 Gbit/s data and Figure 6b shows the data distorted by 10 ps DGD in the PMD emulator. The eye patterns look more open due to the broader pulses caused by the DGD, but the pulse width is now about 15ps. Figure 6c shows the data after restoration in the pulse width restorer and the pulse width comes down to 10 ps.

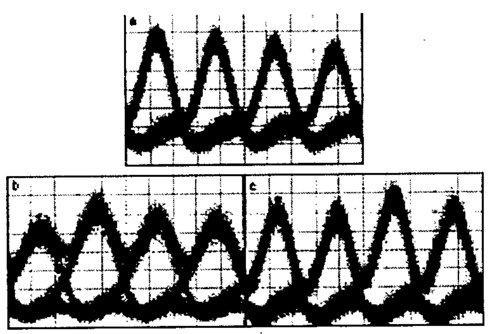


Figure 6 Input 40 Gbps data (a) before PMD distortion and (b) after PMD distortion. Output of PMD compensator is shown in (c).

More severe PMD was imparted on the signal by cascading a second PMD emulator. Figure 7 shows the data after the second PMD emulator with and without the pulse width restorer. In the case of retransmitting the previously restored data, the eye patterns are still clearly open, while without restoration the eye patterns are heavily distorted. However, if the data suffers too much PMD, i.e. the pulses get too broad, the pulse shape can not be restored since the adjacent data channels starts to interfere. This interference distorts the slopes of the pulses that give rise to the spectral broadening in the SPM fiber. In the case of PMD restoration it is thus important that the data does not suffer from too much PMD before being restored, but once restored it can suffer from more PMD again. The amount of allowed PMD before restoration depends then on the input pulse width and pulse shape to the system, as well as the bit-rate.

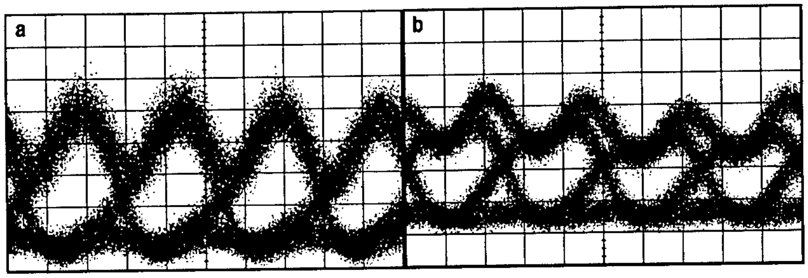


Figure 7 (a) Output restored pulses and (b) PMD distorted pulses at input.

3.4 OTDM to WDM Demultiplexing

We have demonstrated a technique to multiplex four channels from a WDM transmitter with non-return to zero (NRZ) format and convert them to return to zero format and subsequently wavelength convert all four WDM channels to one wavelength to obtain one OTDM channel. The advantage of this scheme is that existing WDM transmitter technology can be used while increasing the single channel transmission bit-rate as well as eliminating some problems with passive OTDM multiplexing. In this experiment we use an ultra fast wavelength converter based on XPM in an optical fiber that in principle can allow operation at several hundred Gbit/s. An advantage with this scheme is that the requirements on the RZ pulses are lower due to the nonlinear transfer function of the wavelength converter, which allows pulses with moderate extinction ratio to be used. The output of the wavelength converter is given by the derivative of the input signal, which also allows broader pulses to be used at the input.

Figure 8 shows the experimental set-up used for the multiplexer demonstration. Four tunable lasers generated continuous wave (CW) light at 1544.0, 1545.6, 1547.2, and 1548.8nm. 10 Gbit/s pseudo random bit-stream (PRBS) NRZ data with a word length of 2^{31}-1 was encoded on all wavelengths, and adjacent wavelength channels were encoded with different data. The four WDM channels were then converted to RZ data by injecting the synchronized WDM channels into an electroabsroption modulator (EAM) followed by a 200m dispersion compensating fiber (DCF) (D=-67ps/nm·km). With this arrangement, pulses with a pulse width between 8 to 9 ps were obtained for all four WDM channels. The WDM RZ signals were then combined with CW light at 1554.5nm and amplified in an EDFA to an average power of 350mW. An 850m dispersion shifted fiber (DSF) with a zero dispersion wavelength of 1550nm was used to impose a phase modulation onto the CW light by XPM in the fiber. This phase modulation was then converted to amplitude modulation by a filter arrangement, which consisted of a fiber Bragg grating to remove the intense original data channels signals as well as an optical band-pass filter to select one of the generated side bands of the CW light. An electroabsorption modulator driven at 10GHz was used to demultiplex the 40Gbit/s data to 10 Gbit/s where bit-error-rate (BER) measurements could be performed.

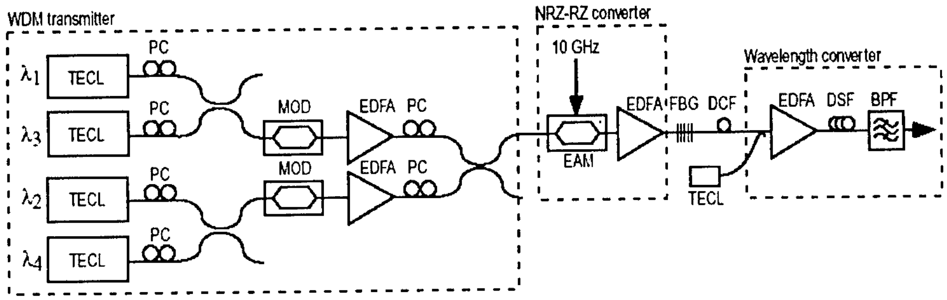


Figure 8 Experimental setup for OTDM to WDM optical conversion.

Figure 9 shows the optical spectrum in various points of the system. The solid line shows the spectrum into the wavelength converter with the four 10 Gbit/s RZ signals and the CW-light, the dashed line shows the spectrum after the DSF in the wavelength converter, and the dotted line shows the output signal from the wavelength converter. BER measurements were performed on the output 40 Gbit/s data by demultiplexing the data into four 10 Gbit/s data channels and the BER of all four channels were measured and are presented in Figure 10. Figure 10 also shows the back-to-back measurements for one of the original 10 Gbit/s channels after conversion from NRZ to RZ without the presence of the other WDM channels in the EAM. About 3 dB receiver power penalty at a BER of 10^{-9} was observed for all channels in the output 40 Gbit/s OTDM data. This penalty is primarily due to crosstalk between the WDM channels in the first EAM in the NRZ to RZ conversion process, and also partly due to the high loss in the EAM, which decreases the signal to noise ratio (SNR) after the following EDFA.

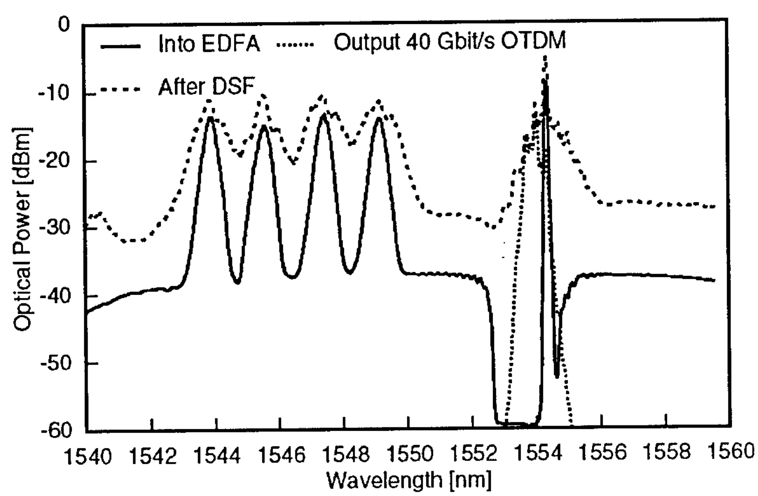


Figure 9 Optical spectra of OTDM to WDM demultiplexer at input and output.

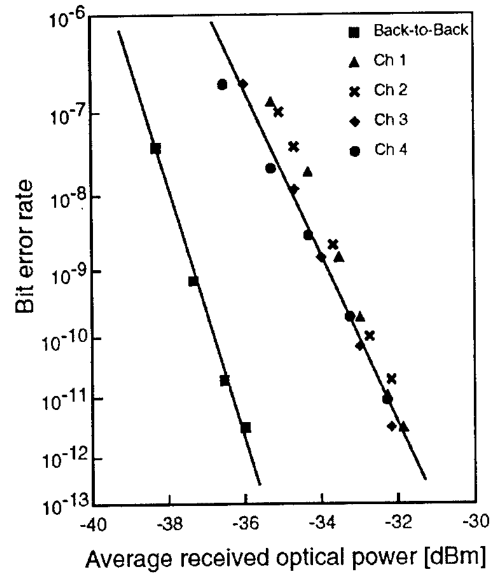


Figure 10 Measured BER for OTDM to WDM optical conversion using XPM in optical fiber.

3.5 Tunable Wavelength Converter using Multisection Lasers

Optical switching architectures require Wavelength Conversion (WC) that can be tuned at very high bit rates. These techniques require a rapidly tunable source (laser) to switch the output within nanosecond switching times. In this work we have demonstrated that the same rapidly tunable laser can be used as a rapidly tunable WC. WC at 10Gbps to one wavelength at a time was demonstrated using Grating Assisted Coupler Sampled Reflector (GCSR) laser. Here, we demonstrate dynamic conversion of any wavelength to any wavelength using a single GCSR laser, where the output wavelength is set by rapidly changing the current in one of the laser sections. Wavelength conversion in this case is achieved through the gain suppression of the lasing mode by the injected signal light. Among the most important advantages of this technique are the modulation format transparency, tunability of the converted signal wavelength, high conversion efficiency and extinction ratio and single element simplicity.

The GCSR laser used in this work consists of a gain section, a coupler section for coarse tuning, a reflector section for medium tuning and a phase section for fine tuning. Device fabrication, tuning mechanisms and performance of these lasers has been described elsewhere. GCSR lasers can be made to operate at any of the wavelengths within the tuning range (typically >60nm) by proper setting of the coupler, reflector and phase sections' currents.

The schematic of the experiment is shown in Figure 11. A tunable CW light source and electro-optic modulator (EOM) were used to generate the 10Gb/s signal that was launched into the gain section of the GCSR laser using a circulator and a AR coated lensed fiber. The output signal was collected at the other port of the circulator and analyzed with OSA, BERT and Digital Oscilloscope.

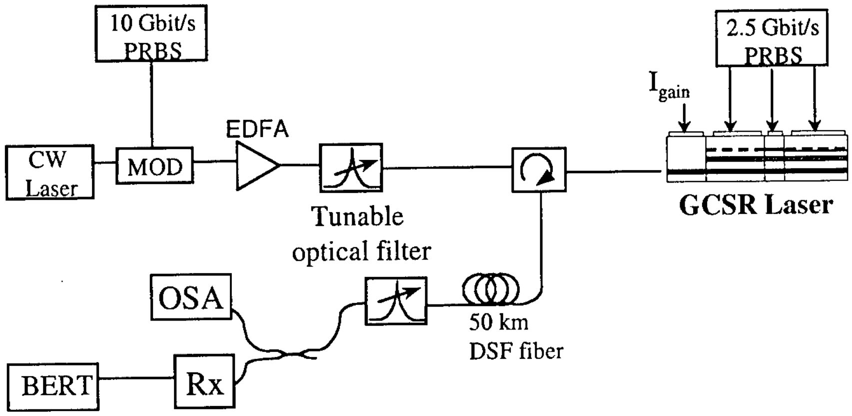


Figure 11 Experimental sestup of 10 Gbps wavelength conversion in a rapidly tunable multisection laser.

Next we performed wavelength conversion at 10Gb/s while switching the output converted wavelength at a rate equivalent to 2.5Gb/s modulation. Each bit at 10Gb/s is converted from the pump wavelength (λ=1550nm) to the output wavelength, while the output wavelength is changed between different λ's every 4^{th} bit. Converted data was then propagated over a distance of 50km of dispersion shifted fiber and the BER was measured. Figure 12 shows WC and WC+50km transmission BER for different wavelengths. The power penalty of approximately 2dB is observed due to transmission effects, and a small power penalty (of approximately 0.5 dB) is observed for transmission at different wavelengths. The transmission power penalty of 2dB is presumably due to the chirp of the laser, more on this study will be reported later.

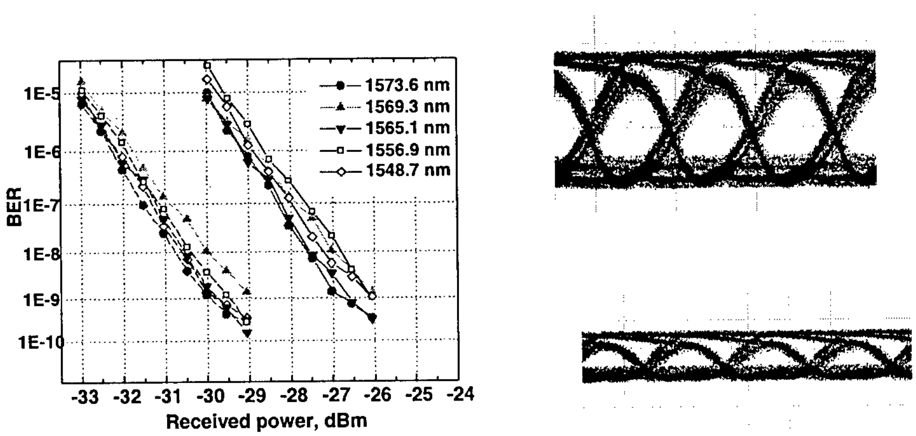


Figure 12 WC and WC+50km transmission BER for different wavelengths

4 Publications

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9 "Pulse Extinction Ratio Improvement Using SPM in an SOA for OTDM Systems Applications," M. L. Nielsen, B. E. Olsson, and D. J. Blumenthal, *IEEE Photonic Technology Letters*, February (2001)

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