Monolithically integrated InP-based tunable wavelength conversion

John M. Hutchinson*[1], Jonathon S. Barton, Milan L. Mašanović, Matthew N. Sysak, Jeffrey A. Henness, Leif A. Johansson, Daniel J. Blumenthal, Larry A. Coldren
[1]Intel Corporation, MS FM6-30, 1900 Prairie City Rd. Folsom, CA 95630-9598;
University of California, ECE Dept, Santa Barbara, CA 93106

ABSTRACT

In this work, we describe tunable wavelength converters based on a photodiode receiver integrated with a tunable laser transmitter. Devices are fabricated on a robust InP ridge/InGaAsP waveguide platform. The photodiode receiver consists of an integrated SOA pre-amplifier and a PIN diode to improve sensitivity. The laser transmitter consists of a 1550 nm widely tunable SGDBR laser modulated either directly or via an integrated modulator outside the laser cavity. An SOA post-amplifier provides high output power. The integrated device allows signal monitoring, transmits at 2.5 GB/s, and removes the requirements for filtering the input wavelength at the output. Integrating the SGDBR yields a compact wavelength agile source that requires only two fiber connections, and no off-chip high speed electrical connections. Analog and digital performance of directly and externally modulated wavelength converters is also described.

Keywords: Optoelectronics, Indium Phosphide, Wavelength Conversion, Tunable lasers

1. INTRODUCTION

Tunable wavelength converters represent a novel class of highly sophisticated photonic integrated circuits that are crucial in the functions or functioning or for functions of future optical networks[1]. They allow for the manipulation of wavelengths in WDM optical switches, routers and add/drop multiplexers. Many different implementations of non-tunable wavelength converters have been proposed: using cross phase modulation (XPM) in semiconductor optical amplifiers (SOAs), and fiber [2,3], and cross absorption modulation (XAM) in EAMs[4]. In our previous work, we have demonstrated tunable photocurrent driven wavelength converters utilizing a photodiode driving a laser or a modulator[5, 6]. High-speed integrated photodiodes and electroabsorption modulators suitable for wavelength conversion have also been proposed by other groups [7, 8]. Many of these architectures have been demonstrated to perform the significant feature of digital signal regeneration – including improvements in extinction ratio, signal to noise ratio, pulse width control, etc. Monolithically integrated, widely-tunable all-optical wavelength converters (TAO-WC)[9] have been demonstrated and have shown promise to allow for the conversion of one wavelength to another without requiring the signal to pass through electronics. In this paper, we will describe our work on *tunable* photocurrent driven WC's, and compare them against one another as well as against the TAO-WC approach pursued at UCSB.

2. PHOTOCURRENT DRIVEN TUNABLE WAVELENGTH CONVERSION

The simplest photocurrent-driven wavelength converter (PD-WC) consists of a photodiode receiver directly modulating a laser diode (Figure 1 left). Optical input is incident upon a reverse biased photodiode, which generates a photocurrent directly modulating the gain section of an integrated laser. The laser, and therefore the wavelength converter, can be made tunable by embedding the gain section within tunable mirrors such as implemented in the sampled-gating distributed Bragg reflector (SGDBR) laser [10]. A separate DC electrode connected to the gain section can bias the laser to a level suitable for high output extinction. Above laser threshold, the design affords linear operation, which is of importance for application in analog links. In the direct mod. approach, the extinction ratio of the converted output is proportional to the photocurrent and the laser differential efficiency. In order to improve the extinction ratio, we implement integrated optical pre-amplifiers with on-chip SOAs to generate increased photocurrent.

Modulation bandwidth of the directly modulated PD-WC is ultimately limited by the relaxation resonance frequency of the laser, typically ~ 6GHz in SGDBRs. External modulation of the laser, via an electro-absorption modulator (EAM) or a Mach-Zenhder modulator (MZM), represents a second important class of tunable photocurrent-driven wavelength converter approaches (Figure 1 right). In these configurations, the photocurrent generates a voltage via a load resistor, which in turn, modulates the transmission of the light through an EAM or MZM. Utilizing either EAMs or MZMs may lower the photocurrent requirements, and offers reduced (and perhaps tunable) chirp suitable for higher data rates.

The semiconductor optical amplifier Mach-Zehnder interferometer (SOA-MZI) wavelength converter is another important class of tunable integrated wavelength converters that also implements the significant feature of digital signal regeneration**.** Instead of being photocurrent driven, the SOA-MZI WC is based upon the cross-phase modulation, where all of the light interaction between the original data and the new signal takes place in the one arm of an MZI. The monolithically integrated SOA-MZI WC consists of an InP SGDBR laser integrated with a MZI (Figure 2). The laser and the interferometer are connected via a multimode interference (MMI) splitter. The input signal is coupled onto the chip through a tapered input waveguide, and then amplified by an 800 μm long input semiconductor optical amplifier. The same MMI splitter/combiner design is used to connect the data input waveguide with one of the interferometer's SOAs, as well as to combine the light from the two branches at the interferometer output. Waveguides in Mach-Zehnder branches are of the same width and length, hence, with no external stimuli the signal traversing the two interferometer arms will experience no phase change, compared to each other, and thereby add constructively at the output.

All of the designs described in this section have the significant capability for electronic signal monitoring which is a key function required for high speed data networks.

3. DEVICE DESIGN

3.1. Device structure design

Tunable PD-WC's consist of a receiver stage, which collects, amplifies, absorbs and converts the light into a photocurrent, and a transmitter stage which has a tunable laser and perhaps a modulator. Our designs are fabricated on a robust exposed InP ridge platform with a quarternary InGaAsP waveguide. SOAs are used for optical pre-amplification of the input signal, and to boost the converted output signal. Photodiodes are all waveguide type utilizing either Franz-Keldysh (no QWs) or quantum confined stark effect (QW) absorption. SOAs are typically 3μm wide by 500 to 800 μm long. Photodiode ridges are 3μm wide by 50 to 100 μm long.

The transmitter stage consists of a SGDBR laser, tunable over the entire C-band. The exposed ridge waveguide laser consists of 5 sections: front and rear SGDBR mirror sections, phase section, gain section and a backside absorber. The Laser output wavelength tuning is achieved by current injection into the SGDBR front and rear mirrors that utilize the vernier effect to select dominant lasing mode. The front mirror consists of 5 4 μm wide burst on a 68.5 μm pitch. The rear mirror consists of 12 6 μm wide bursts on a 68.5 μm pitch. The gain section is 550 μm long and the phase section is 75 μm long.

3.2. Device fabrication and testing

The devices are fabricated on an exposed ridge strip design with a single blanket P–type InP regrowth. The layer structure consists of a 350 nm thick 1.4Q quarternary waveguide with seven compressively strained (1%) 1.55μm quantum-well active regions grown on top, separated by a thin InP etch stop layer (Figure 3). Epi growth is performed in a Thomas Swan near-atmospheric MOCVD reactor using tertiary-butyl phosphine and tertiary-butyl arsine for the group V precursors, and diethylsilane and diethylzinc for the dopants. Passive sections, such as SGDBR mirrors, phase and franz-keldysh modulators/detectors are formed by selectively etching off the quantum wells in a wet etch process. The sampled grating DBR laser mirrors are defined using a two-step lithography/holography process and etched directly into the top of the waveguide using a $CH_4/H_2/Ar$ RIE process. Blanket regrowth of a thick p-InP cladding and an InGaAs cap. 3 μm wide exposed ridges are formed after regrowth lithographically using a combined dry-wet etch process to provide smooth sidewalls and minimize scattering loss. E-beam evaporated Ni/AuGe/Ni/Au metal is used to contact the N-type semiconductor and Ti/Pt/Au is used to contact the P-type semiconductor. Selectively removing the regrown P-type InGaAs and implanting protons provides carrier confinement between adjacent device sections. The temperature of the N-type contact anneal is ~ 430C, which significantly repairs the proton induced damage used for section isolation, requiring that N-metal formation and anneal occur prior to proton implant. The implant is designed to penetrate through the p-InP cladding and stop just above the waveguide to avoid creating defects in the intrinsic region that would lead to increased optical loss. In order to reduce the capacitance, a multiple layer dielectric stack of PECVD silicon nitride and biscyclobutene (Dow Chemical Cyclotene 4024) is used to separate the semiconductor from the pad metallization. Following Ti/Pt/Au P-type metallization and anneal, devices are lapped back to 100 um thickness, cleaved into bars and AR coated. Working devices are mounted on probable AlN carriers with Pb/Sn/Ag solder.

Figure 4 shows a schematic of the experimental arrangement. An Agilent 70841A 2.5 Gbps pseudo-random bit sequencer (PRBS) was used to drive an Agilent 83433A optical transmitter. The modulated optical signal was amplified and coupled into the wavelength converter. Flextronics conical tip lensed fibers mounted on Melles Griot piezo-electric three axis stages were used to couple the light onto and off of the wavelength converters. Wavelength converters were mounted on AlN carriers on top of a thermoelectric cooler to provide temperature stabilization. The output power of the wavelength converter is controlled by an optical attenuator before it is received by an Agilent 83434A optical receiver, connected to an Agilent 70842B 2.5 Gbps bit error rate tester (BERT). The received eye could also be directly observed in an Agilent 86100A high-speed oscilloscope. The amplified monitor signal from the OEIC-WC device could also be observed in the oscilloscope. For back-to-back testing, i.e. without wavelength conversion, the optical transmitter was directly connected to the optical receiver via an optical attenuator.

4. WAVELENGTH CONVERTER COMPONENT RESULTS

Crucial to the operation of photocurrent driven wavelength converters is a high efficiency receiver. Two types of photodiodes have been investigated: Franz-Keldysh and QW absorbers. Figure 5 (left) shows the detected photocurrent of an optically pre-amplified QW photodiode of 50 and 100 μm length. Current saturation is observed and is due to both power saturation in the SOA, and QW band filling. An improved photodetector can be fabricated using Franz-Keldysh absorption. Figure 5 (right) shows the detected photocurrent vs. reverse bias for different fiber optical power levels for such a device without any optical pre-amplification on chip. No saturation is observed up to photocurrents of at least 30 mA. Others using the same structure have observed even higher saturation currents, up to 70 mA [11]. Coupling efficiency from the lensed fiber to the waveguide mode was ~ 25%.

Figure 6 shows the modulation bandwidth of the directly modulated SGDBR tunable laser. The relaxation resonance frequency of the laser limits the modulation bandwidth to a few GHz. To obtain a flat bandwidth response to above 2.5 GHz, the laser must be DC biased at least to 100 mA. For directly modulated wavelength converters, the resulting extinction ratio is limited by the available photocurrent from the receiver

Externally modulated wavelength converters utilize a DC biased SGDBR laser with an additional EAM or MZM modulator. The potential used to drive the modulator is developed across a 50 Ω load resistor connected in parallel. As discrete components, the crucial figure of merit for modulators is modulation efficiency in dB/Volt. Figure 7 (left) shows the extinction of a bulk franz-Keldysh EAM and Figure 7 (right) shows the extinction vs. bias for a MZM. The maximum obtained EAM efficiency, for a 10 dB transmission loss is ~ 10 dB/V at 1530 nm, and the efficiency drops as the wavelength moves away from the waveguide absorption edge. Higher modulation efficiencies can be obtained by operating at larger DC biases, at the expense of overall transmission. The MZM exhibits an increased ~ 20 dB/V modulation efficiency, at the expense of device area and complexity compared to the EAM.

5. WAVELENGTH CONVERTER MODULATION RESULTS

All of the wavelength converter implementation were successfully fabricated and were tested using the setup described in Figure 4 previously. Figure 8 shows input and output eye diagrams at 2.5 GB/s for the directly modulated WC, the MZM WC and the SOA-MZI WC. All three demonstrated clearly open eyes at 2.5 GB/s data rates across at least a 20 nm SGDBR laser tuning range. Extinction ratio for the directly modulated WC was ~ 3 dB as the photocurrent was limited in fully integrated devices due to a fabrication error resulting in higher than expected contact resistance. Extinction ratio for both MZM-WC and SOA-MZI WC was greater than ~ 8dB.

All of the wavelength converter approaches fabricated demonstrated error-free operation at 10^{-9} BER with a 2.5 GB/s 2^{31}-1 PRBS signal (Figure 9). Power penalties were 8 dB, 1-2 dB and <1 dB for the direct mod WC, MZM and SOA-MZI WC respectively. The larger power penalty for the direct mod WC was due to the lower than expected extinction.

6. CONCLUSIONS

We described tunable wavelength converters based on a photodiode receiver integrated with a tunable laser transmitter. Devices are fabricated on a robust InP ridge/InGaAsP waveguide platform. The photodiode receiver consists of an integrated SOA pre-amplifier and a PIN diode to improve sensitivity. The laser transmitter consists of a 1550 nm widely tunable SGDBR laser modulated either directly or via an integrated modulator outside the laser cavity. An SOA post-amplifier provides high output power. The integrated device allows signal monitoring, transmits at 2.5 GB/s, and removes the requirements for filtering the input wavelength at the output. Integrating the SGDBR yields a compact wavelength agile source that requires only two fiber connections, and no off-chip high speed electrical connections. Analog and digital performance of directly and externally modulated wavelength converters is also described.

7. ACKNOWLEDGEMENTS

The financial support of Intel Corporation, DARPA CS-WDM and NSF IGERT is gratefully acknowledged. Tom Mates (Materials Department, UCSB) provided SIMS.

REFERENCES

1. S. J. B. Yoo, "Wavelength Conversion Technologies for WDM Network Applications", IEEE J. Lightwave Technology, 14, 944-966 (1996).
2. L.H. Spiekman, U. Koren, M.D. Chien, B.I. Miller, J.M. Wiesenfeld, J.S. Perino, "All-Optical Mach-Zehnder Wavelength Converter with Monolithically Integrated DFB Probe Source", IEEE Photonics Technology Letters, 9, IEEE, 1349-51. (1997)
3. B.-E. Olsson, P. Ohlen, L. Rau, D. J. Blumenthal," A simple and robust 40-Gb/s wavelength converter using fiber cross-phase modulation and optical filtering", IEEE Photonics Technology Letters, 12, IEEE, 846 –848 (2000)
4. N. Edagawa, M. Suzuki, S. Yamamoto, "Novel wavelength converter using an elecroabsorption modulator," IEICE Trans. Electron., E81-C, 1251-1257 (1998).
5. J. M. Hutchinson, J. A. Henness, L. A. Johansson, J. S. Barton, M. L. Masanovic, "2.5 Gb/sec wavelength conversion using monolithically-integrated photodetector and directly modulated widely-tunable SGDBR laser," IEEE LEOS 2003 Annual meeting proceedings, WU4, 6 50-651 (2003).
6. J. S. Barton, M. L. Mašanović, M. N. Sysak, J. M. Hutchinson, E. J. Skogen, D. J. Blumenthal, L. A. Coldren, "A novel monolithically-integrated widely-tunable wavelength converter based on a SGDBR-SOA-MZ transmitter and integrated photodetector" Photonics in Switching proceedings, Versailles France (2003).
7. H. Demir, V. Sabnis, O Fidaner, S. Latif, J. Harris, D. A. B. Miller, J Zheng, "Novel optically controlled optical switch based on intimate integration of surface-normal photodiode and waveguide electroabsorption modulator for wavelength conversion," IEEE LEOS 2003 Annual Meeting proceedings, WU1, 644-645, (2003).
8. H. Takeuci, T. Saoitoh, H. Ito, "High-speed electroabsorption modulators with traveling-wave electrodes," OFC 2002 Technical Digest, 336-338 (2002).
9. M. L. Masanovic, V. Lal, J. S. Barton, E. J. Skogen, D. J. Blumenthal, L.A. Coldren, "Monolithically Integrated Mach-Zehnder Interferometer wavelength converter and widely-tunable laser in InP ", IEEE Photonics Technology Letters, 15, 1117-1119 (2003)
10. B. Mason, G. A. Fish, J. Barton, L. A. Coldren, S. P. DenBaars, "Design of sampled grating DBR lasers with integrated semiconductor optical amplifiers", IEEE Photonics Technology Letters, 12, 762-764 (2000).
11. L.A. Johansson, Y.A. Akulova, G.A. Fish, L.A. Coldren, "High optical power electroabsorption waveguide modulator," Electron. Lett., 39, 364-365 (2003).

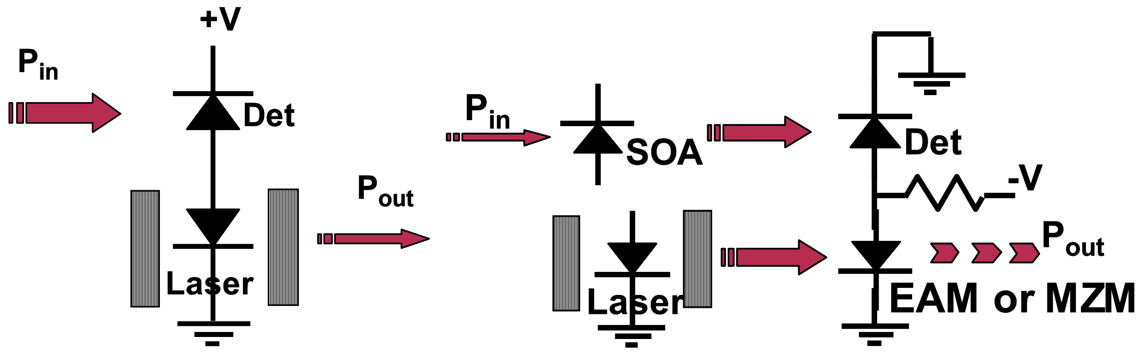
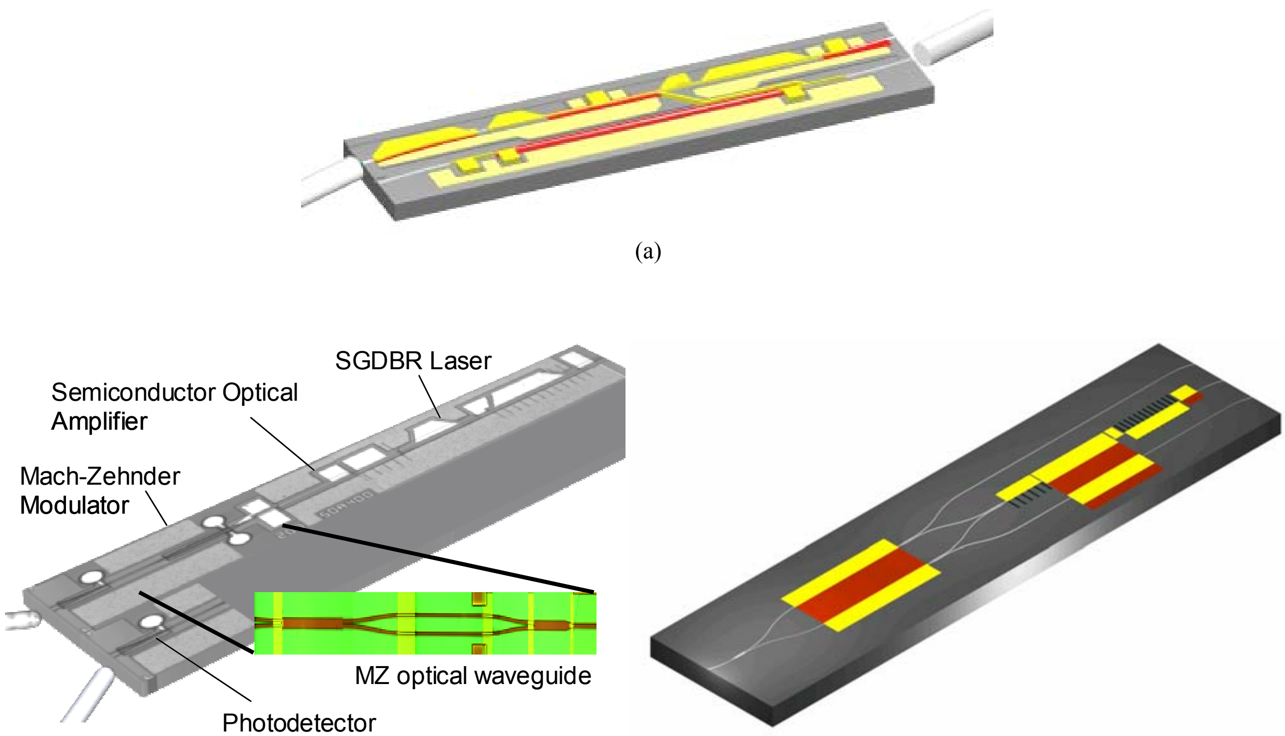


Figure 1. Left: Equivalent circuit of directly modulated wavelength converter
Right: Equivalent circuit of externally modulated wavelength converter



(a)

(b) (c)

Figure 2. Schematic of three different wavelength converters based on a common InP SGDBR laser process, (a) directly modulated, (b) MZM modulated and (c) SOA-MZI all-optical

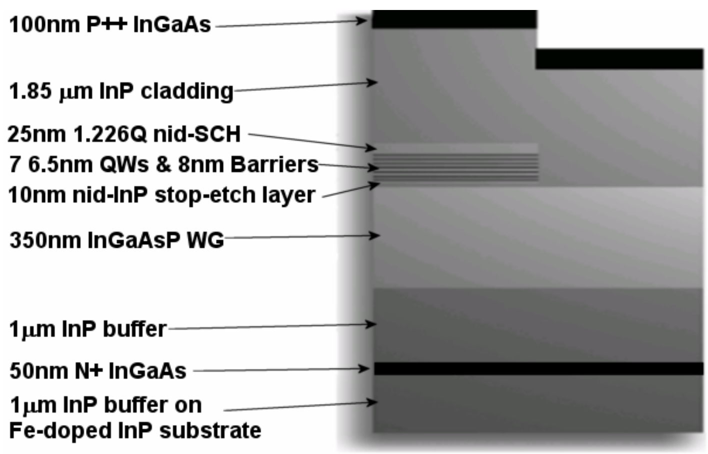


Figure 3. InP MOCVD epitaxial structure of directly modulated WC.

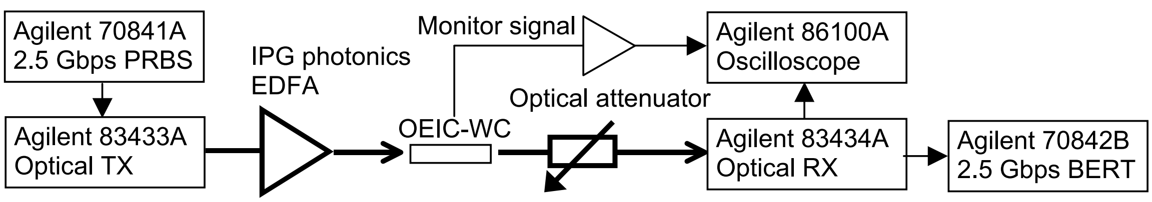
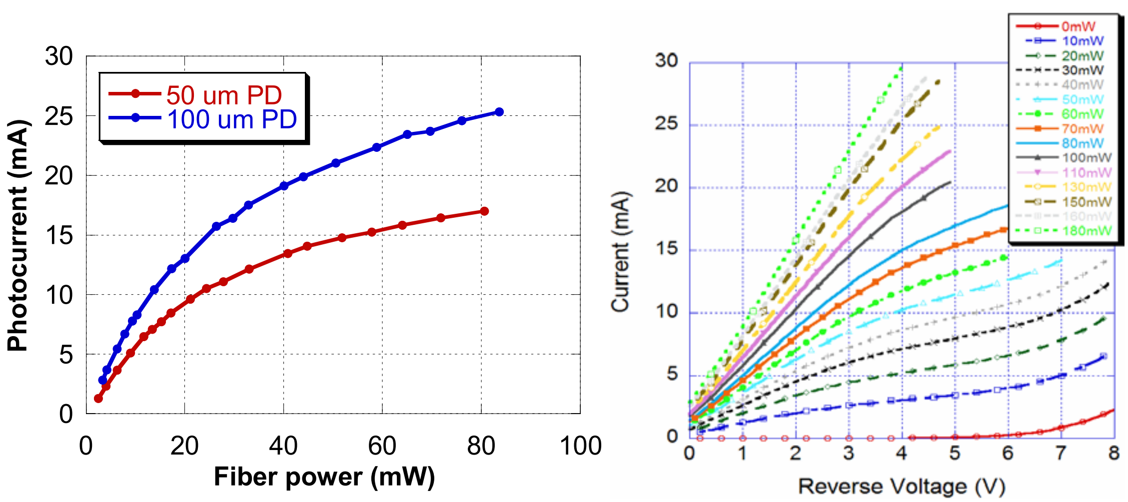


Figure 4. Experimental arrangement for 2.5 Gbps wavelength conversion demonstration. Thick line indicates optical path while thin line indicated electrical path.



(a) (b)

Figure 5. (a) QW absorber photodiode I-L response and (b) Franz-Keldysh absorber photodiode I-V.

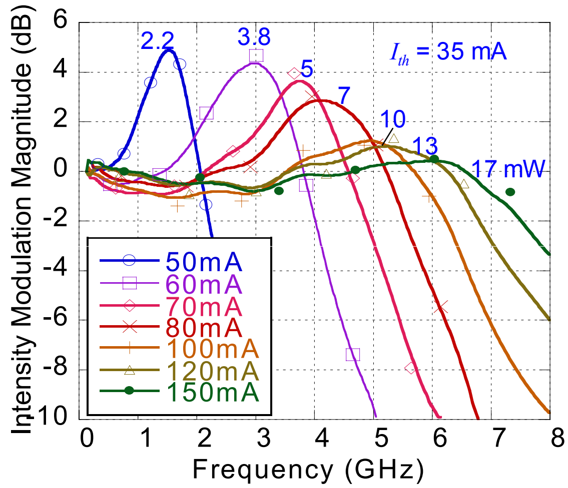


Figure 6. Modulation bandwidth of an SGDBR laser as a function of gain section bias current. Optical power output is labeled on individual curves.

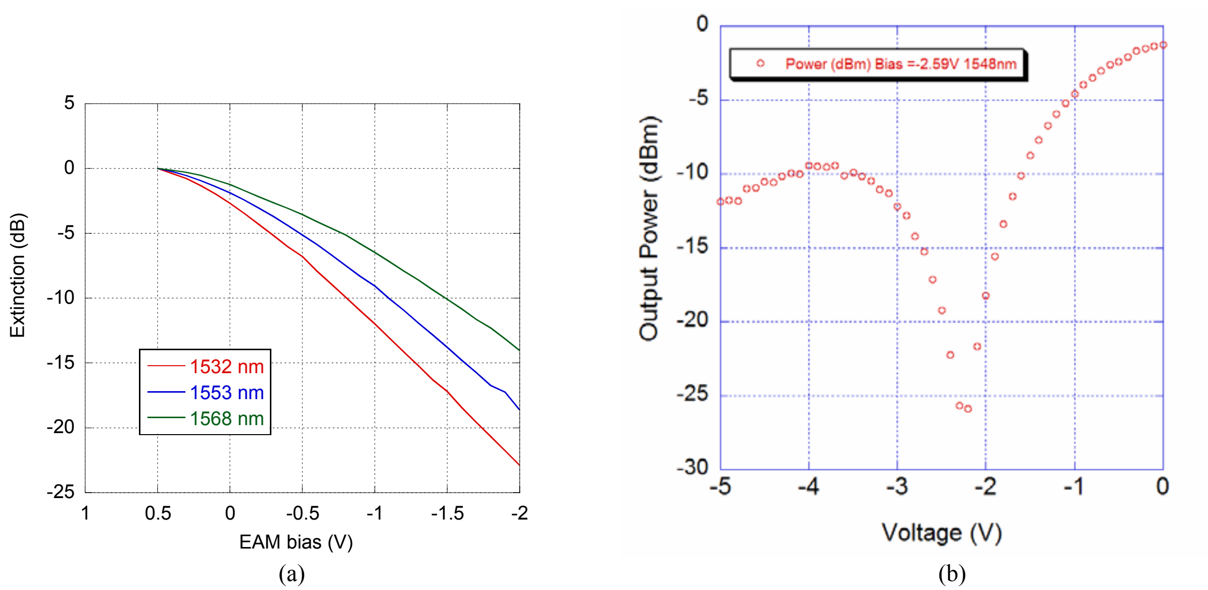


Figure 7. Optical Extinction vs. Voltage for (a) 600 um long EAM and (b) Mach-Zender modulator

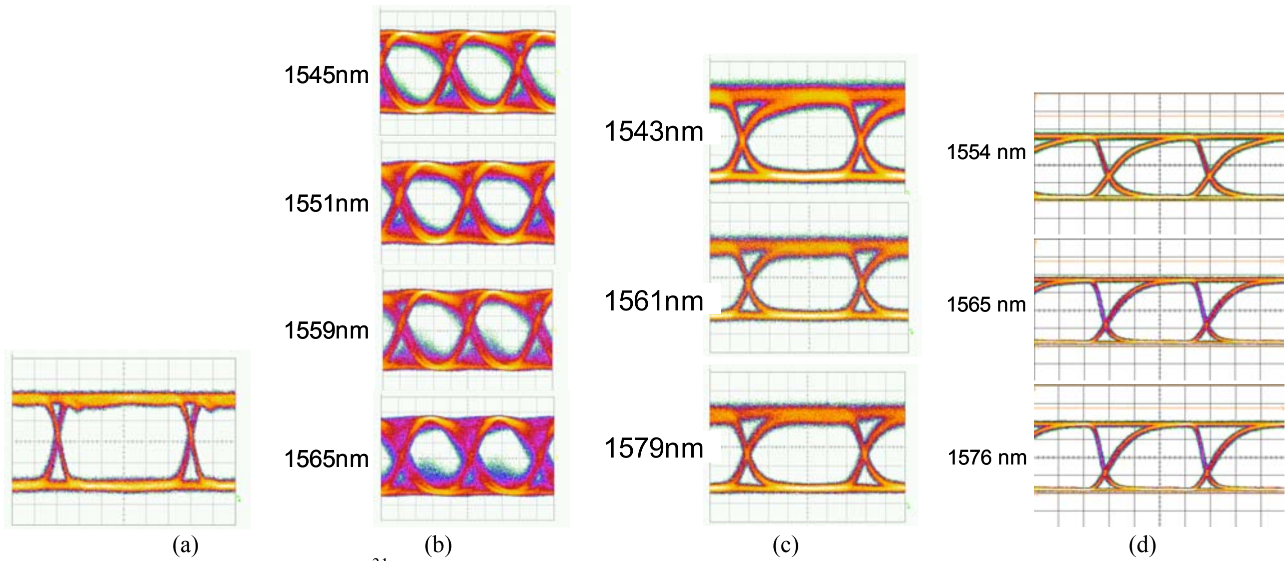


Figure 8. 2.5 Gb/s optical eyes, 2^{31}-1 NRZ pattern, (a) input signal, (b) directly modulated WC output eye, (c) MZM WC output eye and (d) SOA-MZI all-optical output eyes.

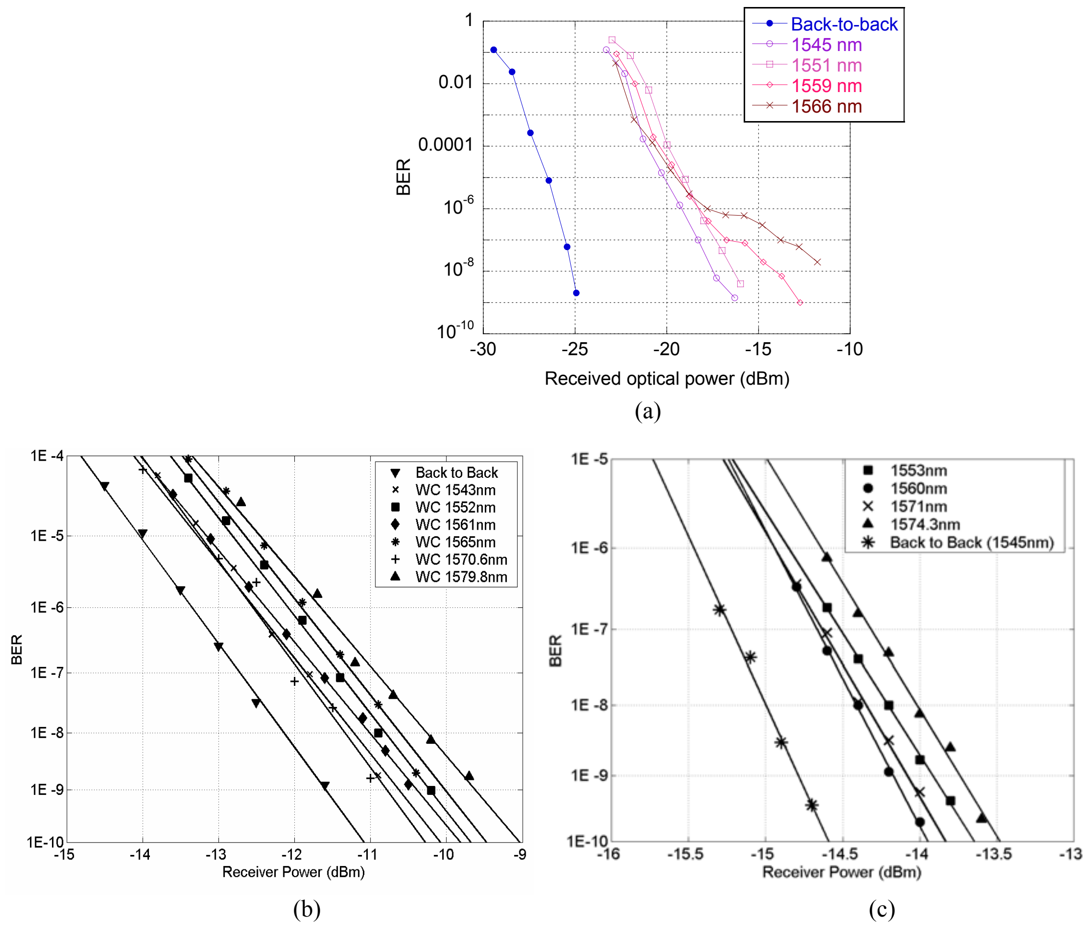


Figure 9. 2.5 GB/s bit-error rates as a function of received optical power for (a) directly modulated WC, (b) MZM WC and (c) all-optical SOA-MZI WC.