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Index words: optical, wavelength conversion, monolithic, indium phosphide, tunable

ABSTRACT

Monolithic approaches to wavelength converters have been demonstrated and show promise to allow for the high-speed conversion of one wavelength to another without requiring the signal to pass through off-chip electronics. In this paper, we describe our research, undertaken jointly with the University of California at Santa Barbara and with Stanford University, into novel approaches for monolithically integrating Wavelength Converters (WCs) in Indium Phosphide.

In the first approach, undertaken jointly with the University of California at Santa Barbara, we describe Photonic-IC (PIC) tunable wavelength converters that are 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 optical pre-amplifier and a pin photodiode to improve sensitivity. The laser transmitter consists of a 1550 nm widely tunable Sampled Grating Distributed Bragg Reflector (SGDBR) laser modulated either directly or via an integrated modulator outside the laser cavity. An optical post-amplifier provides high output power. The Photonic-IC (PIC) tunable WC (PIC-WC) device allows signal monitoring, transmits at 2.5 Gb/s, and removes the requirements for filtering the input wavelength at the output. Integrating the widely tunable laser on-chip yields a compact wavelength agile source that requires only two fiber connections, and no off-chip high-speed electrical connections.

In the second approach, undertaken jointly with Stanford University, we present a compact, low-power, dual-diode photonic switch architecture that allows for scalable multi-channel wavelength conversion. These photonic switches are scaled into a two-dimensional array to construct the first wavelength-converting crossbar switch on a single chip. Each of the wavelength-converting switches in the crossbar consists of an InGaAsP/InP quantum-well waveguide modulator monolithically integrated with a surface-normal InGaAs photodiode in its close vicinity as a part of a novel integrated optoelectronic circuit. The confinement of optically induced high-speed electrical signals within the lumped circuit elements of each switch node leads to efficient wavelength conversion, requiring low optical input power (mW range) for high extinction ratio (>10 dB), and eliminating the need for on-chip transmission lines and off-chip high-speed electrical connections. In addition to optical switching, the ability to enable and disable the

switch nodes electrically further allows for the electrical reconfiguration of the wavelength-converting crossbar switch as necessary. Experimental demonstrations include unlimited wavelength conversion at 2.5 Gb/s using single switch elements and multi-channel wavelength conversion at 1.25 Gb/s using 2x2 crossbar switches, all exhibiting >10 dB extinction ratio and spanning the entire C-band. Theoretical analysis predicts the feasibility of operation at 10 Gb/s with a 10 dB extinction ratio.

INTRODUCTION

The high-speed fiber optic network of today forms the backbone of the Internet. As the Internet data bandwidth continues to climb, the optical devices used to manipulate these data must demonstrate increased line data rates, functionality, and efficiency while maintaining small size and low cost. Wavelength Converters (WC) represent a novel class of highly sophisticated photonic integrated circuits that are crucial in the function of future optical networks [1]. They allow for the manipulation of wavelengths in Wavelength Division Multiplexing (WDM) optical switches, routers, and add/drop multiplexers.

A key application of WCs is in all-optical "wavelength continuous" networks. In such networks, the interconnection between two nodes (typically optical fiber) is fixed to a given wavelength that cannot be changed along the route. Any new connection to the network must use a different wavelength; if a new connection uses a wavelength already allocated to another connection, it is blocked. Two connections cannot use the same wavelength on a given portion of the same fiber. Wavelength conversion at the nodes of the networks enables the network to avoid this "wavelength-continuity constraint" improving efficiency and flexibility.

The lowest risk and also the most expensive and bulky implementation of wavelength conversion is the use of an Optical/Electrical/Optical (O/E/O) line card that incorporates a tunable laser for its output. The additional problem with this approach is that because of the digital regeneration circuits, the line card typically only functions at a particular data rate. Such O/E/O line cards may be undesirable, because they are one of the major high-cost items that have thwarted the scaling down of system costs as needed to bring optical networking, especially WDM networking, into the metropolitan and local area distribution networks.

Many different implementations of non-tunable WCs have been proposed: using Cross-Phase Modulation (XPM) in Semiconductor Optical Amplifiers (SOAs), fiber [2,3], and Cross Absorption Modulation (XAM) in Electro-Absorption Modulators (EAMs) [4,5]. In our previous work, we have demonstrated photocurrent-driven WCs utilizing a photodiode driving a laser or a modulator [5,6,7]. High-speed integrated photodiodes and EAMs suitable for wavelength conversion have also been previously proposed [8]. Many of these architectures have been demonstrated to perform digital signal regeneration– including improvements in extinction ratio, signal to noise ratio, pulse width control, etc. The SOA Mach-Zehnder interferometer (SOA-MZI) WC is another important class of tunable integrated WC that also implements the significant feature of digital signal regeneration [9,10]**.** Instead of being photocurrent driven, the SOA-MZI WC is based upon the XPM, where all of the light interaction between the original data and the new signal takes place in the one arm of an MZI. These previous demonstrations of WCs exhibited promising results for a single-channel operation [2-8]; however, a multi-channel wavelength conversion system has not been previously proposed.

In this paper, we first describe our work at the University of California at Santa Barbara on *tunable* photocurrent driven WCs made by monolithically integrating a widely tunable laser source with detectors and modulators. Next, we discuss our work at Stanford University based on a scalable, compact, dual-diode optical switch suitable for reconfigurable multi-channel wavelength conversion.

WIDELY TUNABLE APPROACH (UCSB)

Design

The simplest photocurrent-driven wavelength converter (PD-WC) consists of a photodiode receiver directly modulating a laser diode (Figure 1 top). Optical input is incident upon a reverse-biased photodiode, which generates a photocurrent directly modulating the gain section of an integrated tunable laser. The Sampled Grating Distributed Bragg Reflector (SGDBR) tunable laser is a four-section device consisting of SGDBR front and rear mirrors and phase and gain sections [11]. A separate DC electrode connected to the gain section can bias the laser to a level suitable for high output extinction. Above threshold, the directly modulated design affords linear operation, which is important for applications in analog links. In this 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 Semiconductor Optical Amplifiers (SOAs) to generate increased photocurrent.

Modulation bandwidth of the directly modulated PD-WC is limited by the relaxation resonance frequency of the laser, typically ~6 GHz. External modulation of the laser, via an Electro-Absorption Modulator (EAM) or a Mach-Zehnder Modulator (MZM), represents a second important class of tunable photocurrent-driven WC approaches (Figure 1 bottom). 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 offer reduced (and perhaps tunable) chirp, suitable for higher data rates.

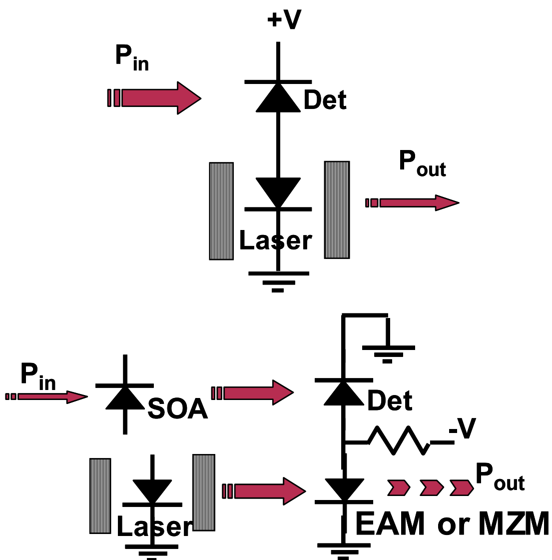

Figure 1: Schematic of UCSB Tunable WCs in direct modulation (top) and external modulation (bottom) implementations

Fabrication

The UCSB design uses a quaternary InGaAsP waveguide structure for the laser, modulator, amplifier, and photodetector sections grown on a semi-insulating Fe-doped InP substrate. Removing conducting semiconductor down to the semi-insulating substrate between the two ridges electrically isolates the ridge waveguides for the photodetector and laser sections. An N+ InGaAs layer underneath the quaternary waveguide material provides contacts to the n side of the diodes. The optically passive sections are formed by etching off the offset quantum wells down to the 10nm InP stop-etch layer prior to blanket InP regrowth. Completed devices vary in size depending on the specific design and are typically 0.5 mm wide and 2.5 to 3.5 mm long. An example micrograph of a fabricated wavelength converter with an SGDBR laser, MZM, and receiver is shown in Figure 2. More details on fabrication can be found in Reference 12.

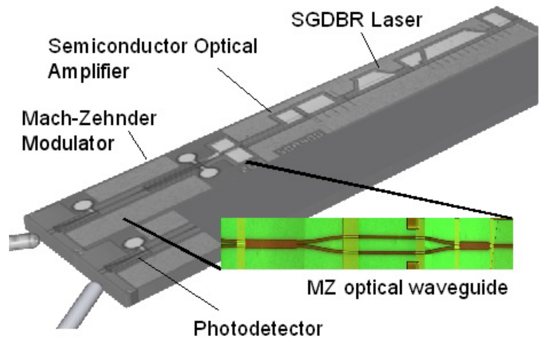

Figure 2: Fabricated MZM WC (~0.5 mm x 3 mm)

RESULTS

Laser, Receivers, and Modulators

Crucial to the operation of photocurrent-driven WCs is a high-efficiency receiver. Two types of photodiodes have been investigated: bulk absorbers, utilizing the Franz-Keldysh (FK) effect, and Quantum Well (QW) absorbers, utilizing the quantum confined Stark effect. Figure 3 (top) 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 saturation photodetector can be fabricated using FK effect absorption. Figure 3 (bottom) 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 [13]. Coupling efficiency from the lensed fiber to the waveguide mode was ~25%. Note that the QW photodiodes incorporate an on-chip SOA preamp, and the bulk photodiodes do not.

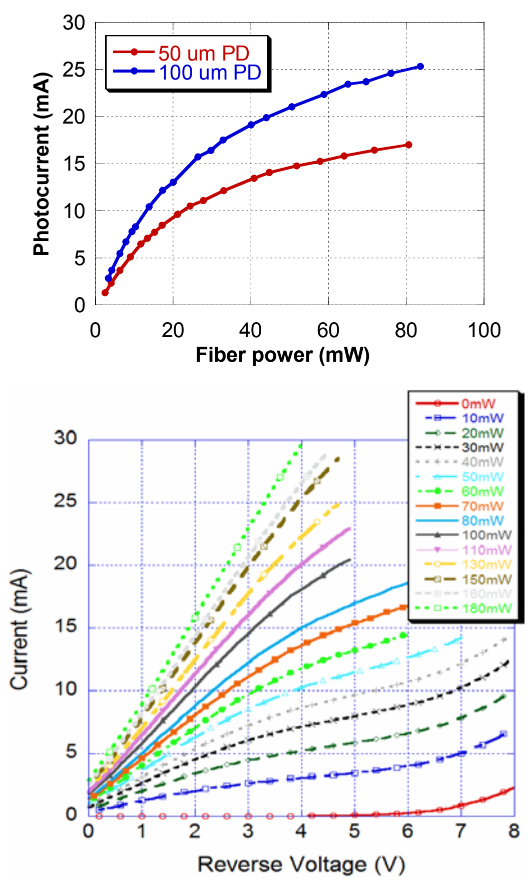

Figure 3: Photodiode optical response for quantum-well photodiodes of 2 lengths with 350 μm SOA preamp (top) and bulk photodiodes (200 μm long, No SOA preamp)

Figure 4 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.

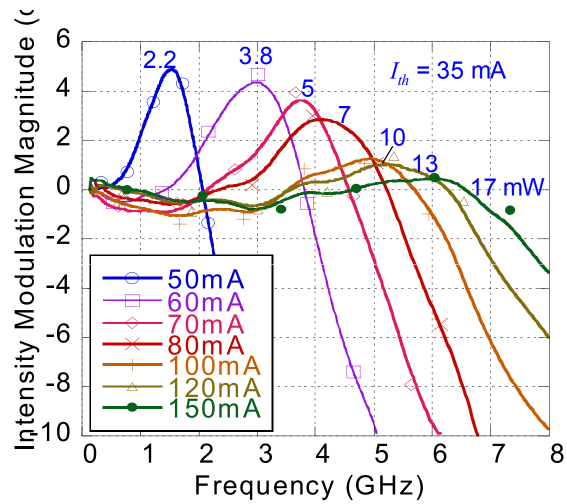

Figure 4: SGDBR laser direct modulation bandwidth

For improved chirp and larger extinction, WCs incorporating external modulators become attractive. In our implementation, we achieve external modulation in the WC with a DC-biased SGDBR laser followed by an EAM or MZM. The transmission of the modulator is varied through an applied voltage that is developed across a 50 Ω load resistor connected in parallel with the EAM/MZM and the photodetector. As discrete components, one crucial figure of merit for modulators is modulation efficiency in dB/Volt. Figure 5 (top) shows the extinction of a bulk FK EAM and Figure 5 (bottom) shows the extinction vs. bias for an MZM. The maximum obtained EAM efficiency for a 10 dB transmission loss is ~5 dB/V at 1535 nm for a 200 μm long EAM; the efficiency drops as the wavelength moves away from the waveguide absorption edge. Higher modulation efficiencies can be achieved, but at the expense of a larger insertion loss. The MZM exhibits an increased ~15 dB/V modulation efficiency, at the expense of device area and complexity, compared to the EAM.

2.5 Gb/s Wavelength Conversion

All of the WC implementations were successfully fabricated and were tested using a 2.5 Gb/s Non-Return to Zero (NRZ) optical input signal. Figure 6 shows input and output eye diagrams at 2.5 Gb/s for the directly modulated WC, the EAM WC, and the MZM WC. All three demonstrated clearly open eyes at 2.5 Gb/s NRZ 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. The extinction ratio for the EAM WC and MZM-WC devices was > 10 dB for all wavelengths.

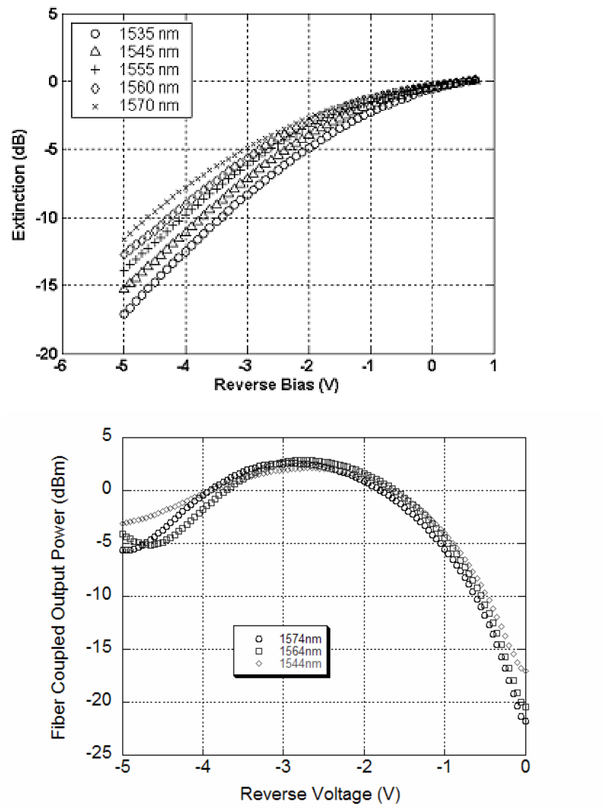

Figure 5: Extinction vs. bias for a 200 μm long EAM (top) and a MZM with 200 μm long electrodes (bottom)

All of the WC approaches fabricated demonstrated error-free operation at 10^{-9} Bit-Error Rate (BER) with a 2.5 Gb/s 2^{31}-1 Pseudo Random Bit Stream (PRBS) signal. Power penalties compared to back-to-back operation without a WC were 6 dB, 1-2 dB, and < 1 dB for the directly modulated WC, EAM, and MZM WC, respectively. The larger power penalty for the directly modulated WC was due to the lower than expected photocurrent and consequently extinction, due to undesirable heating resulting from a fabrication error.

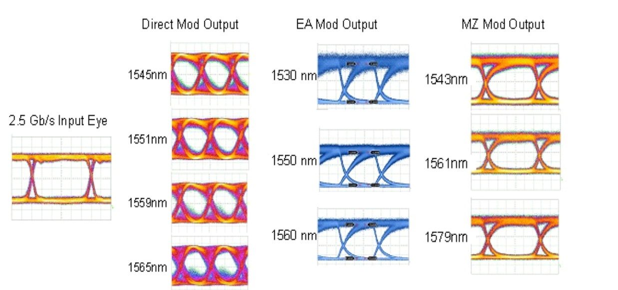

Figure 6: WC output eye diagrams with 2.5 Gb/s NRZ input signal

SCALABLE APPROACH (STANFORD)

Design and Fabrication

The approach taken by the Stanford team is based on the *intimate* integration of an electroabsorption modulator with a photodiode into a compact wavelength-converting switch [8]. Figure 7a illustrates such a dual-diode switch structure that incorporates a waveguide modulator diode and a surface-illuminated photodiode integrated as a part of the novel on-chip lumped optoelectronic circuit shown in Figure 7b. This dual-diode switch is designed to confine the optically generated high-speed electrical signals within its integrated circuit. The localization of the optical switching yields efficient wavelength conversion with a low optical input power requirement (mW range) to achieve high extinction ratios (> 10 dB). Furthermore, this photonic switch architecture naturally leads to a two-dimensional integrated array of these photonic switches to implement a reconfigurable wavelength-converting crossbar switch [14]. Such a photonic switch architecture also provides a convenient photonic integration platform; for example, a (tunable) laser diode and an optical semiconductor amplifier could be conveniently incorporated into the switch because of the fabrication compatibility, if desired [15].

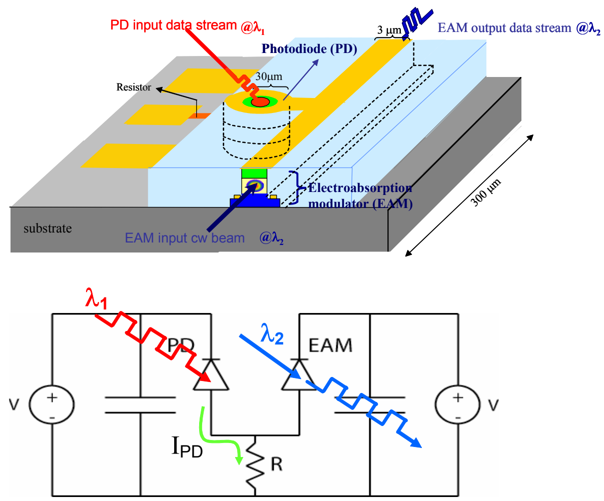

Figure 7 (a): A schematic of dual-diode photonic switch, and (b) its simplified circuit diagram

These wavelength-converting switches are completely insensitive to input signal polarization due to the surface-normal input configuration. They operate over a wide range of wavelengths (e.g., over the C-band) because of the broad-band absorption of the InGaAs photodiode and because of the electroabsorption of the InGaAsP/InP quantum-well modulator that is shifted and broadened with the application of DC bias. These switches provide unconstrained, bi-directional wavelength conversion and multi-wavelength broadcasting in the C-band.

Figure 7b shows a simplified circuit diagram of the integrated photodiode-modulator structure including a local resistor and a pair of bypass capacitors. Because of the lumped circuit operation of the integrated parts, transmission lines are not necessary. In operation, the high-speed optical input signal at λ_1 incident on the photodiode, PD, generates a photocurrent, I_{PD}, that creates a voltage drop across the resistor, R, and swings the voltage across the electroabsorption modulator. Such an optically-induced voltage change across EAM changes the transmission of the EAM quantum wells at λ_2. Thus, the input data at λ_1 is bit-by-bit transferred to the output at λ_2, which thus converts the carrier wavelength from λ_1 to λ_2. The DC biases applied to the EAM and PD can further be used to electrically enable or disable the wavelength conversion.

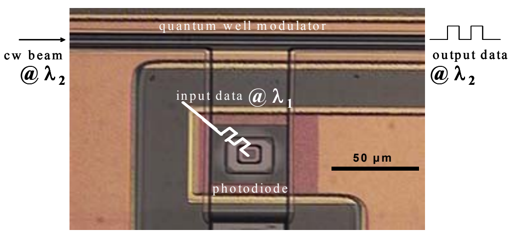

Figure 8: A picture of fabricated dual-diode device

Figure 8 is a part of the optical micrograph of a fabricated wavelength-converting switch that consists of an InGaAsP/InP waveguide quantum-well modulator and an InGaAs surface-normal pin photodiode monolithically integrated through two-step epitaxial growths. The switch is 300 µm x 300 µm in size. It comprises a waveguide modulator with a width of 2 µm, a length of 300 µm and a 0.37 µm thick i-region; a photodiode with a 30 µm x 30 µm mesa and a 1.25 µm thick i-region; and a local resistor with values from 340 to 650 Ohms depending the designed speed of operation. The device is built on a semi-insulator InP substrate to lower parasitic capacitance and to isolate the individual switches. For monolithic integration, a new selective area regrowth technique is used [16]. For the further reduction of the parasitic capacitance and leakage current, a self-aligning polymer planarization and passivation method is developed [17].

The switch simulation that includes the on-chip, integrated optoelectronic circuit and off-chip, biasing circuit predicts optical switching requiring < 10 mW absorbed optical power for > 10 dB extinction ratio at 10 Gb/s. The RC time constant of the integrated optoelectronic circuit determines the operation speed. Figure 9 shows the simulated eye diagram at 10 Gb/s with > 10 dB extinction ratio [17].

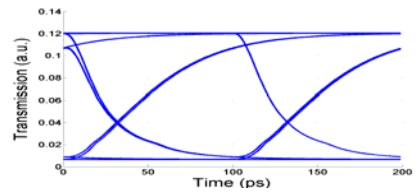

Figure 9: Simulation of 10 Gb/s operation

RESULTS

Figure 10 shows two open eye diagrams from the modulator output in (a) Return-to-Zero (RZ) and (b) NRZ schemes from the WC with a designed operation speed of 2.5 Gb/s. These diagrams exhibit RF-extinction ratios of > 10 dB with absorbed average optical power of < 8 mW at 2.5 Gb/s [18]. In both cases, the input wavelength is 1550 nm, and the output wavelength is 1530.0 nm. With the input beam photogenerating ~5 mA of current, an electric field swing of ~6.5 V/µm is optically induced across the modulator, comparable to the field swing typically required by an electrically driven, conventional EAM. These wavelength-converting switches cover an operation range of 45 nm, from 1525 nm to 1570 nm, centered on the C-band [17].

The switches also allow for multi-channel broadcasting across the entire C-band [17]. For dual-wavelength broadcasting, two CW beams at different wavelengths are coupled into the EAM to be simultaneously modulated by the same optical input signal incident on the PD. Figure 11 (b1-b3 and c) shows the two output optical signals from the EAM with channel spacings of 10 nm and 20 nm, respectively in C-band at 1.25Gb/s [17].

Figure 10: Optical switching in (a1) NRZ and (a2) RZ formats with >10 dB RF-extinction ratios at 2.5 Gb/s

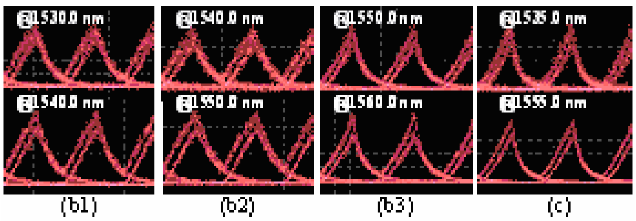

Figure 11: C-band dual-wavelength broadcasting with channel spacings of 10 nm in (b1)-(b3) and 20 nm in (c)

Figure 12 shows a fabricated 2x2 wavelength-converting crossbar switch [13]. Figure 13 depicts the eye diagrams taken from each of the four switch elements at 1.25 Gb/s, all measured with > 10dB extinction ratio. While one of the switch elements is tested, the unused switch along the same waveguide is disabled by slightly forward-biasing its photodiode and modulator. This removes the potential crosstalk between the two input channels and eliminates the background absorption of the quantum-well modulator in the unused WC.

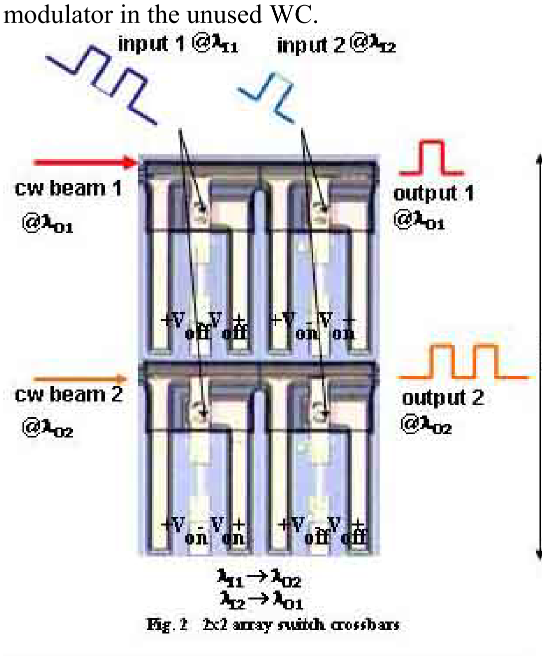

Figure 12: 2x2 wavelength-converting crossbar switch. The size is 1 mm x 600 µm

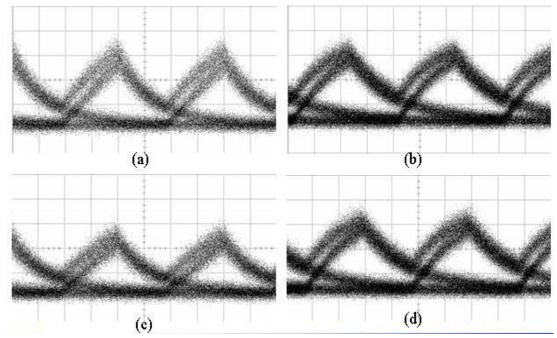

Figure 13: Eye diagrams from each of the four switch elements in a 2x2 array

DISCUSSION

We presented our design and experimental results on a wide variety of wavelength-converter implementations, and showed how these approaches can achieve the desired wavelength-conversion functionality at high bit rates and extinction ratio.

The Directly Modulated (DM) laser approach to wavelength conversion remains the most compact device incorporating an on-chip tunable optical source, but is ultimately limited by the modulation bandwidth of SGDBR lasers, and would achieve bit rates of 10 Gb/s or higher only with significant redesign. In addition, "chirping" in directly modulated lasers would result in an undesirable dispersion penalty.

For bit rates of 10 Gb/s and above, the externally modulated approach, utilizing an EAM or MZM to modulate the laser output, becomes more attractive. Both modulator types have been implemented by the UCSB project, and demonstrate higher extinction at 2.5 Gb/s compared to the direct modulated approach. Our EAM approach utilizes FK absorption. The EAM WC and MZM WC designs incorporate FK photodiodes, in order to take advantage of their improved linearity.

Modulator-type WCs will benefit from increased modulator extinction efficiency (dB/V). Longer EAMs provide increased extinction efficiency at the expense of increasing capacitance (hence lower bandwidth) and on-state transmission. The MZM, by utilizing phase change-induced interference, exhibits higher extinction efficiency than the EAM of similar electrode length allowing it to maintain high bandwidth.

The photonic switch architecture based on the intimate integration of a quantum-well waveguide modulator with a surface-normal photodiode allows for the two-dimensional scalability of the wavelength-converting switches to realize the first reconfigurable wavelength-converting crossbar switches. This technology relies on the tight confinement of optically induced high-speed electrical signals in a single, compact, integrated optoelectronic chip for efficient wavelength conversion with low switching power for high extinction ratios in high-speed operations. Experimental results include unconstrained wavelength conversion up to 2.5 Gb/s and across 45 nm around the C-band, multi-wavelength broadcasting over 20 nm across the C-band, and multi-channel wavelength conversion with a 2x2 wavelength-converter array. Theoretical simulations predict 10 Gb/s operation.

CONCLUSION

In this paper, we described our research into novel approaches for monolithically integrating WCs in InP. The first approach, undertaken with UCSB, consists of an integrated widely tunable laser-transmitter and waveguide photodiode receiver. Several implementations have been designed, fabricated, and tested to exhibit modulation up to 2.5 Gb/s with high extinction ratio and error-free operation. The second approach, undertaken with Stanford University, consists of a scalable, compact, low-power, dual-diode photonic switch architecture that confines high-speed electrical signals in its novel photodiode-modulator integrated optoelectronic circuit. This technology enables reconfigurable multi-channel wavelength conversion. Both approaches are scalable to 10 Gb/s and higher bit rates, crucial for the implementation of advanced optical networking and the continuing explosion of Internet data bandwidth.

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