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Indium Phosphide-Based Optoelectronic Wavelength Conversion for High-Speed Optical Networks

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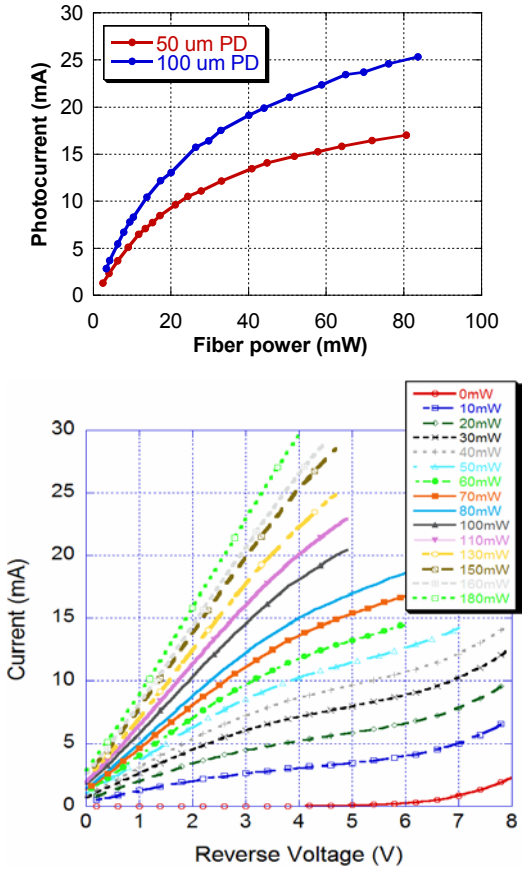

Figure 3: Photodiode optical response for quantum-well photodiodes of 2 lengths with 350 µm SOA preamp (top) and bulk photodiodes (200 µm long, No SOA preamp)

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.

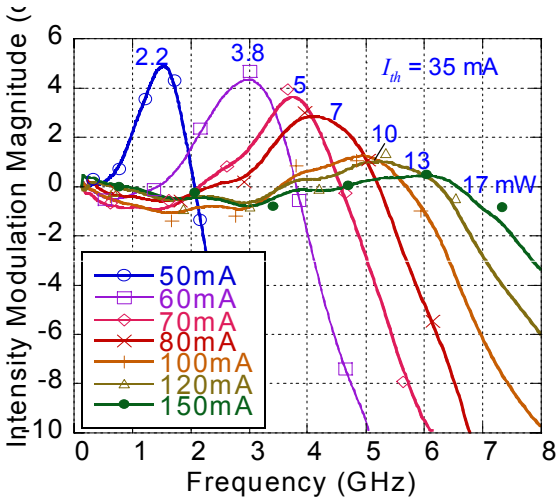

Figure 4: SGDBR laser direct modulation bandwidth

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.

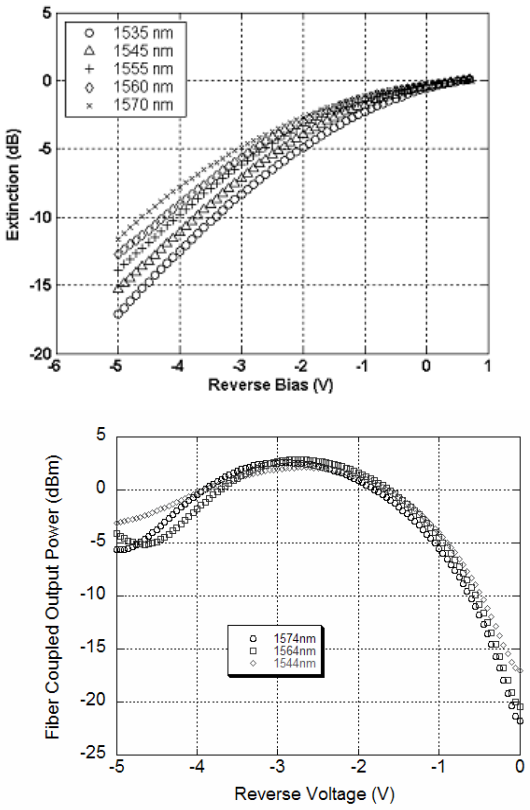

Figure 5: Extinction vs. bias for a 200 µm long EAM (top) and a MZM with 200 µm long electrodes (bottom)

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.

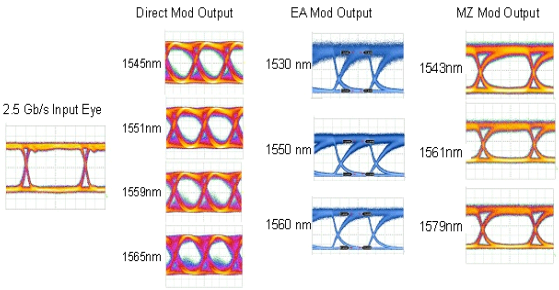

Figure 6: WC output eye diagrams with 2.5 Gb/s NRZ input signal

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].

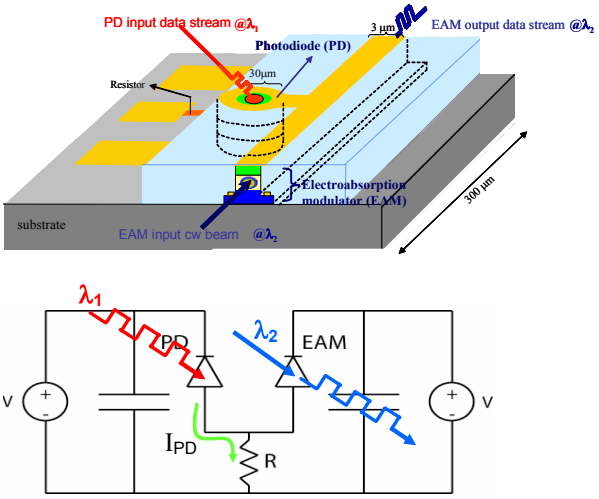

Figure 7 (a): A schematic of dual-diode photonic switch, and (b) its simplified circuit diagram

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.

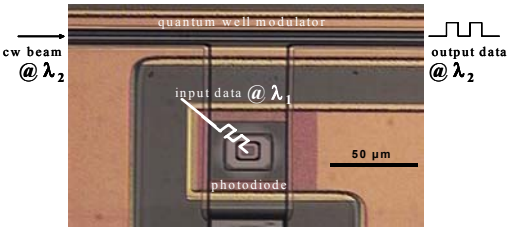

Figure 8: A picture of fabricated dual-diode device

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].

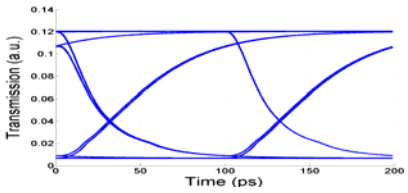

Figure 9: Simulation of 10 Gb/s operation

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].

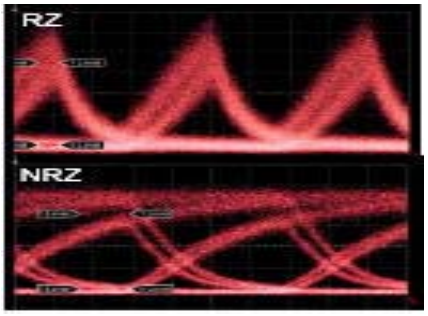

Figure 10: Optical switching in (a1) NRZ and (a2) RZ formats with >10 dB RF-extinction ratios at 2.5 Gb/s

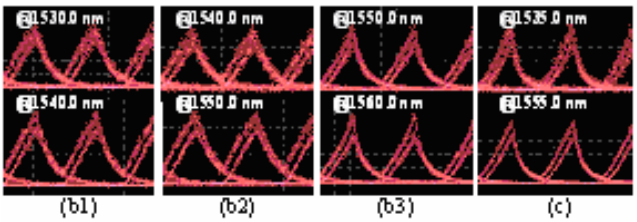

Figure 11: C-band dual-wavelength broadcasting with channel spacings of 10 nm in (b1)-(b3) and 20 nm in (c)

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.

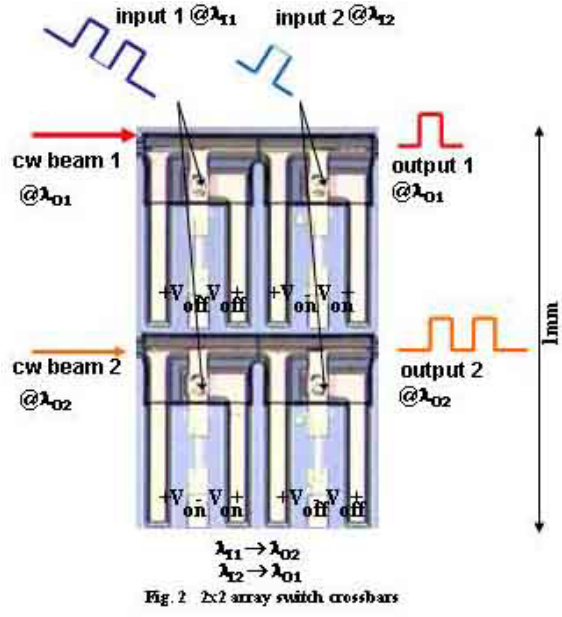

Figure 12: 2x2 wavelength-converting crossbar switch. The size is 1 mm x 600 µm

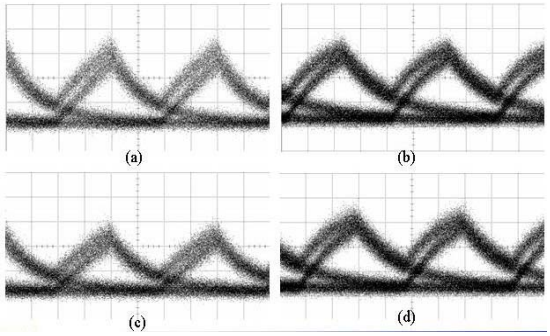

Figure 13: Eye diagrams from each of the four switch elements in a 2x2 array

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