Extinction ratio regeneration, signal re-amplification (2R), and broadband wavelength switching using a monolithically integrated photocurrent driven wavelength converter

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Abstract: Detailed wavelength conversion, extinction ratio regeneration, and signal re-amplification experiments are performed using a monolithically integrated, widely tunable photocurrent driven wavelength converter. A -3.5 dB power penalty is observed in bit error rate measurements at 2.5 Gb/s when the extinction ratio of an incoming signal is regenerated from 4 dB to 11 dB, and the input signal wavelength is switched from 1548 nm to an output wavelength range between 1533 nm and 1553 nm. When the input signal extinction ratio is regenerated from 4 to 11 dB, the wavelength converter provides facet to facet conversion gain of 5 dB, 7.7 dB, and 7.6 dB for conversion from 1548 nm to output wavelengths of 1533, 1545 nm, and 1553 nm.

OCIS codes: (250.5300) Photonic Integrated Circuits; (130.3120) Integrated Optics Devices

References and links

1. M. Webster, A. Wonfor, R. V. Penty, and I. H. White, “All-optical 2R regeneration and wavelength conversion at 10 Gb/s in an integrated semiconductor optical amplifier/distributed feedback laser,” Proc. European Conf. on Opt. Comm. (ECOC) **4**, 578-579 (2001).
2. D. C. Kim, M. Y. Jeon, Y. A. Leem, E. D. Shim, D. S. Yee, and K. H. Park, “Extinction ratio improvement and negative BER penalty for 2R regeneration in Mach-Zehnder wavelength converter,” Proc. European Conf. on Opt. Comm. (ECOC) **3**, 749-750 (2005).
3. P. S. Cho, D. Mahgerefteh, and J. Coldhar, “All-optical 2R regeneration and wavelength conversion at 20 Gb/s using an electroabsorption modulator,” IEEE Photon. Technol. Lett. **11**, 1662-1664 (1999).
4. S. B. Yoo, “Wavelength conversion technologies for WDM network applications,” J. Lightwave Technol. **14**, 955-966 (1996).
5. M. N. Sysak, J. W. Raring, J. S. Barton, M. Dummer, D. J. Blumenthal, and L. A. Coldren, “A single regrowth integration platform for photonic circuits iincorporating tunable SGDBR lasers and quantum well EAMs,” IEEE Photon. Technol. Lett. **18**, 1630-1632 (2006).
6. M. N. Sysak, J. W. Raring, J. S. Barton, M. Dummer, A. Tauke-Pedretti, H. N. Poulsen, D. J. Blumenthal, and L. A. Coldren, “Single-chip, widely-tunable 10 Gbps photocurrent-driven wavelength converter incorporating a monolithically integrated laser transmitter and optical receiver,” IEE Electronics Lett. **42**, 657-658 (2006).
7. A. Tauke-Pederetti, M. Dummer, J. Barton, M. Sysak, J. Raring, L. A. Coldren, “High saturation power and high gain integrated receivers,” IEEE Photon. Technol. Lett. **17**, 2167-2169 (2005).

I. Introduction

Optical signal regeneration, including signal reshaping and re-amplification (2R) and optical wavelength conversion are critical functionalities for increasing transmission distances and reducing blocking probabilities in next generation networks. To perform this function, several devices using a variety of approaches have been proposed and demonstrated. For

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simultaneous regeneration and wavelength conversion, these include optically injected lasers, semiconductor optical amplifier Mach Zehnders, electroabsorption modulators (EAM), and a variety of discrete component optoelectronic approaches [1-3]. Although significant progress has been made in operating speed and regeneration efficiency using these techniques, the majority of currently available wavelength converters that are compatible with regeneration suffer from a variety of drawbacks. These drawbacks include large chirp, high losses between discrete components, high power dissipation, limited dynamic wavelength conversion between identical wavelengths, and additional external optical filtering requirements for separating input and output wavelength converted signals [4].

In contrast to these techniques, recently we have demonstrated a photocurrent driven wavelength converter (PD-WC) that is fully transparent to a range of input and output wavelengths. The PD-WC does not require optical filtering to separate input and output signals and incorporates an on-chip tunable laser source to limit optical losses between discrete components. The device is fabricated using a simple dual quantum well (DQW) integration platform [5] where active regions used for optical gain, passive regions for waveguide routing, and EAM regions are defined using a selective etch technique to remove a set of quantum wells located above the optical waveguide layer. Completion of PD-WC fabrication requires only a single blanket InP regrowth.

In this work we show signal regeneration in combination with broadband wavelength switching using the PD-WC. Signal regeneration is performed through extinction ratio (ER) regeneration and signal reamplification (2R). Using a degraded input signal with a 4 dB ER at a wavelength of 1548 nm, conversion through the PD-WC to wavelengths between 1533 nm and 1553 nm shows extinction ratio improvements from 4 dB to 11 dB, facet to facet device gain of up to 7.7 dB, and a negative power penalty of 3 dB at a bit rate of 2.5 Gb/s.

2. PD-WC wavelength switching and signal regeneration mechanism

The photocurrent driven wavelength converter (PD-WC) consists of a monolithically integrated pre-amplified receiver and externally modulated widely tunable sampled grating DBR (SGDBR) based transmitter [6]. A scanning electron micrograph (SEM) of the device is

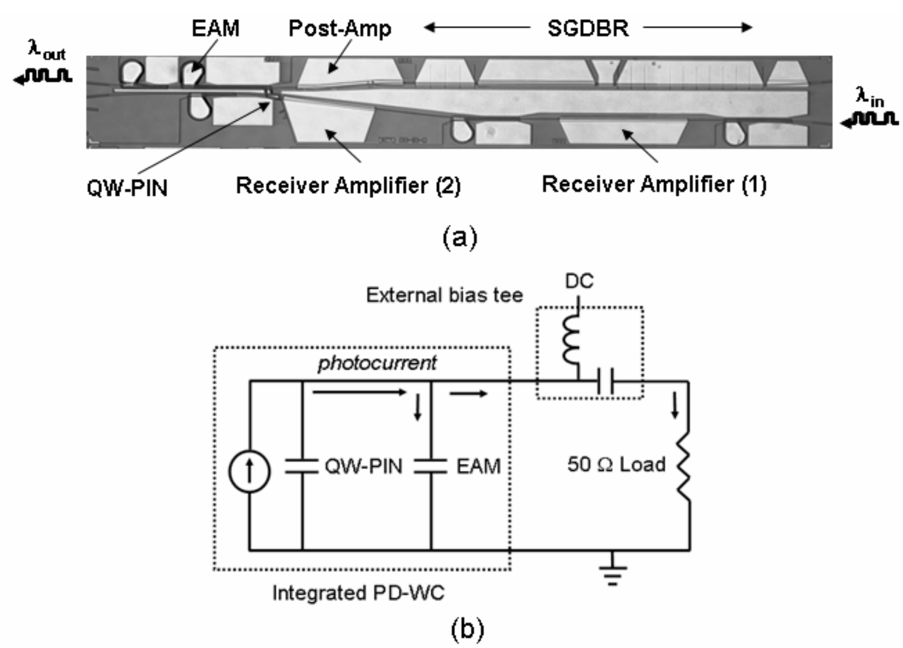

Fig 1. (a) SEM image of monolithically integrated photocurrent driven wavelength converter. (b) Equivalent circuit diagram for switching elements in the PD-WC showing the QW-PIN and EAM. Arrows indicate photocurrent from the QW-PIN photodetector.

shown in Fig. 1(a). Light enters the receiver on λ_{in} and is amplified by a set of two integrated semiconductor optical amplifiers (SOAs). The first SOA is 600 μm long and boosts the optical input power level to just below the 1-dB output power gain compression for a 3 μm wide amplifier. A second 400 μm long SOA with a flared waveguide geometry (3-12 μm) is then used to further boost the optical power before the input signal enters a quantum well (QW)-PIN photodetector [7]. The photocurrent from the receiver is routed over a short 35 μm long metal interconnect to a 400 μm long EAM that shares an optical waveguide with the SGDBR laser and shares a circuit node with an external bias tee and a 50 Ω load resistor. As the photocurrent drops across the load resistor, the EAM potential is changed, resulting in a modulation of its transmission characteristics. Since the EAM shares an optical waveguide with SGDBR laser, when the transmission characteristics are modified, the photocurrent signal from the QW-PIN is transcribed onto the output of the tunable laser operating at λ_{out}, completing the wavelength conversion process. The DC voltage for both QW-PIN and EAM is applied through the external bias tee. The integrated receiver, including the quantum efficiency of the QW-PIN photodetector, has a gain of between 20 and 21 dB with an applied current density of 6 kA/cm^2. The terminated S_{21} optical to optical bandwidth of the device is 7 GHz.

Extinction ratio regeneration in the PD-WC can be understood by examining a small signal equivalent circuit diagram of the active components in the wavelength switching process ([1(b)]. The components consist of a current source, representing the photocurrent in the receiver, two capacitors representing the QW-PIN and EAM, an inductor and capacitor for the external bias tee, and a load resistor. For an input signal that has a degraded extinction ratio, the inductive nature of the bias tee routes very low frequency components (DC offsets) through the inductor to the DC voltage source. Assuming an ideal source, the low frequency components are compensated by additional current, allowing the voltage at the QW-PIN/EAM circuit node to remain fixed. Since the voltage at this node is used to set the off state of the transmitter EAM (and hence the PD-WC), the off state at the output of the PD-WC can be set independently of the DC level at the input. For higher frequency components, the majority of the photocurrent generated in the receiver is routed to the load resistor, where it creates a voltage swing across the capacitor associated with the EAM. As long as the combination of the off state set by the voltage source and the high frequency voltage swing over the EAM is sufficient to generate an output extinction that is larger than that of the input, the PD-WC can provide signal regeneration.

For regeneration at data rates beyond the RC limited bandwidth of the device (7 GHz), the frequency dependent impedance of the PD-WC becomes important. At these high bit rates, although the optical power generated by the integrated receiver SOAs does not change, a reduction in the voltage drop over the EAM occurs due to the lowering of the effective impedance associated with the equivalent circuit shown in Fig. 1(b). The reduction in drive voltage lowers the output extinction of the wavelength converted signals, reducing the ability of the device to perform re-conditioning. As such, scaling the bandwidth and efficiency of the integrated photodetector and modulator is a key improvement in next generation designs of the PD-WC.

3. Regeneration experiments

Device re-amplification and extinction ratio regeneration characteristics were examined by degrading the input signal power and ER to the wavelength converter and measuring the resulting converted signal power and ER. The experimental set-up is identical to that found in [6]. Bit error rate (BER) measurements were performed for both degraded input signals and regenerated, wavelength converted signals. The BER experiments used a non-return to zero (NRZ) signal at 2.5 Gb/s with a 2^{31}-1 pseudo random bit stream (PRBS). Input signal optical signal to noise ratios (OSNR) were greater than 20 dB in all experiments. Receiver

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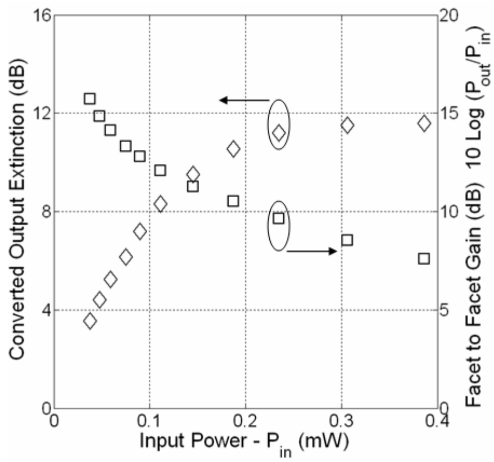

Fig 2. PD-WC converted extinction ratio and facet to facet gain at 2.5 Gb/s as a function of input power. The input and output signals are at 1548 nm and 1550 nm respectively. QW-PIN/EAM bias is -2.0V.

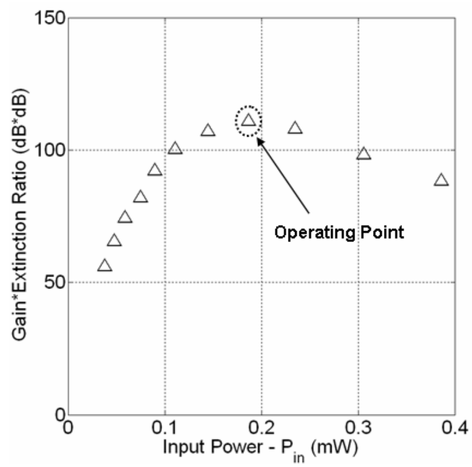

Fig 3. Product of the PD-WC gain and output extinction ratio as a function of input power. Input and output wavelengths are the same as in Fig. 4 as well as bias conditions. Optimal input power level is indicated.

SOAs were biased at 6 kA/cm^2, and SGDBR gain and SOA post amp were biased at 130 mA and 100 mA respectively.

For regeneration and re-amplification it is desirable to obtain the highest possible extinction ratio and the largest possible conversion gain from the PD-WC for a given input signal. To select the optimal input conditions to the device, an experiment was performed where an optical signal at 1548 nm with 10 dB extinction was fed to the PD-WC receiver at various power levels. The converted extinction out of the wavelength converter operating at 1550 nm was measured on an oscilloscope and the facet to facet gain from the device was calculated based on the fiber coupled input and output power, assuming 4.2 dB coupling loss. In these experiments the QW-PIN/EAM circuit node was biased at -2.0V. Results of the conversion gain and the output extinction from the PD-WC are shown in Fig. 2 and show that as the receiver power increases, the extinction from the device increases while the facet to facet gain decreases. To optimize the trade off between these two quantities the product of the

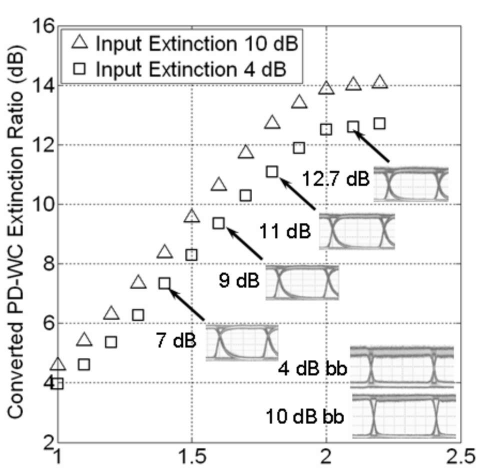

Fig. 4. PD-WC output extinction ratio for input signals with 4 dB ER or 10 dB ER. Back to back eye diagrams and converted etye diagrams are included. Input and output wavelengths are 1548 and 1545 nm respectively.

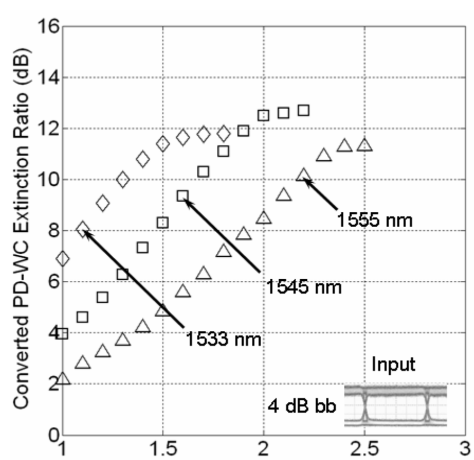

Fig. 5. Broadband PD-WC output extinction as a function of applied bias using a degraded 4 dB ER input signal. Output conversion is shown for operating wavelengths of 1533nm (diamonds), 1545 nm (squares), and 1555 nm (triangles).

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conversion gain and output extinction ratio as a function of input power is shown in Fig 3. From this figure, the input power that maximizes both gain and extinction simultaneously is approximately 0.19 mW (-7.2 dBm).

With the optimized input power level of -7.2 dBm, the regeneration properties of the PD-WC were further characterized using input signals at 1548 nm with extinction ratios of 4 dB and 10 dB. The output extinction ratio as a function of applied bias for these two input conditions is shown in Fig. 4. For wavelength conversion from 1548 nm to 1545 nm the PD-WC can regenerate the 4 dB extinction input signal to greater than 12 dB. Embedded eye diagrams for back to back (bb) conditions and wavelength converted signals with extinction ratios of 7 dB, 9 dB, 11 dB, and 12.7 dB are also included in the figure. The back to back eye diagrams were taken directly out of the transmitter used as an input to the wavelength converter for each input case. For broadband wavelength conversion and regeneration, the output extinction ratio generated by the PD-WC with the 4 dB ER input case is shown in Fig. 5. For output operating wavelengths that range from 1533 to 1553 nm, the converted extinction ratio from the wavelength converter can be regenerated to 11 dB depending on the applied bias to the device.

BER measurements were performed for signal regeneration and wavelength conversion from 1548 nm to a variety of output wavelengths using the 4-dB ER input signal. For conversion from 1548 nm to 1545 nm with applied reverse biases of 1.4V, 1.6V, 1.8V, and 2.1 V, results of the BER as a function of receiver power are shown in Fig. 6. As the reverse bias is increased, the wavelength converted signal ER improves as shown in Fig. 4, leading to improved receiver sensitivity and negative power penalties. At a bias of 2.1 V the converted signal extinction ratio improvement from 4 to 12.7 dB leads to a negative 3.5 dB power penalty.

For broadband wavelength conversion and regeneration, BER measurements were performed where the reverse bias applied to the PD-WC was selected based on data in Fig. 5 to achieve an 11 dB converted ER for each output operating wavelength. For output wavelengths of 1533 nm, 1545 nm, and 1553 nm, the applied bias conditions to achieve this extinction were 1.4V, 1.7V and 2.3V respectively. Results of the BER experiments are shown in Fig 7. For all output operating wavelengths, the 4-dB extinction ratio can be regenerated to 11 dB which leads to improved receiver sensitivity and negative 3-dB power penalty.

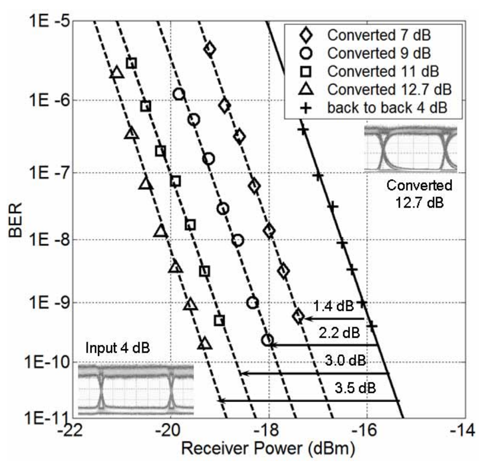

Fig. 6. Wavelength converted (1548 to 1545 nm) BER measurement results for a degraded input signal with 4 dB ER. Converted ER is indicated along with power penalties. Eye diagrams are for converted (2.1 V, 12.7 dB ER) and back to back signals.

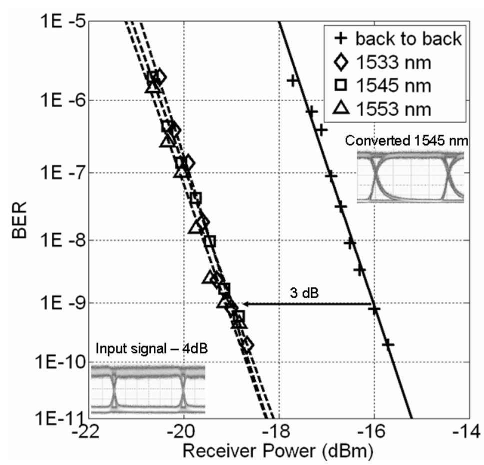

Fig. 7. Broadband wavelength converted BER measurement for degraded input signal with 4 dB ER. For each output wavelength the bias of the PD-WC is set to achieve an output ER of 11 dB. Eye diagrams are for input signal and converted output at 1545 nm.

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Broadband re-amplification characteristics of the PD-WC as a function of applied reverse bias are shown in Fig. 8 using the 4 dB ER input signal. The conversion gain is shown as facet to facet gain where the input and output fiber coupling losses (4.2 dB) have been removed. For output wavelengths ranging from 1533 nm to 1553 nm, the PD-WC conversion gain varies from 2 dB to 15 dB depending on the applied bias conditions. For a fixed output wavelength of 1545 nm, the conversion gain for the applied bias levels used to generate the data in Fig. 6 were 10 dB, 8.7 dB, 7.8 dB, and 5.5 dB. Eye diagrams from the PD-WC at each of these reverse biases have been included. For the conditions indicated to achieve an 11 dB output ER over a range of output wavelengths of 1533 nm, 1545 nm and 1553 nm, the conversion gain is 5 dB, 7.7 dB, and 7.6 dB.

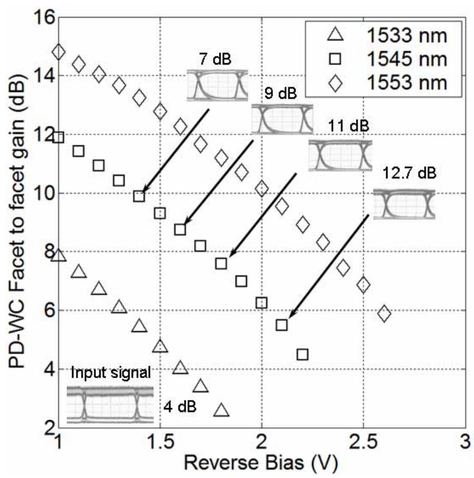

Fig. 8. Broadband PD-WC re-amplification characteristics. Eye diagrams included are for back to back (4 dB ER) and converted eye diagrams for the bias conditions indicated in Fig 6.

4. Conclusion and future work

Signal regeneration in combination with broadband wavelength switching using a monolithically integrated photocurrent driven wavelength converter. Signal regeneration is performed through extinction ratio regeneration and signal reamplification. Using a degraded input signal with a 4 dB ER at a wavelength of 1548 nm, conversion to output wavelengths of 1533 nm, 1545 nm, and 1553 nm shows a regenerated extinction of 11 dB, and conversion gain of 5 dB, 7.7 dB, and 7.6 dB. BER measurements for conversion to each of these wavelengths with an output ER of 11 dB shows a negative 3 dB power penalty. Future improvements in the device include scaling both the bandwidth and efficiency of the integrated photodetector and modulator for regeneration at higher bit rates.

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