Optical 2R and 3R Signal Regeneration in Combination with Dynamic Wavelength Switching Using a Monolithically Integrated, Widely Tunable Photocurrent Driven Wavelength Converter

(Invited)

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Abstract *Optical 2R and 3R signal regeneration along with dynamic wavelength switching is demonstrated for the first time using a monolithically integrated, widely tunable photocurrent driven wavelength converter.*

I. Introduction

Wavelength conversion in combination with optical regeneration, including signal retiming, signal reshaping and signal reamplification, is viewed as a key functionality for improving blocking probabilities and signal quality in next generation optical networks. To perform this function, several devices have been proposed and demonstrated [1,2]. However, prior to this work, regenerators with high levels of integrated functionality, including on-chip tunable laser sources, have not been demonstrated. Here we present wavelength switching and signal regeneration using a single-chip widely tunable, photocurrent driven wavelength converter (PD-WC) [3]. The small form factor highly integrated chip enables reduced packaging complexity and costs along with reduced optical loss between discrete components.

In Section II, we examine the wavelength switching, signal extinction ratio regeneration, and signal reamplification (2R) properties of the device using a degraded non-return to zero (NRZ) input signal. For conversion from 1548 nm to 1545 nm we observe regeneration with an increased extinction ratio from 4 dB to greater than 12 dB, facet to facet gain of up to 12 dB (excluding coupling losses), and a 3.5 dB negative power-penalty in Bit Error Rate (BER) experiments at 2.5 Gb/s.

In Section III, we examine the wavelength switching, signal reshaping, signal reamplification, and signal retiming (3R) properties of the PD-WC using a 10 Gb/s return to zero (RZ) input signal . Error-free wavelength switching is demonstrated with a 1-dB power penalty from 1548 nm to 1545 nm using an ideal input signal. For a degraded input with timing distortion and a 4 dB extinction, wavelength converted signal regeneration shows a negative 2.8-dB power penalty through the device, with facet to facet gain (excluding coupling losses) of +6.4 dB. Measurements of the peak to peak jitter before and after the device show a reduction from 35 ps to 17 ps using input signals with added 10 MHz sinusoidal frequency modulation.

II. 2R regeneration and wavelength switching

II(a). 2R PD-WC device arrangement

The single chip EAM-based photocurrent driven wavelength converter is fabricated in the InGaAsP/InP materials system using a dual quantum well (DQW) integration platform [4].

The wavelength converter is arranged in a parallel ridge architecture as shown in Fig. 1. Light at wavelength λ_{in} enters the device receiver section and is amplified by a set of two linear SOAs. The first SOA is 600 μm long and has a ridge width of 3 μm. The second SOA is 400 μm long and has an exponentially flared ridge width (3 μm to 12 μm) to increase the saturation power characteristics [5]. The amplified signal is fed to a tapered 50 μm long QW-PIN photodetector. Total receiver optical gain at 1548 nm is 21 dB including the quantum efficiency of the

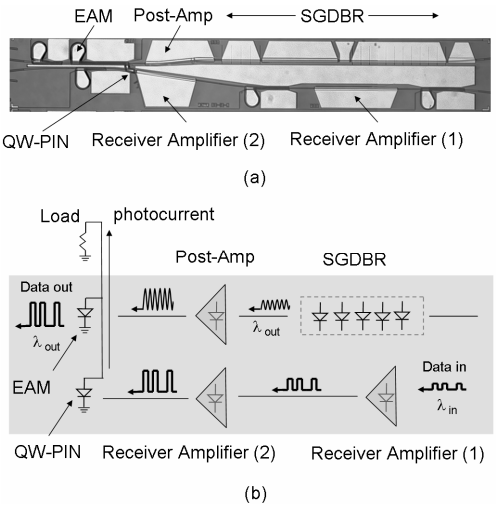

Fig 1. (a) Scanning electron mocrograph of single chip, widely tuneable wavelength converter (b) Functional diagram of integrated components in wavelength converter for 2R regeneration experiments

QW-PIN photodetector. The photocurrent from the receiver is routed 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 altered changing its transmission characteristics. Since the EAM is positioned after the SGDBR laser, it functions to transfer the input signal onto the output of the tuneable laser (λ_{out}), resulting in wavelength conversion. The DC voltage for both QW-PIN and EAM is applied through the external bias tee. Overall device optical 3-dB bandwidth is 6 GHz.

II(b). 2R regeneration experiments

Device re-amplification and reshaping (extinction ratio regeneration) properties were examined by degrading the input signal power and extinction ratio (ER) to the wavelength converter, and measuring the resulting converted signal power and ER. The experimental set-up is identical to that found in [3]. Measurements of the converted signals were performed by examining waveforms on an oscilloscope. To confirm the regenerating properties of the wavelength converter, Bit Error Rate (BER) measurements were performed with non-return to zero (NRZ) signals at 2.5 Gb/s using 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 SOAs were biased at 6.6 kA/cm^2, and SGDBR gain and SOA post amp were biased at 130 mA and 100 mA respectively.

II(c). 2R regeneration results

The wavelength converted output (1545 nm) ER as a function of applied reverse bias is shown in Fig. 2 for input signal (1548 nm) extinction ratios of 4 dB and 10 dB. At both input conditions, the average on-chip

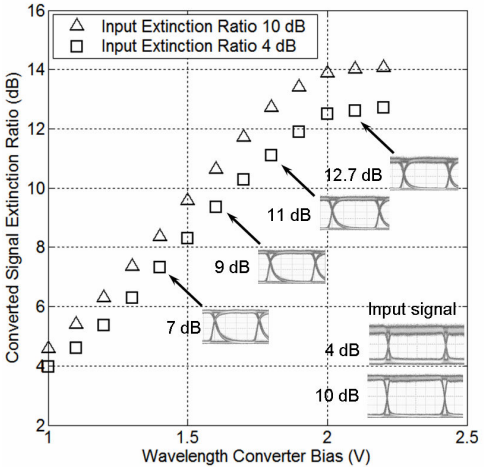

Fig 2. Wavelength converted (1548 to 1545 nm) signal extinction ratio characteristics and eye diagrams as a function of device bias conditions. Input eye diagrams are also included.

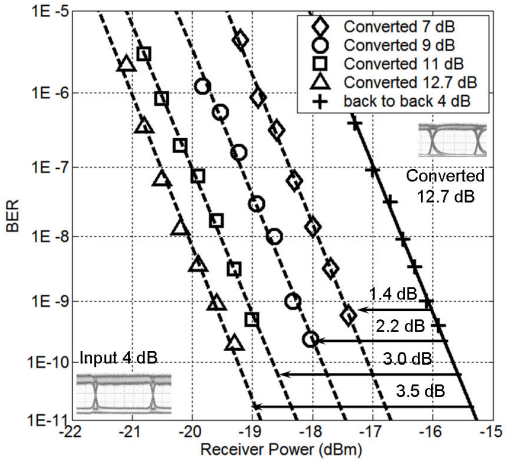

Fig 3. Wavelength converted (1548 to 1545 nm) BER measurement results. Input extinction ratio is 4 dB, output ER are indicated alng wih power penalties. Eye diagrams are for converted (2.1 V, 12.7 dB) and back to back (4 dB) signals.

receiver power was -7 dBm. The wavelength converted signals show ER of greater than 12 dB for the 4 dB ER input case and 14 dB for the 10 dB ER input case with a reverse bias of -2.1 V. Converted eye diagrams and input eye diagrams are also shown in Fig. 2.

Wavelength converted and back to back BER measurements for the 4-dB ER input signal case are shown in Fig 3. The output signal conditions are matched with the eye diagrams that are embedded in Fig. 2. As the reverse bias is increased, the wavelength converted signal ER improves, 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.

The re-amplification characteristics for the device are measured as facet to facet gain, where

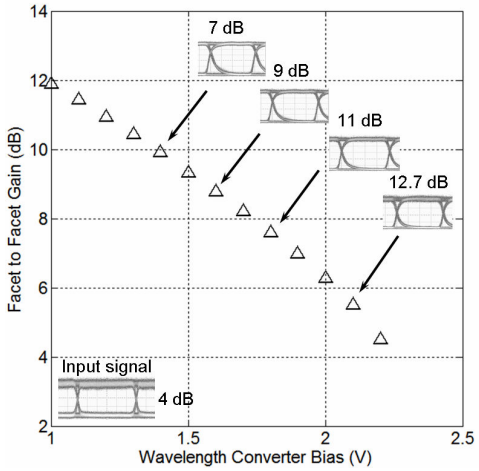

Fig 4. Wavelength converted (1548 nm to 1545 nm) facet to facet gain with fiber coupling loss removed. Input extinction ratio is 4 dB. Eye diagrams are shown for wavelength converted and input signals. Extinction ratios in eye diargams are indicated.

input and output fiber coupling losses (4.2 dB) are removed. Results are shown in Fig. 4 for a range of reverse bias conditions for the 4 dB ER input signal. As seen in the figure, between 4 dB and 12 dB of gain can be achieved depending on the applied bias conditions.

III. 3R regeneration and wavelength switching

III(a). 3R PD-WC device arrangement

For 3R regeneration experiments, the PD-WC chip described in Section I(a) is combined with an external electrical clock recovery circuit, and a second EAM (EAM 2) that spatially follows the EAM (EAM 1) connected to the QW-PIN photodetector. A functional schematic of the wavelength conversion and 3R signal regeneration process in the device, including eye diagrams, is shown in Fig. 5. For clock recovery, the photocurrent generated in the QW-PIN is used to drive an electrical PLL-clock circuit (Fig. 5). The effective 50 Ω impedance of the clock recovery circuit is used as a resistive termination. The recovered 10 GHz clock signal from the PLL is then amplified and fed to EAM 2. The single frequency sine wave controls the transmission properties of EAM 2 and gates the band-limited (3-dB optical bandwidth ~ 6 GHz) wavelength converter signal produced by the combination of EAM 1 and the QW-PIN. This approach has been shown to reduce noise and jitter [6]. Electrical delay lines are used to phase match the clock and data signals and DC bias tees are used to apply a reverse bias to the wavelength converter and to EAM 2.

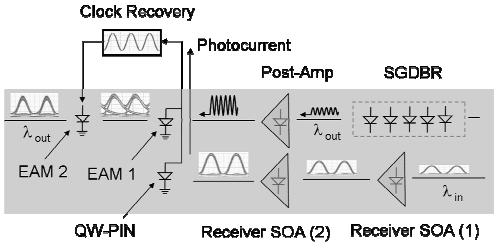

Fig. 5. Functional overview of monolithically integrated PD-WC and data/clock recoverv circuitrv.

III(b). 3R regeneration experiments

Device wavelength switching, and signal regeneration properties have been examined using a return to zero (RZ) 10 Gb/s pseudo random bit stream (PRBS) with a 2^{31}-1 word length. For wavelength switching with an ideal input, a signal with an extinction ratio (ER) of 15 dB at 1548 nm was fed to the wavelength converter. The converted signal ER and output power were measured using waveforms on an oscilloscope. Bit error rate (BER) measurements were performed using the set-up shown in Fig 6.

For regenerative wavelength switching of signals with eye shape distortion, measurements of

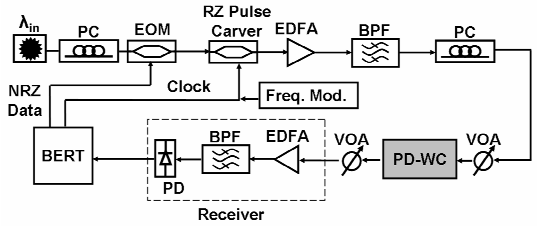

Fig 6. Experimental set up for measuring RZ signal regeneration and wavelength switching with the PD-WC.

the BER, wavelength converted ER, and output power were been performed. To degrade the signal ER and eye-shape, the polarization of the laser transmitter is rotated before entering the electro-optic modulator (EOM) in Fig. 6. The ER of the degraded input was 4 dB and the pulse width was broadened.

Jitter experiments were performed by adding a 10 MHz sinusoidal frequency modulation to the data signal from the BERT tester before being fed to the EOM. Input optical signal to noise ratios (OSNR) were greater than 25 dB in all experiments.

Receiver SOAs were biased at 6.6 kA/cm^2, and SGDBR gain section and SOA post amp were biased at 130 mA and 100 mA respectively. The amplified peak to peak 10 GHz clock tone used to drive EAM 2 was 3 V measured before the device. The wavelength converter EAM and QW-PIN (EAM 1) was biased at -2.2 V and EAM 2 was biased at -1.5 V.

III(c). 3R regeneration results

BER measurements results for wavelength conversion and signal regeneration are shown in Fig 7. Using an ideal input signal at 1548 nm with average on-chip input power of -7 dBm, BER measurements show a 1-dB power penalty for conversion to 1545 nm. Fiber coupled wavelength converted average output power was -8.2 dBm into a lensed fiber and ER was 13 dB. Measured fiber coupling loss was 4.2 dB giving an overall facet to

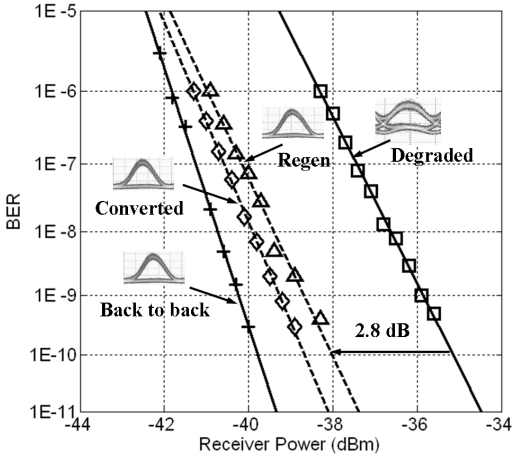

Fig 7. BER measurement results for wavelength conversion between 1548 nm and 1545 nm uisng an ideal input signal with 15 dB ER and degraded input (4 dB ER).

facet conversion gain of +7.2 dB.

For the degraded input signal, back to back BER curves and regenerated BER curves in addition to eye diagrams are shown in Fig 7. Degraded signal input extinction ratio is 4 dB at 1548 nm, and average input power to the wavelength converter was -7 dBm. After conversion the output ER at 1545 nm was 11 dB. BER measurements of the regenerated input signal show a negative 2.8 dB power penalty compared with back to back. The converted average output power was -9 dBm which gives a facet to facet conversion gain of +6.4 dB.

Device input and wavelength converted eye diagrams and their corresponding values of peak to peak jitter are shown in Fig 8. Wavelength conversion through the device provides a reduction in the input jitter by 7 ps, 12 ps and 18 ps for input jitter levels of 15 ps, 25 ps and 35 ps respectively.

Input Eyes

Jitter In (ps)	Jitter Out (ps)
15	8
25	13
35	17

Converted Eyes

Fig 8. Input and wavelength converted eye diagrams with various amounts of added peak to peak jitter. Wavelength conversion is from 1548 to 1545 nm.

IV. Summary

We have demonstrated wavelength switching in combination with both 2R and 3R regeneration using a monolithically integrated widely tunable PD-WC.

In 2R regeneration experiments with NRZ data, signal extinction ratios are improved from 4 dB to greater than 12 dB with facet to facet gain ranging from 4 dB to 12 dB. BER measurements show negative power penalties of up to 3.5 dB when the converted signal extinction ratio is regenerated from 4 dB to 12.7 dB.

In 3R regeneration experiments with RZ data, facet to facet gain for conversion of degraded input signals is +6.4 dB, and a negative power penalty of 2.8 dB is observed in BER measurements. Jitter experiments show a reduction from 35 ps to 17 ps through the PD-WC.

V. References

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