2.5-Gb/s Error-Free Wavelength Conversion Using a Monolithically Integrated Widely Tunable SGDBR-SOA-MZ Transmitter and Integrated Photodetector

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***Abstract*—Error-free operation at 2.5 Gb/s was demonstrated for the first monolithically integrated widely tunable photocurrent-driven Mach–Zehnder based wavelength converter. Power penalties of 1–2 dB were measured across the 37-nm wavelength range of the sampled grating distributed Bragg reflector.**

***Index Terms*—Optical modulation, optical planar waveguide components, optical receivers, optical transmitters, photodiodes, quantum-well (QW) lasers, tunable lasers, wavelength conversion.**

I. Introduction

FUTURE OPTICAL networks will benefit greatly from the development of widely tunable wavelength converters (WCs). This novel class of sophisticated photonic integrated circuits (PICs) allows for the dynamic manipulation of wavelengths in wavelength-division-multiplexing optical switches, routers, and add–drop multiplexers. A number of different implementations of WCs have been proposed using optical gates comprised of a photodiode and electroabsorption modulator (EAM) [1], cross-phase modulation in semiconductor optical amplifiers (SOAs) and fiber [2], [3], and cross-absorption modulation of EAMs [4]. Many of these architectures have been demonstrated to perform digital signal regeneration—including improvements in extinction ratio, signal-to-noise ratio, pulsewidth, etc. More recently, fixed wavelength integrated laser sources have been explored [5] and monolithically integrated widely tunable all-optical WCs [6] have been demonstrated. This approach has shown promise to allow for wavelength conversion without requiring the signal to pass through electronics. In this letter, we describe the first results from one configuration of a new class of WCs that consist of a monolithically integrated tunable transmitter with Mach–Zehnder (MZ) modulator [7] and waveguide photodetector to generate photocurrent that is used to drive the modulation of the transmitter. The broad class of tunable photocurrent driven wavelength converters (TPD-WC) can use either an external modulator or directly modulate the gain section of an sampled grating distributed Bragg reflector (SGDBR) tunable laser [8].

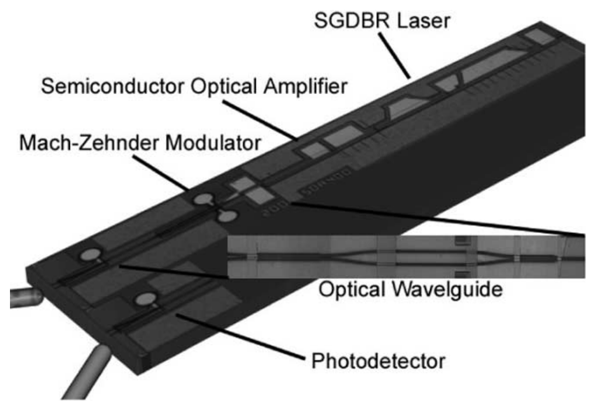

Fig. 1. TPD-MZ-WC wavelength converter.

This particular implementation uses a monolithically integrated widely tunable WC based on an SGDBR-SOA-MZ transmitter and integrated Franz–Keldysh photodetector (TPD-MZ-WC) (Fig. 1). The MZ design has high extinction (>20 dB) with a low drive voltage (~3 V) making it suitable as a driving modulator for the device (Fig. 2). The modulation efficiency is high due to the large change in index and absorption in the branches of the waveguide (bandgap energy corresponds to $\lambda = 1.4\ \mu$m). This device offers advantages over [5], [6] as wavelength filtering of the input wavelength at the output is not required. The challenge of successful TPD-WC design lies in providing adequate photocurrent generation to achieve high extinction with relatively low input powers. Integrating the SGDBR gives a compact wavelength agile source that requires only two fiber connections—with low loss coupling between the SGDBR and the modulator. This design ultimately yields a small footprint, low cost, and transmits at high speed with inherent signal monitoring capabilities.

II. Wavelength Converter Design

The device uses a ridge-based SGDBR with laser and modulator design similar to the one described in [7]. An absorber section is on the back-end of the device for measurement of power, and to decrease the requirements of the backside

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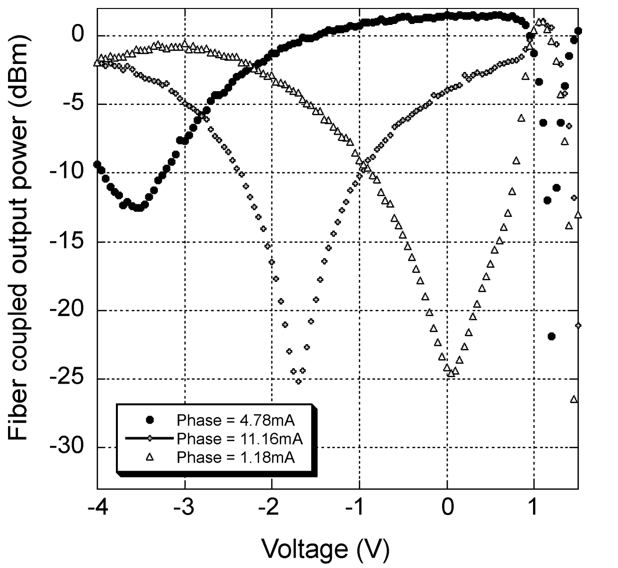

Fig. 2. DC extinction data for a 200-μm-long electrode Mach-Zehdner modulator—with SOA 100 mA, Gain = 100 mA, $\lambda = 1561$ nm.

TABLE I
EPILAYER STRUCTURE

Layer	Thickness (nm)	Composition – Doping
InGaAs	100	Lattice Matched 1e19 cm^{-3} Zn
p-InP	1800	1e18 cm^{-3} Zn
1.226LM	25	
7QWs		Nid 8nm barriers 6.5nm wells
nid InP	10	
Waveguide	350	Emission wavelength 1.4µm
n-InP Buffer	1800	1e18 Si InP
S Doped Substrate	10000000	5e18 Sulfur doped

antireflective (AR) coating. The MZ modulator utilizes one 1 × 2 multimode interference (MMI) coupler (97 μm long) at the input of the interferometer with curved waveguides extending to a separation of 20 μm in between the two branches and a 172-μm 2 × 2 MMI at the output of the MZ modulator section (inset of Fig. 1). The output waveguides are angled to reduce the AR coating requirements. The total device chip size is 1 × 3.5 mm. For the TPD-MZ-WC, the pads on both the bulk (Franz–Keldysh) detector and the MZ are both 200 μm long. This bulk detector drives one of the branches of an SGDBR-SOA-MZ transmitter at the output wavelength λ_2. This current design employs lumped element components. Conceivably with traveling wave electrodes, this device could achieve 3-dB bandwidths greater than 40 GHz.

This design uses a common waveguide structure in which the passive sections are formed by etching off the quantum wells (QWs) down to the 10-nm InP stop-etch layer. The process is similar to other SGDBR-based PICs [6]–[8]. The epi-layer structure consists of an offset QW structure, as shown in Table I.

III. PHOTODETECTOR CHARACTERISTICS

The bulk Franz–Keldysh detector in this WC offers high photocurrent generation without saturation at high optical input powers. Fig. 3 demonstrates the photocurrent characteristics as a function of reverse bias and optical input power. In other

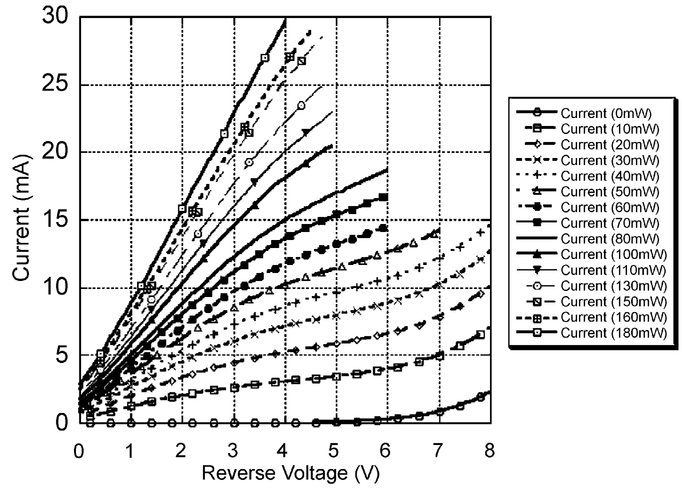

Fig. 3. Photodetector IV characteristics as a function of incident optical power at 1548 nm.

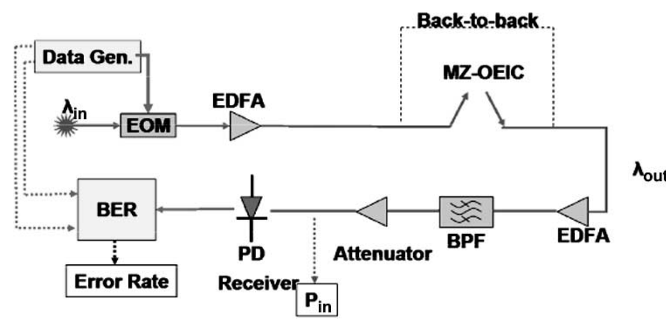

Fig. 4. Schematic of BER test setup.

designs [8], SOA preamplifiers were employed to reduce the input power requirements to <1 mW. In this case, no on-chip SOA was used. Determination of the bias point of the detector is based on concerns of excessive device heating with high bias (−6 V) and optical facet damage with high optical power (>200 mW). For these reasons, the detector was biased at −4 V to generate 30-mA photocurrent using 180 mW of optical power. Due to the flaring and angling of the waveguide and the use of lensed fiber, we experience approximately 5 dB of coupling losses at the facet.

IV. BIAS CONFIGURATION

Conceivably, the two devices could be directly connected together with a metal trace with proper design. In this device configuration, one would like to reverse bias the detector highly (−4 V) to achieve sufficient photocurrent and resulting voltage swing, but leave the MZ at a lower bias (−1 V) where there is not excessive absorption. For the purposes of this letter, both devices were probed with CPS probes using Picosecond Labs model 5542 bias-Ts. For improvement of the lumped bandwidth, a 50-Ω parallel resistor was connected between the MZ p-metal and ground contacts.

V. EXPERIMENT

Bit-error-rate (BER) curves as a function of receiver power were generated using an experimental setup, as shown in Fig. 4. Nonreturn-to-zero $2^{31} - 1$ pseudorandom binary sequence

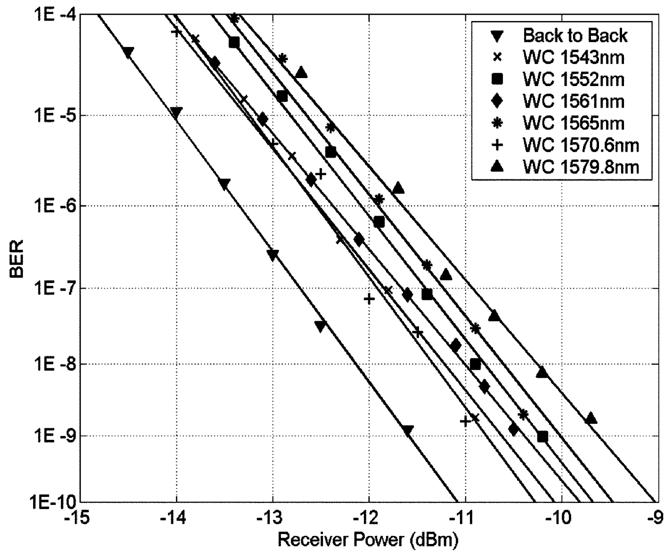

Fig. 5. BER data for different wavelengths with original wavelength at 1548.1 nm [1–2-dB power penalty].

(PRBS) 2.5-Gb/s data was generated at an input wavelength of 1548.1 nm using a 3-Gb/s BER tester and Agilent 83 433 A transmitter. An erbium-doped fiber amplifier (EDFA) was used to boost the power to 180 mW and generate 30 mA of photocurrent in the detector at a bias of -4 V on the detector which provides adequate drive voltage on the modulator, and ultimately high extinction ratio output. The converted signal from the integrated transmitter at λ_2 was fed into an EDFA/filter then attenuated and the power measured just before the PIN receiver, as shown in Fig. 4 (Agilent 11 982 A). Separate filters were tuned for each wavelength in the C- and L-bands.

VI. Results

Typical BER measurements results are shown in Fig. 5. The PRBS 2.5-Gb/s output waveforms corresponded to 7.5–8.3-dB extinction across the wavelength range. Error-free wavelength conversion was achieved over a wide range (37-nm output) corresponding to a 1–2-dB power penalty over this range. The power penalty variation can be attributed mostly to a change in extinction ratio and signal-to-noise ratio over the wavelength range. Using a higher termination resistor than 50 Ω would lower the power penalty at the expense of the optical bandwidth. The device was biased with the following currents: Gain section $=$ 120 mA, SOA $=$ 70 mA, MZ branch #1(modulated) $= -1$ V, MZ branch #2 $= -3.6$ V. The tuning was performed by current injection into the rear mirror.

VII. Conclusion

We have demonstrated error-free wavelength conversion over 37 nm with <2-dB power penalty using a novel TPD-MZ-WC wavelength converter. We see great promise in this monolithically integrated approach to wavelength conversion. These devices should become practical for network applications with the improvement of on-chip coupling losses and with the eventual integration of a preamplifier before the photodetector, which will provide significant optical gain and supply sufficient photocurrent to drive the MZ modulator with much lower optical power requirements. Improvements in biasing can be made using either an integrated capacitor on chip or devices isolated on semi-insulating substrates so that bias-Ts are not required or an active detector employed that can absorb more of the light with lower bias.

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