Widely Tunable 10 Gbps Separate Absorption and Modulation Mach-Zehnder Wavelength Converter

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A fully monolithic separate absorption and modulation region wavelength converter requiring no bias tees has been fabricated. The device consists of a transmitter comprised of a sampled-grating DBR laser and series-push-pull Mach-Zehnder modulator, and a receiver composed of a linear semiconductor optical amplifier and a quantum well pin *photodetector. The wavelength converter has a 13 GHz bandwidth and demonstrates error-free operation at 10 Gbps with unity gain.*

Introduction: Wavelength converters will be an important part of the next generation of optical networks, allowing for dynamic wavelength management and enabling all-optical routers. Devices with bit-rate transparency, small form factors and low power consumption will best meet the demands of these networks. Monolithic devices lend themselves particularly well to these challenges. Semiconductor optical amplifier (SOA) based devices have been extensively studied, however these devices are inherently limited by carrier lifetime. Efforts in overcoming the carrier lifetime limitation with delayed interference have been successful, however these devices still have optical filtering requirements and are limited to return-to-zero (RZ) data formats [1], [2]. Recently there has been success with the separate absorption and modulation (SAM) approaches to wavelength conversion [3], [4] with electroabsorption modulators (EAM). Due to the spatial separation of the input and output waveguide, these devices have the advantage of no optical filtering requirement and are capable of converting to the input wavelength. Replacing the EAM with a Mach-Zehnder modulator (MZM) will allow for high extinction ratios and zero or negative chirp.

This paper presents a fully monolithic SAM wavelength converter utilizing a series-push-pull MZM. The wavelength converter is composed of a linearly flared SOA pre-amplifier, a tapered quantum well photodiode, a five section widely tunable laser and a series-push-pull MZM. External bias tees were not used; instead a capacitor and resistor were monolithically integrated on the wavelength converter chip to reduce signal attenuation and simplify biasing.

Device: The device was fabricated on an offset quantum well integration platform using ridge waveguides [5]. The epitaxial structure consists of an InGaAs n-contact layer, n-InP cladding, InGaAsP waveguide and a set of seven quantum wells all grown on a semi-insulating InP substrate. The use of a semi-insulating substrate is essential in order to isolate the semiconductor resistor as well as the receiver and transmitter grounds as required for biasing; an added benefit is a capacitance reduction for high-speed pads. The offset quantum wells (λ_{PL} = 1540 nm) provide gain for the SGDBR and SOAs when forward biased and absorption for the photodetector when reverse biased. The selective removal of the offset quantum wells from the passive sections and the etching of holographically defined sampled gratings is followed by a blanket regrowth of the p-InP cladding and p-InGaAs contact layer.

The SGDBR laser consists of five sections – an active absorber, a rear mirror, a phase section, a gain section, and a front mirror. A 500 μm-long SOA following the laser increases the output power of the device and compensates for propagation losses. A flared and curved output waveguide combined with an AR coating is used to reduce optical reflections and to enhance coupling efficiency.

The 300 μm-long MZM is operated in a series-push-pull fashion with the photocurrent signal applied across tops of the Mach-Zehnder arms. The capacitance associated with the two MZM arms are in series effectively halving the device capacitance and increasing the bandwidth. This configuration also provides small chirp values since the push-pull modulation cancels the modulation induced chirp [6]. An integrated 32 Ω semiconductor resistor fabricated from the n-contact layer provides on chip termination. The MZM was designed to operate as a traveling-wave device in order to achieve the bandwidth necessary for high speed operation. Due to the capacitance and resistance associated with the modulator ridge, the MZM coplanar striplines were periodically capacitively loaded using six 50 μm long T-electrodes in order to achieve a characteristic impedance close to 40 Ω [6], [7]. To further reduce the capacitance photo-bis-benzocylcocutene (BCB) is used as a low-k dielectric under the high-speed electrodes and the ridge width is reduced from 3 μm in the laser and SOA regions to 2 μm within the modulators. A forward biased phase section tunes the Mach-Zehnder interferometer to maximize the extinction ratio.

The receiver section consists of a 500 μm long straight SOA, a 550 μm long high-saturation power SOA and a 35 μm long tapered quantum well detector [8]. The high-saturation power amplifier employs lateral flaring from 3 μm to 12 μm in order to increase the output saturation power. Both SOAs are operated below their 1 dB saturation point to prevent signal distortion. The photodetector makes use of the offset quantum wells to obtain a high absorption coefficient. The 9 μm wide front end prevents saturation due to high photocurrent levels and lateral tapering down to 2 μm reduces capacitance. An on-chip parallel plate capacitor has been fabricated to provide an on-chip path to ground for the microwave signal components. This 20 pF capacitor is formed by sandwiching 300 nm of SiN_x between the n-contact layer and p-metal.

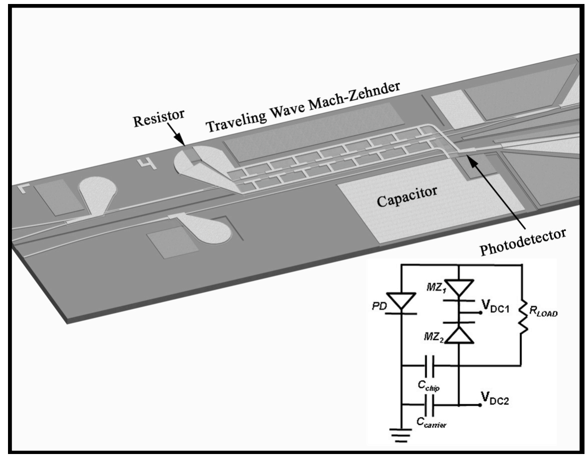

Fig. 1. Close-up of the modulator and photodiode section of the SAM wavelength converter. The schematic of the biasing scheme is shown in the lower right.

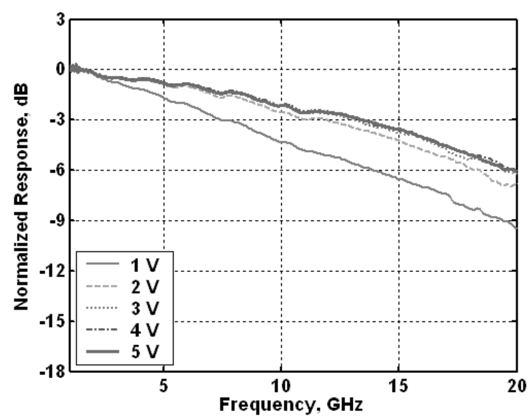

Fig. 2. Small signal response of the wavelength converter for sweeping V_{DC2} with the voltage across the MZM arm held at V_{MZ1} = 1 V.

Experiments: Following fabrication, the device was mounted on an AlN carrier, all contacts were wirebonded to the carrier and a DC probe card was used to apply all biases. An on-carrier chip capacitor was wirebonded in series with the on chip capacitor to act as a low frequency bypass capacitor. Additionally, a small (2 Ω) resistor was placed in series with the carrier capacitor to dampen LC resonances from the wirebonds. This simple biasing configuration keeps the microwave signal components on chip and increases scalability. The wavelength converter biasing configuration is shown in Fig. 1. All measurements were taken at a stage temperature of 15^o C.

Small signal measurements of the wavelength converter showed a 3-dB bandwidth of 13 GHz (Fig. 2). The voltage across the photodiode was swept for this measurement. There is a bandwidth improvement with voltage due to the depletion of the waveguide which decreases the capacitance. Characterization of discrete 300 μm MZMs demonstrated a 3-dB bandwidth greater than 20 GHz when terminated in 25 Ω and a V-pi of 2.25 V from single-sided DC extinction measurements. The detectors require reverse bias voltages of -5 V to prevent trapping the photo-generated carriers in the quantum wells which would create space charge effects that degrade the device bandwidth. When operated at this bias point discrete 50 μm long

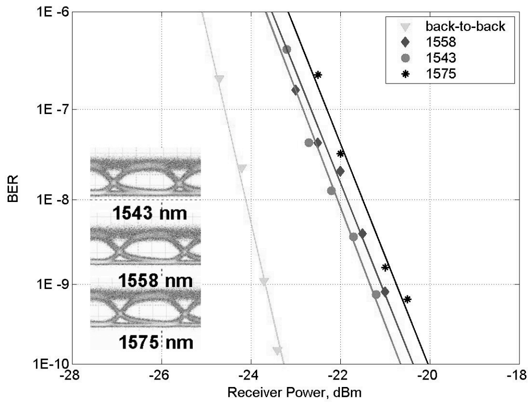

Fig. 3. BER measurements at 10 Gbps for wavelength conversion from 1548 nm to 1543 nm,1558 nm and 1575 nm.

photodetectors displayed no saturation characteristics for photocurrent levels as high as 40 mA and 3-dB bandwidths of 20 GHz when terminated in 25 Ω.

Bit-error-rate (BER) measurements at 10 Gbps were taken with a non-return-to-zero (NRZ) 2^{31}-1 pseudo-random bit stream (PRBS). The measurement setup consisted of a commercial transmitter which was amplified by an erbium-doped fiber amplifier (EDFA). The signal then passed through an optical filter and polarization controller before being fiber coupled into the device. The output of the wavelength converter was attenuated and then detected by a commercial lightwave receiver.

Error-free operation (BER of 1×10^{-9}) was demonstrated across the SGDBR tuning range with power penalties less than 3.5 dB (Fig. 3). Eye diagrams exhibited extinction ratios of 11.6 dB, 11.3 dB and 11.5 dB for conversion from 1548 nm to 1543 nm, 1558 nm and 1575 nm respectively. The device achieved facet-to-facet unity gain with input and output powers of 0.5 mW. The bias conditions for these measurements were as follows: SGDBR gain: 95 mA, transmitter SOA: 120 mA, straight receiver SOA: 180 mA, flared SOA: 250 mA, Mach-Zehnder: -1 V, photodiode: -5 V with 22 mA of photocurrent.

Conclusion: We have demonstrated a 10 Gbps monolithic SAM Mach-Zehnder wavelength converter. The device consists of a widely tunable laser, a series-push-pull MZM and a high saturation power receiver. The simple biasing configuration requires no external bias tees due to the on-chip resistor and capacitor. Error-free operation at 10 Gbps using NRZ data was achieved across the 32 nm tuning range of the integrated tunable laser with power penalties less then 3.5 dB and unity gain.

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