Monolithically Integrated Mach–Zehnder Interferometer Wavelength Converter and Widely Tunable Laser in InP

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***Abstract*—The first monolithically integrated widely tunable wavelength converter, consisting of a sampled-grating distributed-Bragg-reflector laser (SGDBR) and an SOA-based Mach–Zehnder interferometer, is reported. The integration process requires only a single regrowth step. Static extinction ratios (electrical/optical) better than 18 dB and 13 dB, respectively, were measured over a 22-nm wavelength tuning range. Digital wavelength conversion at bit rate of 2.5 Gb/s was demonstrated to be error free, with 2.6-dB power penalty.**

***Index Terms*—Mach–Zehnder interferometer, photonic integrated circuits, tunable laser, wavelength conversion, wavelength converter.**

I. Introduction

THE MONOLITHIC integration of complex functions onto a single chip is a critical step for the future deployment of optical networks. The tunable all-optical wavelength converter is a crucial component for WDM optical switches and add/drop multiplexers and to date has not been realized on a single chip. Tunable all-optical wavelength converters allow data to be transferred from an input wavelength to a tunable output wavelength without passing the signal through electronics. The semiconductor optical amplifier Mach–Zehnder interferometer (SOA-MZI) wavelength converter is an important class of integrated wavelength converters that work for both RZ and NRZ data formats while also acting as a 2R signal regenerator due to their nonlinear transfer function. InP integration of SOA-MZIs has been reported [1]–[3] and an SOA-MZI was integrated with a nontunable DFB laser but with severe performance tradeoffs due to reflections from the MZI back to the laser [4].

To the best of our knowledge, a monolithically integrated tunable laser and wavelength converter has never been reported. We also report regenerative, error free operation at 2.5 Gb/s. Chip-scale integration reduces the coupling loss between laser and converter as well as improves the converter noise figure, conversion efficiency and size/complexity/cost of the entire component. For wide, on-chip wavelength tunability, the sampled-grating distributed Bragg reflector (SGDBR) laser is well suited for integration with other components due to its lithographically defined mirrors that enable lasing without a facet reflection[5]. Since the laser itself consists of a combination of active and passive waveguides, additional elements can be integrated on the same chip without increasing the level of complexity of the fabrication process. The fabrication platform used in this work, offset quantum wells, represents a versatile integration platform that enables abrupt transition between active and passive regions on chip with very low reflections at the interfaces, which are some of the critical requirements for high-density PICs technologies. Also, a single epitaxial overgrowth of p-InP is required to fabricate the devices, which makes this platform simple and robust. Integration of tunable lasers with other elements has been reported, for example the SGDBR laser with an SOA [6] and Mach–Zehnder modulator [7].

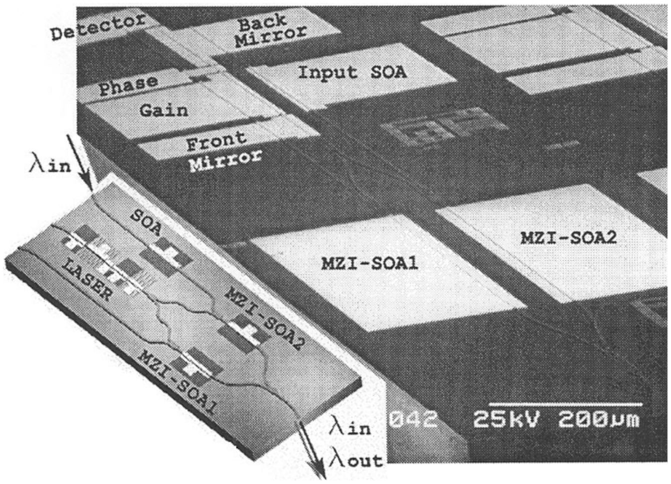

Fig. 1. Electron micrograph and schematic of the device.

II. Device Design and Fabrication

The device consists of an InP SGDBR laser integrated with a MZI (Fig. 1). The laser is 1.5 mm long and has five sections: front mirror, gain section, phase section, back mirror and back facet detector. The back facet detector has been monolithically integrated for measurement of power, and to decrease the requirements of the backside antireflective coating.

The interferometer branches are defined by two S-bends and 1-mm-long SOAs (Fig. 1). The laser and the interferometer are

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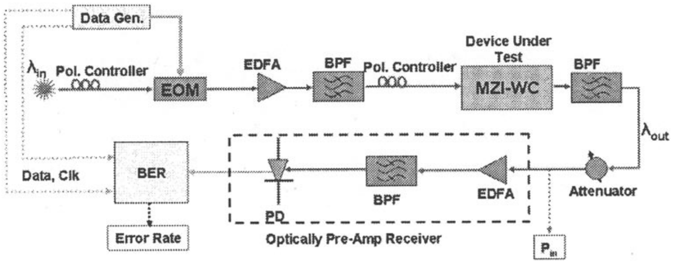

Fig. 2. Schematic of the test setup.

connected via a multimode interference (MMI) splitter and the total waveguide separation in the interferometer is 70 μm. The input signal is coupled onto the chip through a tapered input waveguide, and then amplified by a 800-μm-long input semiconductor optical amplifier. The same MMI splitter/combiner design is used to connect the data input waveguide with one of the interferometer's SOAs, as well as to combine the light from the two branches at the interferometer output. The total device length is 4.8 mm.

Fabrication using the offset quantum-well integration platform is performed by selective removal of the active regions in the passive sections of the device (using wet chemical etching) followed by grating formation and a single epitaxial regrowth. The epitaxial structure and the process are similar to [6]. There are no additional processing steps required to fabricate this device beyond the SGDBR fabrication process.

III. Experimental Results

For the experimental demonstration, the device was placed on a gold plated copper stage and cooled to 17 °C using a thermoelectric cooler. Light was coupled to and out of the device using conical-tipped lensed-fibers mounted on piezo-controlled translational stages. The device has curved, tapered waveguides at both input and output. This improves the coupling to the device; we estimated approximately 4 dB of coupling loss to the waveguides on chip. The input signal was generated using a tunable laser source and modulated using a lithium–niobate electrooptic modulator, as shown in Fig. 2. Polarization controllers were used at both the input to the modulator and wavelength converter since the device is polarization sensitive. For static measurements, the output of the device was optically filtered and input to an optical power meter. The data was generated using a BERT with NRZ $2^{31}-1$ PRBS data at 2.5 Gb/s. The converted output wavelength was filtered using a 1.2 nm thin-film tunable filter and detected with a pre-amplified receiver.

Overlapped optical spectra of the on-chip laser over its 22 nm tuning range are shown in Fig. 3. These spectra were taken through the back facet of the device. The front and rear mirrors of the laser consist of periodically sampled DBR gratings to form a comb-like reflectivity spectrum [5]. Since the sampling periods of the mirrors differ, they have different peak reflectivity spacing, so that only one set of mirror reflectivity peaks is aligned within the desired tuning range. By differentially tuning the front and back mirrors a small amount, adjacent reflectivity peaks can be aligned, and the laser will operate at this new wavelength [5].

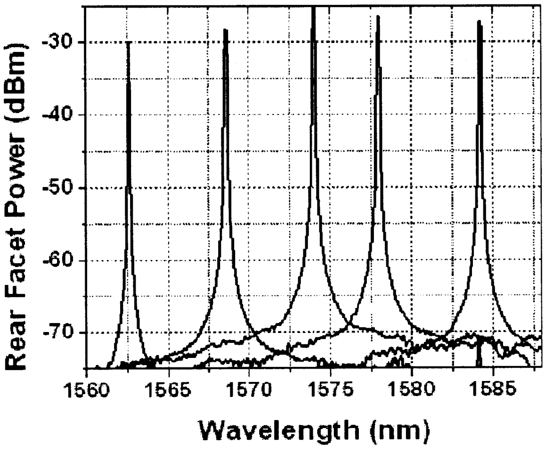

Fig. 3. Overlapped optical spectra of the on-chip tunable laser.

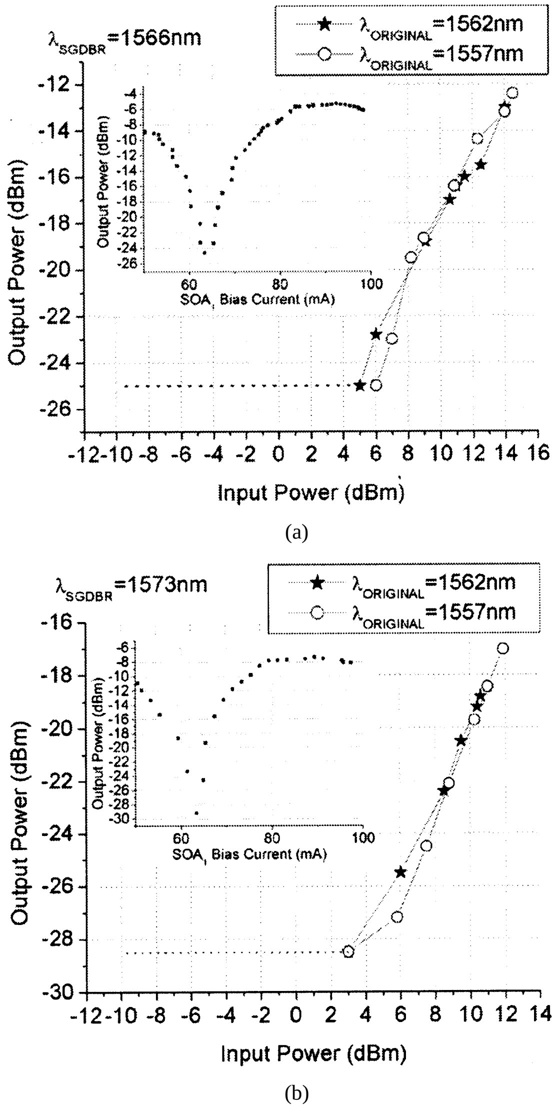

Fig. 4. Static electrical and optical control of the interferometer.

The output of the interferometer can be modulated by adjusting the bias of the SOA in one branch of the interferometer. Representative electrically controlled optical transfer functions are shown in the inserts of Fig. 4(a) and (b) for two

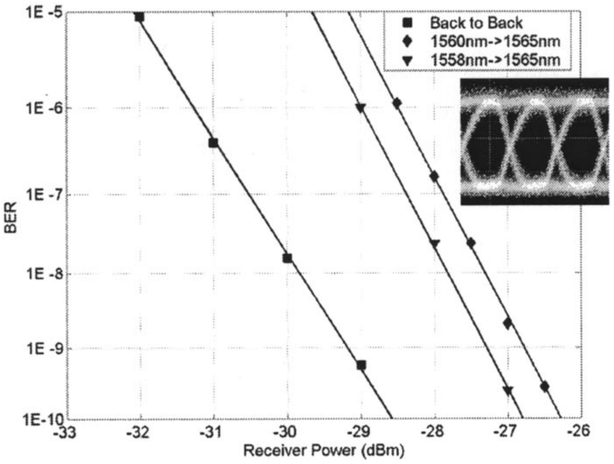

Fig. 5. BER curves and eye diagram of the converted signal.

different input wavelengths converted to two different output wavelengths (set by the on-chip laser). The output extinction measured was better than 18 dB over 22 nm range.

The optically controlled dc optical transfer characteristics depend on the bias currents of the SOAs in the branches of the interferometer, as well as the length of the SOAs. Typical measured results are shown in Fig. 4(a) and (b) for SGDBR wavelength set at 1566 and 1573 nm, respectively. Each measured transfer function is plotted for two different input signal wavelengths (1562 and 1557 nm, respectively). For these curves, the operating point is at the notch of the electrical transfer function [63 mA in Fig. 4(a) and (b)] in order for optical modulation in the noninverting regime. Optical extinction ratios were measured to be better than 13 dB over the same wavelength range. Due to the coupling and passive loss in the waveguides, we required around 12 dBm of input power to achieve a maximum phase shift in the MZI.

Measured BER results and a converted eye diagram at 2.5 Gb/s are shown in Fig. 5. The wavelength conversion was performed from two different input wavelengths, using PRBS $2^{31}-1$ input data. We believe that the reduction in slope between back-to-back and wavelength converted BER measurements can be attributed to the regenerative properties of the wavelength converter, and we are currently investigating this issue further. The power penalty for bit-error rate of 10^{-9} was measured to be 2.6 dB. Wavelength conversion is error-free, with no error floors. The peak of the gain curve for our SOAs is around 1570 nm, therefore, we notice a decrease in the conversion efficiency at 1558 nm (relative to 1560 nm), which results in an increased power penalty of 0.5 dB for that case.

IV. CONCLUSION

We have demonstrated, to the best of our knowledge, the first InP monolithically integrated tunable laser and MZI wavelength converter. The device was fabricated using a simple offset quantum-well technology with a single epitaxial regrowth.

We measured a static electrical extinction ratio better than 18 dB over a 22-nm tuning range. The static optical extinction ratio was measured to be better than 13 dB over the same wavelength range.

Error-free digital wavelength conversion at 2.5 Gb/s was demonstrated with error free operation and a power penalty of 2.6 dB for two different input wavelengths converted to one output wavelength.

The speed of wavelength conversion is controlled by the SOA gain and carrier dynamics. By further optimizing our integration platform, we believe that it would be possible to increase the bit rate of wavelength conversion to at least 10 GB/s.

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REFERENCES

[1] X. Pan, J. M. Wiesenfeld, J. S. Perino, T. L. Koch, G. Raybon, U. Koren, M. Chien, M. Young, B. I. Miller, and C. A. Burrus, “Dynamic operation of a three-port, integrated Mach–Zehnder wavelength converter,” *IEEE Photon. Technol. Lett.*, vol. 7, pp. 995–997, Sept. 1995.

[2] W. Idler, K. Daub, G. Laube, M. Schilling, P. Wiedemann, K. Dutting, M. Klenk, E. Lach, and K. Wunstel, “10 Gb/s wavelength conversion with integrated multiquantum-well 3-port Mach–Zehnder interferometer,” *IEEE Photon. Technol. Lett.*., vol. 8, pp. 1163–1165, Sept. 1996.

[3] C. Janz, F. Poingt, F. Pommereau, W. Grieshaber, F. Gaborit, D. Leclerc, I. Guillemot, and M. Renaud, “New all active dual order mode (DOMO) Mach–Zehnder wavelength converter for 10 Gbit/s operation,” in *ECOC 99*, Nice, France.

[4] L. H. Spiekman, U. Koren, M. D. Chien, B. I. Miller, J. M. Wiesenfeld, and J. S. Perino, “All-optical Mach–Zehnder wavelength converter with monolithically integrated DFB probe source,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 1349–1351, Dec. 1997.

[5] V. Jayaraman, Z. Chuang, and L. Coldren, “Theory, design, and performance of extended tuning range semiconductor lasers with sampled gratings,” *IEEE J. Quantum Electron*, vol. 29, pp. 1824–1834, June 1993.

[6] B. Mason, J. S. Barton, G. A. Fish, L. A. Coldren, and S. P. Denbaars, “Design of sampled grating DBR lasers with integrated semiconductor optical amplifiers,” *IEEE Photon. Technol. Lett.*, vol. 12, pp. 762–764, July 2000.

[7] J. S. Barton, E. J. Skogen, M. L. Mašanović, S. P.Steven P. DenBaars, and L. A.Larry A. Coldren, “Monolithic integration of Mach–Zehnder modulators with Sampled Grating Distributed Bragg Reflector lasers,” in *Proc. IPR 2002 Conf.*, vol. 14, Vancouver, Canada, 2002, pp. 1249–1251.