First Demonstration of both Analog and Digital Wavelength Conversion using a Monolithically-Integrated InP Widely Tunable All-Optical Wavelength Converter (TAO-WC)

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Abstract: The first demonstration of both analog and digital wavelength conversion using an InP monolithically-integrated widely-tunable wavelength converter is reported. The SFDR was measured to be better than 82.7 dB-Hz$^{2/3}$ and a BER of better than 10^{-9} at 2.5Gbps over a wide wavelength range (50nm input, 22nm output) with a power penalty of 2.1 dB acheived

Keywords: Wavelength conversion, spurious-free dynamic range, analog systems, tunable wavelength converter, photonic integrated circuits.

1. Introduction

Monolithically-integrated tunable all-optical wavelength converters (TAO-WC) are key components for WDM optical switches, add/drop multiplexers and for deployment of all optical networks. TAO-WCs allow data to be transferred from an input wavelength to a tunable output wavelength without passing the signal through electronics [1,2]. Applications such as large sensor networks require switching and transmission technologies that support both analog and digital signals. An InP TAO-WC based on a SOA-MZI structure has been reported for digital transmission [1,2]. This structure and other non-integrated converters have been shown to perform 2R signal regeneration for digital signals [4,5,6]. For wavelength conversion of analog signals, the performance of a nonlinear optical fiber AOWC without integrated tunable sources has been reported [3].

In this paper we describe the first demonstration of a semiconductor based chip-scale TAO-WC capable of supporting both analog and digital signals and characterize both its analog and digital performance. The converter is based on a monolithically integrated Sampled-Grating Distributed Bragg reflector laser (SGDBR) and an SOA-based Mach-Zehnder interferometer [1,2].

2. TAO-WC Design and Operation

The TAO-WC consists of an InP SGDBR laser integrated with a SOA-MZI (Fig. 1) [1]. The interferometer branches are defined by two S-bends and 1mm long SOAs. The laser and the interferometer are connected via a multimode interference (MMI) splitter. The input signal is coupled onto the chip through a tapered, angled input waveguide, and amplified by an input SOA.

The total device length is 4.8mm. This device is fabricated using our offset quantum well integration platform, and the process requires a single MOCVD regrowth of InP. Details about the device design and fabrication process can be found in [1,2,7].

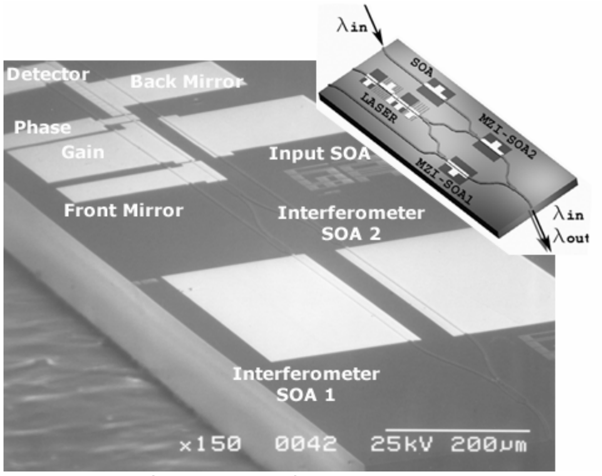

Figure 1 - SEM image of the wavelength converter

The front and rear mirrors of the laser consist of periodically sampled DBR gratings to form a comb-like reflectivity spectrum [7]. Differential tuning of the front and

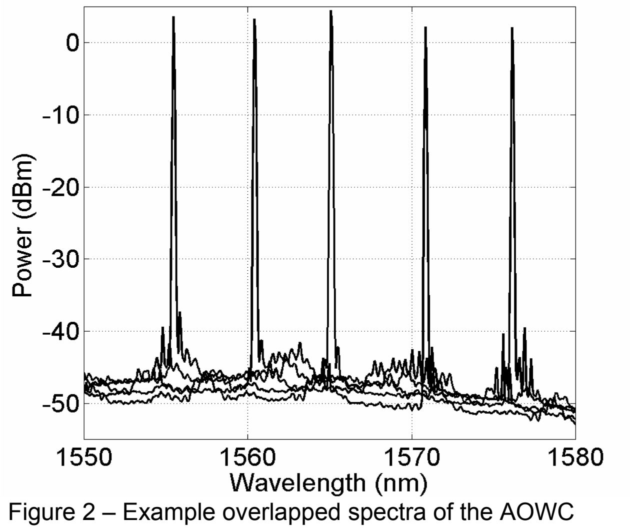

Figure 2 – Example overlapped spectra of the AOWC

back mirrors enables adjacent reflectivity peaks to be aligned, and the laser will operate at this wavelength [7]. An example overlapped optical spectra for 5 wavelengths at the TAO-WC output obtained by tuning the integrated laser are shown in Figure 2. The total output tuning range is 22 nm. These spectra were taken through the front facet with SOAs in the interferometer arms biased to 200 mA.

The optical signal to be converted is injected into the

common branch of the interferometer. Amplitude modulation at the input changes the phase difference between the two arms and drives the interferometer through its optical input/output transfer function. The shape and qualities of this transfer function depends on the bias currents of the SOAs in the branches of the interferometer, SGDBR output power, as well as the lengths of the SOAs. The input signal wavelength range of operation is from 1535nm to 1585nm. This range is governed by the SOA gain spectrum.
A typical measured optically-controlled static transfer function for inverting and non-inverting mode of operation is shown in Figure 3. Depending on the bias condition of the converter, it can be run in either a linear analog mode or a saturating digital mode. For digital operation a static extinction of 15dB or more is obtained over the entire range of input and output wavelengths. The quality of analog operation must be carefully measured using harmonic distortion techniques and is a focus of this paper.

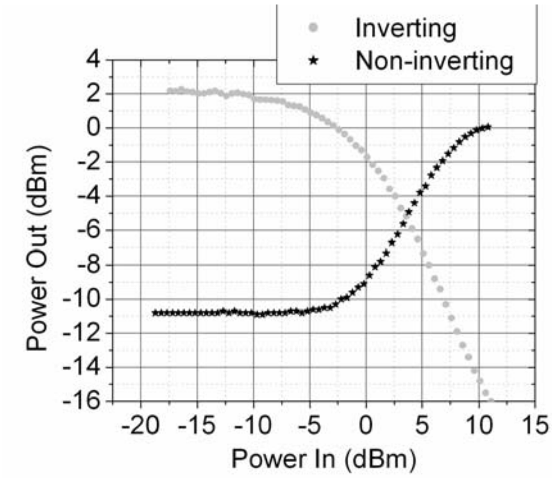

Figure 3 – Typical optical static transfer functions

The TAO-WC was soldered and wirebonded onto an aluminum nitride submount, and placed on a stage which was cooled to 17°C using a thermo-electric cooler. Light was coupled to and out of the device using conical-tipped lensed-fibers mounted on piezo-controlled translational stages. The estimated coupling loss to the waveguides on chip is 4dB per fiber. The input signal was generated using a tunable laser source and modulated using a lithium-niobate electro-optic modulator. Polarization controllers were used at both the input to the modulator and wavelength converter since the device is polarization sensitive.

3. Analog Performance

In order to assess the analog performance of wavelength conversion the spurious-free dynamic range (SFDR) was measured as a function of input and output wavelength. A two-tone technique was implemented by directly modulating a widely tunable integrated EML with two RF tones at frequencies of 1.00GHz and 1.0001GHz. The average output power from the EML was 10mW and was coupled into the wavelength converter. The bias point of the wavelength converter was set to minimize the 3rd order IMD terms. The particular TAO-WC device used in these measurements had an average output power of -5dBm at the optimum set point.
After wavelength conversion, the signal was optically filtered, detected by a low noise photo diode, electrically amplified and the resulting signal and 3rd order IMD terms measured using an electrical spectrum analyzer.
A typical SFDR measurement result is shown in Figure 4, for conversion from 1561nm to 1550nm. The results for 2 input – 2 output wavelengths combinations are summarized in table 1.

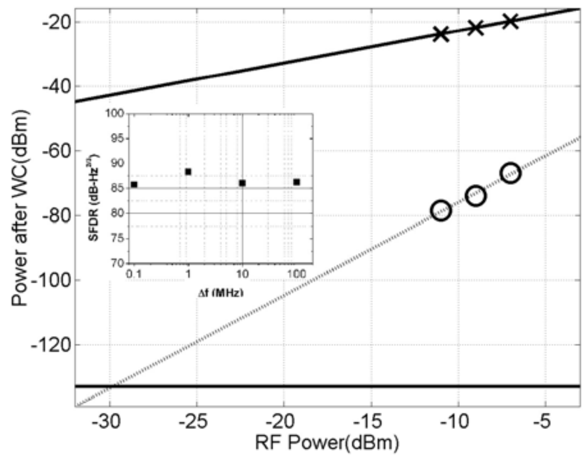

Figure 4 – SFDR and Δf dependence (inset)

SFDR [dB-Hz$^{2/3}$]		λ_{out} [nm]	
		1550	1564.2
λ_{in} [nm]	1538	86.7	85.8
	1561	84.3	82.7

Table 1 – Summary of SFDR results

Similar SFDR measurements were taken over a range of RF tone spacing to characterize Δf dependence. Results of these measurements are shown in the inset of Figure 4. The SFDR remained greater than 82.7 dB-Hz$^{2/3}$. There are several limiting factors in device performance – coupled output power and non-saturated SOAs being the most important ones. These SFDR measurements were limited by a noise floor of -130dBm/Hz at the receiver.

4. Digital Performance

Optical NRZ data was amplified through an EDFA to constant power levels of approximately 10dBm before being coupled into the device. For L-band operation, an additional spool of 60m of Er-doped fiber was used in line with the C-band EDFA. The data was generated using a BERT with NRZ 2^{31}-1 PRBS data at 2.5Gbps. The converted output wavelength was filtered using a 1.2nm thin-film tunable filter and detected with a PIN receiver. Average input power of -3dBm was measured at the receiver.

Typical BER measurements are shown in Figure 5. Error free wavelength conversion was achieved over wide wavelength range (50nm input, 22nm output), with maximum power penalty of 2.1dB. Figure 6 shows the interferometer transfer characteristics measured for 0.5mW going into the device, and for 10mW of external light going into the common branch of the Mach-Zehnder

Interferometer (MZI). The power level of the SGDBR laser at the input branches of the MZI is around 1.5mW per branch. This power level will not drive the

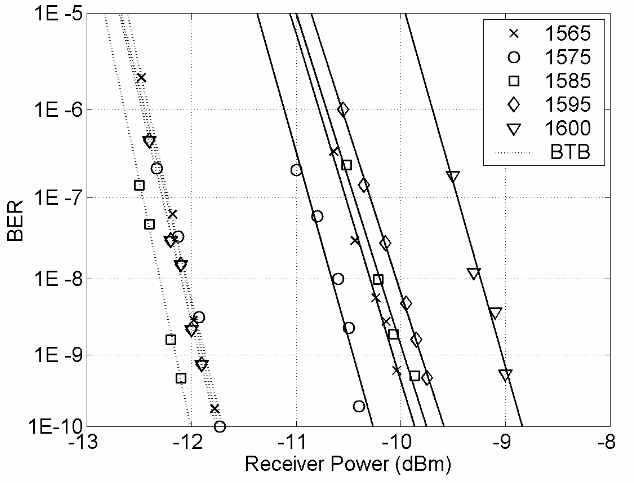

Figure 5 - BER curves for 5 input wavelengths

SOAs in the MZI into complete saturation, leading to lower efficiency of cross-phase modulation. Because of the interdependence of phase and gain change in the SOAs, extinction ration in the inverting mode of operation will always be higher and ultimately lead to better performance of the device in this mode. This is illustrated in Fig. 6. Nevertheless, we were able to obtain error-free wavelength conversion in both modes of operation. A power penalty increase is observed at higher wavelengths due to higher ASE noise levels as the laser is tuned

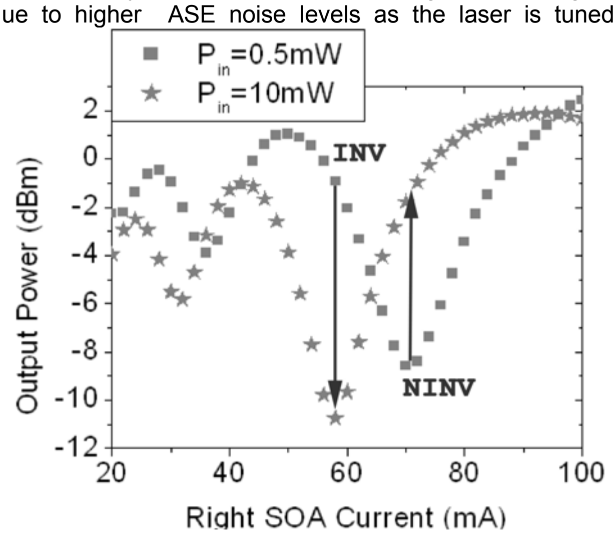

Figure 6 - Electrical transfer functions vs input signal power

away from the SOA gain peak. The carrier dynamics in the SOAs is influenced, among other things, by bias current and optical power level in the SOA. Therefore, an optimized SGDBR design with higher output power and wider tuning range would further improve the device performance.

5. Conclusion

We have demonstrated for the first time both analog and digital all-optical wavelength conversion using a monolithically-integrated InP widely-tunable AOWC. We measured the SFDR to be better than 82.7 dB-Hz$^{2/3}$ and digital BER at 2.5Gbps over wide wavelength range (50nm input, 22nm output) to be better than 10^{-9} with maximum power penalty of 2.1 dB. With improvements in coupling and on-chip losses as well as optimized SOA design, we believe these figures of merit can be improved and make this a feasible technology for networks that must support switching and transmission for both analog an digital signals.

6. Aknowledgments

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7. References

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8. Glossary

TAO-WC: Tunable all-optical wavelength converter

SOA: Semiconductor optical amplifier

SFDR: Spurious-free dynamic range

BER: Bit error rate

IMD: Intermodulation distortion

MOCVD: Metal organic chemical vapour deposition

SGDBR: Sampled-grating distributed Bragg reflector

MMI: Multimode interference

MZI: Mach-Zehnder interferometer

ASE: Amplified spontaneous emission

NRZ: Non return to zero