Measurements and Analysis of a Monolithical Integrated All-Optical Wavelength Converter and a 4-Channel Digitally Tunable Laser

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We have realized the monolithical integration of an all-optical Mach-Zehnder interferometric wavelength converter and a 4-channel digitally-tunable laser as CW source. The InP-based device operates in the 1.5 μm window and shows excellent static extinction ratios of over 20 dB in the converted wavelength and an extinction ratio improvement of 13 dB. BER measurements of the converter in combination with an external CW-source showed a 1 dB improvement in the received power sensitivity at 2.5 Gbit/s. In addition we present the analysis of the dynamic behavior of the integrated device. It explains how the performance beyond 0.5 Gbit/s can be improved.

Introduction

Wavelength converters are key components in advanced WDM networks. Most wavelength converters reported so far require a separate tunable laser for the wavelength to which the signal wavelength has to be converted. Integration of the converter with the laser will reduce the number of components and fiber connections. Owen et al [1] reported 2.5 Gbit/s conversion in a 4-channel digitally tunable laser that provided wavelength conversion using cross gain modulation in a common Semiconductor Optical Amplifier (SOA). Integration of a more sophisticated All-Optical Wavelength Converter (AOWC) of the Mach-Zehnder Interferometer (MZI) type [2] with a fixed DFB-laser was reported by Spiekman et al [3]. It operated up to 2.5 Gbit/s and was speed limited due to feedback that cause instabilities in the DFB laser. In this paper we report results on a MZI converter that has been monolithically integrated with a digitally tunable laser based on a PHASAR multiplexer. An advantage of a PHASAR-based laser over a DFB laser is the large tuning range and filtering of the ASE noise coming from the converter. The chip requires only two fiber connections, which makes it, in principle, suitable for standard SOA packaging.

Design and Fabrication

The circuit scheme of the integrated device and the measurement set-up are shown in Fig. 1. At the left side of the chip the digitally tunable laser can be seen. It consist of a 4-channel PHASAR-(de)multiplexer integrated with four 1000-μm-long SOAs and a

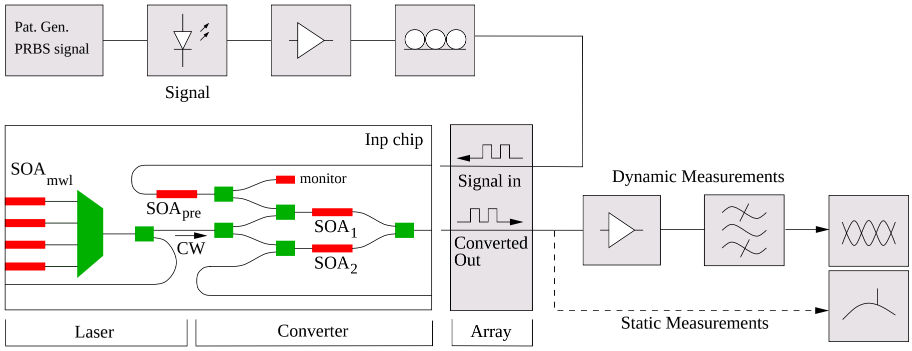
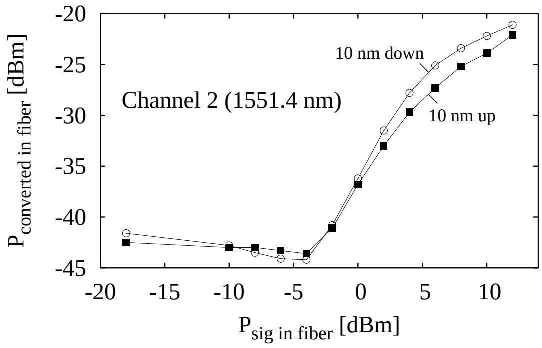


Figure 1: *Measurement set-up and circuit scheme of the MZI wavelength converter with a 4-channel PHASAR multi wavelength laser.*

3 dB MMI coupler for coupling power out of the cavity. The laser has a 400 GHz channel spacing and a Free Spectral Range (FSR) of 19.2 nm [4]. The laser facet was HR coated. The right side of the chip in Fig. 1 shows the MZI wavelength converter with 500 μm long SOAs. It can be driven with the data signal via both the lower and the upper MZI-branch. The upper input port (”Signal in”) contains a pre-amplifier SOA and a monitor-photodiode (a reversely biased SOA). The monitor reading can be used for feedback in order to increase the input dynamic range of the chip. An anti-reflection (AR) coating was applied to the converter outputs. The chip has been fabricated with the MOVPE-based three-step epitaxy process for butt-joint integration of passive and active (SOA-based) circuits that is similar to the process that we reported earlier [5]. The layer stack is suitable for integration of fast optical switches and modulators that were reported by us previously [6]. Dimensions of the chip are 3.5×7.5 mm^2.

Results on the Separate Converter and Laser

The converter and the laser were characterized separately first. The MZI-wavelength conversion (co-propagating, non-inverting) performance was measured using an external laser as CW source [7]. The converter showed a static extinction ratio (ER) of over 30 dB and an optical signal to noise ratio (OSNR) of over 40 dB. BER measurements at 2.5 Gbit/s demonstrated regeneration with 1 dB improvement in the receiver sensitivity. No error floor was detected. BER measurements at higher bit rates have not yet been performed, but very clear eyes and a fast responds at 2.5 Gbit/s demonstrates the converters potential for operation at higher bitrates.
In measurements on the tunable laser, we observed that all laser channels lased in the central order of the PHASAR around 1555 nm as designed, due to the chirping [8]. Side mode suppression ratios (SMSR) of all laser channels are more than 25 dB. The threshold current of the HR-coated laser was around 90 mA for all channels; Note that the MMI in the laser cavity is responsible for about 8 dB round trip loss: 3 dB intrinsic loss in both directions of propagation and two times 1 dB excess loss.



channel	10 nm up		10 nm down	
	ER	ER_{im}	ER	ER_{im}
1	12.7	1.5	2.2	0
2	23.1	11.7	21.3	8.2
3	20.8	9.8	20.3	8.1
4	15.7	2.4	23.1	12.9

Figure 2: *Wavelength conversion (non-inverting)* **(left)** *to channel 2 of the MWL from 10 nm shorter and longer signal wavelengths. SOA injection currents were:* $I_1 = 100$ *mA,* $I_2 = 175$ *mA,* $I_{pre} = 75$ *mA.* **(right)** *Output ERs (ER) and best case ER improvements* (ER_{im}) *of both 10 nm up conversion and 10 nm down conversion.*

Results on the Integrated Converter and Laser

The static conversion properties of the integrated converter and laser was measured with the set up that is shown in Fig. 1. Fiber-chip coupling was performed with an array of tapered lensed fibers. The CW probe was generated on-chip by biasing one of the SOAs in the MWL at $I_{MWL} = 105$ mA, which generated approximately -10 dBm of optical power just before injection into the converter. The signal wavelength was generated by an external tunable laser and subsequently amplified, polarization controlled and fed into the chip (Fig. 1). The output was detected using an optical spectrum analyzer. We found excellent ERs in the converted probe of over 20 dB as can be seen in Fig. 2.
The dynamic performance of the integrated device was measured using a directly modulated DFB laser. The output was amplified, filtered and detected by an optical oscilloscope. Good eye openings at lower bit-rates were observed, but the eyes closed at bit rates beyond 0.5 Gbit/s (Fig. 3). Rise and fall times in the eyes at 1.5 Gbit/s are about 3 times slower than those at 0.5 Gbit/s. The degrading rise and fall times are explained by mode instabilities in the laser due to residual reflections from the AR-coated facet at the converter output. These reflections are amplified in the converter SOA twice before they re-enter the laser. As a result, the laser phase locks to both arms that are connected to the MMI behind the PHASAR, and the laser starts to behave like an asymmetric Y-laser (upper part Fig. 4). That this is indeed the case can be seen from the multiple wavelength peaks in the laser spectra with a 0.27 nm spacing (Fig. 4). The phase of the reflected signal from the converter arm is depending on the phase transmission in the converter SOAs, which changes continuously in dynamic operation. This results in instabilities in the laser that are typically in the order of the round trip time in the cavity: $\tau_{rt} = 2n_g L/c = 2$ ns or 0.5 Gbit/s. Here L denotes the laser cavity length, n_g the group index and c the speed of light. This explains the degraded dynamics beyond 0.5 Gbit/s. Several measures can be taken to keep the reflections from the converter from destabilizing the laser. For instance, by making angled output waveguides or by increasing the power in the passive arm of the Y-laser by inserting another SOA.

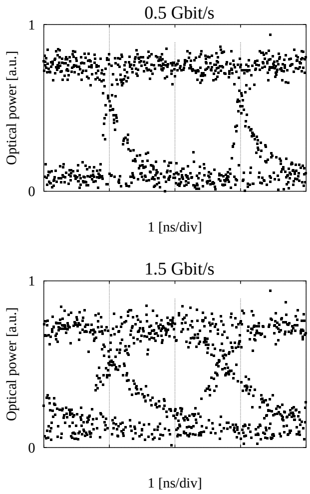


Figure 3: *Eye patterns of the integrated device.*

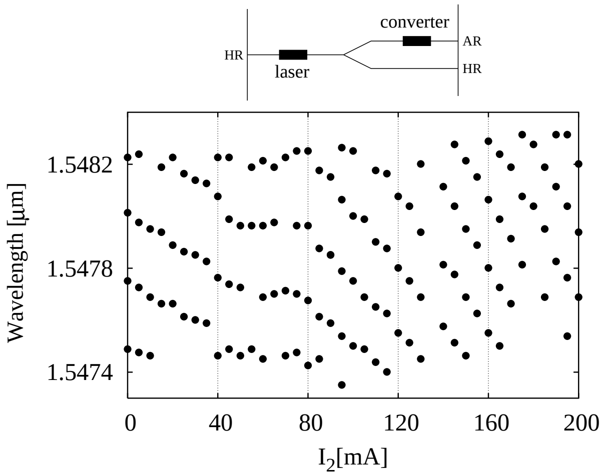


Figure 4: *Position of wavelength peaks of the laser as function of the current in converter SOA_2.*

Conclusions

We have realized the monolithic integration of an all-optical Mach-Zehnder interferometric wavelength converter and a digitally tunable laser. The converted wavelength showed ERs of over 20 dB and ER improvement compared with the input of over 12 dB. All MWL channels lased at the designed wavelengths and showed a SMSR over 25 dB. Dynamic measurements revealed instabilities in the laser, which were found to originate from residual facet reflectivity from the AR-coated converter facet. Reflections can be reduced in a new design.

Acknowledgements

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