Experimental and theoretical investigation of electro-optic and all-optical implementations of wavelength converting 2R-regenerators

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WB2 Fig. 3. BER for conversion of a 1552-nm PRBS of length $2^{23} - 1$ to 1560 nm at 2.5 Gbit/s. The penalty of 2 dB is caused by a combination of extinction ratio degradation (to 11 dB) and intersymbol interference effects. No error floors are observed.

Dynamic operation of the device is demonstrated by means of the bit-error-rate measurements presented in Fig. 3, which show wavelength conversion at 2.5 Gbit/s from 1552–1560 nm. Although the lossy waveguides limit the speed and thus add to the conversion penalty, a clean and open eye was observed for the converted signal, and error-free wavelength conversion has been obtained.

In summary, a Mach-Zehnder wavelength converter with variable input and output wavelengths has been presented. The integrated signal and probe pre-amplifiers potentially reduce input power requirements. Around 25-dB extinction ratio has been demonstrated, as well as operation at 2.5 Gbit/s.

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WB3

9:00am

Experimental and theoretical investigation of electro-optic and all-optical implementations of wavelength converting 2R-regenerators

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Wavelength-division multiplexing (WDM) networks will require bit-rate transparent wavelength converters/adapters to interface fiber links

utilizing different sets of wavelengths. Additionally, suppression of noise at the interfaces will be needed. Hence, wavelength converters with a 2R functionality (re-amplification and re-shaping) are highly desired.

In this paper we investigate and compare the regenerative capability of electro-optic (E/O) wavelength converters based on electrically controlled external Mach-Zehnder (MZ) modulators and all-optical (A/O) wavelength converters based on all-optically controlled external MZ-modulators. The latter incorporates semiconductor optical amplifiers (SOAs) as optically controlled phase shifters.¹ Experiments demonstrate a 5–6 dB noise suppression capability for both the electro-optic and the all-optical implementation of the wavelength-converting regenerators. The performance can be further improved by cascading two converters resulting in 8-dB noise suppression. This is considered a realistic approach for the compact all-optical converter. The experiments are supported by detailed modeling.

The two wavelength converters are shown schematically in Fig. 1. The E/O-converter consists of a detector/front-end, an electronic amplification stage followed by an external MZ modulator used to modulate a cw-source. V_{pp} of the modulator is 4 Volt and the 3-dB modulation bandwidth of the entire converter is 4 GHz. The all-optical converter is a polarization-insensitive interferometric wavelength converter where SOAs are monolithically integrated into an interferometric structure.²

Due to the sinusoidal transfer function of both converters a noise reduction capability is obtained when they are deployed between noise

Electro-optical converter

All-optical converter

WB3 Fig. 1. Schematic of an electro-optic and all-optical converter.

WB3 Fig. 2. Measured and calculated (lines) penalty (@BER = 10^{-9}) vs. input power of the EDFA with EDFA alone and EDFA followed by regenerative converters. E/O: electro-optical, A/O: all-optical.

sources,^{3,4} e.g., erbium-doped fiber amplifiers (EDFAs) adding amplified spontaneous emission (ASE) or receivers adding thermal noise. The noise reduction by the E/O-converter is demonstrated in Fig. 2, where the penalty as function of the input power to an EDFA is shown for the case with and without a converter following the EDFA. In this experiment, a 2.5-Gbit/s signal is converted from 1555 to 1557 nm. As seen, the E/O-converter allows 5 dB lower input power to the EDFA (@ 1 dB penalty). Replacing the E/O-converter with an all-optical converter results in a further improvement of 1 dB due to a steeper transfer function of the latter.

The transfer function of a wavelength-converting regenerator can be made steeper by cascading two converters, and thereby improving the reshaping. Figure 2 also gives the experimental results when the EDFA is succeeded by two all-optical converters. In this case an almost 8 dB lower input power to the EDFA is possible @ 1 dB penalty. The measured distributions for marks and spaces after the EDFA and after the two converters are shown in Fig. 3. A clear redistribution of the noise after the converters is seen and when thermal noise is added in the receiver this redistribution results in a lower penalty. A model that takes the redistribution into account has been developed and the results (also given in Fig. 2) show very good agreement with experiments.

In summary, we have demonstrated and compared the reshaping capability of E/O and all optical wavelength converters. Besides being compact and featuring low power consumption, the all-optical converter have the best regenerative capability. Finally, we have demonstrated that the noise reduction can be further improved by cascading converters, which is considered to be practical only for the all-optical implementation due to its compactness.

WB3 Fig. 3. Measured distributions for marks and spaces after the EDFA and after the EDFA followed by one and two A/O-converters, respectively. Input power to the EDFA correspond to 1 dB penalty with the EDFA alone (-31 dBm).

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WB4

9:15am

Efficient wavelength conversion based on difference frequency mixing in LiNbO₃ waveguides with integrated coupling structures

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Wavelength conversion is a useful function required for wavelength-division multiplexed (WDM) networks.¹ Among numerous wavelength-conversion technologies, difference-frequency mixing (DFM) is attractive because it offers strict transparency to amplitude, frequency, and phase information, excess-noise-free and chirp-reversed signal output, extremely high input dynamic range and a bit rate limited only by the extremely wide parametric conversion bandwidth.² DFM-based devices can also convert multiple wavelengths simultaneously. Wavelength conversion using DFM in AlGaAs³ and annealed proton exchanged LiNbO₃⁴ waveguides has been demonstrated. One practical issue is the low efficiency, 17-dB conversion loss with a 90-nm conversion bandwidth for 65 mW of pump power.³ Another critical problem with guided-wave DFM is the launching of short-wavelength (typically half the signal wavelength) pump light into the fundamental mode of a multimoded (at the pump wavelength) waveguide required for confining a single mode of the signal. In this paper, we address the mode launching problem using integrated mode coupling structures, resulting in mixing efficiency, normalized to the pump power, of 259%/W and wavelength conversion loss of 7 dB.

Our integrated waveguide structure is shown in Fig. 1. Pump light is coupled into a single-mode waveguide (mode filter). A subsequent adiabatic taper⁵ permits efficient coupling of the pump radiation into the fundamental mode of the highly multimoded (at the pump wavelength) waveguide, which is optimized for wavelength conversion. The signal is routed into the wavelength conversion region with a directional coupler. Both the mode filter and the taper are implemented using periodically

WB4 Fig. 1. Schematic of integrated waveguide structure. A mode filter and an adiabatic taper, both implemented with periodically segmented waveguides, couple the pump into the fundamental mode of a waveguide, which is multimoded at the pump wavelength and was designed for single-mode operation of the signal wavelength and for efficient wavelength conversion. A directional coupler routes the signal into the single-moded wavelength conversion region.

WB4 Fig. 2. Measured optical spectrum on a logarithmic scale for a signal at 1539 nm and its converted output, which has been shifted 58 nm to 1597 nm. The central peak at 1568 nm is the second-order spectrometer response of the pump wavelength of 784 nm. The wavelength conversion loss is 7 dB, corresponding to a internal mixing efficiency of ~259%/W. (After correction for waveguide propagation losses and Fresnel losses.)

segmented waveguides, allowing for independent optimization of each section.

The samples were fabricated on a 3-inch-diameter wafer of LiNbO₃ periodically poled with a 14.5-μm period. Waveguides were formed by proton exchange to an exchange depth of 0.55 μm, followed by annealing at 333°C for nine hours. The integrated device consists of a 2.5-mm-long mode filter (with segmentation duty cycle of 35%), a 5-mm-long periodically-segmented taper, a 1.5-mm-long directional coupler, and a 30-mm-long wavelength converter. The theoretical internal conversion efficiency of this device, neglecting propagation losses, is ~800%/W, while characterization by second-harmonic generation (SHG) yielded 270%/W and a bandwidth 1.3 times the theoretical calculation, indicating nonideal waveguide uniformity.

Static wavelength conversion tests were performed using a cw Ti-sapphire laser at 784 nm for the pump and a cw tunable erbium-doped fiber laser for the signal. During the measurement, the sample was maintained at 60–90°C. Figure 2 shows a measured optical spectrum for a signal at 1539 nm and its converted output, which has been shifted by 58 nm to 1597 nm. With 67 mW of pump power exiting the waveguide, we observed a stable wavelength conversion loss of 7 dB, corresponding to a mixing efficiency of 259%/W (assuming 0.4-dB/cm propagation

WB4 Fig. 3. Conversion loss curve as a function of input wavelength. The closed circles are the measured results, the solid line is the theoretical calculation. The measured conversion bandwidth is wider than the theoretical calculation due to nonideal waveguide uniformity.