Efficient Wide-Band and Tunable Midspan Spectral Inverter Using Cascaded Nonlinearities in $LiNbO_3$ Waveguides

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***Abstract*—We report on efficient (–7-dB fiber-to-fiber), wide-band (over 70 nm), tunable, and excess-noise-free mid-span spectral inverters based on cascaded second-order nonlinearities in periodically poled $LiNbO_3$ waveguides. We demonstrate their performance in a 4 × 10 Gb/s transmission over 150 km of standard single-mode fiber.**

***Index Terms*—Dispersion compensation, optical fiber communications, phase conjugation, time-division multiplexing, wavelength conversion, wavelength-division multiplexing.**

I. Introduction

In HIGH-SPEED transmission systems, chromatic dispersion is one of the main limiting factors for system performance. For example, at 40 Gb/s, the maximum transmission distance is about 4 km over standard single-mode fiber (SMF, $D = 17$ ps/nm·km). In order to increase transmission distances, some technique for dispersion compensation is needed. Some of the most popular ones are the use of dispersion compensating fibers [1], chirped fiber gratings [2], [3] and midspan spectral inversion [4]–[7], etc.). In the first two, the dispersion of one fiber span is negated by another span of fiber with opposite dispersion or by an optical element that provides the opposite chirp. In the last one, optical phase conjugation is used at the middle point of the total fiber length.

Among different dispersion compensation techniques, midspan spectral inversion (MSSI) has some interesting properties. MSSI does not require accurate knowledge of the dispersion of each fiber section, as long as one has access to the middle point of the total fiber span and the two resulting halves produce similar accumulated dispersion. MSSI has a natural appeal at high bit rates, since it is usually implemented using an ultrafast optical nonlinearity [typically four-wave mixing (FWM)]. Previous implementations of MSSI were based on FWM in semiconductor optical amplifiers (SOA's) [5] or optical fibers [6], [7]. Those approaches suffer from difficulties, namely amplified spontaneous emission (ASE) noise in the SOA and low conversion efficiency in optical fibers. In this paper, we report on the implementation of MSSI using a cascaded second-order nonlinearity ($\chi^{(2)}$) in a highly efficient nonlinear material, namely periodically poled $LiNbO_3$ (PPLN) waveguides [8].

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II. Principle of Operation

In cascaded-$\chi^{(2)}$ mixing [8]–[10], a strong pump at ω_p is launched simultaneously with signals at ω_s. Both pump and signals lie in the 1.5 µm band. The pump is frequency doubled to $2\omega_p$ by second-harmonic generation inside the waveguide and simultaneously difference frequency mixed with the signals in order to generate shifted outputs $\omega_{\rm out} = 2\omega_p - \omega_s$. The converted electric field is the complex conjugate of the input signal electric field, a feature that is used to invert the chirp of the input signals. This phase conjugation is nondegenerate and thus the dispersion cancellation will not be exact for large wavelength shifts. For shifts of up to tens of nanometers, this effect can be neglected to first. Phase matching can be assured by the proper choice of the periodic poling period of the $LiNbO_3$ crystal. From an external point of view, this process mimics FWM in other nonlinear materials but it has a large effective $\chi^{(3)}$ [the effective $\chi^{(3)}$ of a 5-cm PPLN waveguide is equivalent to that of more than a few km of dispersion-shifted fiber]. This device has all the advantages of FWM in passive media, such as instantaneous response and very low excess noise. In addition, it does not suffer from stimulated brillouin scattering (SBS) as do fibers (a process that makes launching of a high power pump difficult), and zero dispersion wavelength fluctuation is inherently irrelevant.

III. Experiments and Results

$_{00}$We fabricated the MSSI waveguides by annealed proton exchange in periodically poled $LiNbO_3$. The waveguide used in this experiment is 5 cm long, has a QPM period of 14.7 µm, waveguide width of 12 µm, proton exchange depth of 0.7 µm, and was annealed for 26 h at 325 °C. The above parameters allow phase matching at room temperature between the TM_{00} mode of the pump at 1536 nm and the TM mode of its second harmonic wave at 768 nm. The phase matching wavelength can be temperature tuned by ~0.1 nm/°C. We operated the device at ~120 °C to avoid photorefractive effects. The devices are fiber pigtailed and show a typical fiber-to-fiber insertion loss of ~3.5 dB.

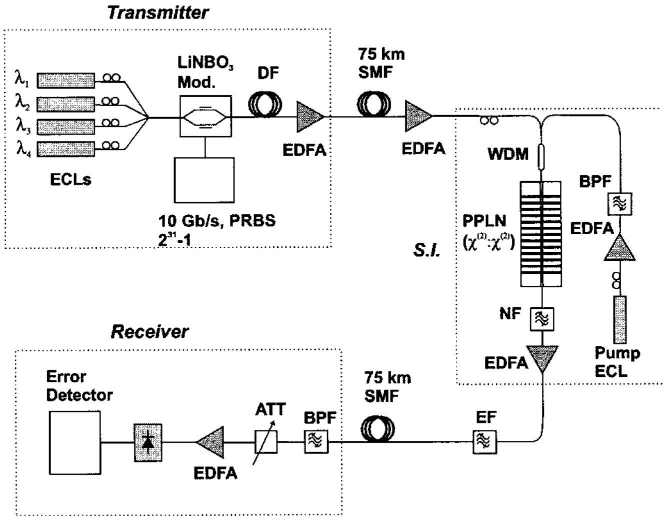

Fig. 1. Experimental setup used to demonstrate the performance of the PPLN waveguide spectral inverter. NF: Notch filter. EF: Equalizing filter (>5-nm bandwidth). DF: Decorrelation fiber.

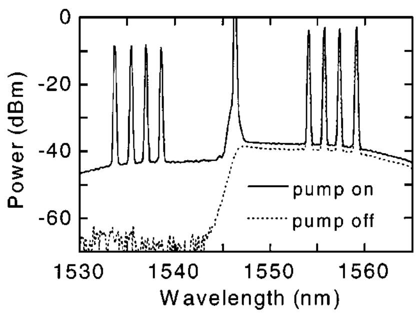

Fig. 2. Spectrum of converted and original channels at the output of the MSSI device with and without pump. The original channels lie on the right-hand side of the pump peak. Pump power ~200 mW.

The experimental setup used for the MSSI experiment is shown in Fig. 1. Four WDM channels at 200-GHz spacing are provided by four tunable lasers. They are modulated in a $LiNbO_3$ modulator at 10 Gb/s with a $2^{31}-1$ pseudorandom binary sequence. The combined channels are then decorrelated in 9 km of SMF, preamplified to a level of ~0 dBm per channel in an erbium-doped fiber amplifier (EDFA) and launched into 75 km of standard SMF. After the fiber, another EDFA is used to restore the power level to ~0 dBm per channel. The pump laser for the spectral inverter is an external-cavity laser (ECL) amplified by an EDFA to a level of 100–200 mW and filtered through a bandpass filter in order to suppress its ASE. The spectral inverter module can be made more compact by using a high power DFB laser as a pump source. The pump and signals are combined in a WDM coupler and launched copolarized into the $LiNbO_3$ waveguide. After the waveguide, the spectrally inverted channels are isolated with a broad bandpass filter (>5 nm), amplified and launched into a second 75-km spool of SMF. Finally, the individual channels are filtered in a narrow bandpass filter (0.8 nm) and detected in an optically preamplified receiver.

A typical spectrum of the original and spectrally inverted channels is shown in Fig. 2. The internal (external,

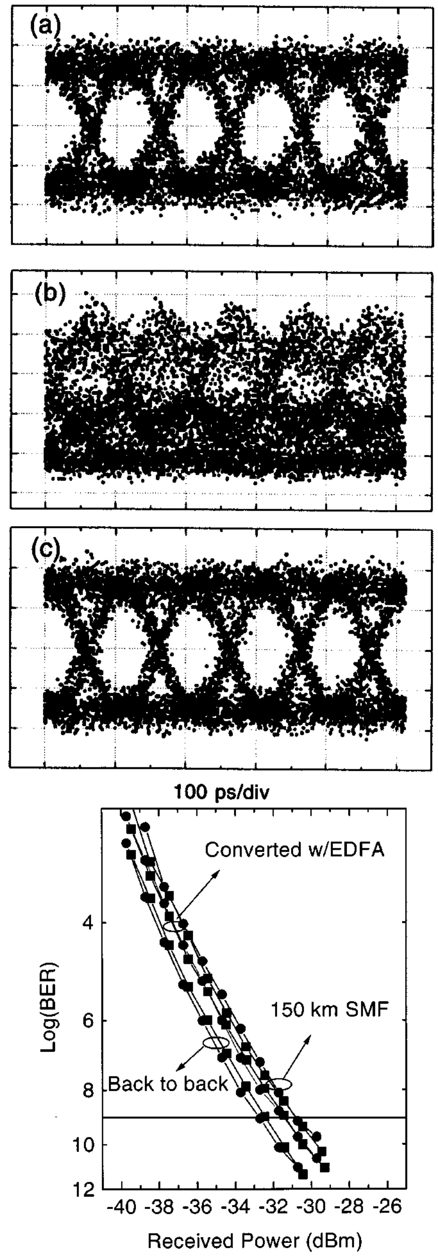

Fig. 3. (I) Eye diagrams for one of the channels. (a) Back to back. (b) Unconverted after 150 km of SMF. (c) After MSSI by our device and 150 km of SMF. (II) BER curves for the two center channels back to back; after conversion in the MSSI device and amplification by one EDFA (no fiber), and after MSSI and transmission through the full 150 km of SMF.

fiber-to-fiber) conversion efficiency for a pump power of ~100 mW is –10 dB (–13.5 dB). When the pump power is raised to ~200 mW, the efficiency rises to –5 dB (–7 dB). The power level difference between the solid line and dashed line in the right side is the signal parametric gain (1.5–2 dB) for this conversion process, indicating that the parametric wavelength conversion is very efficient. We believe that this is the most efficient waveguide spectral inverter presented to date using a *CW pump*. Unity efficiency can be achieved with improved processing and waveguide optimization. Also note that the signal-to-noise ratio (SNR) of the converted channels is about the same as that of the input channels. The intrinsic SNR degradation of this device is limited only by quantum noise; in

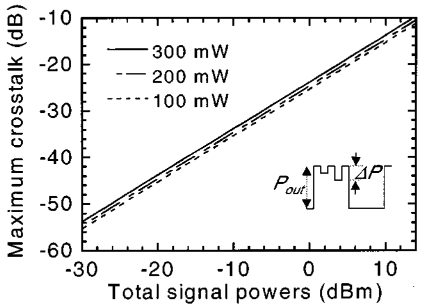

Fig. 4. Calculated maximum crosstalk versus total input signal powers for pump powers of 100, 200, and 300 mW. The maximum crosstalk is defined by $10\ \log(\Delta P/P_{\rm out})$.

practice the SNR is dominated by the stability and noise of the amplified pump laser.

We measured the bandwidth of the wavelength converters by tuning the input signal wavelength with the pump fixed. The 3-dB conversion bandwidth is ~70 nm. The linearity of this device in the signal power is similar to that of the previously reported cascaded $\chi^{(2)}$ wavelength converter [8], showing constant conversion efficiencies for a range of signal powers spanning more than 50 dB.

The eye diagrams for one of the channels, back to back, and after transmission through 150 km of standard SMF, are shown in Fig. 3(I). Similar traces are obtained for all four channels. Fig. 3(Ia) shows the eye diagram for the unconverted signal channel after 150-km fiber, with the impairment of dispersion clearly visible. When the filter is tuned to its spectrally inverted counterpart, the eye appears completely open showing the effectiveness of MSSI in counteracting the fiber dispersion. The bit error rate curves for the two inner channels are shown in Fig. 3(II). These channels represent the worst case in our four-channel transmission system as they maximize any penalty due to nonlinearities or crosstalk. There is a penalty of ~1 dB in a back-to-back measurement of the spectrally inverted channels. This is possibly due to the use of a high-power EDFA in the pump path and to some additional noise added by the EDFA present immediately after the waveguide device (noise figure of 8). The additional penalty after transmission over 150 km is only ~0.5 dB, showing the effectiveness of dispersion compensation by our MSSI arrangement.

IV. Discussion

One of the main concerns for the multiple channel operation of the current device is the crosstalk between the different channels. Although this device can be characterized by an effective $\chi^{(3)}$, it is inherently based on $\chi^{(2)}$ so FWM crosstalk will not happen. The crosstalk in this cascaded $\chi^{(2)}$-based spectral inverter is incoherent and mainly due to pump depletion, which is less than –22 dB for an input power per channel of less than 0 dBm in this experiment. Fig. 4 shows the calculated maximum crosstalk (or gain compression) versus total input signal power for pump powers of 100, 200, and 300 mW, assuming 100 channels. the calculation assumes a 5-cm-long device, normalized efficiency of 50%/W·cm^2, waveguide propagation losses of 0.35 (0.7) dB/cm at 1550 (780) nm, and fiber-waveguide coupling loss of 1 dB. The (fiber-to-fiber) conversion efficiency is ~–13, –7, and –4 dB for pump powers of 100, 200, and 300 mW, respectively.

V. Conclusion

We have shown a new type of midspan spectral inverter based on cascaded second-order nonlinearities in PPLN waveguides. The device has an external (fiber-to-fiber) efficiency of –7 dB, 70 nm of conversion bandwidth, has negligible excess noise and can be temperature tuned by more than 8 nm. We successfully used this device in dispersion compensation of 4×10 Gb/s channels transmitted through 150 km of SMF. Currently, the device is sensitive to the input polarization. However, this can be resolved based on polarization diversity [5], [6]. The availability of a compact and integrable spectral inverter with almost unity efficiency will lead to the revision of the role of spectral inversion in optical networking.

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