Simultaneous all-optical inverted and non-inverted wavelength conversion using a single-stage fiber optical parametric amplifier

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Abstract: We have demonstrated, for the first time to our knowledge, simultaneous all-optical inverted and non-inverted wavelength conversion by using a single-stage two-pump fiber optical parametric amplifier with extinction ratio between 7 and 14dB over 24nm.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.2330) Fiber optics communications; (190.4370) Nonlinear optics, fibers

1. Introduction

Wavelength conversion is an important function for advanced optical networks to be flexible and efficient in terms of wavelength channel usage. All-optical wavelength converters have been realized by using cross-gain modulation (XGM), cross-phase modulation (XPM), cross-polarization modulation (XPolM) or four-wave mixing (FWM) in semiconductor amplifiers (SOAs), [1]–[3] or by using nonlinear effects, such as XPM or parametric process, in optical fibers [4]–[6]. Inverted and non-inverted wavelength conversions have been achieved by XPolM and by interferometric wavelength converters based on XPM [1]–[3]. In XGM techniques, an inverted replica of the input signal is obtained at the target wavelength due to SOA gain saturation. The realization of non-inverted wavelength conversion by XGM can be performed by cascading two wavelength converter stages [7]. The wavelength converters using XGM or XPM in SOAs are very efficient, but their speed is essentially limited by the carrier lifetime. So, careful designs in SOA structure or configuration are required to use them at more than 10 Gb/s [3]. The wavelength converters based on fiber nonlinear effects, though less efficient, have almost no speed limitation because nonlinear effects are very fast phenomena; they are promising for future transport networks with extremely high-speed signals.

A novel scheme of wavelength conversion that utilizes XGM in a one-pump fiber optical parametric amplifier (OPA) has been proposed [8]. OPAs are natural wavelength converters since signal amplification in OPA is always accompanied by an idler whose frequency ω_i is $2\omega_p - \omega_s$, where ω_p, ω_s are the pump and signal frequencies [9]–[10]. It provides advanced features, namely: (1) the converted wavelength can be tunable regardless of ω_p or ω_s, and (2) the linewidth of the converted signal is not broadened by the phase modulation which is often applied to the pump to suppress stimulated Brillouin scattering (SBS). However, the idler spectrum itself is still broadened.

Therefore, we propose another scheme here, using a two-pump OPA, which has the potential to avoid this problem [11]. Furthermore, we will be able to obtain both inverted and non-inverted all-optical wavelength conversion, with single-stage two-pump OPA configuration simpler than the two cascaded SOAs proposed before [7]. We confirmed experimentally that the signal at 1554 nm could be flexibly converted to the C band (1532–1556 nm) with an extinction ratio (ER) between 7 dB and 14 dB.

2. Experiment

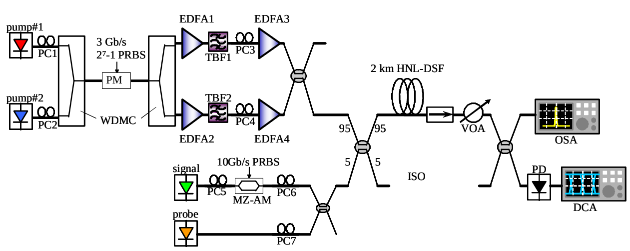

Fig. 1. 2-pump OPA configuration. TLS: Tunable laser source. PC: Polarization controller. PM: Phase modulator. VOA: variable optical attenuator. OSA: Optical spectrum analyzer. ISO: Isolator.

The mechanism of XGM-based wavelength conversion in an OPA is similar to that in an SOA. An amplitude-modulated signal is fed into the OPA, and modulates the OPA gain through pump depletion. Efficient gain modulation can be expected, since large pump depletion can be achieved in OPA [12]. The probe, simultaneously fed into the OPA, is modulated by the gain modulation, and becomes a converted signal whose amplitude modulation is inverted with respect to the original signal.

The experimental configuration is shown in Fig. 1. The parametric gain medium consists of 2 km of HNL-DSF (OFS Ltd.) with a nominal zero-dispersion wavelength λ_0 of 1543.4 nm, dispersion slope of 0.019 ps/nm^{2}km and nonlinear coefficient γ of 10.4 W^{-1}km^{-1}. Two tunable laser sources, TLS1 and TLS2, set at 1529.45 nm and 1556.8 nm, respectively, serve as the pump sources. The pump wavelengths are selected to flatten the ASE gain spectrum, with the average wavelength approximately equal to λ_0. The CW pumps are combined by a WDM coupler (WDMC) and then phase-modulated (PM) by a 3 Gb/s 2^7-1 pseudo-random bit sequence (PRBS) to suppress SBS. The polarization controllers, PC1 and PC2, align the pump SOP's with PM, which helps to reduce the insertion loss. The two pumps are then separated by another WDMC, amplified by two C-band EDFA's (EDFA1 & 2), and followed by tunable bandpass filters (TBF) with 0.84 nm (TBF1) and 1.96 nm (TBF2) bandwidth, respectively. Each pump is amplified by second EDFA with a maximum output power of 21 dBm. Polarization controllers (PC3 and PC4) are used to ensure that the two pumps incident on the HNL-DSF are parallel. This is achieved by maximizing the ASE noise level at the optical spectrum analyzer (OSA). The signal is amplitude-modulated by a 10 Gb/s PRBS. The input signal power is 1.9 dBm while the probe power is -4.9 dBm. The signal gain is about 14 dB, so that the signal output power is about 16 dBm. The signal and probe are combined with the output of EDFA3 & 4 by a 95/5 coupler. The polarization states of pump, signal and probe were optimized with polarization controllers (PC6 and PC7) to maximize the wavelength conversion efficiency. Both PC6 and PC7 contain a half-wave plate (HWP) and a quarter-wave plate (QWP). The power of each pump at the input of HNL-DSF is about 20 dBm. The output spectrum of HNL-DSF, followed by an isolator which prevents any reflection from the variable optical attenuator (VOA), is observed at the OSA. The modulated probe signal derived from the OPA was filtered by a tunable bandpass filter whose full width at half maximum was 0.22 nm. It was connected to either a digital communication analyzer (DCA) for eye diagram measurement, or to a pin-PD receiver for bit error rate (BER) measurement.

3. Results and Discussion

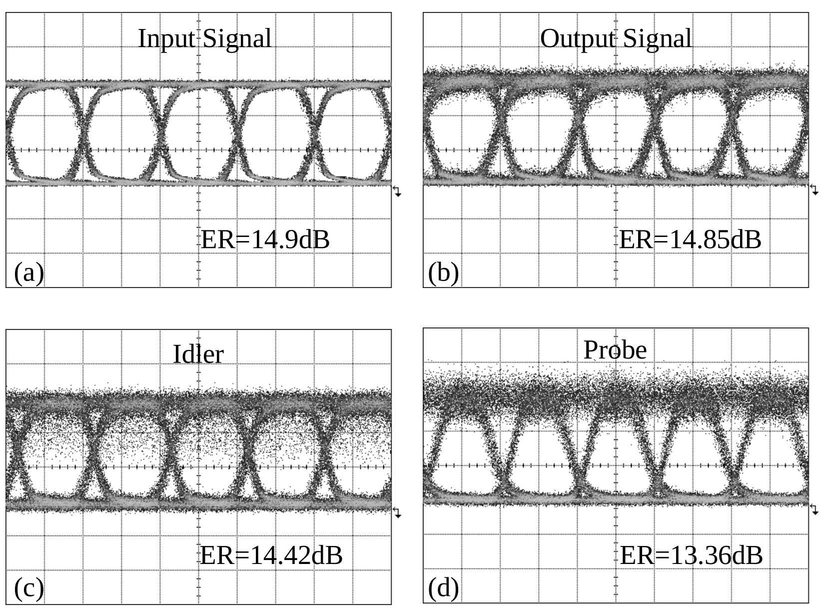

Fig. 2 Eye diagrams for (a) input signal; (b) output signal; (c) idler; (d) probe with the corresponding extinction ratios of (a) 14.9 dB; (b) 14.85 dB; (c) 14.42 dB; (d) 13.36 dB

Fig. 2 show the eye diagrams of (a) input signal, (b) output signal, (c) idler, (d) probe and their corresponding extinction ratios. Both output signal and idler show very good ERs; while the ER of the probe shows only a slight degradation. The ER is defined as the ratio between space and mark powers, and it was measured using the eye diagram. The eye opening of the idler is reduced compared to that of the output signal, which may due to ineffective SBS suppression.

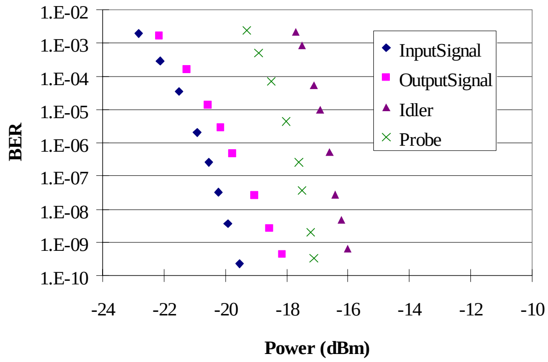

Fig. 3 Bit error rate of converted signals.

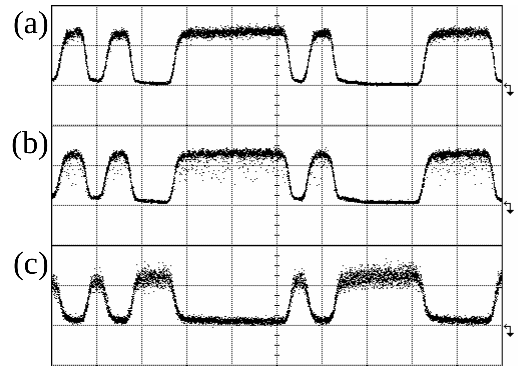

Fig. 4. Measured waveforms: (a) output signal; (b) idler; (c) probe.

We measured the BER performance to evaluate the quality of the converted signals, as shown in Fig. 3. The measurement was performed for the input signal, output signal (with wavelength at 1550.9 nm), idler and probe wavelength at 1551.65 nm, and 1535.8 nm, respectively. The results show that the probe was successfully modulated with a power penalty of less than 3 dB compared with the output signal.

The extinction ratio was especially high around 1536.6 nm and 1551.7 nm, which are near the edge of OPA gain band. The high extinction ratio is due not only to gain compression, but also to OPA gain spectrum changes. When the “1” state of the signal is fed into the OPA, the gain is compressed via pump depletion. Since the gain bandwidth is proportional to γP_p, it shrinks for large pump depletion, which results in a high extinction ratio near the two edges of the gain bandwidth.

Fig. 4 shows the timing diagrams for the output signal, idler and probe, which precisely demonstrate the inverted and non-inverted nature of the waveforms. While both signal and idler are in phase with each other, the probe is exactly inverted with the former. Note that it was not required to fine tune the time delay effect of the pump as in the two-cascaded-SOA device [7], because the inversion and non-inversion of the waveforms occurs inherently in this single-stage two-pump OPA configuration.

4. Conclusion

We have demonstrated, for the first time to our knowledge, simultaneous all-optical inverted and non-inverted wavelength conversion by using a single-stage two-pump fiber optical parametric amplifier with extinction ratio between 7 dB and 14 dB over a range of 24 nm.

References

1. T. Durhuus et al., “All-optical wavelength conversion by semiconductor optical amplifier,” *J. Lightwave Technol.*, **14**, pp. 942–954 (1996).
2. Y. Liu et al., “Wavelength conversion using nonlinear polarization rotation in a single semiconductor optical amplifier,” *IEEE Photon. Technol. Lett.*, **15**, pp. 90–92 (2003).
3. T. Fjelde et al., “Demonstration of 20 Gbit/s alloptical logic XOR in integrated SOA-based interferometric wavelength converter,” *Electron. Lett.*, **36**, pp. 1863–1864 (2000).
4. S.L. Danielsen et al., “Bit error rate assessment of 40 Gbit/s all-optical polarization independent wavelength converter”, *Electron. Lett.*, **32,** pp. 1688–1690 (1996).
5. J. Yu et al., “Broad-band and pulsewidth-maintained wavelength conversion based on a high-nonlinearity DSF nonlinear optical loop mirror”, *IEEE Photon. Technol. Lett.*, **13,** pp. 344–346 (2001).
6. K. Inoue et al., “Wavelength conversion experiments using fiber four-wave mixing”, *IEEE Photon. Technol. Lett.*, **4,** pp. 69–72 (1992).
7. A. Hamié et al., “All-optical inverted and noninverted wavelength conversion using two-cascaded semiconductor optical amplifiers,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 6, pp. 1229–31, Jun. 2005.
8. T. Sakamoto et al., “Tunable wavelength converter using cross-gain modulation in fiber optical parametric amplifier,” *OFC2002*, paper TuS4 (2002).
9. J. Hansryd et al., “Broad-band continuous-wave-pumped fiber optical parametric amplifier with 49-dB gain and wavelength conversion efficiency,” *IEEE Photon. Technol. Lett.*, **13,** pp. 194–196 (2001).
10. M.-C. Ho et al., “200-nm-bandwidth fiber optical amplifier combining parametric and Raman gain”, *J. Lightwave Technol.*, **19,** pp. 977–981 (2001).
11. K. K. Y. Wong et al., “Phase-Conjugate Pump Dithering for High-Quality Idler Generation in a Fiber Optical Parametric Amplifier,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 1, pp. 33–35, Jan. 2003.
12. M.E. Marhic et al., “92% pump depletion in a continuous-wave one-pump fiber optical parametric amplifier”, *Opt. Lett.*, **26,** pp. 620–622 (2001).
13. K. Inoue, “Noise transfer characteristics in wavelength conversion based on cross-gain saturation in a semiconductor optical amplifier”, *IEEE Photon. Technol. Lett.*, **8,** pp. 888–890 (1996).