Simultaneous All-Optical Inverted and Noninverted 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 noninverted wavelength conversion by using a single-stage two-pump fiber-optical parametric amplifier with an extinction ratio between 7 and 14 dB over 24 nm.**

***Index Terms*—Cross-gain modulation (XGM), four-wave mixing, optical amplifiers, optical fibers, optical transmission, parametric amplification.**

I. Introduction

WAVELENGTH conversion is an important function to ensure flexibility and efficiency, in terms of wavelength channel usage, in advanced optical networks. 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 in semiconductor optical amplifiers (SOAs), [1]–[3], or by using nonlinear effects, such as XPM or parametric process, in optical fibers [4]–[6]. Inverted and noninverted 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. On the other hand, noninverted wavelength conversion by XGM can be realized by cascading two wavelength converter stages [7]. The wavelength converters using XGM or XPM in SOAs are highly efficient, but their speed is essentially limited by the carrier lifetime. Subsequently, careful designs in SOA structure or configuration are required for a speed more than 10 Gb/s [3]. The wavelength converters based on fiber nonlinear effects, though less efficient, have almost no speed limitation as nonlinear effects are very fast phenomena, rendering them promising candidates 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]. They provide advanced features, namely 1) the converted wavelength is tunable regardless of ω_p or ω_s; 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.

In this letter, we propose another scheme, using a two-pump OPA (2P-OPA), which can potentially avoid this problem [11]. Furthermore, we are able to obtain both inverted and noninverted all-optical wavelength conversion, with single-stage 2P-OPA configuration simpler than the two cascaded SOAs proposed before [7]. Experiments have confirmed that the signal at 1554 nm could be flexibly converted to the C-band (1532–1556 nm) with an extinction ratio (ER) between 7 and 14 dB.

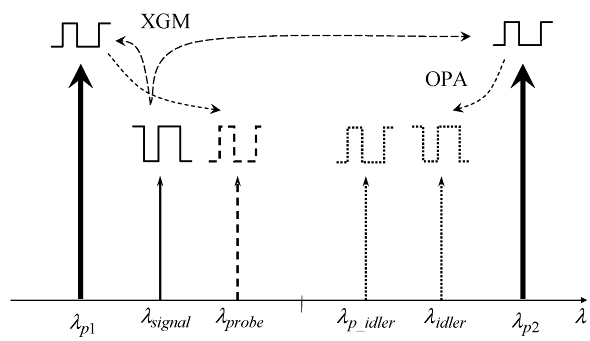

Fig. 1. Illustration of the inverted and noninverted wavelength conversion due to XGM effect in a 2P-OPA configuration. See the text for details.

II. Principles

The mechanism of XGM-based wavelength conversion in an OPA is similar to that in an SOA [7], except that only one-stage fiber OPA is required compared with the two-stage SOA configuration. XGM in a fiber OPA corresponds to the mechanism as shown in Fig. 1. An intensity-modulated (IM) signal ($\lambda_{\rm signal}$) is amplified by the parametric gain (with pump wavelengths at λ_{p1} and λ_{p2}). As it grows, it absorbs power from the pumps, while the total optical power remains constant. As a result, the pump power now has IM. Consider a probe ($\lambda_{\rm probe}$ in Fig. 1) without initial IM, traveling with pump and signal; it will exhibit different gains at different times, depending on whether it travels with a depleted part of the pump [12] or an undepleted one. The amplified probe will, therefore, exhibit IM, which is an exact

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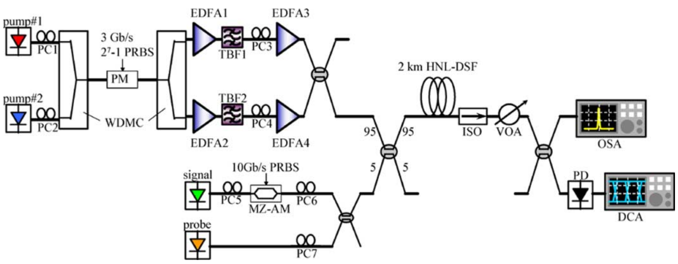

Fig. 2. 2P-OPA configuration. TLS: tunable laser source. PM: phase modulator. Refer to the text for details. (Color version available online at http://ieeexplore.ieee.org.)

inverted version of the input signal. Efficient gain modulation can be expected since large pump depletion is achieved in OPA. The probe, which is 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. Furthermore, there is another newly generated wavelength, idler (λ_{idler} as in Fig. 1), which is the noninverted version of the input signal, except that the wavelength has been converted. Therefore, a simultaneous all-optical inverted and noninverted wavelength conversion using a single-stage fiber OPA can be achieved. Note that there is another newly generated wavelength, λ_{p_idler}, which is the inverted version of the input signal (λ_{signal}), thereby broadening the range of possible output wavelengths.

III. Experiment

In order to verify our hypothesis in Section II, the experimental configuration as shown in Fig. 2 was implemented. The parametric gain medium consists of 2 km of highly nonlinear dispersion-shifted fiber (HNL-DSF) with a nominal zero-dispersion wavelength λ_0 of 1543.4 nm, dispersion slope of 0.019ps/nm^2 $\cdot$ km, and nonlinear coefficient γ of 10.4W^{-1} $\cdot$ km^{-1}. Two tunable laser sources, TLS1 and TLS2, set at 1529.45 and 1556.8 nm, respectively, serve as the pump sources. The pump wavelengths were selected to flatten the amplified spontaneous emission (ASE) gain spectrum, with the average wavelength approximately equal to λ_0. The continuous-wave pumps were combined by a wavelength-division-multiplexing coupler (WDMC) and then phase-modulated (PM) by a 3-Gb/s $2^7 - 1$ pseudorandom bit sequence (PRBS) to suppress SBS. The polarization controllers, PC1 and PC2, aligned the pump SOPs with PM, which helped to reduce the insertion loss. The two pumps were then separated by another WDMC, amplified by two C-band erbium-doped fiber amplifiers (EDFA1 and 2), and followed by tunable bandpass filters (TBFs) with 0.84- (TBF1) and 1.96-nm (TBF2) bandwidth, respectively. Each pump was amplified by a second EDFA with a maximum output power of 21 dBm. Polarization controllers, PC3 and PC4, were used to ensure that the two pumps incident on the HNL-DSF were parallel. This was achieved by maximizing the ASE noise level at the optical spectrum analyzer (OSA). The signal was amplitude-modulated by a 10-Gb/s PRBS. The input signal power was 1.9 dBm while the probe power was -4.9 dBm. The signal gain was about

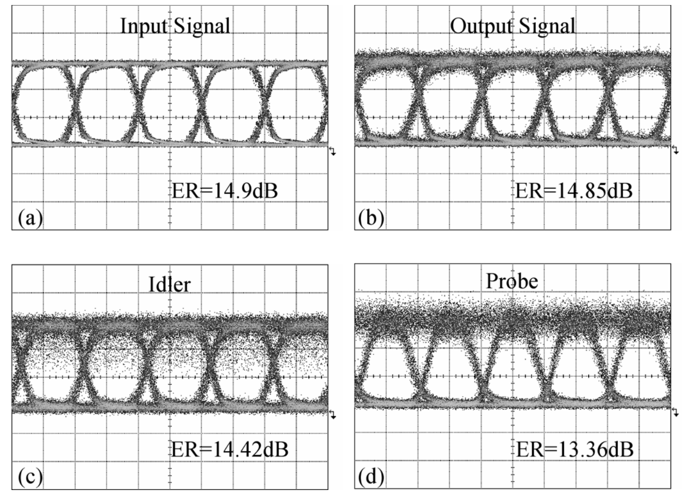

Fig. 3. Eye diagrams for (a) input signal, (b) output signal, (c) idler, and (d) probe with the corresponding extinction ratios (ER) of (a) 14.9, (b) 14.85, (c) 14.42, and (d) 13.36 dB.

14 dB and the signal output power was about 16 dBm. The signal and probe were first combined with a 50/50 coupler and then combined with the output of EDFA3 and 4 by a 95/5 coupler. The polarization states of signal and probe were tuned using polarization controllers, PC6 and PC7, respectively, to maximize the conversion efficiency and optimize the performance of the idler and probe. The power of each pump at the input of HNL-DSF was about 20 dBm. The output spectrum of HNL-DSF, followed by an isolator used to prevent any reflection from the variable optical attenuator, was 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 for eye diagram measurement, or to a pin-PD receiver for bit-error-rate (BER) measurement.

IV. Results and Discussion

Fig. 3 shows the eye diagrams of (a) input signal, (b) output signal, (c) idler, (d) probe and their corresponding ERs. Both output signal and idler exhibit very good ERs, while the ER of the probe shows only a slight degradation. The ER is defined as the ratio between mark and space powers, and was measured using the eye diagram. The eye opening of the idler was reduced compared to that of the output signal, which was possibly due to spectral broadening of in-phase pump dithering.

We measured the BER performance to evaluate the quality of the converted signals, as shown in Fig. 4. The measurement was performed for the input signal, output signal (with wavelength at 1550.9 nm), idler, and probe wavelength at 1535.8 and 1551.65 nm, respectively. The results show that the probe was successfully modulated with a power penalty of less than 1 dB compared with the output signal, while the idler was noninversely modulated with around 2-dB power penalty. The higher power penalty for the idler may be attributed to the degraded noise performance due to the XGM-modulated pump. Note that there is an extra 2-dB power penalty for the worst ER at 7 dB, as shown in Fig. 4.

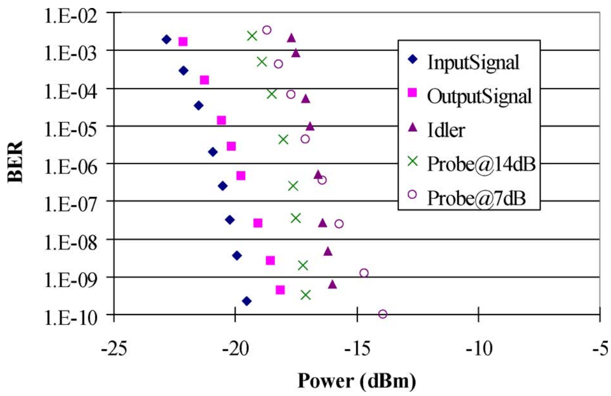

Fig. 4. BER of output signal, idler, and probe (at ER = 7 and 14 dB). (Color version available online at http://ieeexplore.ieee.org.)

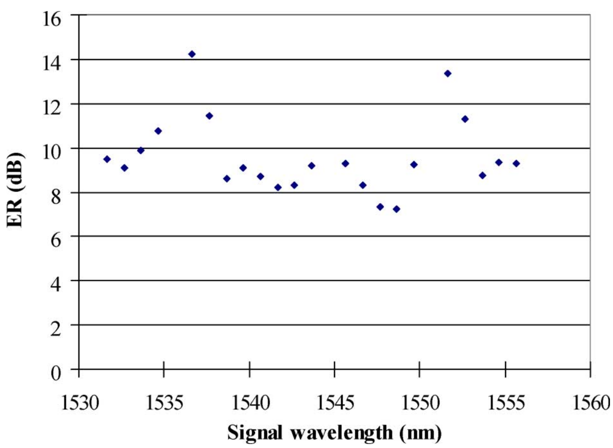

Fig. 5. ER of idler versus input signal wavelength.

As shown in Fig. 5, the ER of idler varied between 7 and 14 dB within the input tuning range of 24 nm, which also depicted the conversion bandwidth. The ER was especially high around 1536.6 and 1551.7 nm, which were near the edge of OPA gain band. The high ER is due not only to gain compression, but also to OPA gain spectrum changes. In fact, the conversion efficiency shows similar behavior. The efficiency was high around the probe wavelength due to the higher XGM effect. 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 [8], it shrinks for large pump depletion, which results in a high ER near the two edges of the gain bandwidth.

Fig. 6 shows the timing diagrams for the output signal, idler, and probe, which precisely demonstrate the inverted and noninverted 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 is unnecessary to fine tune the time delay effect of the pump as in the two-cascaded-SOA device [7] because the inversion and noninversion of the waveforms occur inherently in this single-stage 2P-OPA configuration.

V. Conclusion

We have demonstrated, for the first time to our knowledge, simultaneous all-optical inverted and noninverted wavelength conversion by using a single-stage two-pump fiber OPA with ER between 7 and 14 dB over a range of 24 nm. Experimental results have demonstrated another versatile solution of designing high-performance OPAs as photonics signal processor in next-generation optical networking systems.

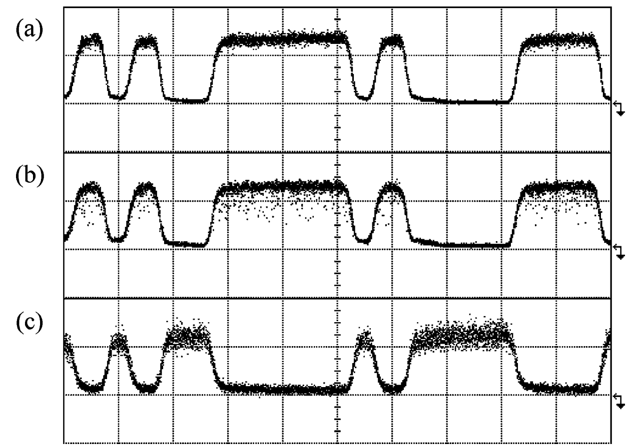

Fig. 6. Measured waveforms: (a) output signal, (b) idler, and (c) probe.

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