Fiber-optic parametric amplifier and oscillator based on intracavity parametric pump technique

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A cost-effective fiber optical parametric amplifier (FOPA) based on the laser intracavity pump technique has been proposed and demonstrated experimentally. The parametric process is realized by inserting a 1 km highly nonlinear dispersion-shifted fiber (HNL-DSF) into a fiber ring-laser cavity that consists of a high-power erbium-doped fiber (EDF) amplifier and two highly reflective fiber Bragg gratings. Compared with the conventional parametric pump schemes, the proposed pumping technique is free from a tunable semiconductor laser as the pump source and also the pump phase modulation. When the oscillating power of 530 mW in the EDF laser cavity is achieved to pump the HNL-DSF, a peak parametric gain of 27.5 dB and a net gain over 45 nm are obtained. Moreover, a widely tunable fiber-optic parametric oscillator is further developed using the FOPA as a gain medium. © 2009 Optical Society of America

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Fiber-optical parametric amplifiers (FOPAs) based on the highly efficient four-wave mixing (FWM) in optical fibers have attracted considerable interest owing to their promising applications [1], such as all-optical signal processing, wavelength conversion [2], pulse generation, and optical time-division multiplexing. To achieve a highly efficient fiber parametric amplification, a high-power pump source is generally necessary. Some researchers have utilized the pulsed sources to employ their high peak pump power for a parametric process [3]. However, the pulsed-pump FOPA requires the strict synchronization between signal and pump pulses and also suffers from self- and cross-phase modulations. As a result, a cw-operated pump source is preferred for a practical FOPA. At present, the most commonly used cw-pump technique in previously reported FOPAs [4–7] has been using a cw tunable semiconductor laser (TL) as the pump source. The output from the TL is spectrally broadened by phase modulation (PM) to suppress the stimulated Brillouin scattering (SBS), amplified by a high-power erbium-doped fiber amplifier (EDFA), and then injected into the parametric gain fiber. The pump PM usually needs to use one- [4,5] or two-cascaded [6,7] phase modulators driven by either several sinusoidal rf signals [4,5] or a pseudorandom bit sequence (PRBS) at bit rates of 3–10 Gbits/s [6,7]. Such a pumping scheme is relatively complex and significantly elevates the system cost. Moreover, it is demonstrated that the pump PM can cause a large power fluctuation in the amplified and wavelength-converted signals [8].

In this Letter, we propose a cost-effective parametric pumping configuration by introducing an intracavity pump laser. Our proposed system does not need the TL and the subsequent PM-based SBS suppression technique. A spool of 1 km highly nonlinear dispersion-shifted fiber (HNL-DSF) is inserted into a high-power EDFA ring laser to complete the intracavity parametric pump. The pump SBS in the HNL-DSF is suppressed owing to the broadened linewidth of intracavity lasing light by controlling the bandwidths of fiber Bragg gratings (FBGs) that act as the wavelength selection components in the laser cavity. With an oscillating power of 530 mW at 1558.8 nm as the intracavity pump, the FOPA provides a broadband gain from 1538 to 1585 nm with a peak parametric gain of 27.5 dB. This allows the FOPA to be used as the gain medium in a tunable fiber optical parametric oscillator (FOPO), which is also presented here.

Figure 1 shows the experimental setup of our proposed FOPA (or FOPO). By using two optical circulators (CIRC1 and CIRC2), a pair of highly reflective FBGs (FBG1 and FBG2), and a high-power EDFA, a fiber ring laser is formed. A 1 km HNL-DSF is inserted into the laser cavity to provide the parametric gain. The measured zero-dispersion wavelength (ZDW), dispersion slope, nonlinear parameter, loss coefficient, and effective core area of the HNL-DSF are 1557 nm, 0.02 ps/nm^2/km, 10 W^{-1} km^{-1}, 0.75 dB/km, and 13 μm^2, respectively. By designing the Bragg wavelengths of FBG1 and FBG2 at

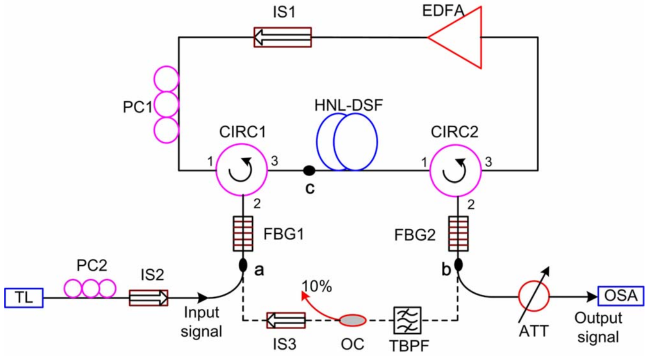

Fig. 1. (Color online) Experimental setup of the proposed FOPA and oscillator.

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1558.8 nm, the EDFA-based ring laser can thus oscillate at the vicinity of ZDW of the HNL-DSF to be able to conduct efficient parametric amplification. The highly reflective (>95%) FBG1 with a 3 dB bandwidth of 0.38 nm not only suppresses the SBS of the pump laser in the HNL-DSF but also filters out the amplified spontaneous emission (ASE) noise from the EDFA. The FBG2 with a reflectivity of ~80% and a narrower 3 dB bandwidth of 0.10 nm is selected to further reduce noise light injected into the EDFA. The polarization controller (PC1) is used to control the polarization state of the oscillating light at 1558.8 nm (i.e., the parametric pump light). The isolator (IS1) prevents any possible light from reflecting back to the EDFA. The EDFA can provide a highest saturated output power of ~1.3 W. By inserting a 10/90 optical coupler (OC) at the **c**-point in Fig. 1, we observed that the highest oscillating power of ~530 mW can be effectively launched into the HNL-DSF. The laser with the Lorentzian-like spectrum has a 3 dB linewidth of 0.1 nm, and no competing laser modes were observed. The power decline from ~1.3 W to 530 mW is attributed to the insertion loss of the components, such as PC1, IS1, CIRC1, and FBG1. The signal light from a TL is injected into the HNL-DSF through the CIRC1 (port2 → 3). The polarization state of the input signal light is controlled by the PC2. The IS2 avoids the leaking ASE light from FBG1 to protect the TL. The amplified signal output from port2 of CIRC2 is attenuated by a 15 dB optical attenuator (ATT) and monitored by an optical spectrum analyzer (OSA). In addition, when we remove the signal input/output ports, including the TL, PC2, IS2, and ATT, an FOPO can be built by connecting the dot-line components from point **a** to **b** as shown in Fig. 1. The desired oscillating wavelength is selected using a tunable bandpass filter (TBPF) with a 1.3 nm bandwidth and a tunable range from 1535 to 1560 nm. The insertion loss of the TBPF is ~4 dB. A 10/90 OC is used for the laser output. The IS3 is used to prevent the parasitical oscillation possibly formed by the EDFA, CIRC1 (port1 → 2), the dot-line components, and CIRC2 (port2 → 3).

To obtain a high parametric gain, we maintain the parametric pump power at ~530 mW in the HNL-DSF. Figure 2 shows an example of the output spectrum of our proposed FOPA with and without an intracavity parametric pump when the input signal is −23 dBm at 1544 nm. A fiber-to-fiber parametric gain of 27.5 dB can be obtained. The measured optical signal-to-noise ratio is more than 20 dB with a spectral resolution of 0.1 nm for the OSA. Such a net gain of 27.5 dB with a pump power of only 530 mW is comparable to those results achieved by other researchers using the conventional parametric pumping schemes [5,7]. Since CIRC1 is used to inject the signal in our proposed FOPA instead of a 10/90 coupler as in [5,7], the internal fiber gain can be fully utilized and there is no additional insertion loss from the 10/90 coupler at the signal input port.

By tuning the signal wavelength (λ_s) from 1535 to 1585 nm with a fixed input power ($P_{\sin}$) of −23 dBm, we measured the small-signal gain spectrum of the FOPA as shown in Fig. 3. The squares represent the measured parametric gain, and the solid curve shows the theoretical estimation by numerically solving the coupled-wave equations [1]. The theoretical and experimental results are in good agreement. The gain of FOPA ranges from 10 to 27.5 dB over a 45 nm bandwidth centered at 1558.8 nm. A broader and flatter gain profile can be expected by (1) optimizing the intracavity pump lasing wavelength and (2) using the dual-pumped FOPA scheme with two pairs of FBGs [9].

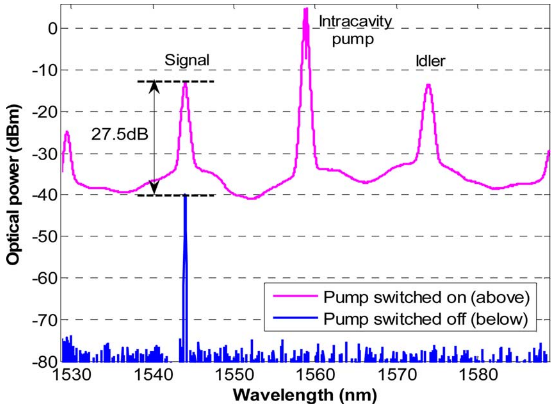

Fig. 2. (Color online) Output optical spectra of the FOPA with and without the intracavity pump of 530 mW.

For different values of the intracavity pump power at 1558.8 nm, we measured the corresponding small-signal gain for $P_{\sin}=-23$ dBm at $\lambda_s=1544$ nm as shown in Fig. 4. The parametric pump threshold for generating a 3 dB parametric gain is very low (~150 mW), and the gain slope is as high as 61.7 dB/W. The lower pump threshold and higher gain slope are comparable to those in previous reports using the conventional pump scheme, such as an ~600 mW pump threshold and a 50 dB/W gain slope in [5] and an ~250 mW pump threshold and a 45 dB/W gain slope in [7]. The improved performance is mainly attributed to the smaller dispersion slope (0.02 ps/nm^2/km) and the sufficient fiber length (1 km) of the HNL-DSF [1], respectively.

However, one can find from Fig. 2 that the signal light is spectrally broadened to ~0.3 nm. This phe-

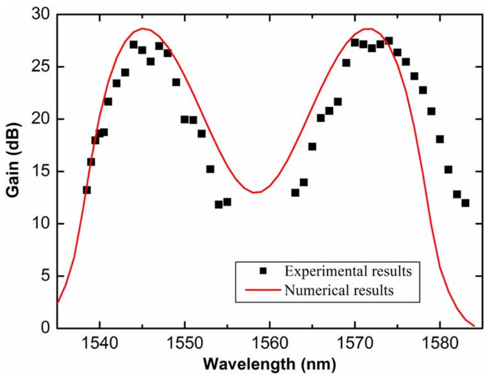

Fig. 3. (Color online) Measured and calculated parametric gain versus signal wavelength with an input signal power of −23 dBm. Squares, experiments; solid curve, theory.

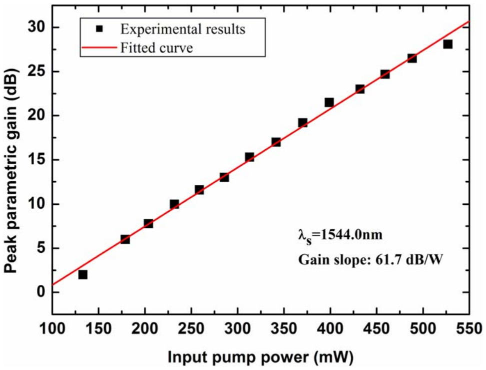

Fig. 4. (Color online) Small-signal gain versus the intracavity pump power into HNL-DSF for $\lambda_s = 1544$ nm and $P_{\mathrm{sin}} = -23$ dBm. Squares, experimental results; solid line, fitted curve.

nomenon may be caused by the underlying FWM [5] with a broad linewidth of the intracavity pump laser. The spectral broadening can be eliminated if the bandwidths of FBG1 and FBG2 are appropriately reduced. The spectral broadening of the amplified signal may deteriorate its transmission performance. Although in our experiment the FBGs are not ideal, this FOPA can still be used to effectively amplify the signal bit sequence, which is verified by the time-domain experiments. The input signal is externally modulated using a $\mathrm{LiNbO_3}$ Mach–Zehnder modulator with 10 Gbits/s nonreturn-to-zero, 2^7-1 PRBS. The amplified signal is filtered by a narrowband FBG and then detected by a 10 GHz bandwidth photodetector. The eye diagrams of the 1544 nm input signal and the amplified output signal are shown in Figs. 5(a) and 5(b), respectively. The measured Q factor of the input signal and amplified output signal are 8.8 and 5.6, respectively. Although the parametric amplification induces intensity noise to some extent, the FOPA can still be applicable for the real amplification systems confirmed by the measured Q factors.

By connecting the dot-line components from point **a** to **b** as shown in Fig. 1, we have further obtained an FOPO. The FOPO has a lasing threshold of 380 mW at a lasing wavelength of 1545 nm. With a pump power of 530 mW, we measured the output laser spectra by tuning the TBPF. As shown in Fig. 6, the output wavelength is tunable from 1540 to 1555 nm, which is limited only by the tunable bandwidth of the TBPF. The linewidth and the slope coversion efficiency of the FOPO at 1545 nm are ~0.1 nm and 1.06%, respectively, which are comparable to those reported FOPOs using the conventional parametric pump scheme [10]. The output power can be increased by optimizing the HNL-DSF length, the output coupling ratio of the OC, and reducing the insertion loss of TBPF.

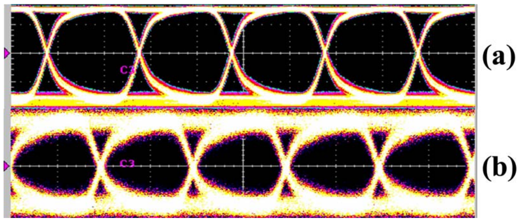

Fig. 5. (Color online) Measured eye diagrams of (a) input signal and (b) amplified signal with $\lambda_s = 1544$ nm, $P_{\mathrm{sin}} = -23$ dBm, and a pump power of 530 mW.

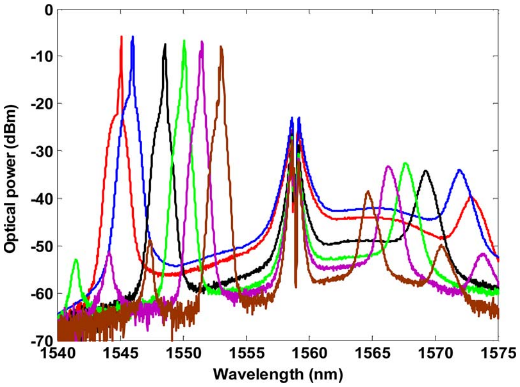

Fig. 6. (Color online) Tunable output spectra of the proposed FOPO with a pump power of 530 mW.

In conclusion, we have demonstrated, for the first time to our knowledge, an FOPA using a laser intracavity parametric pump technique without phase modulation and TL as a pump source. The FOPA has comparable performances to the reported FOPAs using the conventional parametric pump scheme. A peak gain of 27.5 dB at only 530 mW pump power has been achieved with a gain bandwidth of more than 45 nm. The relatively low parametric pump threshold (150 mW) and the high gain slope of 61.7 dB/W further strengthen the competence of our proposed system. In addition, the proposed parametric pump technique has been used to build a widely tunable all-fiber parametric oscillator.

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