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Ultra-Widely Tunable, Narrow Linewidth Picosecond Fiber-Optical Parametric Oscillator

Yue Zhou, Kim K. Y. Cheung, Sigang Yang, P. C. Chui, and Kenneth K. Y. Wong

Abstract—We demonstrate a picosecond fiber-optical parametric oscillator with an ultrawide tuning range pumped by a relatively low-cost intensity-modulated pump. The tuning range of the oscillator is from 1320 to 1520 nm and from 1580 to 1820 nm, which is as wide as 440 nm, with a wavelength span of 500 nm. A 40-m dispersion-shifted fiber is employed inside a cavity as the parametric gain medium. In the wavelength region from 1320 to 1395 nm and from 1720 to 1820 nm, the linewidth of the sideband is less than 1 nm without the use of any wavelength-selective element inside the cavity. Pulses with pulsewidths from 7 to 17 ps are generated.

Index Terms—Optical parametric amplifier, optical parametric oscillator (OPO), optical pulse generation.

I. INTRODUCTION

FIBER-OPTICAL parametric amplifier (FOPA) based on the $\chi^{(3)}$ nonlinear effect of optical fibers offers large gain, wide bandwidth, and fast response [1], and it is an important mechanism to amplify signals. Its corresponding fiber-optical parametric oscillator (FOPO) configuration [2], which does not require any seeding light, has been proposed and investigated as a useful means of realizing widely tunable optical sources. FOPOs based on both conventional optical fibers [3], [4] and photonic crystal fibers [5], [6] have been demonstrated. Compared with the optical parametric oscillator (OPO) based on the $\chi^{(2)}$ nonlinear effect of crystals [7], FOPO eliminates the need of a delicate alignment and allows further integration with other fiber components.

Wavelength tunability is a key feature of FOPOs and has been the subject of numerous publications. Continuous-wave (CW) FOPO with a tuning range of 240 nm [4] and nanosecond FOPO with a tuning range of 560 nm [3] have already been demonstrated. Since an ultrashort pulse such as picosecond pulse generation is a challenging topic of considerable interest

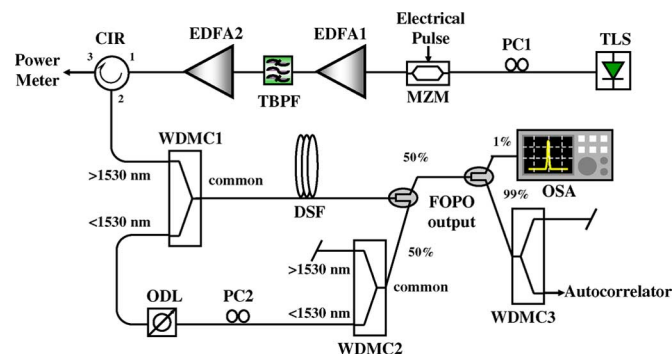


Fig. 1. Experimental setup of the FOPO. EDFA: erbium-doped fiber amplifier. TBPF: tunable bandpass filter. OSA: optical spectrum analyzer. MZM: Mach-Zehnder modulator. ODL: optical delay line. PC: polarization controller. WDMC: wavelength-division-multiplexing coupler. CIR: circulator.

in the field of optical communications, building a widely tunable picosecond FOPO is highly desirable. In [5], a picosecond FOPO with a tuning range of 200 nm around 1000 nm was demonstrated. In our previous work [8], picosecond FOPO with a 250-nm tuning range around 1550 nm was demonstrated. In both [5] and [8], the FOPOs were synchronously pumped by mode-locked fiber lasers (MLFLs). However, an MLFL is relatively expensive, so it is desirable to build a picosecond source simply from a CW pump.

In this letter, we demonstrate a fully fiber-integrated picosecond FOPO with a wavelength tuning range of 440 nm pumped by a simple intensity-modulated pump. Tuning is achieved by changing the pump wavelength from 1532 to 1549 nm. A 40-m dispersion-shifted fiber (DSF) is employed inside a cavity as the parametric gain medium. Moreover, in the wavelength region from 1320 to 1395 nm and 1720 to 1820 nm, the linewidth of the FOPO output is less than 1 nm without the use of any wavelength-selective element inside the cavity. Within the narrow linewidth region, pulses with pulsewidths from 7 to 17 ps are generated. Compared with our previous work using highly nonlinear dispersion-shifted fiber (HNL-DSF) in [8], the use of DSF in this letter offers two key advantages: a wider tuning range and a narrower linewidth. We will elaborate further in the following text. This scheme has the potential to be a cost-effective source in generating short pulse for ultrafast optical communications outside the conventional wavelength window.

II. EXPERIMENTAL SETUP

The experimental setup of the FOPO is shown in Fig. 1, which is similar to our previous work in [8]. Instead of using an MLFL as in [8], the pump source we use here is a tunable

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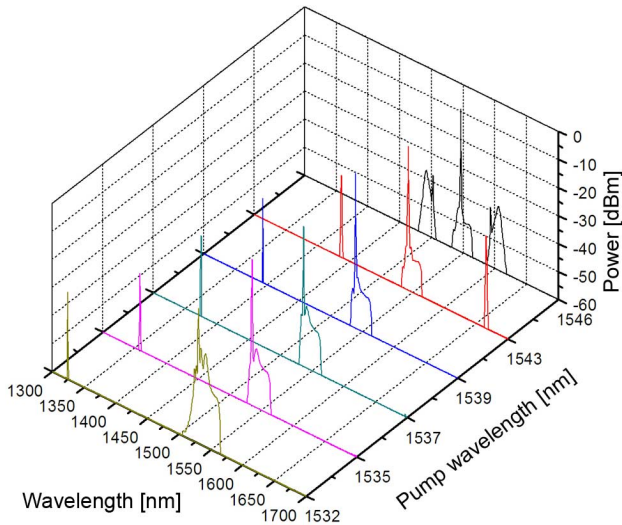


Fig. 2. Optical spectra measured at DSF output using OSA.

laser source (TLS), which is tuned from 1532 to 1549 nm to achieve the widest tuning range. The CW output of the TLS is intensity-modulated by a 10-MHz electrical pulse with duty ratio of 1/1000 to produce optical pump pulse with pulsewidth of 100 ps. It is then amplified, filtered, and further coupled into the cavity for parametric amplification. The peak power of the pump is measured to be 25 W at the DSF input. The gain medium inside the cavity is a spool of 40-m DSF, which has a nonlinear coefficient of $2 \text{ W}^{-1} \cdot \text{km}^{-1}$, a core diameter of $8 \mu\text{m}$, an attenuation of 0.2 dB/km, a zero-dispersion wavelength (ZDW) of 1548.7 nm, a dispersion slope of $0.07 \text{ ps/nm}^2/\text{km}$ and $\beta^{(4)}$ of $-4.75 \times 10^{-55} \text{ s}^4 \cdot \text{m}^{-1}$. A 50/50 coupler in the cavity provides 50% feedback and 50% output. The feedback branch is filtered by the WDMC2 with a cutoff wavelength of 1530 nm, so that only the signal (shorter wavelength component) returns to the DSF through WDMC1, and the idler (longer wavelength component) is blocked. The total length of the discrete standard single-mode fiber (SMF) used to connect the components in the cavity is 20 m, so the total cavity length is 60 m.

The FOPO output spectrum is monitored by an OSA through a 1/99 coupler. WDMC3 is used to filter out the desired signal or idler. The pulsewidth of the signal (idler) is measured using an autocorrelator.

III. RESULTS AND DISCUSSION

Fig. 2 shows the optical spectra measured at the FOPO output port. Tunability is achieved by tuning the pump wavelength from 1549 to 1532 nm, and the pump power is slightly adjusted to maintain almost the same peak for all spectra. As the pump wavelength decreases, the detuning of the sidebands increases. When the ODL is tuned at the same time to synchronize the signal with the pump, the achievable output tuning range is from 1320 to 1520 nm and from 1580 to 1700 nm. Since the operating wavelength of our OSA ends at 1700 nm, the idler beyond this wavelength is not shown in Fig. 2.

In Fig. 3, we show the experimentally measured sideband wavelengths (circles) and the idler wavelengths above 1700 nm

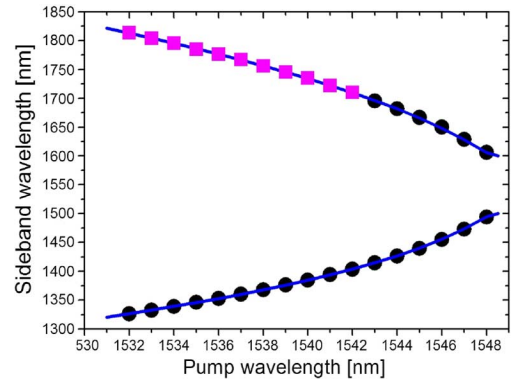


Fig. 3. Experimentally measured sideband wavelengths as a function of pump wavelength (circles). The rectangles are idler wavelengths calculated from the experimentally measured signal wavelengths. Theoretical sideband wavelengths predicted by equation (1) (solid curves).

(rectangles) calculated from the experimentally measured signal wavelengths as a function of pump wavelength. The longest idler wavelength is calculated to be 1820 nm. The superimposed solid curve is the theoretical prediction using the phase matching condition in [8]. The agreement between the experimental and theoretical wavelengths is excellent. Therefore, the tuning range of our FOPO is from 1320 to 1520 nm and from 1580 to 1820 nm, which is as wide as 440 nm, with a wavelength span of 500 nm. The tuning range is larger than those picosecond FOPOs reported in [5] and [8]. There are three factors which may combine to limit the further enhancement of the tuning range. First, the DSF is not polarization maintaining, and random birefringence causes polarization-mode dispersion, which then causes reduction of four-wave mixing (FWM) efficiency at large detuning [1]; second, the walk-off between the signal and pump increases with their wavelength separation, thereby decreases their interaction length and reduces the parametric gain; the third factor is the fluctuation of the ZDW along the DSF, which will also limit the tuning range of this kind of FOPO [9]. Since DSF has much smaller dispersion fluctuations than HNL-DSF, we can achieve a much wider tunability than our previous work in [8].

The experimentally measured linewidths of the sidebands are plotted as a function of wavelength in Fig. 4 (green rectangles). The linewidth of the sideband is relatively broad when the pump wavelength is close to the ZDW (~ 10 nm when pump at 1548 nm) but becomes narrower quickly as the pump is tuned away from the ZDW in the normal dispersion region. This trend is in agreement with the analytical expression for the gain bandwidth of the FOPO versus sideband wavelength using the DSF parameters (black solid line), which can be calculated by the following equation [10]:

$$\delta\lambda \approx \frac{24}{C^4} \left| \frac{\gamma P_0}{\beta^{(4)}(\Delta\lambda)^3} \right| \quad (1)$$

where $\delta\lambda$ is the FOPO gain bandwidth, $\Delta\lambda$ is the wavelength separation of between the pump and the signal, P_0 is the peak power of the pump, γ is the nonlinear coefficient, and $C \approx 7.85 \times 10^{20} \text{ s}^{-1} \cdot \text{m}^{-1}$. Between 1320 and 1395 nm, the linewidths of the sidebands are below 1 nm. Since signal and idler at each sideband should be symmetrical in frequency, thus

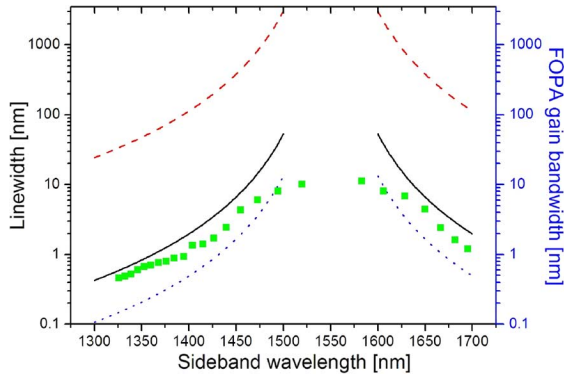


Fig. 4. Linewidth of the sideband versus wavelength (green rectangles). Theoretical FOPA gain bandwidth versus sideband wavelength when using current DSF (black solid line), HNL-DSF (red dashed line), and a DSF with a larger $\beta^{(4)}$ (blue dotted line).

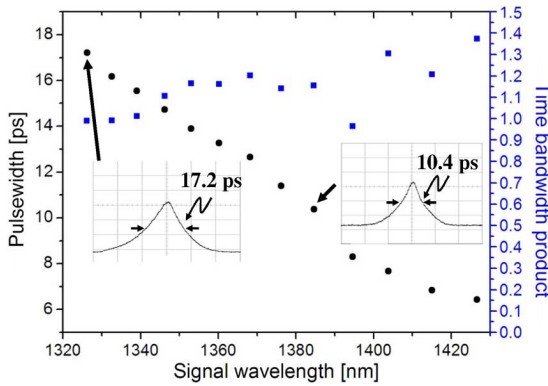


Fig. 5. Signal pulsewidth versus wavelength (black circles). The blue rectangles are signal time bandwidth products (TBP) as a function of wavelength. Insets are autocorrelation traces at some wavelengths.

approximately symmetric in wavelength, the linewidth of the sideband between 1720 and 1820 nm is also expected to be less than 1 nm. The narrow linewidth (~ 1 nm) of the output signal or idler requires no additional bandpass filters inside the cavity to select the wavelengths is a highly desirable feature for this configuration, as the availability of filter at certain wavelength may limit the tuning range of the FOPO. This linewidth is narrower than our previous work in [8], where we used an HNL-DSF as a gain medium. The fairly large nonlinear coefficient ($14 \text{ W}^{-1} \cdot \text{km}^{-1}$) and small $\beta^{(4)}$ ($-5.8 \times 10^{-56} \text{ s}^4 \cdot \text{m}^{-1}$) of the HNL-DSF we used will result in a much broader gain bandwidth, which is shown in the red dashed line of Fig. 4. Furthermore, if we can use a DSF with a larger $\beta^{(4)}$ (four times larger than that of the DSF used in this experiment), the gain bandwidth can be reduced further (blue dotted line). Thus, this scheme has the potential to generate pulses with narrower linewidths.

Fig. 5 shows the output pulsewidths (circles) and signal TBPs (rectangles) as a function of signal wavelength when the linewidth of the signal is narrower than 1 nm, which is the wavelength region of our primary interest. Insets are autocorrelation traces at some wavelengths measured by the autocorrelator.

The real full-width at half-maximum (FWHM) pulsewidth is calculated by assuming a sech^2 pulse shape, multiplied by the FWHM correlation width using a deconvolution factor of 0.648. The pulsewidth increases from 7 to 17 ps when the signal detunes further from the pump, thus the walk-off between the signal and the pump becomes larger which broaden the signal pulsewidth. The output pulses are narrower than the pump pulses (100 ps) because of the pulse narrowing effect of FOPO [11]. The TBP is calculated to be around 1, which is larger than that of the transform-limited soliton pulse, 0.315. The fairly large TBP is primarily due to the cross-phase modulation (XPM) between the pump and the signal. The peak power of the output signal at 1320 nm is measured to be 970 mW, thus, the conversion efficiency of the FOPO is calculated to be 3.88%. The conversion efficiency is perceived to be limited by the walk-off between the signal and the pump. We also use a digital communication analyzer at the FOPO output to measure the pulse shape of the signal; there is no observable pulse shape variation over 1 hour. This indicates that the FOPO output is reasonably stable.

IV. CONCLUSION

An all-fiber widely tunable picosecond OPO was demonstrated. The output is continuously tunable from 1320 to 1520 nm and from 1580 to 1820 nm. Pulses are generated with pulsewidths from 7 to 17 ps. This scheme has the potential to be a cost-effective source in generating short pulse for ultrafast communications in the nonconventional wavelength bands.

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