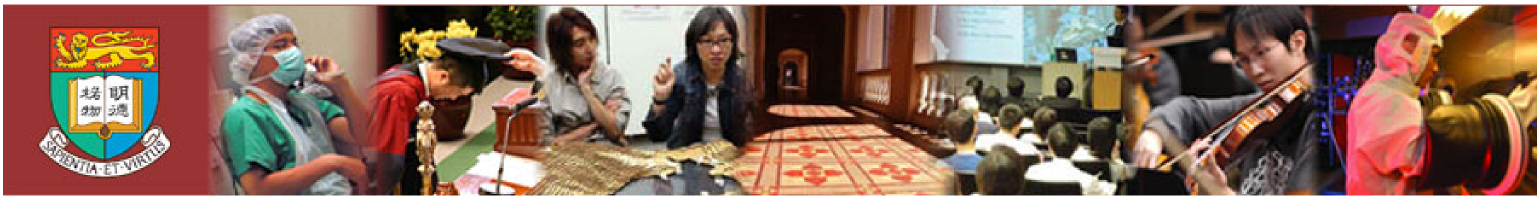

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# A Tunable $S$-Plus $L$-Band Continuous-Wave Single-Longitudinal-Mode Fiber-Optical Parametric Oscillator

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***Abstract*—We demonstrate an all-fiber continuous-wave single-longitudinal-mode fiber-optical parametric oscillator. The output tuning range extends from 1487 to 1541 nm and from 1570 to 1630 nm, which covers the $S$- and $L$-bands. Single-longitudinal-mode oscillation with a side-mode suppression ratio greater than 43 dB is achieved while the linewidth of the output is 1.5 kHz. This scheme has the potential to be a useful source in wavelength-division-multiplexing networks and optical communications in the nonconventional wavelength bands.**

***Index Terms*—Optical fiber laser, optical parametric amplifier, optical parametric oscillator.**

## I. Introduction

SINGLE-LONGITUDINAL-MODE (SLM) fiber lasers play important roles in wavelength-division multiplexing (WDM) networks and optical communications [1]. Previous efforts on SLM lasers have been demonstrated in erbium doped fiber (EDF) lasers [1]–[3] and semiconductor optical amplifier (SOA) based lasers [4]. For instance, a fixed wavelength EDF laser using the passive multiple-ring cavity configuration [1] and a 76-nm tuning range SOA-based fiber laser using an unpumped EDF as a narrow bandwidth autotracking filter have been demonstrated [4]. However, the output bandwidths were limited to the $C$ [1]–[3] or the $C$ plus $L$-bands [4] due to the properties of the gain medium. On the other hand, fiber-optical parametric oscillators (FOPOs) [5]–[10] allow both signal and idler extraction at the output port, thus the tuning range of the SLM lasers can be further increased. In previous work [11], a 28-nm tuning range continuous-wave (CW) SLM FOPO was achieved by adopting a saturable-absorber-based autotracking filter, which consisted of a $C$-band unpumped EDF and an optical loop mirror to guarantee SLM operation. However, it is highly desirable to extend the performance of these optical sources by increasing their wavelength tunability.

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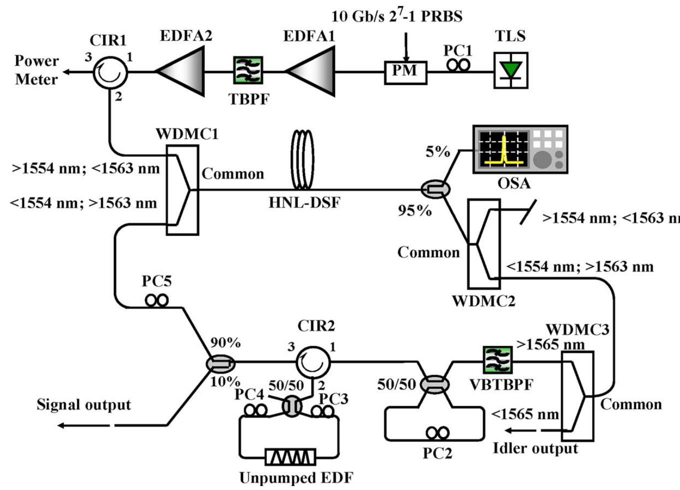


Fig. 1. Experimental setup of the FOPO. EDFA: erbium-doped fiber amplifier; TBPF: tunable bandpass filter; OSA: optical spectrum analyzer; MZM: Mach–Zehnder modulator; ODL: optical delay line; PC: polarization controller; WDMC: wavelength-division multiplexing coupler; CIR: circulator; HNL-DSF: highly-nonlinear dispersion-shifted fiber; VBTBPF: variable bandwidth tunable bandpass filter.

In this letter, the tuning range of this kind of FOPO is increased by replacing the $C$-band EDF in [11] with an $L$-band EDF and adopting a gain fiber with a positive $\beta^{(4)}$, instead of a negative $\beta^{(4)}$ as used in [11]. The output tuning range extends from 1487 nm to 1541 nm and from 1570 nm to 1630 nm $(\mathrm{signal} - \mathrm{void} - \mathrm{idler} = 54 - 29 - 60\ \mathrm{nm})$, covers both the $S$- and $L$-bands. SLM oscillation with a side-mode suppression ratio (SMSR) greater than 43 dB is achieved. The linewidth of the output signal is measured to be 1.5 kHz. This scheme has the potential to be a useful source in WDM networks and optical communications in nonconventional wavelength bands. Furthermore, a frequency swept optical source with SLM operation can also be achieved by inserting a fiber Fabry–Pérot tunable bandpass filter (FFP-TP) inside the cavity [12].

## II. Experimental Setup

Fig. 1 shows the experimental setup of the FOPO, which is similar to the setup reported in [11]. The pump was generated by a CW tunable laser source (TLS) with wavelength fixed at 1555.5 nm through the experiment. The PC1 was used to align the state of polarization (SOP) of the pump with the transmission axis of the phase modulator (PM). Afterwards, the pump was amplified, filtered, and coupled into the cavity for parametric process. The power of the pump was measured to be 3 W after the EDFA2. Note that the cavity included a 150-m long HNL-DSF (manufactured by Sumitomo Electric) as the gain medium which had nonlinear coefficient of 30 $\mathrm{W}^{-1}\mathrm{km}^{-1}$, zero-dispersion wavelength of 1554 nm, dispersion slope of 0.02 $\mathrm{ps/nm^2/km}$, and $\beta^{(4)}$ of $6.0 \times 10^{-5}$ $\mathrm{ps^4/km}$. WDMC2 and WDMC3 were combined to ensure that only the signal (longer wavelength sideband) can oscillate inside the cavity. The signal was filtered by a 0.4-nm (50 GHz) VBTBPF which served as a convenient wavelength selective element. In order to achieve SLM operation, a sub-ring cavity with a cavity length of 4.9 m and a fiber loop mirror with a 3-m unpumped $L$-band EDF were added inside the cavity. The PC5 inside the cavity was used to align the SOP of the signal with that of the pump. A 90/10 coupler in the cavity provided 90% feedback and 10% output. Wavelength tuning was achieved by adjusting the center wavelength of the VBTBPF.

## III. Results and Discussions

The signal oscillating wavelength was set to be 1600 nm and the mode spacing was measured by a self-homodyne method, which was the same method used in [11]. The mode spacing of the main cavity without the sub-ring cavity and the loop mirror was measured to be 1.175 MHz. After that, the sub-ring cavity was inserted. Fig. 2(a) shows the measured spectra from the electrical spectrum analyzer (ESA). With the sub-ring cavity inserted, the free spectral range (FSR) was increased from 1.175 MHz to 83.4 MHz, which was the least common multiple of 1.175 MHz and 41.7 MHz (41.7 MHz was the FSR of the sub-ring cavity). The spectrum was very noisy and unstable owing to the mode hopping. Finally the fiber loop mirror was connected, the beating signal disappeared and no mode-hopping was observed as shown in Fig. 2(b). We can estimate the FWHM of the fiber loop mirror with a self-induced fiber Bragg grating (FBG) as $\Delta f < 6.5$ MHz [3]. Therefore, the loop mirror allowed only one longitudinal mode to oscillate, Fig. 2(c) is simply Fig. 2(b) replotted to show the source's narrow linewidth. It indicated that the EDF loop and the sub-ring cavity were successful in enabling SLM operation with a SMSR of at least 43 dB. The linewidth of the signal was measured to be 1.5 kHz. Similar RF spectrum could be achieved when measuring the idler using the same self-homodyne method. Therefore, both the signal and the idler were SLMs.

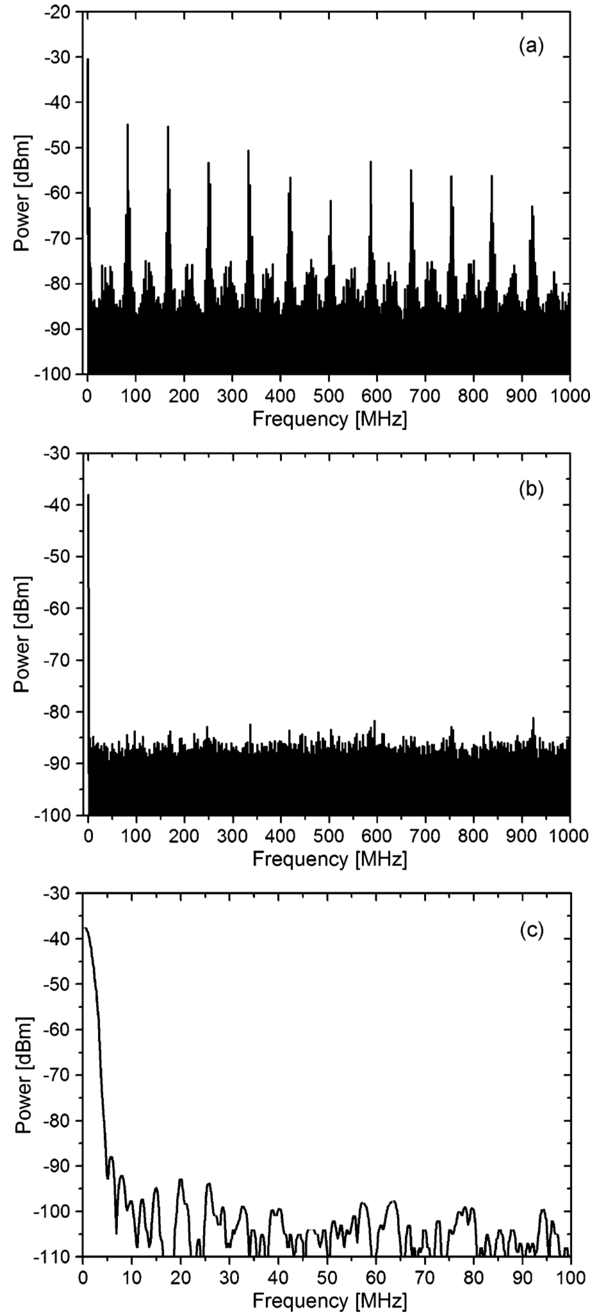


Fig. 2. Measured self-homodyne spectra for the signal wavelength at 1600 nm: (a) with sub-ring cavity inserted while EDF loop is removed, (b) with sub-ring cavity and EDF loop connected, and (c) plot (b) repotted to show the source's narrow linewidth.

Fig. 3 shows the optical spectra measured at the 5% HNL-DSF output port. The pump wavelength was fixed at 1555.5 nm and the pump power remained the same for each tuning. Wavelength tuning was achieved by changing the center wavelength of the VBTBPF, while no other component was adjusted. The achievable tuning range was 54-29-60 nm. The tuning range was much wider than the 14-24-14 nm tuning range reported in [11] since a postive $\beta^{(4)}$ is used in this letter instead of a negative $\beta^{(4)}$ used in [11]. As discussed in [5], all else being equal, a positive $\beta^{(4)}$ is better than a negative $\beta^{(4)}$ for obtaining a fiber-optical parametric amplifier (FOPA) with a wide gain bandwidth. The FOPA gain can be calculated using the following equation shown in [5]:

$$G = 1 + \left[\frac{\gamma P}{g}\sinh(gL)\right]^2 \tag{1}$$

where $\gamma$ is the fiber nonlinear coefficient, $P$ is the pump power, $L$ is the fiber length and $g$ is the parametric gain parameter given by [5]

$$g^2 = (\gamma P)^2 - \kappa^2/4 \tag{2}$$

$$\kappa = \beta^{(2)}(\Delta\omega)^2 + \beta^{(4)}(\Delta\omega)^4/12 + 2\gamma P \tag{3}$$

where $\kappa$ is the nonlinear phase mismatch, $\Delta\omega$ is the frequency difference between the signal and the pump, $\beta^{(\mathrm{m})}$ is the $\mathrm{m}^{\mathrm{th}}$ order derivative of the propagation constant at the pump wavelength. As shown in Fig. 3, the circles predict the simulated FOPA gain as a function of signal wavelength, which have the

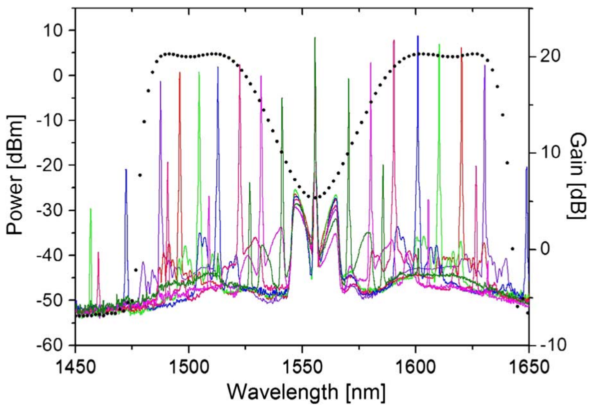


Fig. 3. Optical spectra measured at FOPO output using OSA. The circles are the calculated FOPA gain as a function of signal wavelength.

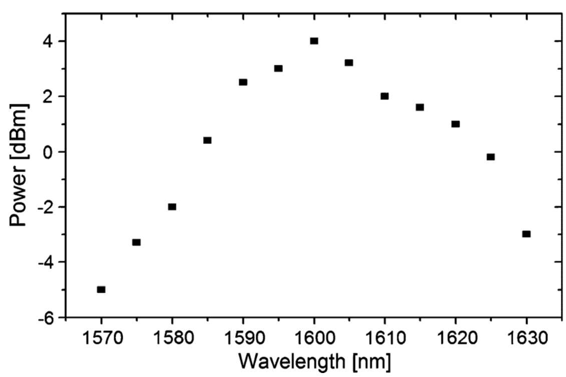


Fig. 4. Signal output power as a function of wavelength.

same trend as the experimental FOPO spectra. The gain bandwidth of the FOPA can be approximated when $g$ is greater than 0, as

$$-4\gamma P \leq \beta^{(2)}(\Delta\omega)^2 + \beta^{(4)}(\Delta\omega)^4/12 \leq 0 \quad (4)$$

By using the (4), the FOPA spectral gain is calculated to be 220 nm (FWHM), which is larger than the FOPO tuning range (114 nm) we obtained because 1) the FOPA gain must exceed the cavity loss (16.5 dB) for the signal to start oscillation 2) the zero dispersion wavelength fluctuations along the fiber will also decrease the FOPO tuning range. The flat-top gain spectrum obtained using a positive $\beta^{(4)}$ is quite different from conventional "M" shape FOPA gain spectrum using a negative $\beta^{(4)}$, which maybe a quite interesting topic and need further investigation, as Bragg scattering in these fibers is shown in [13]. Further tuning was limited by the gain region of the fiber-optical parametric amplifier (FOPA) when the pump wavelength was fixed at 1555.5 nm, which can be further improved by pursuing different fibers.

Fig. 4 shows the signal output power as a function of wavelength. The FOPO had largest output power at 1600 nm, corresponding to the FOPA gain peak, while the output power decreased when the wavelength was tuned away from 1600 nm due to the gain spectrum of the FOPA when the pump wavelength was set at 1555.5 nm.

## IV. Conclusion

In conclusion, we demonstrated an all-fiber CW FOPO with SLM operations. The tuning range of the FOPO is 54-29-60 nm covering the $S$- and $L$-bands and the linewidth of the FOPO output is measured to be as narrow as 1.5 kHz. This scheme has the potential to be a useful source in WDM networks and optical communications in the nonconventional wavelength bands. Furthermore, a frequency swept optical source with SLM operation can also be achieved by adopting this scheme.

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