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<td><strong>Author(s)</strong></td>
<td>Zhou, Y; Chui, PC; Wong, KKY</td>
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Widely-Tunable Continuous-Wave Single-Longitudinal-Mode Fiber Optical Parametric Oscillator

Yue Zhou, P. C. Chui, and Kenneth K. Y. Wong*
Photonic Systems Research Laboratory, Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong.
*E-mail: kywong@eee.hku.hk

Abstract: A continuous-wave fiber optical parametric oscillator with a tunability of 114 nm, a wavelength span of 143 nm and single-longitudinal-mode oscillation is demonstrated. The short-term linewidth of the output is as narrow as 1.5 kHz.

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1. 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 [1-2] and semiconductor optical amplifiers (SOAs) based lasers [3]. 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 [3]. On the other hand, fiber optical parametric oscillators (FOPOs) [4] allow both signal and idler generating at the output, thus the tuning range of the SLM lasers can be further increased. In our previous work [5], 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 improve the performance of this kind of optical source, such as the wavelength tunability.

In this paper, we increase the tuning range of this kind of FOPO to 114 nm by replacing the C-band EDF in [5] with an L-band EDF and adopting a gain fiber with a higher nonlinear coefficient. The linewidth of the output signal 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 non-conventional wavelength bands.

2. Experimental Setup

Fig. 1. Experimental setup of the FOPO. EDFA: erbium-doped fiber amplifier, TBPF: tunable band-pass filter, OSA: optical spectrum analyzer, HNL-DSF: highly-nonlinear dispersion-shifted fiber, PC: polarization controller.

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Fig. 1 shows the experimental setup of the FOPO. The pump was generated by a CW tunable laser source (TLS) with wavelength fixed at 1555.5 nm through the experiment. The output of the laser was phase modulated by a phase modulator (PM) using a 10 Gb/s pseudorandom binary sequence (PRBS) with pattern length $2^7-1$ in order to increase the threshold of stimulated Brillouin scattering (SBS). The PC1 was used to align the state of polarization (SOP) of the pump with the transmission axis of the PM. Afterwards, the pump was amplified by erbium-doped fiber amplifiers (EDFAs), EDFA1 and EDFA2, and filtered by a tunable bandpass filter (TBPF) with a 1-nm bandwidth to produce a high-power, low-noise pump. The power of the pump was measured to be 3 W after the EDFA2. The pump then passed through a circulator, and the reflected power by SBS was monitored using a power meter. It was then coupled into the cavity for parametric amplification through the wavelength-division multiplexing coupler (WDMC1), which had separation wavelengths from 1554 nm to 1563 nm. Note that the cavity included a 150-m long HNL-DSF as the gain medium which had nonlinear coefficient of $30 \text{ W}^{-1}\text{km}^{-1}$, zero-dispersion wavelength of 1554 nm and dispersion slope of 0.02 ps/nm$^2$/km. The FOPO output spectrum was monitored by an optical spectrum analyzer (OSA) through a 5/95 coupler. WDMC2 was used to filter out the signal and idler by blocking the undesired pump, and WDMC3 was used to filter away the idler (shorter wavelength sideband) to ensure that only the signal (longer wavelength sideband) can oscillate inside the cavity. The signal was filtered by a 0.4-nm variable bandwidth tunable bandpass filter (VBTBPF) which determined the lasing wavelength. In order to increase the longitudinal mode spacing, a sub-ring cavity with a cavity length of 4.9 m was inserted after the VBTBPF. It was consisted of a PC and a 50/50 coupler. Then, a fiber loop mirror was added via the CIR2, which was consisted of a 50/50 coupler, two PCs (PC3 and PC4), and a 3-m unpumped L-band EDF that served as the saturable absorber. In the unpumped EDF, two counter-propagating waves formed a standing wave and produced a periodic spatial hole burning (SHB). This acted as an autotracking narrowband filter and enable SLM operation, in combination with the sub-ring 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.

3. Results and Discussion

The signal oscillating wavelength was set to be 1600 nm. The mode spacing was measured by a self-homodyne method, which consisted of a photodetector with a 3 dB bandwidth of 26 GHz and a Mach-Zehnder interferometer that included an optical interferometer with a delay time of 3.5 $\mu$s in one arm. At first, the sub-ring cavity and the loop mirror were absent; the mode spacing of the main cavity was measured to be 1.175 MHz, and then the subring cavity was inserted while the loop mirror was still absent. Fig. 2(a) shows the measured beating signal 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 fundamental and higher orders beating signal could be observed clearly, while the spectrum was very noisy and unstable owing to the mode hopping. Once the fiber loop mirror was also connected, the beating signal disappeared and no spike signals were 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 $\Delta f < 6.5 \text{ MHz}$ [6]. Therefore, the loop mirror allowed only one longitudinal mode to oscillate, Fig. 2(c) shows the zoom-in version of the spectrum up to 100 kHz. Only the direct current peak could be observed, while other longitudinal modes of the signal cavity were suppressed. It indicated that the EDF loop and the sub-ring cavity were successful in enabling SLM operation with a side-mode suppression ratio of at least 43 dB. The short-term 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. 3 (a) 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 from 1487 nm to 1541 nm and from 1570 nm to 1630 nm, which was as wide as 114 nm, with a wavelength span of 143 nm. The smaller peaks were high order parametric components. 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. The tuning range was much larger than 28-nm we reported in [5] because 1) the C-band EDF used in [5] was replaced by an L-band EDF and 2) a HNL-DSF with a higher nonlinear coefficient was used as a parametric gain medium.

Fig. 3 (b) 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.

4. Conclusion

In conclusion, we demonstrated an all-fiber CW FOPO with SLM operations. The tuning range of the FOPO is from 1487 nm to 1541 nm and from 1570 nm to 1630 nm, which is as wide as 114 nm, with a wavelength span of 143 nm. The short-term 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 non-conventional wavelength bands.

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6. References