Front. Optoelectron. 2013, 6(1): 25–29
DOI 10.1007/s12200-012-0303-9

REVIEW ARTICLE

Fiber optical parametric oscillator based on highly nonlinear dispersion-shifted fiber

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Abstract The development of fiber optical parametric oscillators (FOPO) based on highly nonlinear dispersion-shifted fiber is reviewed in this paper. Firstly, the background and motivation are introduced, and it is pointed out that the FOPO is promising to act as optical source in non-conventional wavelength bands. Subsequently, the context focuses principally on the problem of inherent multiple-longitudinal-mode characteristic of FOPO and the corresponding solutions to it. The primary technique is by locking the phase of multiple longitudinal modes. The first reported actively mode locked FOPO is also presented in this article. However, it is not probable to realize passively mode locked FOPO because of the random phase dithering of the pump required for suppressing stimulated Brillouin scattering. Furthermore, a regeneratively mode locked FOPO is demonstrated, which can generate wide band tunable radiation in non-conventional wavelengths. Besides mode locked FOPO, the single-longitudinal-mode FOPO is also introduced. Finally, potential future directions are discussed.

Keywords fiber optical parametric amplifier (FOPA), fiber optical parametric oscillator (FOPO), mode locking, single longitudinal mode

1 Introduction

Optical amplifier is a milestone invention, which has promoted the development of the long haul high-capacity optical fiber communications vastly. Early optical amplifiers include mainly doped fiber amplifiers and semiconductor optical amplifiers (SOAs). The fiber based amplifiers make use of rare-earth elements as the gain medium by doping the fiber core during the manufacturing process. The gain wavelength bands are dependent on the energy band structures of doped ions [1]. Usually, specific doped ions correspond to specific gain wavelength bands. Hence, it is not a kind of wavelength-agile amplification scheme. SOAs are another kind of amplifiers, which use a semiconductor to provide the gain medium. Basically, SOA is quite similar with a laser structure but simply eliminates the feedback segment. It has the same problems confronted by the doped fiber amplifiers.

Many new applications have emerged recently demanding the deployment of non-conventional wavelength-band optical sources. For example, biologic technologies have brought increasing requirement for new wavelength optical source. In addition, optics and photonics have been extended their applications in marine sciences and atmospheric physics [2]. All these applications have put forward the demand for optical sources emitting in non-conventional bands.

However, most of the state-of-the-art optical amplifiers and lasers operate in the conventional wavelength band and have been developed for long time by the corporations, universities and institutes around the world. It is not possible to develop new gain materials that can emit in the nonconventional bands. Instead of developing new band sources, the alternative method is to use nonlinear wavelength convertor, which adopts conventional optical sources as the pump to generate widely tunable coherent radiations in nonconventional bands.

Parametric amplifiers in optical fibers can afford wide bandwidth amplification in specific band according to the pump scheme [3]. To meet the phase matching condition, the pump wavelength is usually located in the vicinity of the zero-dispersion wavelength of gain fiber [4]. If the pump wavelength is located in a region of anomalous

Received December 5, 2012; accepted December 18, 2012

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dispersion, the phase matched wavelengths located symmetrically with respect to the pump are close to each other. If the pump is located in a region of normal dispersion, the phase matching wavelengths are relatively far apart [5]. The band widths of the phase matched wavelengths for pumping in the anomalous dispersion region are relatively wide. As a comparison, the phase matched wavelengths demonstrate pretty narrower bands and large detune from the pump when the pump is in the normal dispersion region [6].

If a feedback mechanism is introduced to fiber optical parametric amplifier (FOPA), it can be converted to an oscillator [7]. Since the gain bandwidth and wavelength region is very flexible according to the specific pump scheme mentioned above, oscillators based on parametric amplification in optical fibers promise to generate coherent radiation in unconventional wavelength bands.

To investigate parametric oscillators in optical fiber, the primary choice is to use the well-developed pump source with its wavelength in the traditional 1550 nm band. Thanking for the development of optical fiber communication technology, laser sources and amplifiers have been studied and developed comprehensively in this band. High power light sources in this band are very mature. The phase matching condition decides that the dispersion-shifted fiber is the good candidate for FOPA based on the above mentioned reason. The gain fiber with small core area and large refractive index contrast between the core and the cladding is preferred due to its large nonlinear coefficient. Recently technical advancement in fiber drawing can afford optical fibers with large nonlinear coefficient [8]. Hence, highly nonlinear dispersion-shifted fiber (HNL-DSF) is dominantly used in the investigation of fiber optical parametric oscillator (FOPO) as its rather large nonlinear coefficient means large optical parametric amplifier (OPA) gain through relative short length of fiber.

The most commonly used scheme is to pump HNL-DSF using a tunable laser seed source amplified by a high power Erbium-doped fiber amplifer (EDFA). The research in this field is classified into two categories: continuous wave (CW) pump scheme and pulsed pump scheme. In the CW case, the pump has only moderate power so that the fiber required is relatively long. Even as HNL-DSF is used, the fiber length is still up to 1 km [9]. In the pulsed pump case, tens of meters of the gain fiber is enough due to the high peak pump power [10].

Several kinds of feedback schemes have been proposed and investigated so as to construct FOPO. The most commonly adopted setups are based on a ring cavity configuration in which no additional feedback device is needed [11]. However, a primary difficulty with FOPO is that the cavity length is typically many meters long, so that the frequency spacing between the longitudinal modes is very small, typically in the order of MHz. As a result, it is difficult to make an intracavity optical filter to select and track a single frequency. Consequently multiple-longitudinal-mode oscillates in optical cavity simultaneously. Under ordinary circumstances, phases of these multiple longitudinal modes have random relationships, and, for CW oscillation beam, intensity shows random time variation [12]. To resolve this problem, either mode locking of longitudinal modes or single-longitudinal-mode oscillation is investigated. The following context discusses mainly on these two topics.

2 Mode locking of FOPO

2.1 Actively mode-locked FOPO

Different from doped fiber amplifier, FOPA does not have gain storage. In an early work, Becker et al. stated that mode locking of an optical parametric oscillator (OPO) was unlikely because of this reason [13]. Here, we prove that FOPO can be mode locked actively by inserting an intensity modulator in the cavity [12,14]. Experimentally, a segment of 400-m HNL-DSF is used as the parametric gain medium. It has a zero-dispersion-wavelength (ZDW) of 1554 nm and nonlinear coefficient of 14 $W^{-1} \cdot km^{-1}$. The accessory problem resulting from the high pump power launched into such a long HNL-DSF is the stimulated Brillouin scattering (SBS), which reflects a large portion of incident pump. The universal method to suppress SBS is to broaden the pump by introducing the phase dithering in it. The SBS can be suppressed by up to 30 dB [12]. Figure 1 shows the schematic diagram of the actively mode locked FOPO.

The basic idea of active mode locking is to introduce periodical loss modulation in the cavity. When the modulation frequency equals to the multiple of the longitudinal mode spacing, which is also called synchronization between the cavity and the modulation rate, stable mode locked pulse train can be generated. Once the synchronization is built up, every time when the cavity pulse passes through the intensity modulator, the modulator is in the status of pass. So the single pulse can have sufficient gain from the OPA process so as to overcome the cavity loss. Hence, the mode locking is built up. Figure 2 shows the repeated scan of the waveform of actively mode-locked pulse train when 10 GHz sinusoidal signal is applied to the modulator [12]. This work proves that mode locking of FOPO is feasible.

2.2 Passively mode-locked FOPO

One may ask if FOPO can be passively mode locked which is comprehensively investigated in fiber lasers. However, as previously mentioned, phase dithering has to be carried out to the pump in order to suppress SBS. When a pulse reenters the HNL-DSF after one round trip, it encounters the pump pulse with different phases. Consequently, the total phase shift in a round trip cannot be maintained to be

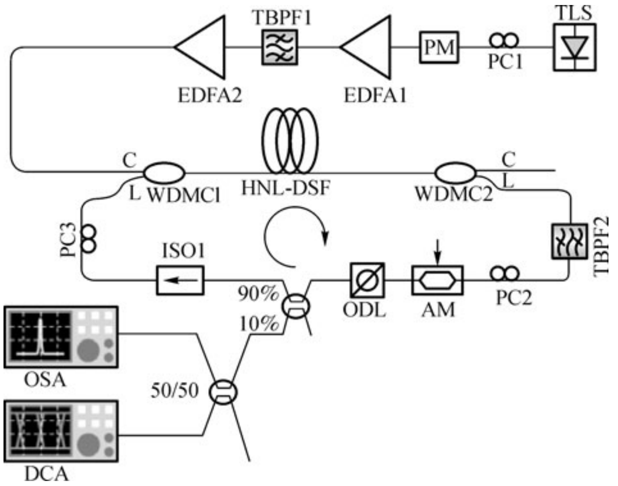

Fig. 1 Schematic diagram of actively mode-locked FOPO (Ref. [12]). TBPF: tunable band-pass filter, PM: phase modulator, PC: polarization controller, TLS: tunable laser source, WDMC: wavelength-division multiplexing coupler, ISO: optical isolator, ODL: optical delay line, AM: amplitude modulator, OSA: optical spectrum analyzer, DCA: digital communication analyzer

multiple of 2π which is essential for the mode locking. Our experiment also confirms that it is not probable to mode lock FOPO passively.

2.3 Regeneratively mode locked FOPO

The drawback of FOPO with CW pump is its relatively low pump power. The alternative scheme is to use optical pulse as the pump so as to get very high peak pump power. To build up the oscillation, the pump pulse train must be synchronized with intra-cavity pulse, as is called the regenerative mode locking [15]. In this case, the repetition rate of the pulse should be the multiple of the longitudinal mode spacing of the cavity. Since the OPA gain provided by the HNL-DSF is instantaneous and there is no gain storage, every time when the intra-cavity pulse enters the HNL-DSF, it must propagate through the fiber simultaneously with a pump pulse so as to obtain the OPA gain [16]. Due to the large peak pump power, the generated signal light can operate at wavelength far from the pump when the pump is located in the normal dispersion region [17,18]. Due to the large separation between the pump and the oscillating wavelength, walk off would occur as consequence of their difference in group velocities because of the dispersion of gain fiber. Hence the gain fiber is shorter than that of the CW pump case. Experimentally only 50-m HNL-DSF is enough for sufficient OPA gain. In the experimental setup, an intra-cavity tunable optical delay line is used to adjust the cavity length so as to synchronize with the pump pulse train [18]. Different from the actively mode locked FOPO, intra-cavity optical filter is not necessary to select oscillating wavelength. Since it requires rigorous synchronization between the pump and the signal pulses, the cavity can select the oscillating wavelength adaptively with the effect of the intra-cavity dispersion. This characteristic can be utilized to realize wavelength tunability. Once the oscillation is built up, the rigorous synchronization between the pump and the signal pulse is realized. If a small detune is introduced intendedly, the cavity can adaptively select a different oscillating wavelength to insure the synchronization to be built up again based on the function of cavity dispersion. Either the cavity length or the repetition rate of the pump pulse can be adjusted to introduce detune and the synchronization can be built up again at new wavelength instantaneously. Figure 3 shows the tunability of FOPO simply by adjusting the cavity length. The generated signal can be tuned from 1413.5 to 1478.0 nm and the idler can be tuned from 1610.1 to 1695.8 nm. It can be observed that the generated wavelengths are in the nonconventional wavelength band.

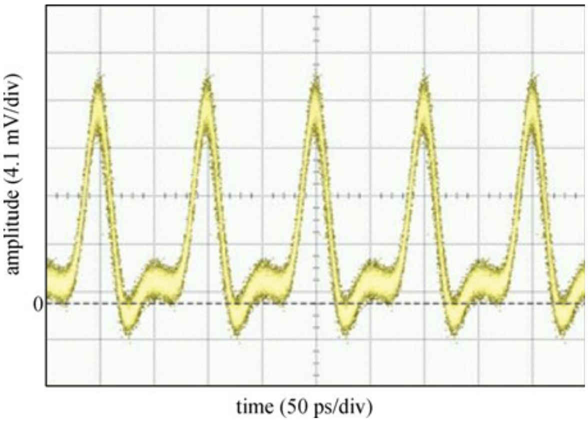

Fig. 2 Generated pulse train from actively mode locked FOPO (Ref. [12])

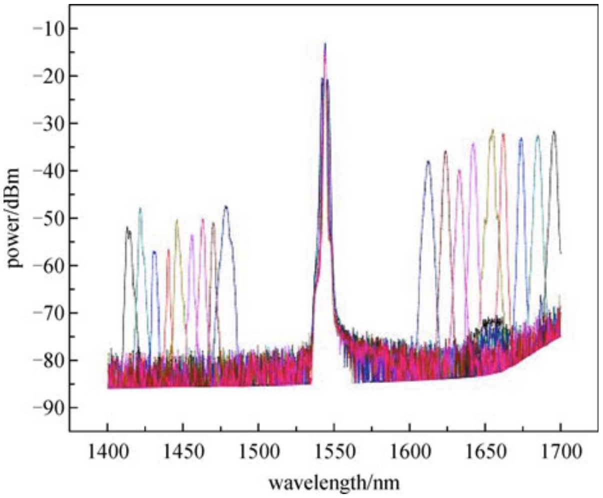

Fig. 3 Tunability of FOPO with HNL-DSF pumped at 1544 nm (Ref. [18])

3 Single longitudinal mode FOPOs

Besides mode locking technology, the alternative method to resolve the inherent multiple-longitudinal-mode problem is to allow only single longitudinal mode to oscillate [19,20]. Because of the long cavity length, the spacing between the adjacent longitudinal modes is at the level of MHz or even KHz. So it is not possible to find a commercial optical filter to filter out only single longitudinal mode. The indirect solution is to broaden the longitudinal modes spacing. First, several coupled subcavities are inserted into the main cavity of FOPO as shown in Fig. 4. Subsequently, an ultra-narrow band optical filter based on a loop mirror composed of an unpumped Erbium-doped fiber (EDF) is inserted. In the fiber loop mirror, two counter-propagating waves form a standing wave and induce spatial-hole burning (SHB) in the unpumped EDF. The refraction index of the unpumped EDF changes spatially due to the SHB and this results in an ultra-narrow bandwidth self-induced fiber Bragg grating (FBG) [21]. Moreover, the transmission band of the ultra-narrow band filter can dynamically track the oscillating wavelength of FOPO. Eventually, it is competent for the loop mirror to pass a single longitudinal mode since the broadened longitudinal modes spacing exceeds the bandwidth of the loop mirror filter. By this way, the single-longitudinal-mode oscillation can be built up successfully. The single-longitudinal-mode oscillation can be confirmed experimentally by using a self-homodyne method. Figure 5 shows the measured electric spectrum from a self-homodyne measurement. No beating signal can be observed so that single-longitudinal-mode is obtained.

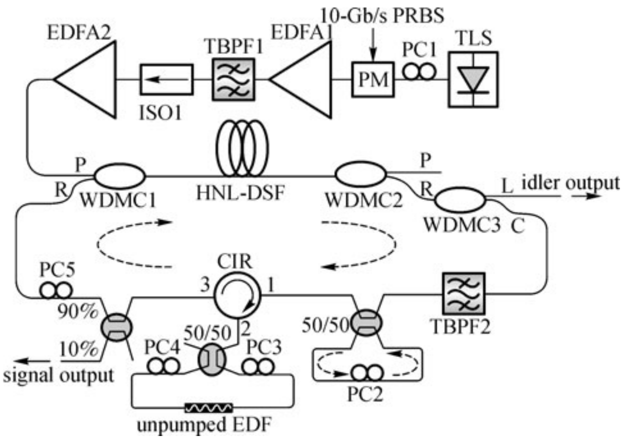

Fig. 4 Schematic setup of single-longitudinal-mode FOPO (Ref. [19]). PRBS: pseudo-random binary sequence

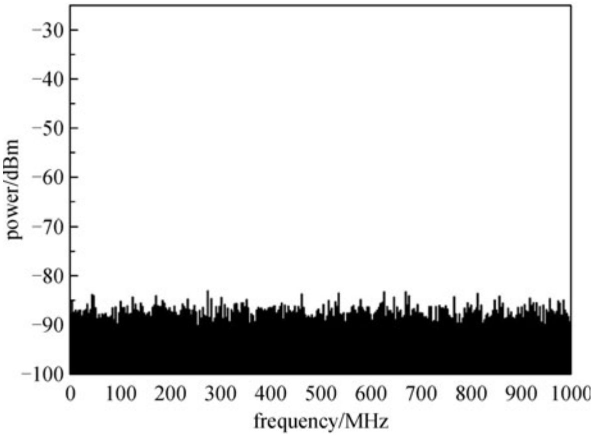

Fig. 5 Measured self-homodyne spectrum (Ref. [19])

4 Future directions

So far, we introduce FOPOs with the traditional fiber based on the doping technology as the gain medium. As mentioned previously, the dispersion profile of the fiber is critical to the phase matching required for the buildup of OPA. However, the traditional fibers based on doping cannot have flexible dispersion characteristics due to its small refractive index contrast and limited parameters to be customized. The advent of photonic crystal fibers (PCFs) has changed the situation. Compared with the traditional fiber, PCFs have more complicated structures which result in greatly enhanced design freedom. It can realize nearly arbitrary dispersion profile. It is possible to obtain zero-dispersion wavelengths in the visible or near infrared region, very far from the intrinsic material value of fused silica (around 1.3 μm) [22]. Theoretically, FOPO based on PCFs as the gain medium can generate coherent radiation at any wavelength from visible to mid-infrared band. We are looking forward to investigating the FOPO based on photonic crystal fibers.

Acknowledgements The authors are grateful to the research group of Prof. Kenneth K. Y. Wong at The University of Hong Kong for their unselfish contribution to this paper. They are also grateful for the supports from the National Basic Research Program of China (973 Program) (No. 2010CB327606), the National Nature Science Foundation of China (Grant No. 61108007) and the Opened Fund of the State Key Laboratory on Integrated Optoelectronics.

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