Progress In Electromagnetics Research, Vol. 167, 11–17, 2020

Generating Picosecond Pulses with the Largest Number of Lasing Wavelengths by an All-Fiber Optical Parametric Oscillator

Xiaogang Jiang[1, 2], Feihong Chen[1, 2], Yi Lu[1], Taoce Yin[1], and Sailing He[1, 2, *]

Abstract—An all-fiber parametric oscillator which is pumped by a mode-locked Er-doped picosecond fiber laser is proposed for the generation of multi-wavelength picosecond lasing pulses. The length of a fiber-coupled optical delay line is adjusted so that the first signal wavelength is tuned closer to the pump wavelength to facilitate the generation of more lasing wavelengths. 10 orders of cascaded four-wave-mixing processes are achieved and picosecond pulses at 17 lasing wavelengths from 1264.7 nm to 1842.4 nm are demonstrated. To the best of our knowledge, this is the largest number of lasing wavelengths reported so far from a fiber optical parametric oscillator pumped with an ultrashort-pulse laser.

1. INTRODUCTION

Multi-wavelength fiber lasers (MWFLs) have attracted considerable attention because of their applications in, e.g., optical fiber sensors [1], microwave photonics [2] and spectroscopy [3]. However, the wavelength ranges of MWFLs, which use rare earth ions doped fibers as gain media for stimulated emission, are limited within the fixed wavelength ranges of gain, for example, 1–1.1 μm for Yb-doped fibers, 1.5–1.6 μm for Er-doped fibers, and 1.8–2.1 μm for Tm-doped fibers. Furthermore, MWFLs based on rare earth ions doped fibers are not easy to achieve stable lasing operation due to the homogeneous broadening property. For stable operation, additional techniques are needed to suppress the mode competition [4–6]. By contrast, fiber optical parametric oscillators (FOPOs) based on the principle of parametric amplification, which use passive highly nonlinear fibers (HNLFs) as gain media, can generate lasing wavelengths that existing rare earth doped fibers cannot provide. Furthermore, FOPOs exhibit inhomogeneous broadening property, and the four-wave-mixing (FWM) effect can ensure the self-stability of multi-wavelength lasing [6, 7].

So far, most of the multi-wavelength fiber optical parametric oscillators (MWFOPOs) were pumped by continuous wave lasers with different kinds of comb filters added inside the FOPO cavities [7–9], while MWFOPOs pumped with ultrashort-pulse lasers were seldom reported. Recently, a 1064 nm picosecond pulsed laser pumped MWFOPO that can support 8 orders of cascaded FWM processes was demonstrated [10]. However, this MWFOPO cavity comprises many free space devices, and consequently is complex and unstable for long term operation. In this paper, a 1550 nm picosecond pulse laser pumped MWFOPO of all-fiber type is proposed. We achieve 10 orders of cascaded FWM processes and picosecond pulses at 17 lasing wavelengths from 1264.7 nm to 1842.4 nm.

2. MWFOPO SYSTEM AND RESULTS

The experimental setup of the all-fiber MWFOPO system includes 3 modules: (1) a mode-locked erbium-doped fiber laser, (2) a fiber amplifier, and (3) an FOPO cavity, as shown in Fig. 1. Each part will be described below.

Received 13 January 2020, Accepted 17 February 2020, Scheduled 17 February 2020

* Corresponding author: Sailing He (sailing@zju.edu.cn).

[1] Centre for Optical and Electromagnetic Research, National Engineering Research Center for Optical Instruments, Zhejiang University, Hangzhou 310058, China. [2] Ningbo Research Institute, Zhejiang University, Ningbo 315100, China.

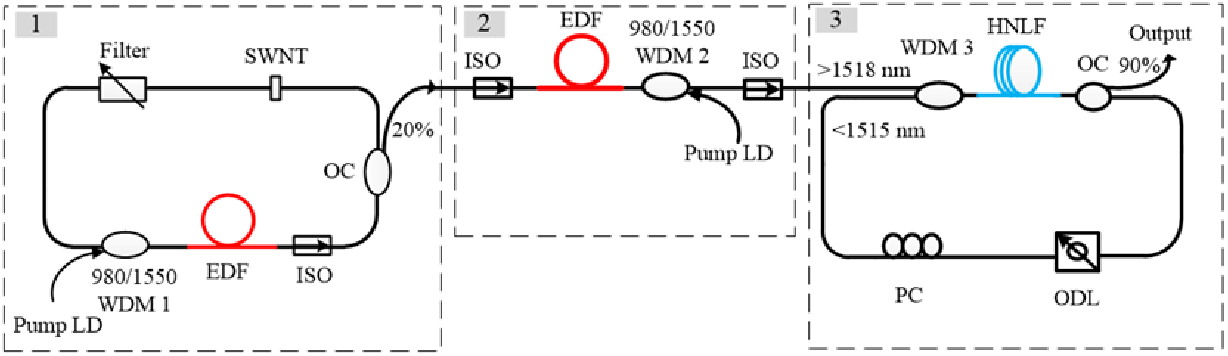


Figure 1. Schematic diagram for the proposed all-fiber MWFOPO system.

The mode-locked erbium-doped fiber laser was designed to generate picosecond laser pulses at 1550 nm band. It has a ring cavity structure and utilizes single wall carbon nanotube (SWNT) film as a saturable absorber [11, 12]. A segment of erbium-doped fiber (EDF) is used as the gain medium, and pumped by a 976 nm laser diode (LD) through a 980/1550 nm wavelength division multiplexer (WDM). An isolator (ISO) ensures unidirectional propagation and an optical coupler (OC) outputs 20% of the laser power from the cavity. A 1 nm band-pass filter with a central wavelength of 1550 nm is used to limit the spectral width for the generation of picosecond lasing pulses. The total cavity length is ~ 9.2 m, which corresponds to a pulse repetition rate of 22 MHz. Self-started single-pulse mode locking was achieved at a pump power of 62 mW. For a stable single-pulse operation, the pump power was fixed at 70 mW with the output of 2.1 mW 1550 nm lasing pulses. Then, the pulses were injected into a fiber amplifier which was backward-pumped by a 976 nm LD. The maximum laser power output from the amplifier is 116 mW. As shown in Fig. 2(a), the laser spectrum is centered at 1550.6 nm with a full width at half-maximum (FWHM) of 0.46 nm. The FWHM of the autocorrelation trace is around 10.4 ps, which means the pulse width is about 6.76 ps if a sech^2 pulse profile is assumed as shown in Fig. 2(b).

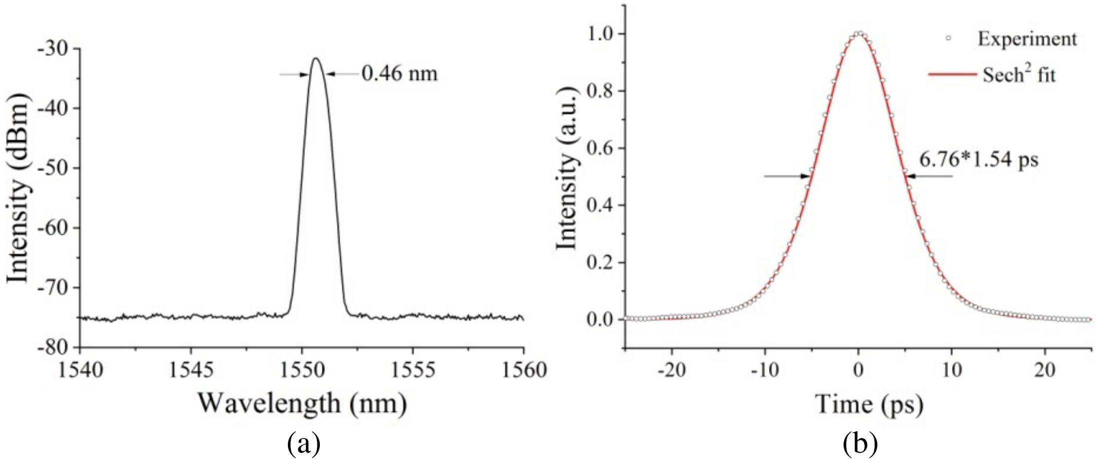
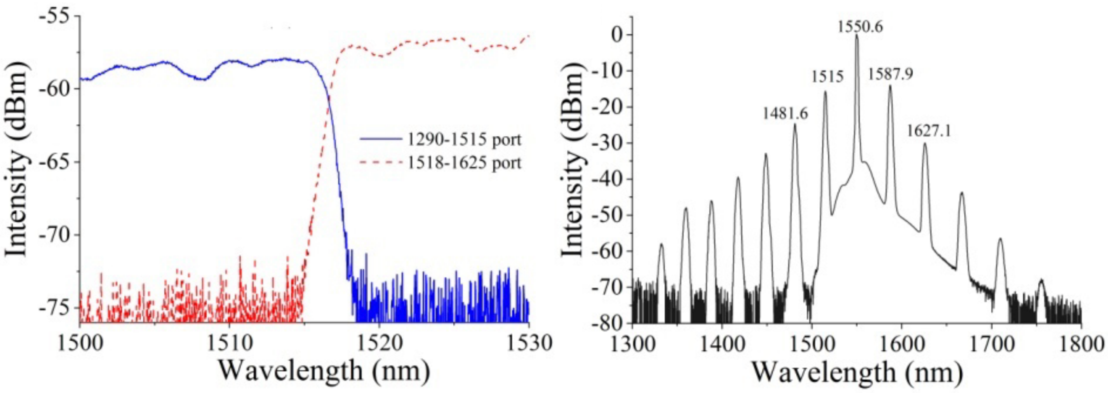


Figure 2. Characteristics of the mode-locked erbium-doped fiber laser. (a) Optical spectrum, and (b) autocorrelation trace measurement and sech^2 fitting curve.

The FOPO cavity comprises a WDM3, a 4 m-long HNLF, a 80/20 OC, a fiber-coupled optical delay line (ODL), and a polarization controller (PC). The transmission wave bands of the two input ports of the WDM3 are 1290–1515 nm and 1518–1625 nm, respectively, and the spectra near the cut-off region are shown in Fig. 3(a). The long wavelength port couples the 1550 nm pump laser into the FOPO cavity and only the signal (anti-Stokes) waves can pass through the short wavelength port to circulate in the



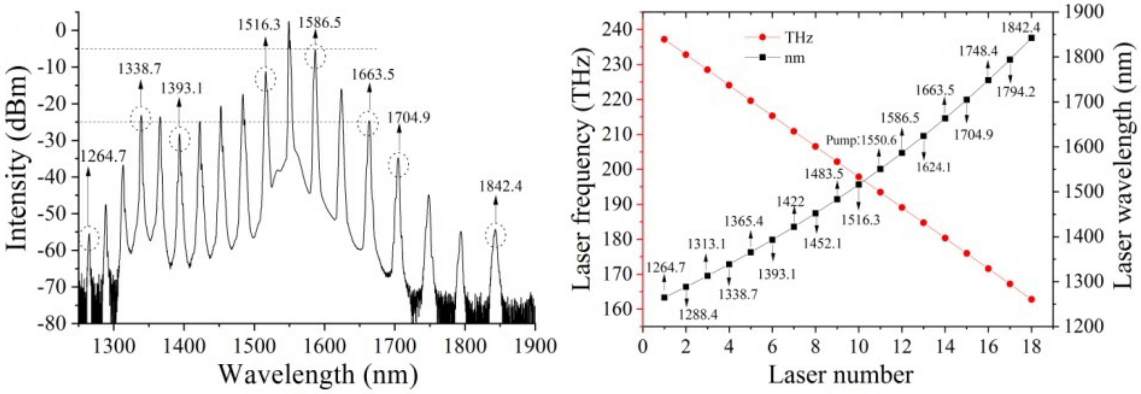
(a) (b)

Figure 3. (a) The transmission wave band of the two input ports of the WDM3. (b) FOPO output spectrum when the input pump power is just at the threshold of 22 mW.

next round. Thus, the FOPO is only singly resonant with the signal light waves. The HNLF is used as the parametric gain medium, whose zero-dispersion wavelength (ZDW), loss coefficient, dispersion slope, and nonlinear coefficient are 1520 nm, 0.82 dB·km^{-1}, 0.015 ps·nm^{-2}·km^{-1}, 10.7 W^{-1}·km^{-1}, respectively. The 80/20 OC provides 20% feedback and 80% output. The PC is used to align the polarization of the fed-back signal with that of the incoming pump pulse. The total length of the FOPO cavity is ~ 9.2 m and can be adjusted within 2.5 cm by tuning the ODL to synchronize the signal pulses with the pump pulses.

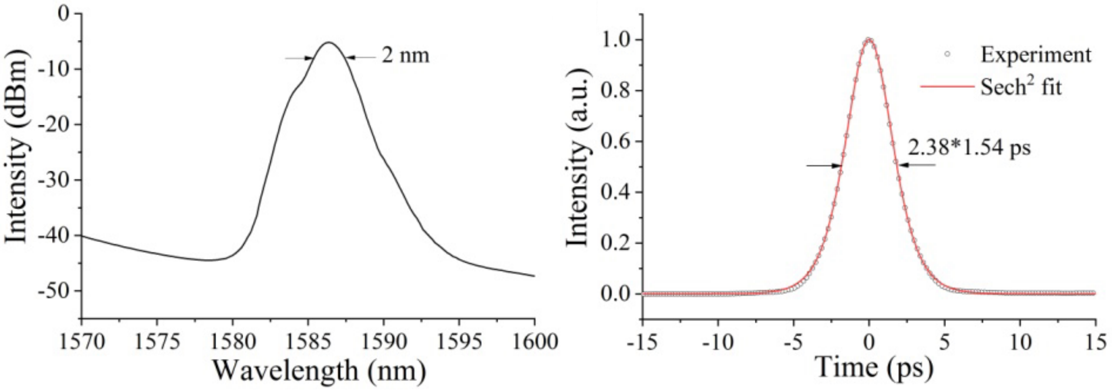
To generate more lasing wavelengths by utilizing cascaded FWM processes, the signal wavelength should be close to the pump wavelength. Thus we tune the ODL length to let the signal oscillate at 1515 nm, which has a threshold pump power of 22 mW (from measurement). The corresponding output spectrum is shown in Fig. 3(b). Firstly, degenerate FWM occurs, i.e., two pump photons at 1550.6 nm annihilate each other to generate a signal photon at 1515 nm and an idler photon at 1587.9 nm, which can be described by the energy conservation law ($2 \times h\upsilon_{\text{pump}} = h\upsilon_{\text{signal}} + h\upsilon_{\text{idler}}$, i.e., $\frac{2}{1550.6} = \frac{1}{1515} + \frac{1}{1587.9}$). It then follows with cascaded FWM processes, which lead to the generation of cascaded lasing wavelengths. For example, a signal photon at 1515 nm and a pump photon at 1550.6 nm annihilate each other to generate an idler photon at 1587.9 nm and a new photon at 1481.6 nm, which can be expressed as $\frac{1}{1515} + \frac{1}{1550.6} = \frac{1}{1587.9} + \frac{1}{1481.6}$. The cascaded FWM process continues on both sides of the pump laser until the cascaded laser power is lower than the FWM threshold. 7 orders of FWM on the shorter wavelength side of the pump and 5 orders on the other side can be observed once the FOPO starts oscillating. Since the ZDW (1520 nm) is closer to the signal wavelength, cascaded FWM processes are easier on the shorter wavelength side.

More cascaded lasing wavelengths (the existing wavelengths will remain) appear as the pump power increases. If we change the ODL length, the lasing wavelengths can also be tuned. We adjust the ODL length so that the first signal wavelength becomes closer (from 1515 nm to 1516.3 nm) to the pump wavelength (1550.6 nm) to facilitate the generation of more lasing wavelengths. As shown in Fig. 4(a), the first signal wavelength is tuned to 1516.3 nm through adjusting the ODL length, and 10 orders of FWM can be observed on the shorter wavelength side when we increase the pump power to 34 mW. Here, the first order signal wave at 1516.3 nm is 6 dB lower than the idler wave at 1586.5 nm. This can be explained as the FWM process between the signal and the pump is stronger than that between the idler and the pump, and consequently transfers more energy effectively from the first order signal to the idlers and the cascaded lasers as compared with the energy transferred from the first order idler to the signals and the cascaded lasers. As shown in Fig. 4(a), there are 17 lasing wavelengths in the range from 1264.7 nm to 1842.4 nm. The value of each lasing wavelength with the unit of nm is shown in Fig. 4(b), and the frequency spacing (with the unit of Hz) between any two adjacent lasing wavelengths (frequencies) is equal, which is about 4.36 THz (i.e., the frequency difference between the pump at 1550.6 nm and the signal at 1516.3 nm or the idler at 1586.5 nm). To the best of our knowledge, this is



(a) (b)

Figure 4. (a) FOPO output spectrum with the input pump power of 34 mW. The intensity difference between the two horizontal dotted lines is 20 dB. (b) The value of each lasing wavelength (with the unit of nm) or frequency (with the unit of Hz).



(a) (b)

Figure 5. (a) Detailed spectrum of the idler laser at 1586.5 nm; (b) Autocorrelation trace measurement of the idler laser and the sech^2 fitting curve.

the largest number of lasing wavelengths generated from an ultrashort-pulse laser pumped FOPO that has ever reported. The 11 lasing waves (excluding the pump) from 1338.7 nm to 1704.9 nm have an optical signal-to-noise ratio (OSNR) of > 30 dB. After passing through a band pass filter, the measured average power of the idler (the first order; at 1586.5 nm) is 5.5 mW. The intensity difference of the idler lasing wave (of the first order; at 1586.5 nm) and the rest 8 lasing waves from 1338.7 nm to 1663.5 nm (except the 1393.1 nm) is less than 20 dB (i.e., the intensity difference between the two horizontal dotted lines shown in Fig. 4(a)), which means the average power for each of these 8 lasing waves is higher than 55 μW. The intensity of each lasing wave will increase when the pump power increases further, but the OSNR will decrease at the same time since the increased nonlinear effects (self-phase modulation and cross-phase modulation between these lasers) will finally make the output spectrum to approach a supercontinuum. To increase the laser average power and keep a high OSNR at the same time, the pump pulse width should be further broadened in order to keep the laser peak power at a similar level. This can be realized by adding a chirped FBG (fiber Bragg grating) to stretch the 1550 nm pump pulse width to a few of tens of picoseconds. Fig. 5(a) shows the detailed spectrum of the idler laser at 1586.5 nm, which has an FWHM of 2 nm. The spectrum shows some slight deformation from a symmetrical shape, which may be the result of the accumulated ASE floor of the pump and nonlinear effects, such as the self-steepening effect. The autocorrelation trace of the idler is shown in Fig. 5(b), which indicates the

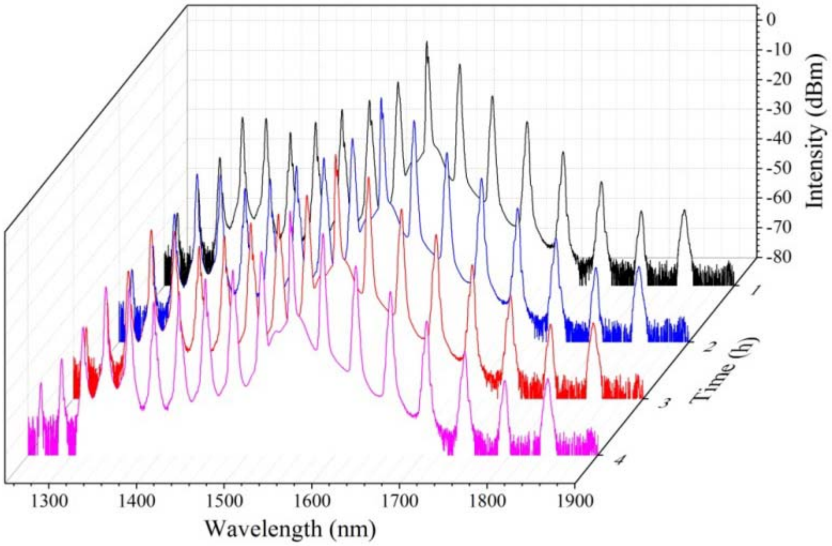


Figure 6. The stability of the FOPO output spectrum.

pulse width is 2.38 ps. The pulse width is shortened because only the central part (with higher intensity) of the pump laser pulses participate in the nonlinear parametric process.

To verify the stability of the FOPO, the output spectrum was recorded every one hour. As shown in Fig. 6, the output spectrum of the FOPO is quite stable without obvious change during four hours.

3. DISCUSSION AND CONCLUSION

Here we give a brief comparison between the MWFOPO we proposed and the Kerr frequency comb (KFC), which is also based on the degenerate FWM and cascaded FWM. In KFCs, one usually uses a continuous wave laser as the input pump and an ultra-high-Q microcavity [13–15] or a nonlinear fiber ring cavity [16] as a resonator. The formation of the frequency comb is similar to the MWFOPO: through the degenerate FWM two pump photons annihilate each other to generate the first pair of comb lines (i.e., the first order signal and idler). Then the signal, idler and pump produce higher-order comb lines through cascaded FWM, which ensures that the frequency difference between the pump and the first-order signal (or idler) is exactly transferred to all higher-order comb lines. Each comb line represents a longitudinal mode of the resonator cavity and the spacing between any two adjacent modes should be equal to the free spectral range of the resonator. These longitudinal modes can be locked to generate temporal cavity solitons [17]. For our MWFOPO, the frequency spacing (with the unit of Hz; 4.36 THz for the case of Fig. 4) between any two adjacent lasing wavelengths is also the same as the frequency difference between the pump and the first-order signal (or idler), which is a feature of cascaded FWM. Different from a KFC, each cascaded laser of the MWFOPO is a picosecond pulse laser, which means itself consists of many phase-locked longitudinal modes (the longitudinal mode spacing is 22 MHz, which is the free spectral range determined by the cavity length of the mode-locked erbium-doped fiber laser). The frequency difference between the pump and the first-order signal (or idler) is equal to the free spectral range of the resonator in a KFC. However, for our MWFOPO the frequency for the first-order signal is determined by both the phase-matching condition and the synchronization condition between the pump and signal pulses. The picosecond pulses at 17 lasing wavelengths output from the MWFOPO can be understood as 17 paralleled frequency combs of different central frequencies. That is to say the picosecond pulses at 1586.5 nm (∼ 189.06 THz) can be considered as a frequency comb centered at 189.06 THz with a comb tooth spacing of 22 MHz. In the same way, the picosecond pulses at another wavelength of 1624.1 nm (∼ 184.71 THz) can also be considered as a frequency comb centered at 184.71 THz with a comb tooth spacing of 22 MHz. The central frequency difference for any two adjacent paralleled frequency combs is ∼ 4.36 THz. However, our MWFOPO is pumped by the mode-locked pulsed fiber laser without any feedback control for the cavity length, which means the mode frequency spacing of the pump picosecond laser is not precisely controlled at 22 MHz, and thus the generated picosecond pulses at 17 lasing wavelengths can not be seen as true frequency combs. Note that a KFC can give more number of lasing wavelengths, however, with a much narrower frequency spacing. If one wishes to generate a new desired lasing wavelength at a very long or short wavelength from a commonly available 1550 nm laser, it would be more energy-efficient to reach the desired new wavelength by the present FOPO with several jumps of much larger frequency spacing, instead of a frequency comb with many jumps of small frequency spacing.

In conclusion, an all-fiber FOPO pumped with a 1550 nm picosecond pulsed laser has been proposed to generate picosecond pulses with the largest number of lasing wavelengths. Picosecond pulses at 17 lasing wavelengths from 1264.7 nm to 1842.4 nm have been demonstrated. Among them, 11 pulsed waves from 1338.7 nm to 1704.9 nm have an OSNR of > 30 dB. Further improvement can be focused on increasing the lasers output average power while keeping a high OSNR at the same time.

Funding

The work is partially supported by the National Key Research and Development Program of China (No. 2018YFC1407503), the National Natural Science Foundation of China (9183303, 11621101) and the Fundamental Research Funds for the Central Universities.

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