Optics Communications 425 (2018) 166–171

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A two-stage optical parametric amplifier for femtosecond fiber laser generation at 920 nm

Zhengru Guo [a], Qiang Hao [a,*], Kangwen Yang [a], Heping Zeng [a,b]

[a] Shanghai Key Laboratory of Modern Optical System, and Engineering Research Center of Optical Instrument and System, Ministry of Education, School of Optical Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

[b] State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China

A R T I C L E I N F O

MSC:
70.030
80.060

Keywords:
Nonlinear optics
Optical parametrical amplifiers
Optical fibers
Four-wave mixing

A B S T R A C T

We demonstrate a cascaded, two-stage, fiber-based optical parametric amplifier (OPA) in which the signal pulses are generated in the first stage via spontaneous degenerate four-wave mixing (DFWM) mechanism and subsequently are used as the seed pulse for the stimulated DFWM in the second stage. A compact femtosecond fiber laser provides the pump pulse with 220-fs duration at 20-MHz repetition rate. Large-mode area (LMA) photonic crystal fibers (PCFs) with zero dispersion wavelength at 1054 nm and a dispersion slope of 0.20 ps/km/nm^2 provide the parametric gain. Pulses with 2-mW average power in spectral range from 850 to 1000 nm are obtained from the first-stage OPA, and they are further amplified to 23.4 mW in the second stage OPA, corresponding to 10.7-dB parametric gain. The output pulse duration and spectral bandwidth are closely related to the temporal delay between the signal and pump pulses in the second stage. With an optimized time delay, pulses with >1 nJ energy and <200 fs duration are obtained at the spectral range from 850 to 1000 nm.

1. Introduction

Two-photon fluorescence microscopy (TPFM) is a powerful technique for deep tissue imaging and in vivo dynamic observation since the first demonstration in 1990 [1,2]. Traditionally, TPFM employs Ti:Sapphire (Ti:S) lasers as the light sources for practically clinical applications [3]. As commercially available Ti:S lasers are tunable in the wavelength range 690–1050 nm, they can excite most of the important fluorophores with ~20 nJ energy and <100 fs durations [4]. However, the bulky size, water-cooling style, and expensive cost of Ti:S lasers more or less hinder the worldwide applications beyond laboratories.

Owing to the compact size, low cost, free-maintenance, and good beam quality, fiber-based ultrafast lasers open an alternative way for TPFM. Up to now, fiber lasers have shown substantial practicability and great potential in applications such as coherent anti-Stokes Raman scattering (CARS) [5], second-harmonic generation (SHG) [6], and stimulated Raman scattering (SRS) [7]. For example, frequency-doubled Er-fiber lasers can provide as high as 6-nJ energy at 785 nm by using divided-pulse nonlinear amplification are the potential laser sources for TPFW at 780 nm and 1550 nm [8–10]. While for the wavelength range from 850 to 1000 nm regime, tunable Ti:S lasers are still the predominant optical sources. Recently, a mode-locked Nd:fiber laser operated in stretched-pulse regime are developed to produce pulse with less than 150 fs duration at 930 nm [11]. Unfortunately, the wavelength tunability of Nd:fiber laser is restricted by the gain bandwidth of the doped ions to 910–935 nm [12]. In other cases, the fiber based nonlinear mechanisms are effective ways to obtain pulses around 920 nm. A wider tunable range are demonstrated by applying the self-phase modulation (SPM) in photonic crystal fiber (PCF), generating ~100-fs pulses around the spectral band at 0.83, 0.88, 1.10, 1.15 and 1.21 μm [13]. This solution suggests an energy scalable approach such as increasing the input pulse energy and shortening the fiber length to optimize the group velocity dispersion (GVD) effect and nonlinearity in PCF. In addition, a suitable closing feedback-loop provides an optical parametric oscillator (OPO) and facilitates tunable pulse at moderate average power [14]. Dechirped by an external compressor, pulses with 30-nJ energy and 560 fs duration at 780 kHz repetition rate were obtained via the fiber based OPO, which can cover the wavelength from 867 to 918 nm. In our previous work, we demonstrated an all PM-fiber OPO system with tuning range from 965 to 1025 nm [15]. In optical parametric amplifier (OPA) systems, the wavelength tuning could be achieved either by controlling the temperature of PCF [16] or by changing signal wavelength [17].

* Corresponding author.
E-mail address: qianghao@usst.edu.cn (Q. Hao).

https://doi.org/10.1016/j.optcom.2018.04.040
Received 5 February 2018; Received in revised form 29 March 2018; Accepted 16 April 2018

In this paper, we present a fiber-based two-stage OPA which consists of a compact home-made 1064-nm femtosecond Yb-doped fiber laser acted as the pump source and two segments of PCFs to optimize the parametric gain and GVD. Simulation and experiment both show that the wavelength tunability of the first-stage OPA covers 900 to 1000 nm. The central wavelength of the blue-shift peak depends on the coupled pump power. In the second stage OPA, pulses with 2-mW average power from the first-stage are further amplified to 23.4 mW, corresponding to 1-nJ pulse energy. Moreover, average power and spectral profile of the pulses delivered by the OPA were both relevant to the pulses interval between signal and pump lasers.

2. Experimental setup

Fig. 1 illustrates the schematic of our experimental setup. The fiber-based OPA was assembled right at the output port of a home-made femtosecond fiber laser which was employed as the pump laser source for OPA. Pulses with average power of 1.5 W were split by a polarized beam splitter (PBS). The splitting ratio could be easily controlled by rotating HWP1. In the first stage, signal pulses were generated by spontaneous degenerate four-wave mixing (DFWM) mechanism [18]. The laser pulses with horizontal polarization (pump pulses A) were directly coupled into a segment of PCF (PCF1: NKT photonics, LMA-PM-5) with 54% efficiency via an aspheric lens (6-mm focal length, 0.21 numerical aperture). The length of PCF1 was set to 9 cm with consideration of optimizing the combined effect of nonlinearity and dispersion. While the laser pulses with vertical polarization (pump pulses B) were prepared for the second stage. To improve the coupling efficiencies and prevent end-facet damage, the input ports of the PCFs were spliced to the PM fiber pigtail of FC/APC connectors. The splice loss between FC/APC connector and PCF was optimized to as low as 1.6 dB [19]. Limited by the length of clamps in the PM fusion splicer, the shortest length of the PM fiber pigtail is ~8 cm. In the second stage, the signal pulses and pump pulses were spatially combined by a dichroic mirror (DM) and temporally synchronized through a delay line. Although the PCF2 with a length of 8.7 cm was processed similarly as PCF1, the coupling efficiencies for the signal pulses and pump pulses B were 13% and 40%, respectively. The degraded coupling efficiency is mainly resulted by the unmatched divergences angle of two beams.

The home-made femtosecond laser source consisted of an Yb-doped fiber picosecond pulse oscillator, a succeeded fiber amplifiers, and the related electronic devices. The cavity of picosecond oscillator was built in Fabry–Pérot type, which employed a semi-conductor saturable absorber mirror (SESAM) and a fiber Bragger grating (FBG) with 0.2 nm reflection bandwidth and 99% reflectivity acting as the two end mirrors. Mode-locking could be initiated by increasing the pump power to a certain threshold. With a repetition rate of 20.7 MHz and a central wavelength of 1063.8 nm, the temporal and spectral widths of the seed pulses are 7.4 ps and 0.06 nm, respectively [see Fig. 2(a)]. The fiber amplifiers, which consists of a single mode fiber (SMF) amplifier and a double-cladding fiber (DCF) amplifier, were established to boost the pulses to an average power of 15 W. As the spectral bandwidth of seed pulse was too narrow to support femtosecond pulse, a segment of SMF was introduced between the two amplifiers to broaden the spectrum by SPM. Fig. 2(a) reveals that the spectrum of seed pulse is broadened to 17 nm after the stretching fiber. At the end of DCF amplifier, a transmission grating pairs with a line density of 1200 l/mm compressed the pulse to 220 fs temporal duration with 66% total efficiency. The autocorrelation trace of the dechirped pulses is depicted in Fig. 2(b). Theoretically, the 17-nm spectral width is able to supporting 100-fs pulses at 1064 nm. However, the accumulated high-order dispersion and high-order nonlinearity combined to limit the pulse duration which are ~2 times larger than the transform-limited duration. All fibers in this laser source are polarization-maintaining. The whole fiber chain, the laser diodes which provide the pump lasers for the fiber laser, and the related electrical driver were compacted in an aluminum box with dimensions of $382.5\times320\times123$ mm^3 (marked as Femtosecond fiber laser in Fig. 1).

3. Results and discussions

For a better understanding of DFWM process inside PCFs, we performed both numerical simulations and experiments. Fig. 3(a) shows the cross section of LMA-PM-5 with high resolution. The air holes have a diameter $d = 1.22 \pm 0.24$ μm, and a pitch distance $\Lambda = 3.25 \pm 0.5$ μm. Thus, the d/Λ ratio is estimated to be 0.36 ± 0.11. With 60 air holes hexagonally surrounding the silica core, the PCF we used has a core diameter of 5.0 μm and a mode-field diameter (MFD) of 4.2 μm at 1064 nm. Such an engineered microstructure enables the PCF supporting the fundamental mode propagation over a broad wavelength range. The nonlinear parameter γ, which could be quantified as $\gamma = n_2\omega_0/(cA_{eff})$, was calculated as $\gamma\sim10$ W^{-1} km^{-1} at 1064 nm. Fig. 3(b) shows the dispersion curve of the PCF. The calculated zero dispersion wavelength (ZDW) and the dispersion slope is 1054 nm and 0.20 ps/km/nm^2. Derived from the dispersion curve, the GVD parameter β_2, third-order dispersion (TOD) parameter β_3, and higher-order dispersion parameter β_4 and β_5 are calculated to be 0.67 ps^2/km, 6.9×10^{-2} ps^3/km, 1.1×10^{-4}ps^4/km, and 2.7×10^{-7}ps^5/km, respectively.

To gain physical insight of the nonlinear spectral broadening inside PCF, we numerically investigated FWM process. Generally, the coupled nonlinear Schrödinger equations (NLSEs) were employed to solve the pulse propagation in OPA system [20,21]. However, only pump laser was involved in our first stage OPA. The generalized nonlinear Schrödinger (GNLS) equation would be practical and efficient to run the simulation [22].

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A + \sum_{n\geq2}\frac{i^{n+1}}{n!}\beta_n\frac{\partial^n A}{\partial T^n} + i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial T}\right) \times A\int_{-\infty}^{\infty}R\left(T'\right)\left|A\left(z,\,T-T'\right)\right|^2 dT',$$

where $A = A(z,t)$ is the complex amplitude envelope of the ultrashort pulses, α is the loss coefficient, β_n denotes the dispersion coefficient at pump frequency ω_0. Taking into account of fiber loss, dispersion, SPM, self-steeping, optical shock formation and stimulated Raman scattering on the right-hand side, this equation was commonly used to fulfill a simulation study on the propagation of ultrashort pulses inside optical fibers.

In view of very short length of PCF, we set the fiber loss coefficient $\alpha\sim0$ dB/km. Other parameters of the fiber are chosen in good accordance with the experimental conditions. The dispersion curve of the PCF was import into the software to specify the dispersion parameters instead of the Taylor expansion of the mode-propagation constant β. The nonlinear parameter γ was set to 10 W^{-1} km^{-1}. Pulse with 220-fs temporal duration, 17-nm spectral width (corresponding to a 100-fs transform-limited pulse with certain 1600-fs^2 GDD and 6850-fs^3 TOD) was applied as the pump laser.

Firstly, we simulated the pulse evolution in the PM-fiber which has a mode field diameter (MFD) of 7 μm and a nonlinear parameter $\gamma\sim3.5$ W^{-1} km^{-1}. The PM fiber pigtail has a dispersion coefficient of −40.56 ps/nm/km with a slope efficiency of 0.19 ps/km/nm^2 at 1064 nm. As in normal dispersion regime, pulse with 220-fs duration and 10-nJ energy at 1064 nm will be stretched to 280-fs in 80-mm PM fiber pigtail. Therefore, this PM fiber pigtail has little effect on DFWM, but improving the coupling efficiency and preventing the end face damage.

To choose an appropriate PCF length for FWM process, we initially set the length of the PCF to 124 mm and the incident pulse energy to 10 nJ in the simulation. Fig. 4 shows the output spectrum evolution versus PCF length. The evolution process could be divided into three segments according to the lengths of 60, 25, 39 mm, respectively. In the first segment, SPM induced phased-matched FWM plays dominate role. As we known, the FWM is very efficient when the pump wavelength is located close to the ZDW in the anomalous dispersion regime. However, when the pump wavelength deviates 10 nm from ZDW (from 1064 to 1054 nm), the phase shift caused by dispersion is possible to be compensated by nonlinearity. New frequency components were