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Generation of all-fiber ultrafast pulses at 2 μm by soliton self-frequency shift in highly nonlinear silica fiber

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Abstract

An efficient and straightforward method to obtain all-fiber pulsed sources at 2 μm is presented and experimentally demonstrated. It is based on the soliton self-frequency shift effect in a highly nonlinear fiber. The output power of a supercontinuum source is previously increased by an optimized homemade thulium-doped fiber amplifier. By coupling the amplified output power in a highly nonlinear fiber, the spectrum is shifted toward 130 nm and the spectral peak is located at 2014 nm. The power conversion factor reaches values as high as 0.93, without employing additional amplifiers. The mean spectral power of the 2 μm source reaches -4.6 dBm/nm (0.35 mW/nm), its output power is 38 mW and the peak power of each pulse is higher than 27 kW. © 2020 Optica Publishing Group

1. Introduction

In the last years, ultrafast fiber laser sources operating at 2 μm have been one of the highlighted topics in Optics due to their high number of applications in a wide range of different scientific areas, such as biomedicine, materials science, spectroscopy and laser detection. In fact 2 μm laser sources are a perfect tool for several kinds of surgeries as for instance, lithotripsy (urinary stone fragmentation) or cardiology injuries [1], due to two reasons. Firstly these ultrashort pulses provide a high intensity in a wide spectral range, which matches with one of the water absorption peaks (due to the energy vibrational levels associated to OH bonds). Moreover, it is also necessary to consider the clotting effect produced by means of laser ablation. In relation to materials science, infrared (IR) lasers have been used to cut, weld or tag polymers since the early 90s leveraging an optimum absorption near 2 μm even without additives [2]. It is not exclusive to polymers, processing studies of semiconductor wafers composed of silicon (Si) or gallium arsenide (GaAs) have recently been carried out [3]. Another of their applications is the monitoring of gases in the atmosphere, as for instance, CO_2 and H_2O, which present absorption lines around 2 μm [4].

In order to obtain ultrashort all-fiber sources at 2 μm, several methods have been reported. A first approach lies in using a mode-locking pulsed laser with thulium doped fiber (TDFL) based on different techniques i.e. nonlinear polarization effect (NPR) [5], saturable absorber [6] or nonlinear mirror [7]. Nevertheless, these paths do not usually reach enough power at 2 μm and their spectrum is relatively narrow (less than 10 nm).

A very versatile technique is based on the generation of a supercontinuum (SC) spectrum with a mode-locked fiber laser by means of a highly nonlinear fiber (HNLF) [8], however its great spectral width limits its output mean power. A clear solution lies in raising the output mean power by means of an optical amplifier operating at 2 μm. In particular a thulium-doped fiber amplifier (TDFA) can be used, since the ion Tm^{3+} can be pumped at the 1650 nm band [9], allowing the design of all-fiber devices [10,11] which are compact, stable, and lightweight. However, its shortcomings are to notably increase the output power around 2 μm because the 2 μm gain is usually low, since, as the input pulses have a high enough peak power, the spectral gain peak is found far away (around 1.85 μm). Therefore, it is fundamental to find some technique that increases the mean power around 2 μm. In order to achieve this, some authors [12] include several prior amplification stages to the TDFA, which implies more complicated and more expensive setups. In this letter, it is demonstrated an alternative method for this purpose, which is based on the soliton self-frequency shift (SSFS) effect in a silica HNLF. This effect is originated from stimulated Raman scattering and it produces a spectral shift of the laser pulse towards larger wavelengths [13-16]. The input pulses in the HNLF sample are generated in other silica HNLF sample pumped with a mode-locked erbium laser and later amplified with a homemade TDFA. Thus, high power ultrashort pulses are obtained at wavelengths around 2 μm by employing a lower number of amplifiers, reducing the complexity of the setup, diminishing its price and increasing simultaneously its efficiency.

2. Experimental setup

The experimental setup is shown in Fig. 1. The thulium-doped fiber (TDF Nufern, model SM-TSF-9/125) is pumped by means of a continuous-wave (CW) laser (part (b)), which is built in ring cavity by an erbium-doped fiber amplifier (EDFA L20) with 20 dBm output saturation power (Keopsys, model KPS-BT2-L20-PB-FA), a 10/90 output coupler, an optical circulator and a fiber Bragg grating (FBG, Technica, λ = 1612.81 nm, Δλ = 0.25 nm at -3 dB) to select the wavelength laser at 1612.81 nm. The output power is raised by means of a second amplifier (EDFA L26) with 26 dBm output saturation power (Manlight, model HWT-EDFA-GM-SC-BO-L26). The TDF sample amplifies a pulsed SC source, which is formed by an ultrafast erbium-doped fiber laser (EDFL) and a silica HNLF sample (YOFC, model NL1016-B) [17]. The EDFL is pulsed by passive mode-locking based on the nonlinear polarization effect. The EDFL emits a 1.4 MHz pulse train. The energy of each pulse is 20 nJ, its temporal width is 0.18 ps and its peak power reaches 1.1 MW. The SC spectrum is extended from 1200 nm up to 2300 nm. The homemade TDFA is represented in part (a) of Fig. 1. The CW pump power and the SC pulses are coupled into the TDF by means of a 1600/2000 wavelength-division multiplexer (WDM). An optical isolator is placed in the amplifier output in order to avoid instabilities due to non-desired reflections. The length of the TDF sample is 1.1 m and it was adjusted to optimize the output mean power from 1.85 μm up to 2 μm. Finally, the state of polarization of the amplified output power is controlled by means of a polarization controller (PC, General Photonics, model Polarite PLC-003) in order to maximize the SSFS effect in the silica HNLF sample of 105 m length (YOFC, model NL1016-C). Typically, this model of HNLF has a negative dispersion of -4 ps/(nm km) at 1550 nm, but with a low positive dispersion slope (< 0.03 ps/(nm^2 km)). In consequence, it can be assumed that its zero-dispersion wavelength will be found beyond 1700 nm, facilitating that the amplified pulses generate nonlinear effects in the HNLF. Additional polarization controllers were not inserted in the experimental setup because it was experimentally verified that the TDFA gain is practically independent on the state of polarization of the pump power and the state of polarization of the SC pulses.

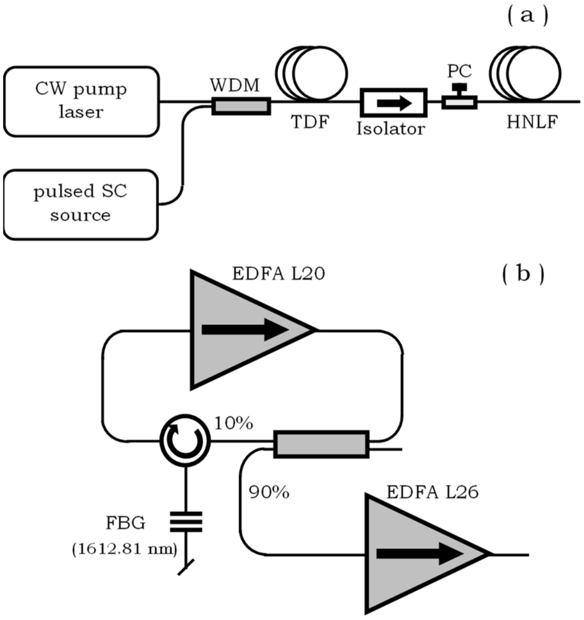

Fig. 1. Experimental setup (a) and CW pump laser (b). SC: supercontinuum, TDF: thulium-doped fiber, PC: polarization controller, HNLF: highly nonlinear fiber, EDFA: erbium-doped fiber amplifier, FBG: fiber Bragg grating.

3. Results and discussion

Input and output spectral mean powers to the TDFA are shown in Fig. 2. By coupling a 331 mW pump power, a high conversion efficiency as high as 0.21 was obtained since input and output mean powers were 21 mW and 89 mW, respectively. As it was expected, TDFA amplifies over a long wide spectral range (244 nm) from 1806 nm to 2050 nm and the output power gets to -3 dBm/nm (0.5 mW/nm) from 1830 nm up to 1930 nm. However, the TDFA output power only reaches -7.4 dBm/nm (0.2 mW/nm) around 2 μm, so the point is to rise it. Nevertheless, commercial diodes cannot be used because they provide typical output powers around 1 mW and with much lower spectral widths.

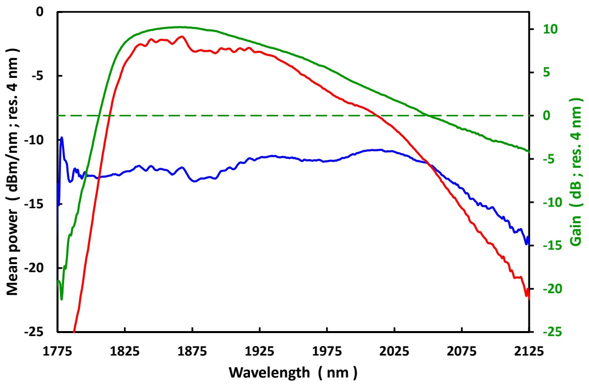

Fig. 2. Input mean power to the TDFA (blue line, left axis), power at TDFA output (red line, left axis), TDFA gain (green line, right axis).

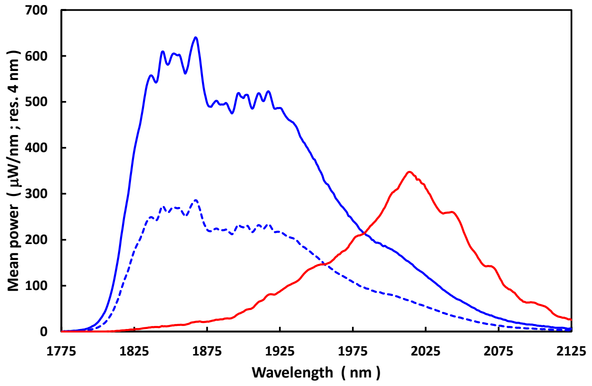

Fig. 3. Input spectral power in the HNLF (blue solid line), output spectral power in the HNLF with (red line) and without nonlinear effect (blue dotted line).

Input and output spectral mean powers in the HNLF sample are shown in Fig. 3. By carefully adjusting the state of polarization of the SC pulses amplified by the TDFA, a large spectral shift greater than 130 nm due to the SSFS effect is observed. In fact, the output mean power is maximum at 2014 nm, reaching -4.6 dBm/nm (0.35 mW/nm). Taking into account that the output power is 38 mW and the temporal width is lower than 1 ps, the energy and the peak power of each pulse will be higher than 27 nJ and 27 kW, respectively. Therefore, the spectral power around 2 µm is clearly improved by the HNLF. In Fig. 3 is also gathered the expected output power if the SSFS effect was not induced, assuming that the input power losses are 3.5 dB due to the two splices of the HNLF and the standard single-mode fiber (Corning, model SMF-28). This value was measured by fixing the state of polarization of the amplified pulses until the SSFS effect does not appear and it agrees with the measurement of power losses made with a low power source.

In order to analyze SSFS dependence on the pump power, input and output spectral mean powers in the HNLF sample were measured by coupling pump powers of 110 mW, 158 mW, 234 mW and 331 mW. In Fig. 4, it is shown the ratio between HNLF output and input powers. As it can be seen, the more pumping power is used, the greater induced nonlinear effect is observed. In addition, it was verified that the SSFS effect disappears without the gain that the TDFA provides, so that the amplifier performance is essential to generate this nonlinear effect.

On the other hand, the nonlinear power is generated from 1950 nm at the expense of the power coupled up to this wavelength. This nonlinear process is more efficient from 2000 nm up to 2100 nm and the wavelength with maximum efficiency raises with the pump power. Obviously, the lost power also grows with the pump power and the shorter wavelengths offer better efficiency. In fact, it would be preferable to get a higher power in wavelengths below 1800 nm. Unfortunately, the spectral gain of the amplifier falls sharply at 1800 nm due mainly to the WDM, which behaves as a high-pass filter whose cut-off wavelength is 1800 nm [18].

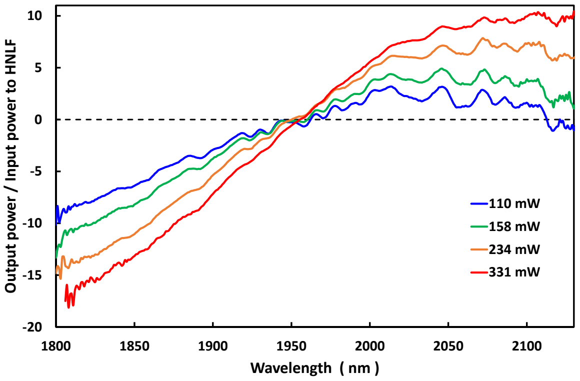

Fig. 4. Ratio between the output and input powers in the HNLF due to the SSFS effect.

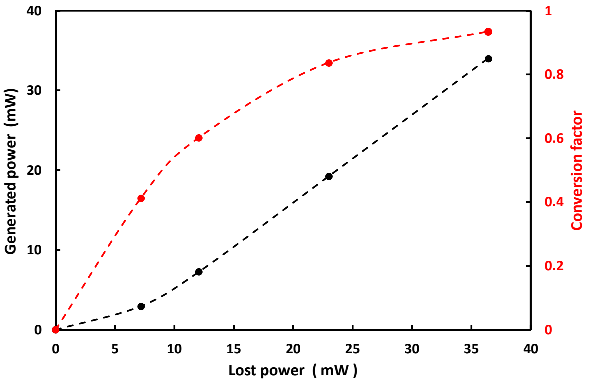

Fig. 5. Generated power (black, left axis) and power conversion factor (red, right axis) as a function of the lost power.

Finally, the lost power and the generated power due to the nonlinear effect are shown in Fig. 5. Both grow as the pump power is increased. The conversion factor is almost saturated for the highest pump power and reaches a value as high as 0.93.

4. Conclusion

In conclusion, an efficient method to obtain all-fiber pulsed sources at 2 μm has been experimentally demonstrated. The pulses of a SC source are amplified by means of a TDFA and coupled in a sample of highly nonlinear fiber. Due to the SSFS effect, a large spectral shift greater than 130 nm is obtained with a conversion factor as efficient as 0.93. In this way, the output mean power reaches -4.6 dBm/nm (0.35 mW/nm) at 2014 nm, the output power is 38 mW and the peak power of each pulse is higher than 27 kW.

Probably the main advantage of the proposed method is its simplicity compared to other reported solutions. However, it is interesting to carry out an analysis in depth of its advantages and disadvantages by means of the results obtained in this work with those obtained with others experimental setups. Nevertheless, it is quite difficult to make a fair comparison between different setups because too many parameters are involved (peak power, temporal width, energy, spectral width, peak wavelength etc.).

The proposed setup provides pulses with much higher peak power (27 kW) than the setups based on SC generation: 0.26 kW [8], 2.3 kW [10], and 0.79 kW [11], taking into account that these powers have been calculated by integrating over the spectral region from 1967 nm to 2058 nm. However, these setups have the advantage that they can be tuned in different spectral regions due to their high spectral width (several hundreds of nm).

On the other hand, in comparison with to the reported setups based on pulsed TDFL, our setup provides pulses with a higher average power (38 mW), whereas they obtain 6.5 mW [5], 23 mW [6] and 1 mW [7]. Moreover its spectral bandwidth is lower (6.8 nm [5], 52 nm [6] and 26 nm [7]) and therefore their tunning range is limited. Finally, the pulse energy (27 nJ) is also higher than the energy obtained by other setups, although it is lower than the 55 nJ of Ref.6 and much lower than the 2.3 μJ of Ref.11, since its TDFA is pumped with a power as high as 30 W.

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