A novel 2-μm pulsed fiber laser based on a supercontinuum source and its application to mid-infrared supercontinuum generation*

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A new method to achieve 2-μm pulsed fiber lasers based on a supercontinuum (SC) is demonstrated. The incident pump light is a pulsed SC which contains a pump light and a signal light at the same time. The initial signal of the seed laser is provided by the incident pump light and amplified in the cavity. Based on this, we obtain a 2-μm pulsed laser with pulse repetition rate of 50 kHz and pulse width of 2 ns from the Tm-doped fiber laser. This 2-μm pulsed laser is amplified by two stages of fiber amplifiers, then the amplified laser is used for mid-infrared (mid-IR) SC generation in a 10-m length of ZrF_4–BaF_2–LaF_3–AlF_3–NaF (ZBLAN) fiber. An all-fiber-integrated mid-IR SC with spectrum ranging from 1.8 μm to 4.3 μm is achieved. The maximal average output power of the mid-IR SC from the ZBLAN fiber is 1.24 W (average output power beyond 2.5 μm is 340 mW), corresponding to an output efficiency of 6.6% with respect to the 790-nm pump power.

Keywords: fiber laser, supercontinuum, mid-infrared, ZBLAN fiber

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1. Introduction

Broadband supercontinuum (SC) generation in optical fibers has been a hot research topic in the last few years. Visible and near infrared SC generation in silica photonic crystal fiber (PCF) has been widely demonstrated in many systems.[1,2] Recently, SC generation in the mid-infrared (mid-IR) region has increasingly become a focus for research. SC sources in the mid-IR spectral region may find many potential applications in spectroscopy, remote sensing, and biomedical surgery. There has been an increasing interest in using soft-glass materials (e.g., fluorides,[3–7] tellurites,[8,9] and chalcogenides[10–12]) for mid-IR SC generation due to their high nonlinearity and low transmission loss in the mid-IR region. More recently, 2-μm pulsed fiber lasers exhibited an excellent performance for efficient mid-IR SC generation.[5–7] Mode-locking and Q-switching are two general methods for pulsed laser generation, and both mode-locked and Q-switched 2-μm fiber lasers have been reported by a few groups.[13,14] Compared with mode-locking and Q-switching, the gain-switching method does not need mode-locked or Q-switched devices in the laser cavity and it can be an effective and simple candidate to obtain 2-μm pulsed lasers. Gain-switched operation of a Tm-doped fiber (TDF) laser by pumping with a 1.55-μm pulsed laser has been demonstrated in several systems.[15–17] However, gain-switched TDF lasers usually generate 2-μm pulses with pulse width ranging from several tens to several hundred ns.[15,16] Short pulses with high peak power are popular in nonlinear wavelength conversion applications. In order to reduce the gain-switched pulse width, a very short cavity length is needed. Such as in Ref. [17], a pulse width of 10 ns was measured from a gain-switched TDF laser with 25-cm cavity length.

In this paper, we report a new method to achieve 2-μm pulsed fiber laser. The system is similar to the gain-switching TDF laser, but in our experiment the incident pump light is a pulsed SC source with spectrum ranging from 1.5 μm to beyond 2 μm. The initial signal of the seed laser is provided by the incident pump light and amplified in the cavity. Based on this scheme, pulses with width of several ns can be generated even in a long laser cavity. We obtain a 2-μm pulsed laser with a pulse repetition rate of 50 kHz and pulse width of 2 ns from a TDF fiber laser with 7.5-m cavity length. In the mid-IR SC generation experiment, this 2-μm pulsed laser is used as a seed source and amplified by two stages of fiber amplifiers. Then the amplified laser is used for mid-IR SC generation in a ZBLAN (ZrF_4–BaF_2–LaF_3–AlF_3–NaF) fiber. An all-fiber-integrated mid-IR SC with spectrum ranging from 1.8 μm to 4.3 μm is achieved.

2. Experimental setup and basic idea

The experimental setup of the all-fiber mid-IR SC generation system is illustrated in Fig. 1. The seed source in Fig. 1 is a 2-μm pulsed fiber laser based on an SC source. The incident pump light of the seed source is a pulsed SC with spectrum ranging from 1.5 μm to beyond 2 μm. The initial signal of the seed laser is provided by the incident pump light (the pump light incident to gain fiber) and amplified in the cavity. This is the basic idea of the seed source; the foundation

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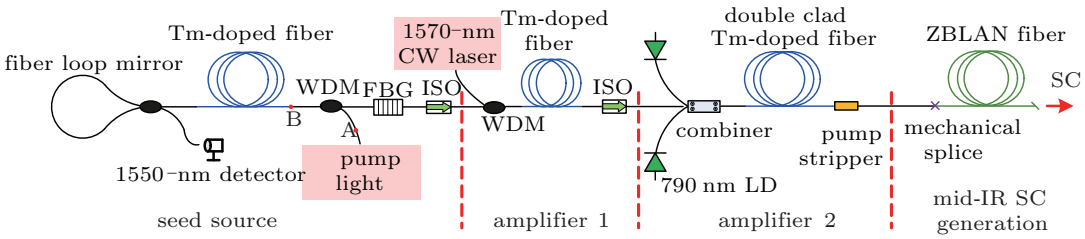


Fig. 1. (color online) Experimental setup of the mid-IR SC generation system.

process of the 2-μm pulsed laser will be discussed in detail in the following sections. In the seed source stage, the pump light is injected into a 2-m length of single mode TDF via a 1550/2000-nm wavelength-division-multiplexer (WDM). The TDF has a core/cladding diameter of 9/125 μm and an absorption coefficient of ∼ 10 dB/m at 1550 nm. The fiber Bragg grating (FBG) used in the experiment has a reflectivity of 50% at 1958 nm with 3-dB bandwidth of 2 nm. The other side of the cavity is ended by a high reflectivity fiber loop mirror based on a 50/50 fiber coupler. The total length of the laser cavity is about 7.5 m. It should be noted that the WDM in Fig. 1 is based on environmentally stable thin filter technology, and it can combine or separate light at different wavelengths over a wide range. The working wavelength ranges of the WDM for the pump and signal are 1400–1700 nm and 1800–2100 nm respectively.

Short pulses with high peak power are popular for the nonlinear wavelength conversion applications. In order to enhance the peak power of the 2-μm pulsed laser, the seed source is amplified by two stages of fiber amplifiers. Then, the amplified laser is used as the pump source for mid-IR SC generation in a 10-m long ZBLAN fiber. The first stage amplifier contains a 1.5-m length of TDF, which has a core/cladding diameter of 9/125 μm and an absorption coefficient of ∼15 dB/m at 1570 nm. The TDF is pumped in-core by an 800-mW CW fiber laser at 1570 nm through a WDM fiber coupler. In the second stage power amplifier, a 7-m length of double clad TDF is used as the gain medium with a core/cladding diameter of 10/130 μm, an effective core/cladding numerical aperture (NA) of 0.15/0.46, and a peak cladding absorption of ∼3 dB/m at 790 nm. A (2+1)×1 pump combiner is used to deliver the pump light to the gain fiber from two fiber-pigtailed multimode diodes with a total pump power of 18.8 W at 790 nm. The output of the double clad TDF is spliced to a single mode fiber, which has a 7/125-μm core/cladding diameter and a core NA of 0.2, allowing for convenient coupling to the ZBLAN fiber. The single mode ZBLAN fiber used in the experiment has a length of 10 m, a high NA of ∼0.27 and a core/cladding diameter of 8/130 μm. The single mode fiber is mechanically spliced to the input end of the ZBLAN fiber with angle-cleaves on both fibers to prevent reflections in the system. The mechanical splicing loss is about 27%.

In this paper, the spectra with range of 1380–1700 nm are measured by using an optical spectral analyzer (YOKOGAWA AQ 6370) and the longer wavelengths (> 1700 nm) are acquired using a monochromator and a liquid-nitrogen-cooled InSb detector. An InGaAs detector with < 50-ps rise time is used to measure the 2-μm output pulses of the seed source. At the output of the fiber loop mirror, a 1550-nm detector with 100-ps rise time is used to monitor the non-absorbed pump light. In seed source research, the pulse evolution of the 2-μm signal was monitored relative to the pump pulse on a fast digital oscilloscope (1.5-GHz bandwidth) with the pump pulse used as the trigger.

3. Results and discussion

3.1. A 2-μm pulsed laser generation based on an SC source (the seed source in Fig. 1)

3.1.1. The pump light of the seed source

Different from the previous reported gain-switched schemes,[15–17] where the pump light is a pulsed laser with narrow spectra, the pump light of the seed source in Fig. 1 is a pulsed SC source. The pump light has a pulse width of 6.6 ns and a pulse repetition rate of 50 kHz. The output spectra of the pump light with different average output powers of 318 mW, 430 mW, and 515 mW (measured at the splicing point of pump light and WDM, shown as point A in Fig. 1) are shown in Fig. 2(a). The spectrum of the pump light has been extended to 1700 nm at 515 mW output power. Thanks to the wide working wavelength range of the WDM in Fig. 1, most of the pump SC source can pass through the WDM. Furthermore, before the pump light is injected into the TDF through WDM, the spectrum of the pump light can further extend to longer wavelength in the pigtail fiber of WDM due to nonlinear effects. The spectra of the incident pump light (measured at the splicing point of WDM and TDF, shown as point B in Fig. 1) as a function of the pump power are shown in Fig. 2(b). The inset of Fig. 2(b) shows the long wavelength SC edge. By comparing with the spectra in Fig. 2(a), an obvious spectral extension can be seen in Fig. 2(b) under the same pump powers. When the power of the pump light is larger than 430 mW, the spectrum of the incident pump light has extended to beyond 2000 nm, which can be seen in Fig. 2(b).

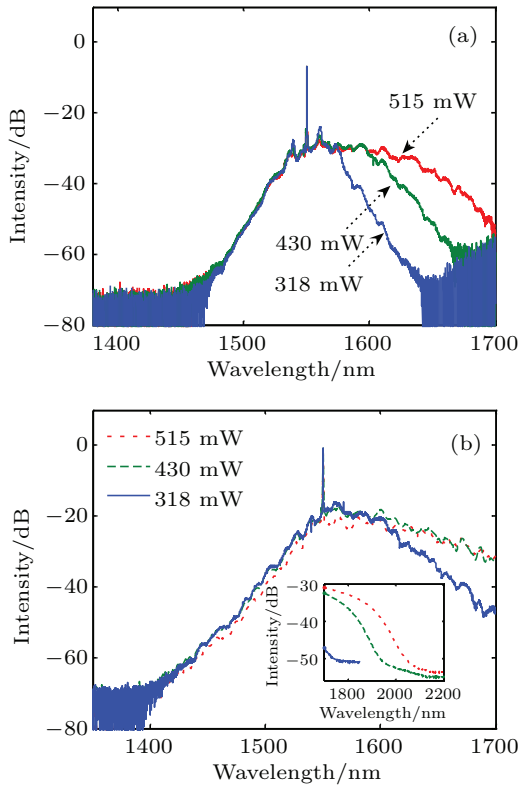


Fig. 2. (color online) (a) Spectra of the pump light with different output powers. (b) Spectra of the incident pump light at the output port of WDM as a function of the pump power (inset shows the long wavelength SC edge).

3.1.2. The foundation process of the 2-μm pulsed laser

As can be seen in Fig. 2(b), when the power of the pump source reaches 318 mW, the long wavelength edge of the incident pump light is 1750 nm. In this case, an unstable gain-switch pulse train is observed.

When the power of the pump light reaches 430 mW, the incident pump light is a pulsed SC with spectrum ranging from 1450 nm to beyond 2000 nm. The 2-μm wavelength region of the incident pump light can be amplified in the laser cavity. In this case, there are two main processes in the laser cavity, the gain-switched operation process of a TDF laser by pumping with a pulsed fiber laser and the amplification process of the 2-μm wavelength region of the incident pump light. The output pulses of the system are attributed to the combined effect of these two processes as shown in Fig. 3(a). The upper trace is the non-absorbed pump light at the output of the fiber loop mirror which is used to trigger the oscilloscope. The bottom trace is the measured 2-μm pulsed laser at the laser output, it consists of amplified signal pulses and gain-switched pulse envelopes, as labeled in Fig. 3(a). Here the amplified signal pulses mean the amplified 2-μm wavelength region of the incident pump light. The delayed time between the peaks of the non-absorbed pump pulse and the gain-switched pulse envelope is about 4.5 μs in Fig. 3(a), and this delayed time is decreasing with the pump power increasing, which is owing to the buildup time of the up-level electron density decreases with the increase of the pump power.[17] However, the delayed time between the non-absorbed pump pulse and amplified signal pulse is only 48 ns, and this delayed time is unchanged with the increase of the pump power. Considering the different optical path, the signal pulse and pump pulse almost overlap in the laser cavity. This result further demonstrates that the signal laser initially comes from the incident pump light.

Further increasing the pump power, the amplitude of amplified signal pulses gradually increases, while the relatively amplitude of the gain-switched pulses is decreased. When the pump power is 515 mW, the observed output temporal profile is shown in Fig. 3(b). In this case, the gain-switched pulses are almost disappeared and the amplified signal pulses have a pulse width of 2 ns. In the laser cavity, there is a gain competition between the gain-switched operation process and the amplification process. The amplified signal pulses are in front of the gain-switched pulse envelopes in the time domain as can shown in Fig. 3(a). When the signal light amplification process consumes a large amount of pump source, the residual pump light for the gain-switching will be reduced, and then the gain switched operation process will be suppressed. In our experiment, the initial signal power of the incident pump SC is increased with the increase of the pump power, this can

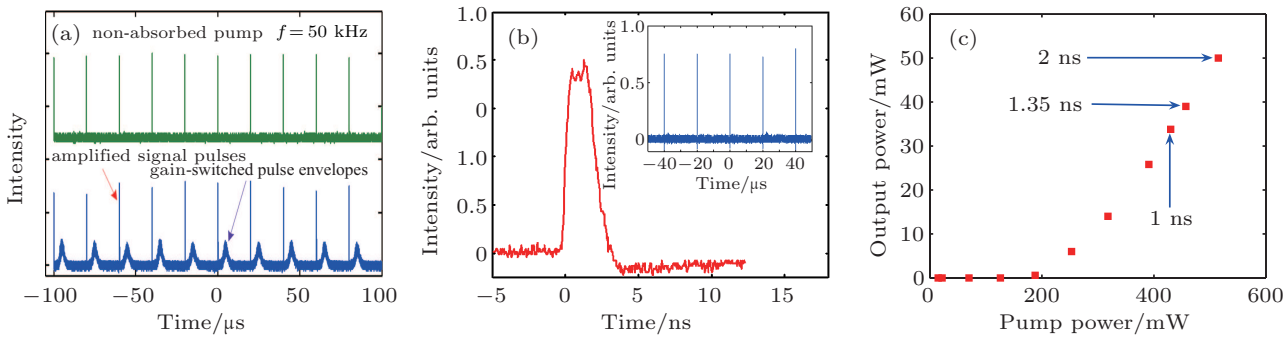


Fig. 3. (color online) (a) Oscilloscope traces of the non-absorbed pump light (upper trace) and 2-μm pulsed laser (bottom trace), when the pump power is 430 mW. (b) The measured single pulse shape and pulse train of the 2-μm fiber laser when the pump power is 515 mW. (c) Average output power as a function of the pump power. The insert text arrows indicate the amplified signal pulse width under different pump powers of 430 mW, 457 mW, and 515 mW.

be presumed from the spectra in Fig. 2(b). With the increase of injected signal power, there should be a noticeable gain-depletion with injected signal radiation being amplified, which will reduce the pump power amount for gain-switched operation process, and we think this is the main reason for the amplitude increasing of the amplified signal pulses and relatively amplitude decreasing of gain-switched pulses.

Figure 3(c) shows the average output power as a function of the pump power. The insert text arrows indicate the amplified signal pulse width under different pump powers of 430 mW, 457 mW, and 515 mW. The amplified signal pulse width is gradually increased from 1 ns to 2 ns when the pump power changes from 430 mW to 515 mW. In our experiment, the amplified signal pulse initially comes from the incident pump SC. When the pump power is lower, only the laser contained in a short time domain near the peak of the pump pulse has sufficient energy and can broaden to 2 μm. This time domain is gradually extending with the pump power increase. Therefore, the amplified signal pulse width is gradually increased with the increase of the pump power.

3.1.3. The output spectrum of the seed source

Figure 4 shows the output spectra of the seed laser at the pump powers of 430 mW and 515 mW. The peak of the output spectrum is at 1958 nm. Actually, the output spectrum has a pedestal structure with a wide wavelength range from 1800 nm to 2150 nm when the pump power is 515 mW. We think the pedestal structure is caused by the wide reflective band of the fiber loop mirror. Owing to the different spectral extending degrees of the pump SC, the pedestal structure is not so wide and obvious when the pump power is lower.

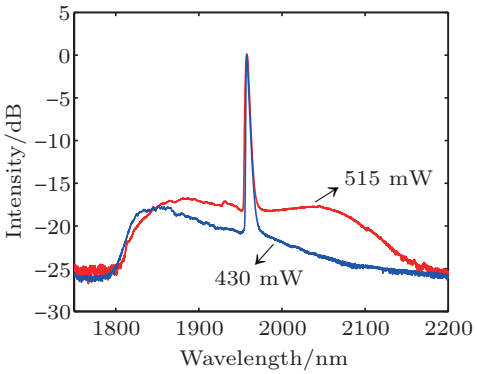


Fig. 4. (color online) Output spectra of the seed laser at the pump powers of 430 mW and 515 mW.

4. Mid-IR SC generation

In the SC generation experiment, the seed laser has a pump power of 515 mW. The output pulse shape of the seed laser is shown in Fig. 3(b). The seed laser is amplified by two stages of fiber amplifiers. Then, the amplified laser is used as the pump source for mid-IR SC generation in a 10-m long ZBLAN fiber. The second fiber amplifier output power, ZBLAN output power in all spectral bands and ZBLAN output power for wavelengths longer than 2.5 μm are plotted against the 790-nm pump power in Fig. 5(a). The output power is measured with a thermal power meter, and power distribution beyond 2.5 μm is measured using a cut-off long-pass filter. The second fiber amplifier can provide 3.3-W output power with an overall efficiency of 18% at 18.8 W of 790-nm pump power. The maximal average output power of mid-IR SC from the ZBLAN fiber is 1.24 W, corresponding to an output efficiency of 6.6% with respect to the 790-nm pump. Considering the 27% mechanical splicing loss, the total power coupled to the ZBLAN fiber is about 2.41 W. Therefore, the SC generation efficiency (SC output power/coupled power) in ZBLAN fiber is about 51.5%. When the total average output power of the mid-IR SC is 1.24 W, the SC power for wavelengths longer than 2.5 μm is 340 mW with a power ratio of 27.4%.

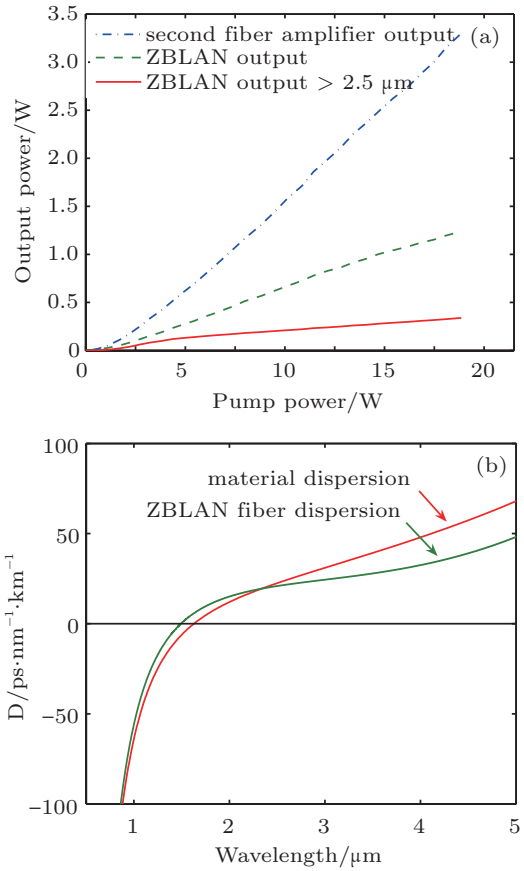


Fig. 5. (color online) (a) The second fiber amplifier output power, ZBLAN output power in all spectral band and ZBLAN output power for wavelengths longer than 2.5 μm versus the pump power at 790 nm. (b) Calculated material and ZBLAN fiber dispersion.

In the ZBLAN fiber, high peak power pulses are useful for the nonlinear wavelength conversion. The generation of new frequency components is affected not only by a multitude of nonlinear effects but also by the dispersive and loss properties of the ZBLAN fiber. The ZBLAN fiber has a

transmission range of 0.35–4.5 μm, mid-IR SC extending in ZBLAN fiber from ∼ 1.9 μm to 4.5 μm has been demonstrated in Ref. [3]. Figure 5(b) presents the calculated dispersion parameter curves. Using experimentally derived Sellmeier coefficients,[18] the calculated material zero dispersion wavelengths (ZDWs) of the ZBLAN fluoride glass and ZBLAN fiber are 1.62 μm and 1.49 μm respectively. Figure 6 shows the ZBLAN output mid-IR SC spectra for different output powers. Similar with that in Refs. [5] and [6], the SC spectrum mainly shifts toward the longer wavelength. When the average output power reaches 1.24 W, the output SC has a continuous spectrum ranging from 1.8 μm to 4.3 μm.

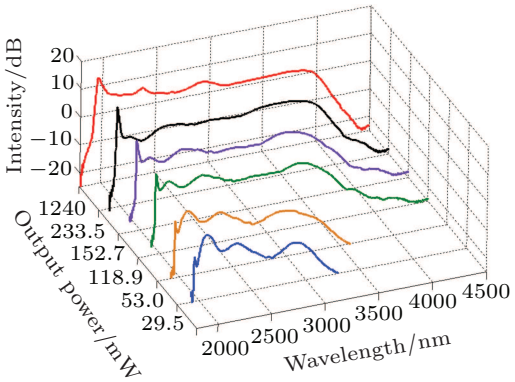


Fig. 6. (color online) Mid-IR SC output spectra for different output powers.

5. Conclusion

In summary, a new method to achieve a 2-μm pulsed fiber laser based on SC source has been demonstrated. The system is similar with the previously reported gain-switched Tm-doped fiber laser, but the key difference is the adoption of a pulsed SC as the incident pump light. When the incident pump light has a spectrum range from 1450 nm to beyond 2000 nm, the signal laser can initially come from the incident pump light and be amplified in the laser cavity. Based on this, we obtain a 2-μm pulsed laser with pulse repetition rate of 50 kHz and pulse width of 2 ns from a Tm-doped fiber laser with 7.5-m cavity length. This 2-μm pulsed laser is amplified by two stages of fiber amplifiers for mid-IR SC generation in a 10-m length ZBLAN fiber. An all-fiber-integrated mid-IR SC with spectrum ranging from 1.8 μm to 4.3 μm is achieved. The maximal average output power of the mid-IR SC from the ZBLAN fiber is 1.24 W (average output power beyond 2.5 μm is 340 mW), corresponding to an output efficiency of 6.6% with respect to the 790-nm pump power. The mid-IR SC average output power can be further scaled up by increasing the power of the 2-μm pulsed laser.

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