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RESEARCH ARTICLE

Record power and efficient mid-infrared supercontinuum generation in germania fiber with high stability

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Abstract

We report the demonstration of a mid-infrared (MIR) supercontinuum (SC) laser delivering a record-breaking average output power of more than 40 W with a long-wavelength edge up to 3.5 μm. The all-fiberized configuration was composed of a thulium-doped fiber amplifier system emitting a broadband spectrum covering 1.9–2.6 μm with pulse repetition rate of 3 MHz, and a short piece of germania fiber. A 41.9 W MIR SC with a whole spectrum of 1.9–3.5 μm was generated in a piece of 0.2-m-long germania fiber, with a power conversion efficiency of 71.4%. For an even shorter germania fiber (0.1 m), an SC with even higher output power of 44.9 W (corresponding to a conversion efficiency of 76.5%) was obtained, but the energy conversion toward the long-wavelength region was slightly limited. A continuous operation for 1 hour with output power of 32.6 W showed outstanding power stability (root mean square 0.17%) of the obtained SC laser. To the best of the authors' knowledge, for the first time, this work demonstrates the feasibility of germania fiber on generating a 40-W level MIR SC with high efficiency and excellent power stability, paving the way to real applications requiring high power and high reliability of MIR SC lasers.

Keywords: fiber laser; high power; nonlinear optics; supercontinuum generation

1. Introduction

Mid-infrared (MIR) supercontinuum (SC) lasers find exciting applications in environmental monitoring[1], biomedical sensing[2], infrared spectroscopy[3], etc. Boosting the output power of fiber-based MIR SC lasers has been the continuous pursuit of researchers in the community. Fiber transparency at the long-wavelength side is one of the fundamental issues when it comes to MIR SC generation, which is largely determined by vibration-related multi-phonon absorption of the glass matrix[4]. As the most mature optical fibers, silica fibers exhibit high phonon energy (~1100 cm^{-1}), which prevents the acquisition of laser generation with wavelengths longer than 2.5 μm within them. As a result, researchers have to turn to fibers with lower phonon energy for MIR SC generation.

Non-silica fibers made of germania[5], tellurite[6], fluoride[7,8] (mainly ZBLAN and InF_3) and chalcogenide[9,10] (mainly As_2S_3 and As_2Se_3) have been taken into consideration. Fluoride fibers have a phonon energy no higher than 550 cm^{-1} and have been extensively exploited for high-power MIR SC generation[11–16]. Recently, the record power of the ZBLAN-fiber-based SC laser was improved to 30 W, with a spectral coverage of 1.9–3.35 μm[17]. It should be noted that, for all MIR SC lasers based on fluoride fibers, OH^--diffusion-induced end facet damage is a critical issue and should be well settled before such SC lasers can be put into application. Chalcogenide fibers have a transparency window to more than 10 μm due to a much lower phonon energy (typically <400 cm^{-1}) and high nonlinearity, which is beneficial for ultra-broadband MIR SC generation and transmission. An MIR spectrum extending to 11 μm was obtained in a chalcogenide fiber cascade, with maximal output power of the hundreds of milliwatt level[10]. Very recently, an SC laser based on As_2S_3 fiber with an output power of 1.13 W and spectral coverage of 2–6.5 μm was reported, thus representing the record power of MIR SC lasers based on chalcogenide fibers[9]. However, the low damage threshold sets a limitation to the power capacity

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Table 1. Overview of SC generation in germania fiber with output power more than 1 W.

Pump laser parameters	Germania fiber core diameter (μm)	SC characteristics: Average power (W)	Spectral range (μm)	Power conversion efficiency (PCE)	References
Er-doped MOPA[a], 1.3–2.4 μm, 1 ns, 1 MHz	3.5	1.44	0.7–3.2	——	[22]
Er-doped MOPA[a], 1.3–2.4 μm, 1 ns, 5 MHz	9	6.4	0.8–2.7	48.6% (6.4/13.17 W)	[22]
TDFA, 1.9–2.6 μm, 1 ns, 2 MHz	3.5	6.12	1.90–3.60	54.4% (6.12/11.25 W)	[20]
TDFA, 1.9–2.4 μm, 250 ps, 115 MHz	8	30.1	1.90–3.10	45.7% (30.1/65.9 W)	[23]
TDFA, 1.9–2.2 μm, 30.4 ps, 44.3 MHz	6	21.34	1.71–3.51	35.6% (21.34/60 W)	[24]
TDFA, 1.9–2.6 μm, 12 ns, 3 MHz	8	44.9/41.9	1.90–3.47	76.5% (44.9/58.7 W)	This work
			1.90–3.50	71.4% (41.9/58.7 W)	

[a]MOPA, master oscillator power amplifier.

of the chalcogenide fibers. As for tellurite glass, recently, fluorotellurite glass (typically made of tellurite glass modified with a certain percentage of fluoride glass) fibers were explored for MIR SC generation, and a maximal output power of 25.8 W with spectral coverage of 0.93–3.99 μm was achieved[18].

Germania glass has a phonon energy of approximately 820 cm^{-1}[19], and germania fibers have been proved to support MIR SC generation with spectral edge up to 3.6 μm at the watt level[20]. In addition, a much higher nonlinear coefficient can be obtained in germania fiber compared with silica fiber, owing to a high nonlinear refractive index (~5×10^{-20} m^2 W^{-1})[21] and a high nonlinear coefficient induced from a high-numerical aperture (NA)-induced smaller effective mode field area. Therefore, just a short segment of germania fiber can provide enough nonlinearity for SC generation. Besides, the comparatively high glass transition temperature (~560°C) indicates the favorable endurance for intense power and heat generation during high-power operation. Fiber lasers operating at approximately 1.5 and 2 μm have been used to pump germania-fiber-based SC lasers. An ultra-broadband SC can be obtained using an Er-doped fiber laser system (working at ~1.5 μm) because such a wavelength is close to the zero-dispersion wavelength (ZDW) of germania fiber and thus the spectrum can be easily extended on both the short- and long-wavelength sides[5,22]. The Tm emission waveband at approximately 2 μm is much closer to the MIR region compared with that of Er (~1.5 μm). Therefore, a higher conversion efficiency toward the MIR can be expected using a Tm-based pump laser instead of an Er-based one. In particular, Tm-based fiber amplifiers with output spectral coverage of 2–2.5 μm are favorable pump lasers for efficient MIR SC generation. Recently, Yin *et al.*[23] obtained an SC of 30.1-W output power in germania fiber with a long-wavelength edge (LWE) of 3.0 μm and a power conversion efficiency (PCE, i.e., the ratio of SC power to the output power of the pump laser) of 45.7%. Very recently, Wang *et al.*[24] demonstrated an SC laser in germania fiber with output power of 21.34 W and a spectral coverage of 1.7–3.5 μm, where the PCE is 35.6%. Both experiments by Yin *et al.*[23] and Wang *et al.*[24] utilized a picosecond pulse seeded thulium-doped fiber amplifier (TDFA) as a pump laser and dispersion compensated fiber as a pulse stretcher before amplification. The literature on SC generation based on germania fibers (>1 W) is summarized in Table 1. One could notice that (i) the PCEs of such SC lasers are comparatively low (no more than 54.4%) and (ii) power scaling with a broadband spectrum up to 3.5 μm is rather challenging. Moreover, no characteristics of long-term power stability of MIR SC lasers based on germania fiber were investigated. In fact, long-term stability and reliability is a crucial issue to be thoroughly addressed for the application of high-power MIR SC lasers.

In this paper, we focus on the efficient, high-power and high-stability operation of MIR SC lasers featuring a spectral coverage up to 3.5 μm. MIR SC generation with maximal output power of 44.9 W (with a PCE of 76.5%) was achieved based on a short piece of germania fiber. Owing to the all-fiber-integrated configuration and robust endcap, ultra-low-power fluctuation of 0.17% (root mean square, RMS) was observed during a continuous operation for over 1 hour.

2. Experimental setup and result

The experimental setup of the germania-fiber-based high-power MIR SC laser is shown in Figure 1. Basically, the laser source involves a pump laser and a piece of germania fiber. To achieve high PCE from the pump laser into the SC laser in the nonlinear germania fiber, it is important to design a configuration with efficient energy pre-distribution toward the long-wavelength region before the pump pulses are injected into the germania fiber. Herein, the pump laser was a high-power single-mode TDFA seeded by an SC seed laser with spectral coverage of 1.5–2.2 μm. Such a seed laser was obtained by launching amplified nanosecond laser pulses at 1.55 μm into single-mode passive silica fiber. The obtained seed pulses consisted of a bunch of ultrafast pulses with central wavelength ranging from 1.5 to 2.2 μm. Such conversion of nanosecond pulses at 1550 nm to broadband ultrafast pulses was induced by nonlinear effects including modulation instability (MI) and soliton dynamics, such as Raman soliton self-frequency shift (SSFS). In the TDFA, the spectral components located at 1.5–1.9 μm were absorbed, while those at 1.9–2.1 μm were amplified. Meanwhile, the

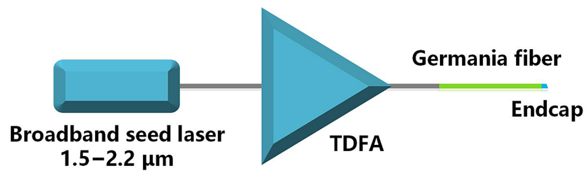

Figure 1. Experimental setup of the germania-fiber-based MIR SC laser. TDFA, thulium-doped fiber amplifier.

Raman SSFS effect continuously occurred and pulse energy was converted to a longer wavelength. At the end of the TDFA, an SC spectrum covering the 1.9–2.6 μm waveband was obtained, with a maximal averaged power of 62 W. The core/cladding diameter was 10/130 μm for the used TDF. Together with the core NA of 0.15, single-mode operation in such a TDF was ensured for wavelengths longer than 1.96 μm. According to previous results based on numerical simulation, it was estimated that the peak power of the bunch of ultrafast pulses was around tens of kilowatt[25]. A piece of germania fiber was used as the nonlinear gain medium. Such germania fiber has a core diameter of 8 μm and a core NA of 0.65. The germania fiber was fusion spliced to the TDFA. A silica fiber endcap was fabricated at the output end of the germania fiber to protect the fiber tip from thermal or optical damage under high-power operation. The fiber endcap is made of core-less silica fiber with a diameter of 125 μm. Precise cleaving at the silica fiber near the germania fiber silica fiber joint yielded an endcap length of approximately 100 μm. Angle-cleaving is needed for reducing feedback into the fiber core. The TDFA together with the germania fiber was placed on an aluminum plate, which was water-cooled at 17°C.

3. Results and discussion

The calculated fundamental-mode ZDW of the used germania fiber is approximately 1.51 μm. Therefore, the whole spectrum of the pump laser is in the anomalous region. Therefore, the dominant nonlinear effect in the germania fiber is Raman SSFS, which indicates that distinct spectral extension would be seen in the long-wavelength side rather than in the short-wavelength side. Spectral evolution for germania fiber length of 0.2 m is shown in Figure 2(a). The curves are offset vertically for clarity. The offset was 10 dB for neighboring curves. As the pump power was increased, the LWE of the spectrum continually red-shifted, together with the spectral intensity strengthening on the long-wavelength side. The SC spectral intensity on the short-wavelength side (1.9–2.1 μm) was also enhanced, which was mainly due to the gain of Tm^{3+} ions rather than nonlinear effects. The spectral peak was shifted from 2840 nm (corresponding to SC power of 4.4 W) to over 3000 nm (corresponding to SC power of 41.9 W). The generated SC has a good spectral flatness owing to the average effect induced from the ultrafast pulse bunch and Raman SSFS effect. The pump laser spectrum at maximal output power is also shown in Figure 2(b) (dash green line). One can notice the energy distribution toward the long-wavelength region (~2.4 μm) of the pump laser spectrum.

The SC spectral comparison for maximal output power for different lengths (0.3, 0.2 and 0.1 m) of germania fibers is depicted in Figure 2(b). The noise floor was set the same for the three cases. One can see the remarkable spectral expansion toward the long-wavelength direction even in short germania fiber. The SC spectra generated in germania fiber with the length of 0.2 m (solid red line) and 0.3 m (dotted gray line) are basically similar to each other, but a slight spectral intensity reduction in the wavebands of 2.8–3.0 μm and 3.2–3.5 μm was observed for the case of 0.3 m. The mechanism mainly responsible is believed to be the attenuation-induced and nonlinearity-induced loss, which is supported by SC power difference, that is, 41.9 W (for 0.2 m) and 40.4 W (for 0.3 m). Although longer germania fiber (0.3 m) is beneficial for spectral extension, it seems that the loss dominates the situation. As seen in Figure 2(b) (solid bronze line), the measured attenuation curve of the used germania fiber grows rapidly and reaches 10 dB/m at 3.06 μm.

The obtained SC spectrum with germania fiber of 0.1 m is shown as a dotted dash blue line in Figure 2(b). Compared with the spectra corresponding to 0.2 and 0.3 m, the spectrum of 0.1 m shows a distinct spectral enhancement at 2.8–3.0 μm, but a slight reduction at the spectral range of 3.0–3.3 μm. At this time, the spectral intensity at 3.3–3.5 μm was not weaker than that of 0.2 or 0.3 m. Such behavior was attributed to the slightly insufficient nonlinearity. In any case, the SC spectra obtained here almost represent the most red-shifted LWE based on germania fibers to date. The inset of Figure 2(b) gives the beam profile captured by a pyroelectric array camera, indicating the efficient excitation of the fundamental mode, although the germania fiber supports several modes in this waveband.

The obtained SC power with respect to the pump power (i.e., the output power of the TDFA) for different germania fiber lengths is shown in Figure 3. A steady increase in SC power along with pump power was observed for every case. The slope of Figure 3 only shows a slight decrease at the maximal pump power, compared with that at low pump power. There is no distinct difference among the slopes of the three cases, mainly due to the fact that all the spectra were extended into the region with high attenuation (i.e., >3 μm). The maximal SC powers for different lengths of germania fiber (0.3, 0.2 and 0.1 m) were 40.4, 41.9 and 44.9 W, respectively, corresponding to PCEs of 65.3%, 71.4% and 76.5% from the pump laser to the SC laser. Undoubtedly, shorter germania fiber results in less power loss and higher PCE. Meanwhile, nonlinear spectral expansion was just a little weaker. The PCE obtained in this work is much higher

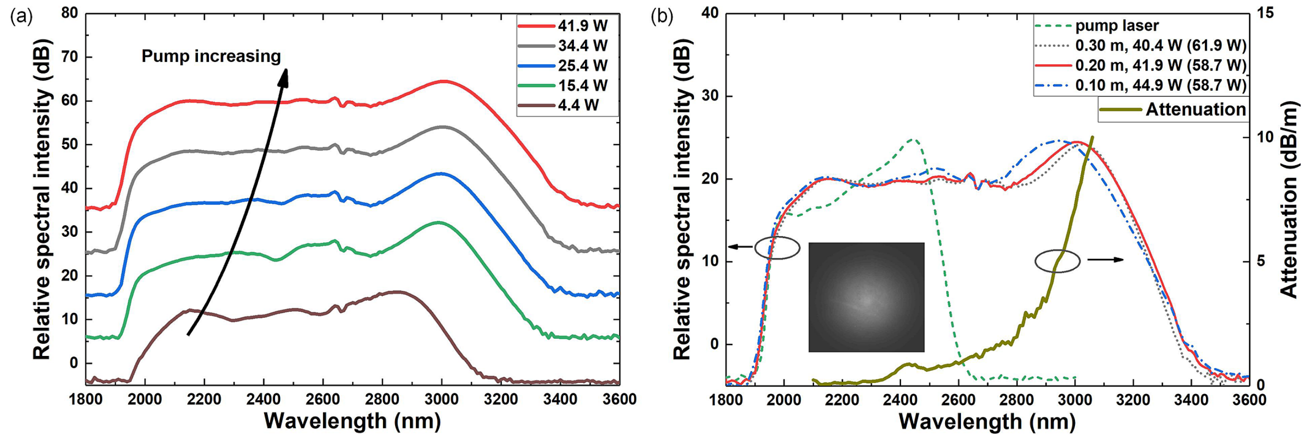

Figure 2. (a) Spectral evolution of the generated SC for a germania fiber length of 0.2 m. The curves are offset vertically for clarity. The offset is 10 dB for every two neighboring curves. (b) Pump laser spectrum and SC spectra comparison for maximal output power for different lengths of germania fiber (0.3, 0.2 and 0.1 m, left-hand axis) and measured attenuation curve of the used germania fiber (right-hand axis). SC power and corresponding pump power are shown in parentheses. Inset depicts the beam profile captured by a pyroelectric array camera.

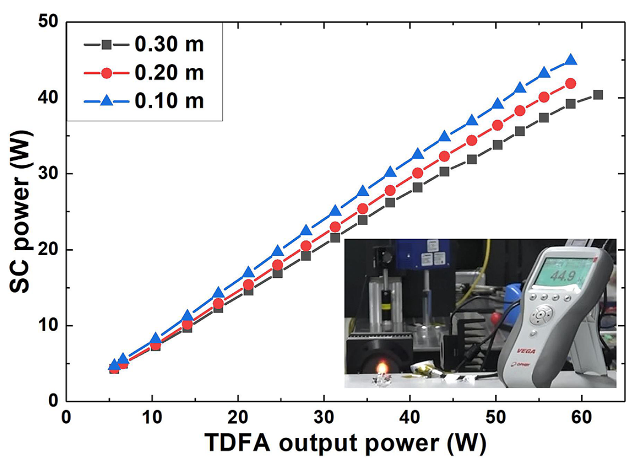

Figure 3. SC power with respect to the pump power. Inset depicts the picture taken in the experiment when the SC power reached 44.9 W.

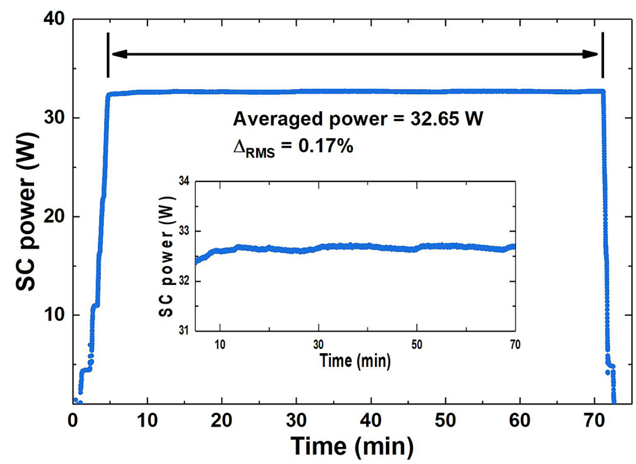

Figure 4. SC power stability test for over 1 h. Inset gives the zoomed power fluctuation from 5 to 70 min after the test began.

than those reported in the literature (see Table 1), which was mainly attributed to (i) the low quantum decay from the pump laser to the SC laser (i.e., efficient energy pre-distribution toward the long-wavelength region before the pump pulses were coupled into the germania fiber) and (ii) the short germania fiber and resultant reduced attenuation-induced loss. The inset of Figure 3 shows a picture taken in the experiment when the SC power reached the maximal value of 44.9 W. Bright visible light was observed, which is mainly the dispersive wave generated in the short-wavelength direction after matching the solitons in the long-wavelength direction.

So far, one of the main problems that hinders high-power MIR fiber lasers being put into practical application is the poor long-term stability induced by the optical or thermal damage of the fiber tip and resultant system failure, especially for those based on fluoride fibers[26]. To investigate the power stability of the germania-fiber-based SC laser, a continuous operation with output power of higher than 30 W for over 1 hour was carried out, as shown in Figure 4. During the high-power test for over 65 minutes, the obtained averaged power was 32.6 W, with an ultra-low fluctuation of 0.17% (RMS). The inset gives the zoomed power stability from 5 to 70 minutes after the test began. No output power decrease occurred during the test, and no sign of damage on the fiber endcap was observed after the test. The ultra-low-power fluctuation and high reliability shown in the test indicated the feasibility of such an SC laser in high-power scenarios. The good thermal conductivity (1.38 W m^{-1} K^{-1}) and high transition temperature (1175 °C) of silica glass ensured good heat dissipation and reliable heat endurance of the fiber endcap. To the best of our knowledge, this is the first hour-level report on power stability tests of high-power (>10 W) MIR SC lasers of all categories to date. Such a result can readily strengthen confidence in both the long-term operation of high-power MIR SC lasers and in the feasibility of high-power MIR SC lasers being put into real applications in the very near future. Currently, in the experiment, the output power of such an SC laser is limited by the output power of the TDFA. As for this scheme, we agree that the damage threshold of the fiber material would set the ultimate limitation to power scaling. Some measures can be adopted for further power scaling before the SC power reaches such an ultimate limitation, for example, mounting the fiber endcap on an actively cooled metallic V-groove.

4. Conclusion

In conclusion, an MIR SC laser with spectral coverage of 1.9–3.47 μm and maximal output power of 44.9 W was demonstrated. The corresponding PCE was 76.5%, which was the highest value ever reported for germania fiber-based high-power MIR SC lasers. It was found that the high nonlinearity and multi-phonon-induced loss played an essential role in spectral behavior and SC power evolution within the germania fiber. The measured power fluctuation of 0.17% (RMS) at over 32 W indicated excellent power stability. With the demonstration of distinct power stability, this work paves the way for high-power MIR SC lasers for practical applications.

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