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6.8 W all-fiber supercontinuum source at 1.9–2.5 μm

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Abstract

We report a simple method of generating a spectrally flat and high average power spectral density (up to 14 mW/nm) optical supercontinuum in the 1.95–2.5 μm range covering a transparency window of the atmosphere. The supercontinuum was generated from the Tm-doped all-fiber MOPA lasers. The average output power of the picosecond linear-cavity SESAM mode-locked seed lasers operating at 46 and 77 MHz was as low as 6.7 and 2.6 mW, respectively. The corresponding one-stage silica-based fiber amplifier generated a supercontinuum with 5.06 and 6.83 W average power, 550 and 500 nm bandwidths at −10 dB level, and 5 and 8 dB spectral flatness, respectively.

Keywords: mode-locked fiber lasers, Raman solitons, optical supercontinuum, mid-infrared lasers

(Some figures may appear in colour only in the online journal)

1. Introduction

Supercontinuum (SC) generation in the mid-infrared wavelength range above 2 μm, and in particular, in the transparency window of the atmosphere between 2 and 2.5 μm is an important topic in applied fiber optics due to its numerous applications such as LIDAR systems [1], optical coherence tomography [2], trace gas sensing [3] and environmental monitoring, as well as defense technologies. More than an octave span (~1–2.5 μm at -20 dB level) broad spectrum was reported for the SC generated from a nonlinear fiber spliced to the Tm-doped fiber amplifier [4, 5]. Moreover, a broadband optical signal (~1.85–2.05 μm) was obtained directly from the oscillator [4, 5]. Unfortunately, the output power of oscillators is usually limited to several tens of milliwatts. So far, a high-power SC generation in this wavelength range has been demonstrated by several methods. For example, the pumping of a Ho-doped fiber amplifier with intense Q-switched pulses at 1.6 μm resulted in an output SC power of 0.4 W [6]. Amplification of gain-switched and mode-locked Tm/Ho-doped laser pulses of a duration of a few microseconds in a Tm-doped amplifier resulted in 2.17 W output power [7]. Amplification of SC generated with a nanosecond Er-doped fiber laser in a Tm or Tm/Ho-doped fiber amplifier [8–11] resulted in up to 2.37 W of output power in the range of 1.95–2.52 μm at −10 dB level [11]. However, a much simpler system based on a master-oscillator–power amplifier (MOPA) configuration with only Tm-doped fibers has not been reported so far.

In this article, we report a novel simple method of producing a high-power supercontinuum in the mid-IR wavelength range without needing to use microstructured specialty, fibers or exotic fiber materials, besides the conventional silica-based Tm-doped fibers. The concept [12] is based on a MOPA system with a mode-locked seed laser thus ensuring the SC stability and quality of the continuum. The system uses only commercially-available single-mode silica components and produces a multi-watt super-flat SC in the 1.9–2.5 μm range with the average power spectral density (PSD) > 10 mW/nm.

2. Experimental

All-fiber core-pumped linear-cavity mode-locked seed lasers utilizing a silica-based Tm-doped fiber and a SESAM semiconductor mirror were realized, similar to [13]. A diode laser operating at the wavelength of 1560 nm was used as a pump source. The seed lasers operated at the wavelengths of 1960 and 1992 nm (figure 1) with full-widths at half maxima of 3.4 and 4.5 nm, respectively; the pulse durations and repetition rates were 2 and 2.5 ps and 44 and 77 MHz, respectively, and average output powers were 6.7 and 2.6 mW, respectively.

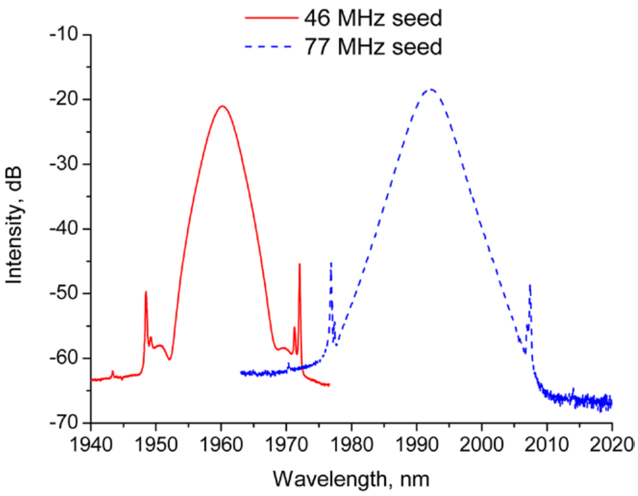

Figure 1. Optical spectra of the seed lasers emission.

Fiber amplifiers based on a piece of a silica-based Tm-doped double-clad fiber were investigated. The fiber piece of 4 m length had 10 and 130 μm core and first clad diameters, respectively, and a 0.15 core numerical aperture. These amplifiers with angle-cleaved output fibers were clad-pumped at the wavelength of 793 nm by a diode laser. The diode laser had an output fiber with a core diameter of 105 μm. A fiber pump/signal combiner was used to launch the pump radiation into the active fiber. The seed laser emission was launched into the amplifiers through an optical isolator.

The amplifier used for the seed laser operating at 44 MHz repetition rate was pumped in a forward direction, figure 2(*a*). Its output emission consisted of the signal (amplified seed laser emission) and unabsorbed pump radiation. The unabsorbed pump radiation was spatially separated from the laser emission by an optical system (a collimating CaF_2 lens and a silica glass prism). At a low pump power the seed laser was turned off and the pump radiation emitted from the amplifier was measured before and after the optical system. The transmission coefficient of the optical system was calculated. Then, the seed laser was turned on and transmitted through the optical system, unabsorbed pump power was measured in the whole investigated pump power range. The transmission coefficient was used to calculate the unabsorbed pump power emitted from the amplifier. Then, the unabsorbed pump power was subtracted from the total output power, thus yielding the laser emission power.

At low pump powers, the signal spectrum was rather narrow, and the cross-section of the laser beam transmitted through the prism was represented by a spot. It allows us to measure the transmission coefficient of the optical system for the laser radiation. We found it to be in good agreement with the one measured for the pump radiation. It indicated that the optical system transmittance had a weak spectral dependence. When increasing the pump power, the spot representing the laser emission was transforming into a strip exceeding the detector aperture so that the direct measurements of the laser emission power were not possible anymore. This effect took place due to a spectral expansion of the laser radiation indicating the formation of the optical SC.

The same amplifier pumped in a backward direction was used for the second seed laser operating at 77 MHz repetition rate, figure 2(*b*). The optical spectra and the pulse trains were detected with an optical spectrum analyzer Yokogawa AQ 6375 (1.2–2.5 μm operation range) and an InGaAs semiconductor optical detector with 1 ns response time.

3. Results

3.1. Forward pumping

The amplifier output emission formed a stable optical pulse train at the 44 MHz seed laser repetition rate. Increasing the amplifier output power up to ~100 mW was accompanied by spectrum broadening, figure 3(*a*). Simultaneously, the spectrum became asymmetric with a noticeable increase of the low-energy side due to the Raman amplification, ending up in formation of a Raman soliton similar to [14].

Beyond 1 W of output power, the spectrum smoothed as a whole and expanded in the long-wavelength direction, forming an SC (figure 4). Spectral expansion stopped at approximately 2.5 μm, with maximum intensity moving to 2.4–2.45 μm.

At high output powers, the SC becomes extremely stable against both variations in pump and signal power (figure 4). For example, a 10% decrease of the seed laser signal from 6.7 to 6 mW did not cause any noticeable change of the SC spectral shape and intensity, except for in the region of the seed signal itself, figure 4(*b*). The small-scale narrowband spectral features in figure 4 do not represent noise, because they appear in each spectrum at the same positions. The dependence of SC average power versus. pump power is shown in figure 5. The slope efficiency of SC generation reaches 21%, slightly saturating at higher output powers.

The maximum output power of 5.06 W was obtained at 27.7 W pump power. The SC bandwidth reached over 550 nm at −10 dB and 520 nm at −5 dB level (1.96–2.48 μm). This corresponds to PSD of 5–16 mW/nm or 10 mW/nm in average, figure 3(*b*).

3.2. Backward pumping

The backward pumped amplifier operating at the repetition rate of 77 MHz showed qualitatively similar behavior, but at higher pump power levels. Up to ~1 W of the output power, the spectrum was relatively symmetric and the Raman soliton was distinctly observed only at 2 W of the MOPA output power (figure 6).

At 5 W of output power, the spectrum of the generated radiation became relatively smooth, and a further amplifier output power increase up to 6.83 W occured mainly at the expense of the spectral shift of the long-wavelength margin of the emission, figure 7. The generated SC had a spectral width of 500 nm at −10 dB level with a spectral flatness of 8 dB. The average PSD was as high as 14 mW/nm. The average slope efficiency of the amplifier with respect to the launched pump power reached 27%, figure 5(*a*).

4. Discussion

We demonstrated that a high-power SC can be directly generated in the Tm-doped fiber laser in a MOPA configuration keeping the high stability and low noise of a mode-locked seed laser.

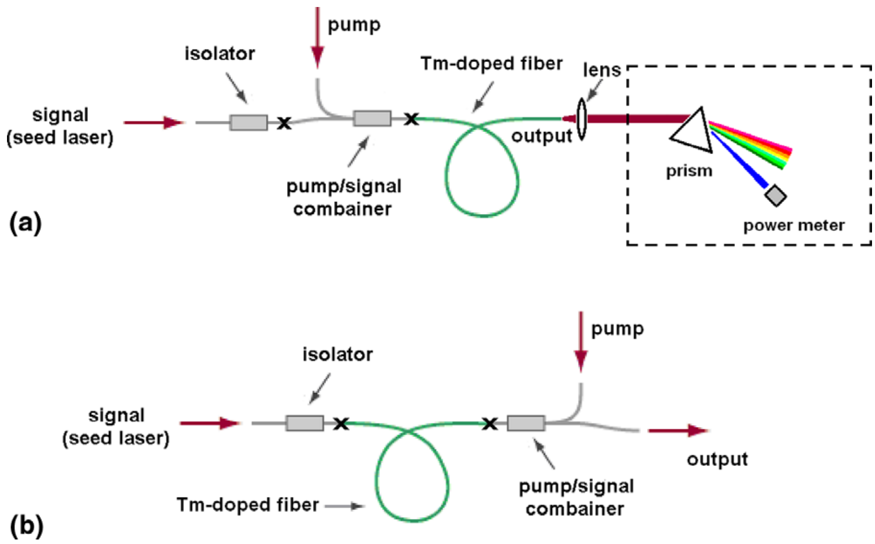

Figure 2. Experimental scheme of (*a*) the forward-pumped amplifier and (*b*) the backward-pumped amplifier.

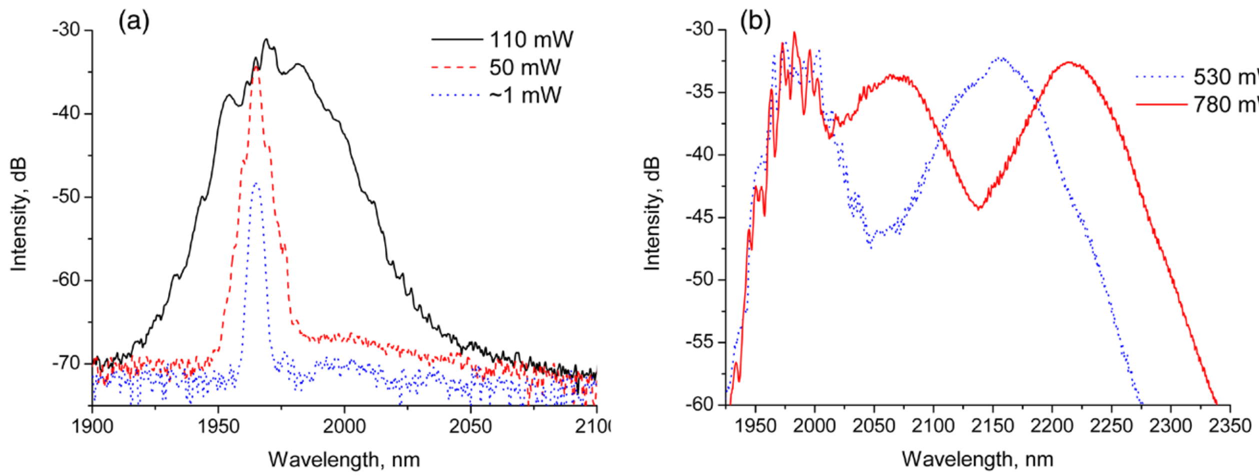

Figure 3. Evolution of the emission spectrum with increase of the output power (*a*) from 1 to 110 mW; (*b*) from 530 to 780 mW.

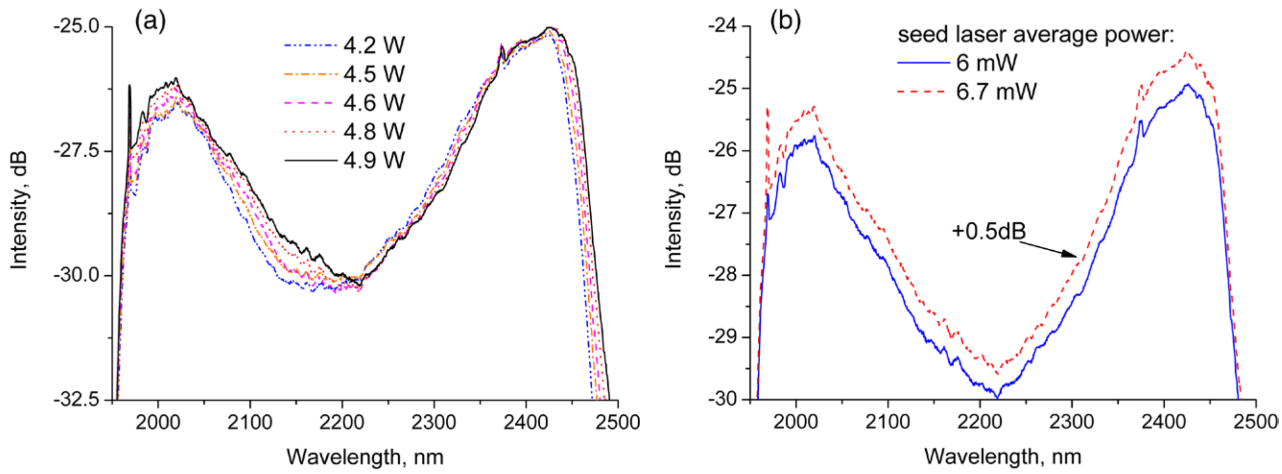

Figure 4. Evolution of the laser output spectrum with (*a*) increase of its power from 4.2 to 4.9 W; (*b*) change of the seed power by ~10% for 5 W of SC average power (0.5 dB added to the 6.7 mW curve for better visibility).

Generation of optical SC in the negative group velocity dispersion region in the reported laser configuration is attractive for the practice features coming from the Raman soliton nature of the SC. Thus, a steep optical loss edge in the long-wavelengths domain does not strongly affect the laser efficiency. The net gain G for the long-wavelengths edge can be written as

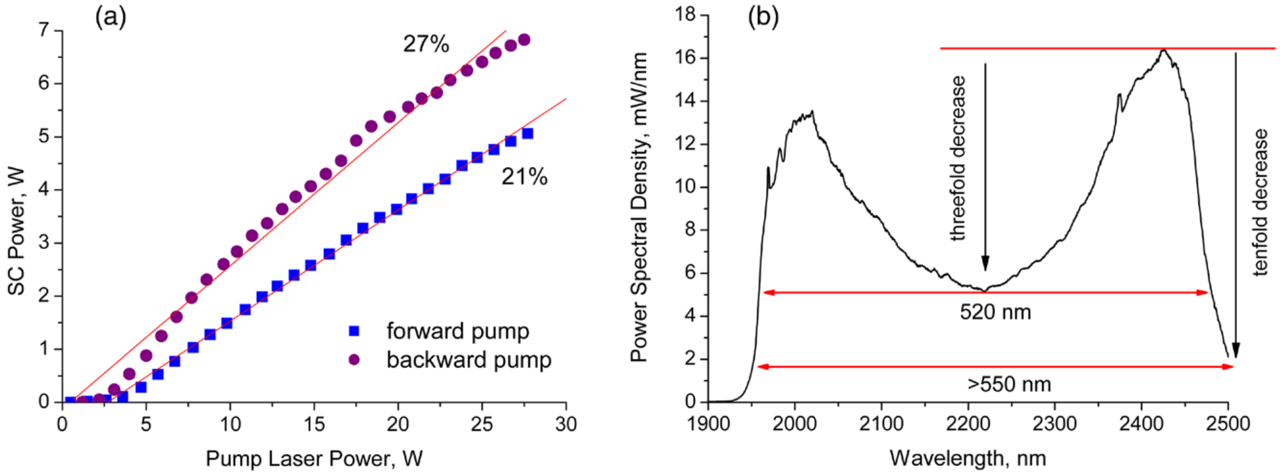

Figure 5. Output power of the SC versus. pump power (*a*), and PSD at 5 W of output power (*b*).

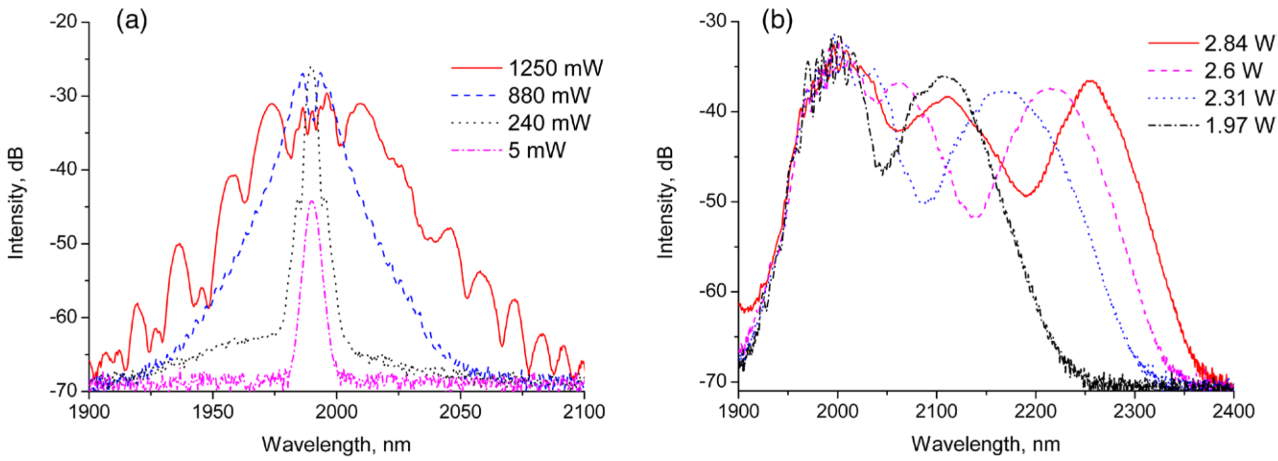

Figure 6. Backward-pumped amplifier emission spectra for the output powers (*a*) from 5 to 1250 mW, and (*b*) from 1.97 to 2.84 W.

$G = G_r - \alpha$, where G_r is the Raman gain and α is the optical loss. If the absorption edge is steep enough, the loss for the spectral area where $G_r > \alpha$ is small. In the spectral region where the loss α becomes too high, the net gain becomes negative and the spectrum expansion in this area does not occur. As a result, we observe the energy accumulation at the 'red' margin of the spectrum. Thus, we expect a better power scalability of such lasers because the thermal load of the fiber is to some extent not a critical issue in spite of the strong absorption due to the OH-groups in silica. The reduction of the amplifier slope efficiency was not dramatic, figure 5(*a*). For the backward-pumped amplifier, the output was transmitted through an approximately 1.5 m length of the passive fiber of the pump/signal combiner (figure 2(*b*)), resulting in a stronger decrease of the slope efficiency at high powers. It is worth noting that a natural confinement of the radiation between the seed spectral position and the host absorption edge favors the increase of SC brightness, which is the main rationale for using SC as opposed to incoherent thermal or luminescent sources. This feature makes such new sources very promising for e.g. lidar applications.

Another attractive feature is that the amplifier starts operating from only 2.6 mW of signal power, producing up to 6.8 W of the output power corresponding to the overall power amplification of 34 dB. In spite of the high gain, no parasitic lasing or amplified spontaneous emission peaks have been observed so far, and the laser output was very stable. Such behavior can be associated with the branching proposed in

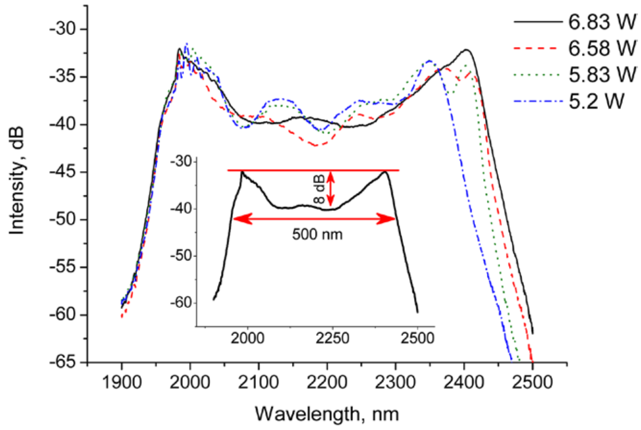

Figure 7. Backward-pumped amplifier emission spectra for the output powers from 5.2 to 6.83 W; inset—the spectrum for 6.83 W.

[11] of the excitation between several excited states at a high pump intensity resulting in lowering of the peak gain together with a spectral broadening of the amplification band (see figure 11 in [11]) as compared to the gain expected from $^3F_4$ level only. Such a broad gain, originated from both the $^3H_4$ and $^3F_4$ excited states of Tm^{3+} ions, would be obviously beneficial for the formation of SC. The practical consequence of the observed experimental phenomenon is that we can expect a further output power increase for the same signal intensities. The proposed scheme is noticeably simpler than the previously reported ones. A higher stability in comparison to nanosecond seed lasers can be expected due to mode-locked seed operation regime.

The forward-pumped amplifier produced a smoother spectrum with a slightly broader bandwidth but the backward-pumped was more efficient, providing about 1.5 times higher optical PSD up to 14 mW/nm. The difference can be attributed to the different pumping schemes and repetition rates of the seed lasers. In the case of forward pumping, the signal amplification at the entrance of the amplifier was faster and the pulse energy was higher, resulting in the pronounced nonlinear spectral transformation. At the same time, increasing the pump power should broaden the spectrum of the backward-pumped amplifier.

The advantage of these all-fiber lasers is that they are based on the available components and can be easily commercialized providing a new cost-effective tool for mid-IR applications.

5. Conclusions

We proposed and realized a novel, particularly simple and elegant, as well as cost-effective, concept for continuum generation based on a MOPA all-silica-fiber laser. The one-stage silica-based Tm-doped fiber amplifiers generated an optical SC in the range of 1.95–2.5 μm with 5 and 8 dB flatness with 5.06 and 6.83 W average powers at 46 and 77 MHz pulse repetition rates, respectively. This was achieved using picosecond linear-cavity SESAM mode-locked Tm-doped fiber seed lasers with power as low as 6.7 and 2.6 mW, respectively. We propose an explanation of the observed spectral self-confinement, and we predict further output power scalability for such systems.

To the best of our knowledge, this is the highest reported SC power with the superb spectral characteristics of SC for an all-fiber Tm-doped fiber laser system, making this novel SC generation technique particularly attractive for practical applications.

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