Generation of high-brightness spectrally flat supercontinuum in 1900-2450 nm range inside a small core thulium-doped fiber amplifier

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Abstract: We demonstrate the generation of high-brightness supercontinuum inside thulium-doped fiber amplifier in 1950-2450nm spectral range with 1.7W output power and 32% slope efficiency, seeded by tunable 2000nm mode-locked laser and assisted by $^3H_4$-$^3H_5$/$^3F_4$-$^3H_6$ thulium transitions.

OCIS codes: (320.6629) Supercontinuum generation; (160.5690) Rare-earth-doped materials; (060.4370) Nonlinear optics, fibers

1. Introduction

Broadband supercontinua (SC) have found applications in spectroscopy, metrology, medical imaging and sensing [1-3]. However, SC generation in the most widely used silica fibers suffers from an exponentially increasing loss when going beyond 2µm. To expand the SC range, some groups reported the use of soft glass fibers, such as ZBLAN [3] and chalcogenides [2]. On the other hand, thulium-doped (Tm) and thulium-holmium (Tm/Ho)-codoped silica fibers were found suitable to generate SC until 2.6µm [4-7]. Thanks to the wideband gain window of Tm^{3+} ions, silica loss can be compensated and thus further expand the SC range. In addition, SC generation in Tm-doped fiber (TDF) was found to be highly flat and bright, with a possibility of expanding a SC to beyond 2.5 µm in silica fibers.

The first demonstration of such a scheme [4] used a 1550 nm mode-locked laser providing ~10 kW peak power pulses was used to trigger Raman solitons around 2000 nm. Raman solitons were consequently sent to a TDF, simultaneously pumped with the residual 1550 nm emission [4]. The nonlinear processes in the doped fiber, seeded with the gain provided by the $^3H_4$-$^3H_5$ and $^3F_4$-$^3H_6$ thulium transitions, result in a supercontinuum ranging from 1900 to 2500 nm with an average output power of 150 mW. Similar experiments, involving an additional pumping of 300 W at 793nm of Tm^{3+} ions in a large-mode area (LMA) TDF resulted in a 100 W SC power with 36% slope efficiency, were demonstrated [5]. Also, in Ref. [6], a SC in a double-clad TDFA, pumped with 793 nm and seeded with a 2000 nm mode-locked laser, was shown to deliver up to 400 mW with 4% slope efficiency.

In this work, we demonstrate the generation of a bright SC inside a core-pumped TDFA (featuring a core as small as 4 µm in a diameter), seeded with a tunable, custom-made mode-locked laser (MLL) emitting around 2 µm. With this MLL, providing relatively low peak power (up to 100W), we were able to produce a spectrally flat and high-power SC inside the TDFA (approximately 1.7 W output power with 32% slope efficiency). The SC generation mechanism was studied by tuning the seed wavelength and the 1600 nm pump power. This SC source is all-fibered and SMF-28 compatible, as we eliminate LMA or double-clad fibers.

2. Experimental setup

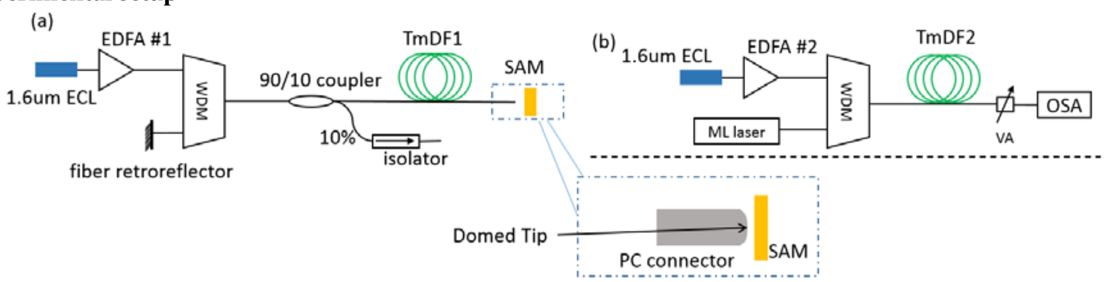

Fig 1. Experimental setup. (a) Seed mode-locked (ML) laser. ECL: external cavity laser; WDM – wavelength division multiplexer; SAM: saturable absorber mirror; EDFA: erbium-doped fiber amplifier. (b) Forward pumped TDFA. VA: variable attenuator; OSA: optical spectrum analyzer (Yokogawa AQ6376)

The setup used for SC generation consists of two parts: a custom-made mode-locked Tm-doped fiber laser, and a Tm-doped fiber amplifier (TDFA). The seed laser incorporates a saturable absorber mirror (SAM) for mode locking as shown in Fig. 1a. Wavelength tuning is achieved by adjusting the distance between a physical contact (PC) connector and the SAM on a translation stage. The domed tip on the PC connector induces wavelength dependent losses in the laser cavity, enabling the selection of the laser wavelength. In addition, the Tm^{3+}ASE center wavelength can be red-shifted by increasing the TDF length. Therefore, 1m and 0.5m of TDF are used in the seed laser to compare the wavelength dependence of the generated SC. The TDF (labelled as TmDF1 in Fig. 1a) has a core diameter of 4μm and doping concentration of 8×10^{25} ions/m^3. For better pumping efficiency, 1610nm laser is used to seed the L-band erbium doped fiber amplifier (EDFA1). The output power of EDFA1 was fixed at 320 mW.

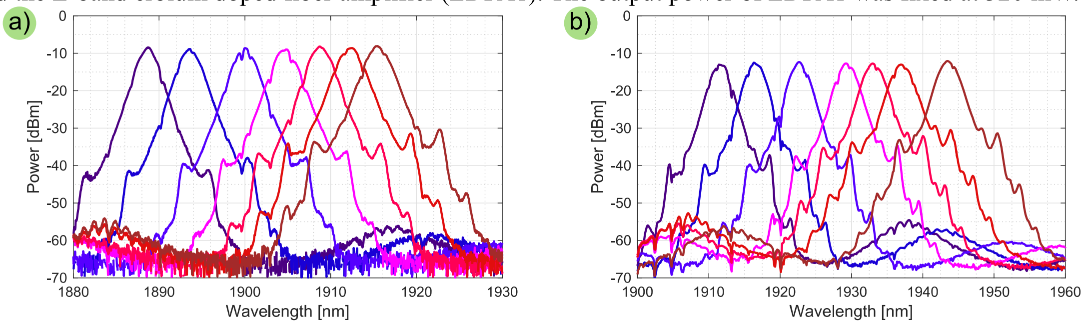

Fig. 2. Emission spectra of TDF MLLs. a) Cavity with 0.5m TDF. b) Cavity with 1m TDF. Presence of Kelly sidebands indicates a sech-like pulse operation.

The MLL tunability range is 29nm, centered around 1900nm, and 32nm, centered around 1930nm, for 0.5m and 1m of TDF, respectively (Fig. 2). Shorter lasing wavelength cannot be achieved due to the fast decrease of the SAM reflection around 1880 nm. The average output power / pulse repetition rate are 2.72mW/15.4MHz, and 2.85mW/13.7 MHz for 0.5m and 1m of TDF, respectively.

A forward pumping scheme is applied to the TDFA in this experiment, as shown in Figure 1b. The gain medium of the TDFA is a 11.5m of Tm-doped fiber (TmDF2) featuring the same physical parameter of TmDF1. A longer section of Tm-doped fiber is used to favor a red-shifted gain. A shutter is used as variable attenuator (VA) before the optical spectrum analyzer (OSA). The L-band EDFA2 is seeded at 1640 nm, and can deliver up to 5W. Two isolators were connected at the output of the MLL to isolate the backward propagating ASE of the TDFA.

2. Results and discussion

First, we investigated a SC generation in TDFA, tuning the MLL wavelength. The 1m TDF fiber was used in the seed laser cavity. Minor wavelength tuning of the MLL does not affect lasing conditions, so the peak and average power are well maintained but, at the same times, it gives some insights about the SC behavior as a function of the seed wavelength. The EDFA2 output power was fixed at 5W. When seeded at 1937nm, the 5dB range spans from 1934nm to 2364nm. Notably, from 1970nm to 2300nm, the SC power fluctuation are within 1dB (Fig. 3). The SC is initiated by a self-shifting of seed laser solitons [7]. A very smooth SC spectrum may be explained by the fact that the MLL laser does not deliver a single soliton per round trip, but rather multiple solitons, slightly shifted in a time domain with respect to each other.

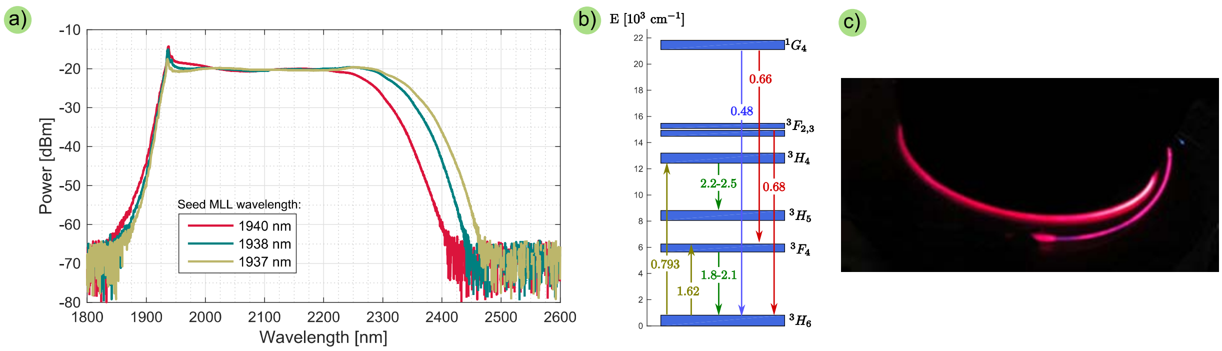

Fig. 3. a) SC spectra, generated in forward pumped TDFA and seeded with different MLL wavelength. 1m TDF seed MLL, 5W pump from EDFA2. b) Energy levels Tm^{3+} ions [8]. Relevant pumping wavelength (793 nm and 1.62 μm), short-wave infrared transitions, participating in SC generation (1.8-2.1 μm and 2.2-2.5 μm), and visible fluorescence transitions (0.48, and 0.66 and 0.68 μm) are indicated. c) Strong red fluorescence of the $^3F_{2,3}$-$^3H_6$ and $^1G_4$-$^3F_4$ transitions of the TmDF2 fiber.

As shown in Fig. 3a, an obvious decrease on the red side of the spectrum can be observed, while tuning the MLL from short to long wavelength. As we initiate the SC in considerably anomalous dispersion region of TDF

($\beta_2 \sim -20\,\mathrm{ps}^2/\mathrm{km}$ around 2000 nm) [9], a strong dependence of SC bandwidth from pump photons energy could indicate a multi-photon absorption inside the TDF. In fact, as it has been already shown, the gain, originating from $^3F_4$-$^3H_6$ (1.8-2.1 µm) and especially $^3H_4$-$^3H_5$ (2.2-2.5 µm) Tm^{3+} transitions, partially compensates for increasing silica losses beyond 2.2 µm. However, $^3H_4$ energy level should be populated in this case. It can be achieved either by resonant pumping at 793 nm [5], or by absorption of several lower energy photons. In our experiments, we believe that the $^3H_4$ population is a result of the absorption of three seed laser photons at ~1938nm ($^3H_6$–$^3F_{2,3}$), followed by non-radiative decay $^3F_{2,3}$ – $^3H_4$. Relatively uniform red fluorescence, which correspond to $^3F_{2,3}$ – $^3H_6$ and $^1G_4$ – $^3F_4$ transitions (Fig. 3a), is observed all over the TmDF2 length, and confirms that Tm^{3+} excitation does not stem from one photon 1640 nm pump exclusively. The non-saturated absorption of the TDF is evaluated to be as high as 53 dB/m at 1640nm, so L-band pumping solely would have kept the middle section of the fiber at the ground energy level.

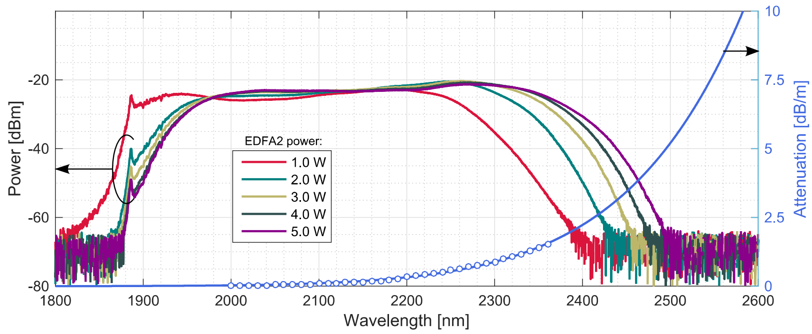

Fig. 4. Left *y*-axis: SC spectra, generated in TFDA, while varying the EDFA2 pump power. 0.5m TDF seed MLL: Right *y*-axis: measured (circles) and extrapolated (solid line) attenuation of SMF-28 fiber.

To further increase the SC span, the 0.5 Tm-doped fiber was used as TmDF1 to blue-shift the lasing wavelength. The lasing wavelength is tuned down to to 1886nm. The wavelength is then fixed to study the effect of photon flux on the SC range by tuning the pump power provided by EDFA2 in the amplifying stage. The EDFA2 power level is varied from 1W to 5W.

From the recorded spectrum in Fig. 4, a clear absorption of 1886nm photons is observed with increasing EDFA2 pump power, supporting the three photon absorption model. The red-shifting of SC peak for higher pump power is in an agreement with a behaviour of Raman solitons. Thanks to the gain provided by the $^3H_4$-$^3H_5$ Tm^{3+} transition, the SC spans from 1970nm to 2370nm with a fluctuation within 5dB. Due to the excessive loss of silica glass and the degraded confinement of SMF-28 at long wavelength, a fast drop of the SC amplitude is observed beyond 2400nm. The total SC power, measured using a power-meter with a thermal detector exceeds 1.7W, with a slope efficiency of 32%.

In conclusion, we have demonstrated the generation of a high-brightness supercontinuum inside a small core thulium-doped fiber, seeded by a tunable around 1900 nm mode-locked laser and assisted by thulium the $^3H_4$-$^3H_5$ and $^3F_4$-$^3H_6$ transitions. The continuum spans from 1950 to 2450 nm and features an output power of 1.7 W with 32% efficiency.

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