ALT 12
Advanced Laser Technologies
2 – 6 September 2012, Thun, Switzerland

ALT 12
c/o Bern University of Applied Sciences
Engineering and Information Technology
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DOI: 10.12684/alt.1.74

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Supercontinuum Generation over 2 μm.

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Abstract

Effective supercontinuum generation in fiber media in spectral range over 2 μm was experimentally demonstrated. Supercontinuum generation was observed in passive optical fibers. Maximum spectral broadening was obtained in germanium-doped fibers with longest wavelength near 2.7 μm. To provide high spectral density we used optical fiber amplifiers. Thus supercontinuum generation was obtained in holmium optical fiber amplifiers medium with spectral density 10 W/nm, in the range from 2 to 2.5 μm. In thulium fiber amplifiers observed amplification not only in conventional range near 1.8 μm, but in spectral range from 2.3 to 2.5 μm, that corresponds to $^3H_4 \rightarrow {}^3H_5$ optical transition possibility in thulium-doped optical fibers.

Introduction

Supercontinuum generation beyond 2 μm is interesting due to the potential application in spectroscopy, atmospheric analysis, medicine, etc. As a rule, to generate supercontinuum in this spectral range special fibers are applied. For example, in [1] sapphire fiber was used, in [2,3] – microstructured fiber based on oxide glass with complex composition. Generation up to 4.8 μm was obtained in ZBLAN fiber [4]. The main disadvantage of such sources is the bad compatibility with standard communication fiber technology.

But one can apply silica-based optical fibers with special properties to provide spectral broadening and all-fiber scheme simultaneously. So we have wide field of investigations. From one point of view, we can use fibers with high nonlinearity, for example, silica based germanium doped fibers and from another we can use media of optical fiber amplifiers.

Application of the active fiber is one of the promising ways to enhance and transform the supercontinuum spectrum. In [5] Yb-doped fiber amplifier was used to amplify a part of the supercontinuum spectra. Paper [6] describes an application of the Yb-doped fiber amplifier as the active and the gain medium simultaneously. As a result, 750-nm broadening from 1 μm to 1.75 μm with tunable spectral power density according to the amplifier gain level was obtained. This approach was used in [7] to get supercontinuum in the mid-IR range in Ho-doped fiber amplifier. In this case Q-switched Er-doped laser [8] was used to generate supercontinuum, and Ho-doped fiber amplifier was separately pumped by Yb-doped fiber laser.

In this paper we consider review of our previous works devoted to supercontinuum generation and an application of Tm-doped fiber in the supercontinuum source scheme. These fibers allow one to get amplification and lasing in the range of 1.9-2.1 μm [9] therefore they are promising for the application in the mid-IR sources. The main objective of our work is to show how the use of Tm-doped amplifier can modify the supercontinuum spectrum.

Experimental setup

Pump source.

Cladding pumped Q-switched Er-doped fiber laser was used as the pump source [8]. Q-switching was realized by emplacement of a self-saturable absorber based on a Tm-doped fiber. Lasing wavelength was of 1.59 μm, maximum output power was near 1 W with repetition rate of 4.4 kHz and pulse duration of 35 ns. Pulse energy of 0.21 mJ and peak power of 6 kW can be estimated.

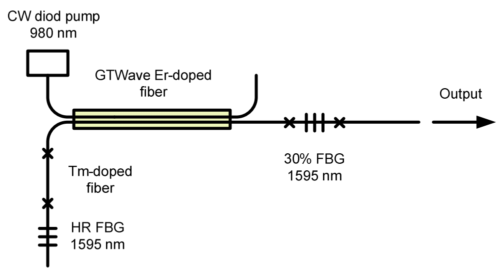

Fig. 1. Scheme of master pulse laser.

Passive media.

We have tested few specimens of the heavily Ge-doped and conventional telecommunication fibers with different lengths. All samples were spliced with output fiber Bragg grating with the excess losses of approximately 3 dB. Using the different fiber length we tried to find an optimal length providing the spectrum with the longest boundary. It is clear that the increase of the length should lead to growth of the loss, but too short fiber cannot provide efficient non-linear conversion.

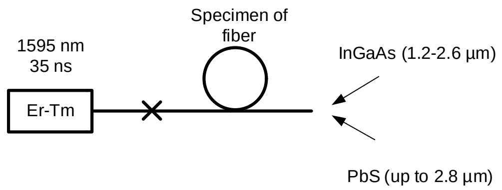

Fig. 2. Experimental setup for passive media.

Active media

Ho-doped fiber amplifier

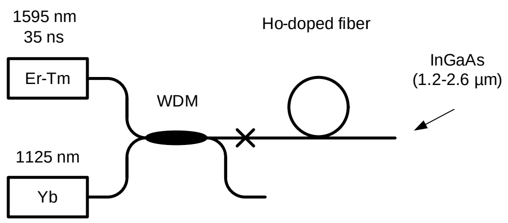

Fig. 3. Experimental setup of supercontinuum generation in holmium fiber amplifier.

We have used two samples of Ho-doped fiber with different concentration of the active ions, as a non-linear medium both fibers have the anomalous chromatic dispersion at the pumping wavelength. It means that the supercontinuum should be caused mainly by the cascade Raman scattering in the field of the anomalous dispersion. To use the amplifying properties of the Ho-doped fiber it was pumped by the Yb-doped fiber laser emitting at 1125 nm. Emissions of Er-doped and Yb-doped lasers were combined by wavelength division multiplexer (WDM).

Tm-doped fiber amplifier

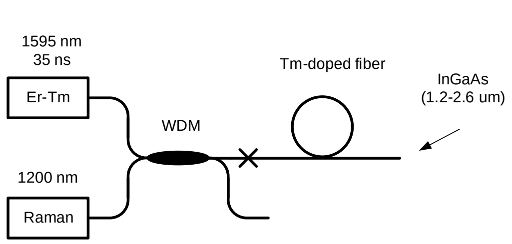

Fig. 4. Experimental setup of supercontinuum generation in thulium fiber amplifier.

Output of the laser was spliced with a piece of the Tm-doped fiber. Its emission wavelength of 1.59 µm corresponds to the transmission $^3H_6 \rightarrow ^3F_4$ for Tm-ions. Small signal absorption in the corresponding band was as high as 300 dB/m. Waveguide parameters were similar to the characteristics of the telecommunication fiber. Also we use scheme with additional pumping on 1200 nm, as shown at fig. 4. This pump provided to obtain better excitation of thulium power levels. And one could expect higher amplification.

Results and discussions.

Ge-doped fiber

We obtained flat output spectrum to 2.7 µm (fig. 5). Average output power was of 0.5 W and the part of power in the range 2-2.7 µm was of 58%. Stimulated Raman scattering is the main effect that leads to broadening of spectrum to the long wavelength range. So fiber with large SRS factor can provide more effective supercontinuum generation in the range 2-2.7 µm. In the heavily germanium doped fiber SRS factor is higher, and losses in this spectral range are less, than in conventional optical fibers. Also in germanium fiber nonlinear factor is higher, that confirms by the short wavelength generation. At the same time these fibers remain to be silica-based ones and can be applied in all-fiber devices as the special nonlinear medium [10].

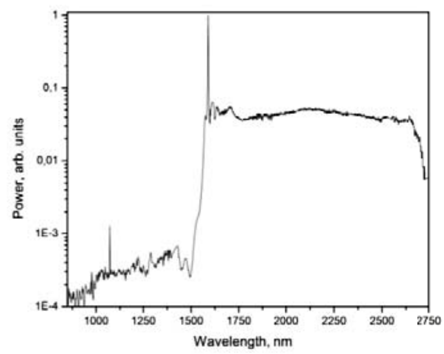

Figure 5. Supercontinuum spectrum obtained in Ge-doped fiber.

Holmium fiber amplifier.

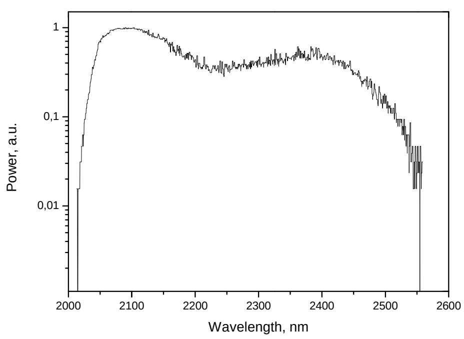

Fig. 6. Spectra of supercontinuum generated in Ho-doped fiber amplifier with high holmium concentration.

It was possible to observe the efficient supercontinuum generation in the range of 2.0 – 2.5 μm with the strong depletion of the emission at the shorter wavelength. Very flat spectrum (fig. 6) was observed in the range of 2.20 – 2.42 nm where power variation is less than 20%. The maximum average power was measured as 0.35 W. Total output pulse energy is 0.1 mJ with spectral density 10 W/nm[7].

Thulium fiber amplifier.

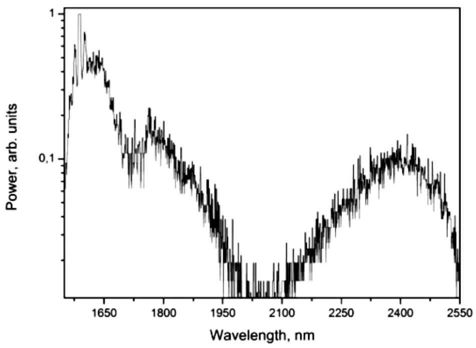

Figure 7. Supercontinuum spectra obtained in thulium-doped fiber.

We have tested the supercontinuum generation in Tm-doped fiber. The corresponding spectrum is shown in fig. 7. One can see that it consists of 3 wide bands. One of them, from 1.55 to 1.7 μm corresponds to the pump emission with non-linear conversion. Second bands centered near 1.8 μm can be attributed to an amplification caused by the $^3F_4 \rightarrow\ ^3H_6$ transmission. Last bands with the maximum at 2.4 μm cannot be explained. Therefore there is reason to believe the existence of the optical transition $^3H_4 \rightarrow\ ^3H_5$ in the Tm-doped silica based fibers.

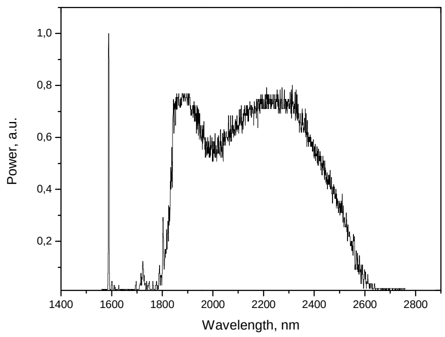

Fig. 8. Spectra of supercontinuum generated in Tm-doped fiber amplifier with low thulium concentration.

One can see the strong peak corresponding to the unconverted pump power. The main part of the output power is contained in a range of 1.58-1.75 μm. The output spectrum is drastically changed when SMF-28 was spliced with Tm-doped fiber having the length of 0.5 m only.

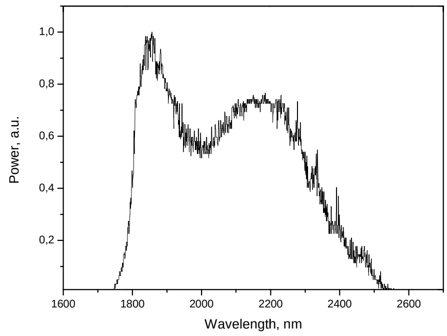

Fig. 9. Spectra of supercontinuum generated in Tm-doped fiber amplifiers with high thulium concentration.

First, there is a strong depletion of the pumping and a suppression of the emission at the wavelength shorter than 1.85 μm. The average output power in this case was measured as 100 mW. Practically all power is contained in a range of 1.85-2.45 μm with the maximum at 2.1 μm. This spectrum shape requires a separate explanation. Amplification in the range of 1.8-2.1 μm is explained by the optical transmission $^3F_4 \rightarrow\ ^3H_6$. It is more difficult to understand an appearance of the emission in the range of 2.1-2.4 μm where amplification caused by this transmission is absent. Also the length of Tm-doped fiber (0.5 m) seems to be very short for the nonlinear conversion of the emission. We can assume that in this case there is an amplification caused by the transmission $^3H_4 \rightarrow {}^3H_5$, with the maximum at 2.3 μm approximately. The filling of the level $^3H_4$ is due to an interaction of excited ions in pairs in the level $^3F_4$. It should be noted that the transmission $^3H_4 \rightarrow\ ^3H_5$ was used in laser crystals to get the lasing at 2.3 μm [11, 12].

Also we used scheme of fiber amplifier to provide higher power density. Output spectra shown at figures 8,9. As one can see we obtain much power at long-wave parts of spectra due to better amplification that was caused by continuous pumping at 1200 nm. But the main mechanism of spectral transformation was the same as in previous case. Total output power was 100 mW, but we obtain higher spectral density in the spectral range from 1800 to 2450 nm.

Conclusion.

All-fiber source of supercontinuum with long-wavelength limit near 2.7 μm was demonstrated. Ho-doped fiber amplifier was used as a non-linear medium of the supercontinuum generator. We have used Tm-doped fiber to enhance the supercontinuum generation under pumping at 1.59 μm. The same source was used for the excitation of Tm-ions. The obtained spectrum occupies the range of 1.85-2.4 μm with the power variation of one decade. The observed spectrum shape allows one to believe the existence of the optical transition $^3H_4 \rightarrow {}^3H_5$ in the Tm-doped silica based fibers.

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