Monolithic Tm-Doped Fiber Laser at 1951 nm with Deep-UV Femtosecond-Induced FBG Pair

P. Peterka, P. Honzátko, M. Becker, F. Todorov, M. Písařík, O. Podrazký, and I. Kašík

***Abstract*—We report on monolithic Tm-doped fiber laser emitting in the region around 2 μm. Pair of fiber Bragg gratings (FBGs) was written into the Tm-doped fiber by using a two-beam interferometry and a deep ultraviolet (DUV) femtosecond laser source at 266 nm. Such monolithic setup allows simple setup of the laser made of single fiber only. This configuration also offers greater reliability because fusion splices inside the resonator cavity could eventually generate failure in the laser cavity. To our knowledge, this is the first rare-earth-doped fiber laser with a FBG pair written by DUV femtosecond laser radiation. Laser characteristics are presented as well as comparison with fiber laser with external FBGs conventionally spliced to the Tm-doped fiber. Dependence of the laser wavelength on the pump power is investigated in detail.**

***Index Terms*—thulium, fiber lasers, fiber Bragg gratings**

I. Introduction

MONOLITHIC fiber lasers refer to compact laser cavities with Bragg gratings inscribed directly into the active fiber [1]. Such configuration improves the laser lifetime as the laser resonator is fully integrated and there are no splices with the fiber Bragg gratings (FBGs) which could generate a failure. Rare-earth doped fiber lasers with FBGs inscribed into the active fibers were reported using various methods, e.g., phase mask inscription using UV light [2] or femtosecond laser in visible [3] and infrared spectrum [4], and by point-by-point technique with infrared femtosecond radiation [5].

In this paper, we report on monolithic Tm-doped fiber laser (TDFL) emitting at 1951 nm. The preliminary results were presented in the conference abstract [6]. To our knowledge, this is the first rare-earth-doped fiber laser with a FBG pair written with DUV femtosecond laser radiation. DUV femtosecond lasers were used for FBGs inscription into passive fibers through phase mask technique [7-9]. The method with Talbot interferometer [10, 11] that we applied has advantages of grating inscription into germanium-free fibers while retaining versatility of the choice of the center wavelength of the FBG, and implementation of small refractive index changes, which makes the method suitable for 1st order FBGs. These features offer unique benefits for the intended application of the presented monolithic TDFL in laser arrays for component manufacturing and testing or in fiber sensing. In the array we need closely spectrally spaced TDFLs with a compact design. A resonator made out of FBG pair is advantageous for the required narrow bandwidth and for the higher stability of the laser upon moderate pumping, while for high-power applications the resonator can be formed by a single FBG and a perpendicularly-cleaved fiber [1, 11]. Moreover, only in the last years the measurement and characterization tools for FBGs in the 2 μm range appeared on the market, which are needed to inscribe well confined high- and lower-reflectivity (HR, LR) grating pairs in the Tm amplification band in non-photosensitive fibers. Laser characteristics of three TDFL samples are presented and compared to a TDFL consisting of the same active fiber but with external FBGs. We discuss the effect of temperature changes and resonant nonlinearity on the laser wavelength.

II. Tm-fiber Laser Setup and FBGs Characteristics

The experimental setup of the fiber laser is shown in Fig. 1 The monolithic TDFL is formed by the Tm-doped fiber (TDF) with two gratings inscribed into it 30 cm apart from each other to create the resonator. The TDF was fabricated by modified

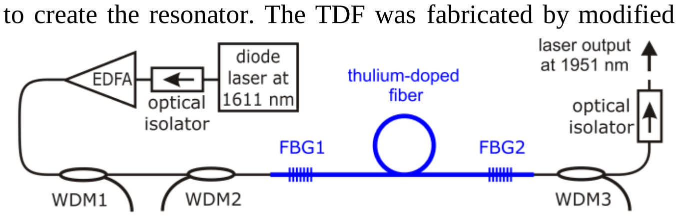

Fig. 1. Tm-fiber laser setup. EDFA: Er-doped fiber amplifier, WDM: wavelength-division multiplexer, FBG: fiber-Bragg grating.

chemical vapor deposition (MCVD) and solution-doping method. The thulium chloride was dissolved in the absolute ethanol together with alumina nanoparticles of <50 nm size. Such nanoparticle doping allows us to reach higher concentration of alumina in the fiber core compared to conventional production from chlorides [12]. The alumina content in the core is 11.2 mol % and no germanium oxide was added. The TDF has LP_{11} cutoff wavelength of 1520 nm,

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P. Peterka, P. Honzátko, F. Todorov, O. Podrazký, and I. Kašík are with the Institute of Photonics and Electronics ASCR, v.v.i., Chaberská 57, 18251 Prague, Czech Republic (email: peterka@ufe.cz)

M. Becker is with the Institute of Photonic Technology, Albert Einstein Str. 9, 07745 Jena, Germany.

Michael Písařík is with SQS Vláknová optika a.s., Komenského 304, 50901 Nová Paka, and Department of Electromagnetic Field, Czech Technical University in Prague, Technicka 2, 16627 Prague, Czech Republic.

hence both pump at 1611 nm and signal at 1951 nm are propagating in the fundamental mode. The fiber absorption of 25 dB/m was measured at the pump wavelength. Mode field diameter at 1611 nm and 1951 nm is 5.6 μm and 6.3 μm, respectively.

A series of three monolithic TDFLs were prepared with FBGs nominal reflectivity of 99 % and 60 %, respectively. The nominal central wavelength is 1951 nm. The reflection spectra of the fabricated FBGs are shown in Fig. 2. The LR gratings are of 0.7 nm bandwidth while HR gratings exhibited larger bandwidths in the range of 1.6 to 2.3 nm. The gratings were inscribed using a two-beam Talbot interferometer with phase mask as a beam splitter [10]. The third harmonics from the Ti:sapphire femtosecond laser system was employed as a DUV source. It should be noted that with DUV femtosecond laser inscription a multiple-photon absorption occurs in contrary to the DUV cw laser inscription with a single-photon absorption only [10]. The different nature of the FBG inscription also lead to different features of these gratings, e.g., variation of their reflectivity with pump power and

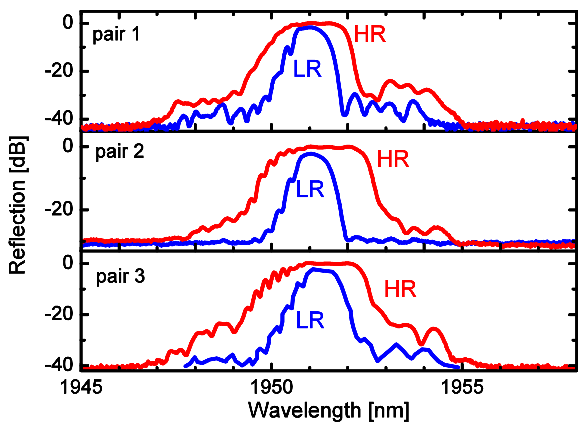

Fig. 2. Reflection spectra of the FBG pairs inscribed into the Tm-doped fiber. HR – high reflectivity grating, LR – lower reflectivity grating.

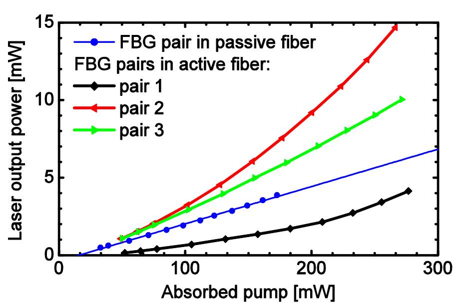

Fig. 3. Laser output vs. absorbed pump for the fiber laser with external FBG pair and for the monolithic configurations.

temperature was observed recently [11].

The TDF was pumped in the core at 1611 nm by a laser diode and an L-band erbium-doped fiber amplifier (EDFA). Most of the amplified spontaneous emission from the EDFA was filtered out by the first wavelength division multiplexer WDM1. The WDM2 can be used to monitor the laser output at around 2 μm generated backward to the pump. The WDM3 removes the unabsorbed pump radiation.

III. Experimental Results and Discussion

The output power characteristics of all three monolithic TDFLs are shown in Fig. 3. The laser output power for the FBG pair No. 1 is considerably lower than for the other two pairs. It is because the TDF length between the HR FBG1 and the standard single-mode fiber pigtail was about 32 cm while for the other pairs both pigtails were 10 cm long. Therefore, the actual pump power at the beginning of the TDFL resonator is lower by about 5 dB than for the other two pairs. The absorbed pump power in Fig. 3 refers to the total absorbed pump power in the TDF, i.e., in the monolithic fiber laser and the two residual sections of the TDF leading to the pigtails. The output power vs. pump power exhibits nonlinear behavior for all three. The most pronounced nonlinear dependence is for the pairs no. 1 and 3. Typical linear characteristics for the output power vs. pump power were found in the case of the TDFL with external FBG pair; see the line with circles in Fig. 3. The HR FBG with a bandwidth of 0.3 nm and reflectivity of 0.99 was placed at the pump end of the TDFL and the LR FBG with a bandwidth of 0.08 nm and reflectivity of 0.95 was used as output port of the laser. Since the output FBG reflectivity differs from that of the output mirrors inscribed directly into the active fiber, the slope efficiency is also different compared to the output FBG in the monolithic TDFL. The laser wavelength of the TDFL with external FBG pair was almost constant. The external FBGs were inscribed in rare-earth free optical fibers that exhibit no resonant nonlinearity (due to population inversion) and negligible temperature increase (due to rare-earth-ions absorption). But for the monolithic TDFL we have observed a wavelength shift with the pump power at the rate of $\delta\lambda_B/\delta P_{abs}\approx 1.41$ pm/mW, see Fig. 4, which is attributed to the change of the refractive index with absorbed pump power, as a result of changes of the temperature and the population inversion within the FBGs. Since the wavelength shifts of the two FBGs of the monolithic TDFL are generally different, their reflectivity varies differently resulting in nonlinear laser output power characteristics. Spectral variation of the thulium cross section should have negligible effect as the emission spectrum at the laser wavelengths is flat compared to the variation of the FBGs reflection spectra.

To evaluate the effect of temperature and population inversion let us consider the following analysis. The thermo-optic coefficient in silica based fibers is $\delta n/\delta T\approx 1\times 10^{-5}$ per K [13]. The wavelength of reflection of the FBG is given by $\lambda_B=2n_{eff}\Lambda_B$, where the n_{eff} is the effective mode index of the fundamental mode of the TDF and Λ_B is the grating pitch (about 650 nm in our case). Therefore, the increase of the refractive index by Δn would cause a shift of the wavelength of reflection by $\Delta\lambda_B=2\Delta n\Lambda_B$. If only the thermo-optic effect would be responsible for the wavelength shift, then from the relation: $\Delta\lambda_B/\Delta T=2\Lambda_B\Delta n_{eff}/\Delta T$, one can find that in the thulium emission band the FBG wavelength shift with temperature is about 13 pm/K. Taking into account the observed laser wavelength shift of 1.41 pm/mW we can deduce that the temperature of the fiber core increased by

30 K for the 300 mW absorbed pump power. The observed FBG's wavelength shift is in good correspondence with 8 pm/K reported in ytterbium-doped fibers [11] and 13 – 30 pm/K recently reported in TDFL with FBG pair inscribed by different method [14].

If only resonant nonlinearity is taken into account, the shift of the FBG wavelength is $\Delta\lambda_B=2\ \Lambda_B\Delta n_{eff}\approx 2\ \Lambda_B\, n_2\, P/A_{eff}$, where effective area A_{eff} is estimated from the mode-field diameter as 25 μm^2. Although the resonant nonlinearities in rare-earth doped fibers have been studied since nineties [15], only little information can be found about the resonant nonlinearity in TDFs. Kim et al. [16] have found nonlinear coefficient of germanosilicate fiber doped with tri- and divalent thulium ions of about $n_2\approx 4\times 10^{-15}$ m^2/W for the TDF with similar thulium concentration to our experiment. Attenuation of their TDF is about 50 dB/m at 1600 nm. Unfortunately, general analysis and required spectroscopic data have not been published yet about resonant nonlinearity for TDFs as it was done for the ytterbium-doped fibers [15]. Therefore, we cannot evaluate the nonlinear refractive index change in the strongly saturated regime of fiber lasers. To achieve the observed wavelength shift of 1.41 pm/mW only by the resonant nonlinearity, the nonlinear refractive index has to be at least 2.7×10^{-14} m^2/W. This number is an order of magnitude higher than the value reported in the literature [16]. It should be noted, that in laser regime the pump is converted mainly to the laser output and the effect of resonant nonlinearity can be much lower than it is in the case of a fiber without resonator studied in [16].

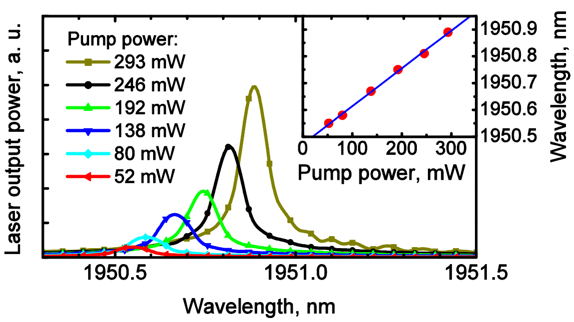

Fig. 4. Laser spectra of the monolithic TDFL with FBG pair No. 2 for various input pump power levels, Inset: Laser wavelength shift with the pump power together with linear fit.

IV. Conclusions

In summary, we have demonstrated a monolithic fiber laser at 1951 nm. A good reproducibility of the gratings fabrication has been shown. We have found that the output wavelength of the monolithic fiber laser varies with the pump power as 1.41 pm/mW while negligible wavelength shift occurred for the TDFL with external FBG pair. We have confirmed that the shift of the laser wavelength with pump power is dominantly determined by the thermo-optic effect rather than resonant nonlinearity. Since the wavelength shifts of the two FBGs of the monolithic TDFL are generally different, their reflectivity varies differently resulting in nonlinear laser output power characteristics. The applied method of FBG inscription offers a great versatility of selection of the center wavelength of the FBG which makes presented monolithic lasers promising solution for compact arrays of lasers for component testing and optical fiber sensors.

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