Kerr nonlinearity of Thulium-doped fiber near 2 μm

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Abstract: The nonlinear coefficient and group velocity dispersion of a thulium-doped fiber near 2μm are evaluated via four-wave mixing. Nonlinearity of thulium-doped fiber can be used for the design of doped-fiber lasers in this spectral region.

OCIS codes: (060.2270) Fiber characterization; (190.4380) Nonlinear optics, four-wave mixing

1. Introduction

Thulium-doped fiber (TDF) lasers have recently attracted a significant interest for various applications, covering spectroscopy, material processing and telecommunications. Depending on the application, TDF laser can be designed for high-energy pulsed operation [1] or to provide sub-Watt continuous-wave (CW) power [2]. As core-pumped fiber laser designs often rely on TDFs with relatively small cores and high refractive index contrast [3], one could expect that the fiber holds a non-negligible nonlinear coefficient. Indeed, while investigating ring-cavity lasers including an 11.5 m long commercial TDF (OFS TmDF200) similar to [2] we noticed a pump-power dependent broadening of the output spectrum, which indicates the presence of Kerr effect. Precise knowledge of the nonlinear coefficient and group velocity dispersion of such fiber could be used not only for obtaining a better understanding of TDF laser behavior but also for enabling efficient soliton modelocking at 2 μm. In this paper, we present the measurement of nonlinear coefficient γ of thulium-doped fiber around 2 μm via degenerate four-wave mixing (FWM). We also evaluate the group velocity dispersion. Nonlinearity 4 to 5 times higher than for single mode fiber can be expected from such commercially available fibers.

2. Experimental setup and results

The Kerr nonlinearity is experimentally studied through degenerated four-wave mixing. The schematic for the setup is shown in Fig.1. In this scheme a continuous wave (CW) signal and a powerful CW pump are launched together in the fiber under test (FUT), and give rise to an idler wave spectrally located symmetrically to the signal with respect to the pump. The signal wavelength is swept, and one can compute the conversion efficiency (CE), i.e. the ratio between idler power at the output of nonlinear media and seed signal power at the input, as a function of signal detuning. The CE spectrum is then fitted to retrieve γ as well as the second order dispersion coefficient β_2 in case of moderate detuning between the pump and the idler [4].

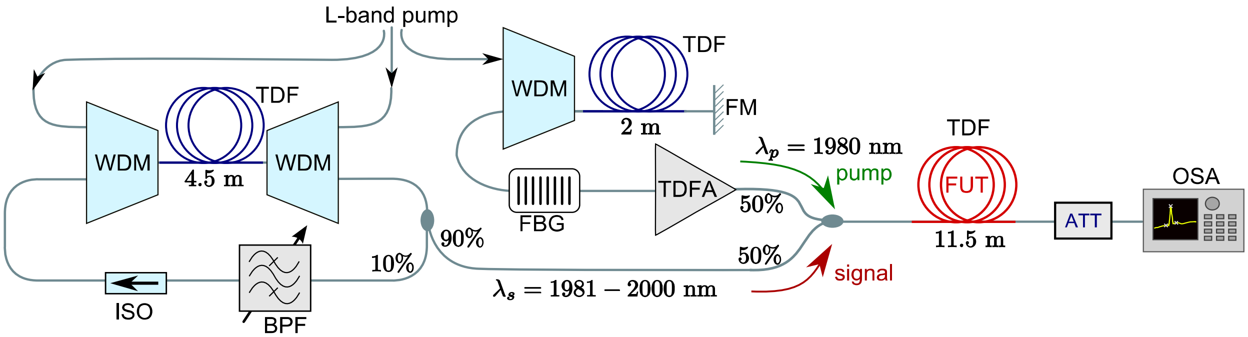

Fig. 1: Experimental setup. WDM: wavelength division multiplexer; ISO: optical isolator; BPF: tunable band-pass filter; FM: fiber mirror; FBG: fiber Bragg grating; TDFA: thulium-doped fiber amplifier; FUT: fiber under test; OSA: optical spectrum analyzer; ATT: fixed attenuator

The experimental setup, shown in Fig. 1, aims at generating an idler wave in an 11.5 m long TDF pumped parametrically (in theory no excitation of the Tm^{3+} ions) with a 1980 nm pump. For this purpose, we first generate the 20 mW CW pump seed using a fixed wavelength oscillator made of a pumped TDF inserted between a fiber-coupled mirror and a fiber Bragg grating (centered at 1980 nm, 80% reflectivity, 0.6 nm bandwidth). This seed is amplified in a commercial TDF booster and coupled to a signal generated in a wavelength tunable ring-cavity laser before both waves are directed toward the TDF under test. The pump launch power is varied from 0.57 W to 1.1 W, while signal power is 150 mW. L-band EDFAs are used to pump the oscillators, but no L-band power remains at the FUT input. At the output of the FUT, the spectrum is monitored on an optical spectrum analyzer (OSA).

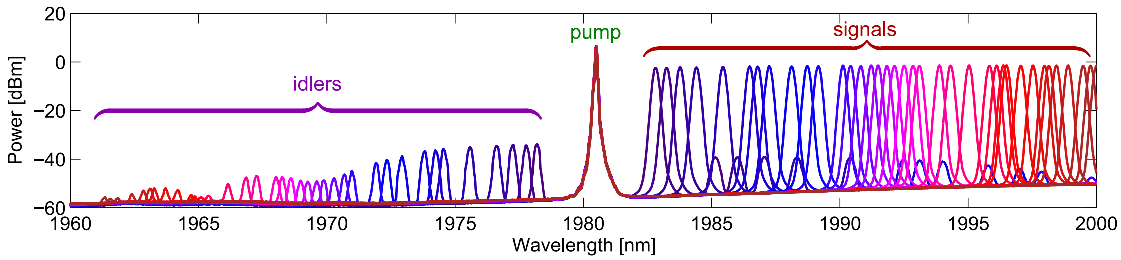

Fig. 2. Superimposed FWM spectra at the output of the FUT when the signal wavelength is swept from 1982 nm to 2000 nm. Pump power at 1980 nm is 1.1 W. OSA resolution is 0.05 nm. Fixed attenuator is inserted prior to OSA.

Fig. 2 shows the retrieved spectra for a 1.1 W pump and a signal swept between 1982 and 2000 nm. Idlers are clearly generated between 1962 to 1978 nm. The CE was then extracted from the spectra and fitted using the analytical 3-waves model taking into account the attenuation at the pump wavelength [4]. Including this attenuation is necessary as the TDF features a slight intra-band absorption at 1980 nm when neither 0.8 µm nor 1.6 µm pump is launched into it. We consider the attenuation it entails as linear. The parameters corresponding to the fitting shown on Fig. 3(a) are the following: $\beta_2 = -20.1$ ps^{2}km^{-1}, $\gamma = 5.3$ W^{-1}km^{-1} and an attenuation coefficient $\alpha = 0.42$ dB/m. The smooth dips between the secondary lobes of the CE curve indicate that loss on the pump does affect FWM. In order to verify the value we obtained for γ, the CE as a function of parametric pump power for a given signal wavelength is measured. The test is performed for 5 values of pump-signal detuning. It is expected that the CE evolves quadratically with pump power [5]. The experimental data and the fitting are displayed on Fig. 3(b), the retrieved coefficient γ varies from 3.8 to 4.6 W^{-1}km^{-1} depending of the detuning. The agreement with the value obtained after CE fitting is good and confirms the relatively high value of γ. Knowing the FUT mode field diameter (5 µm at 1700 nm) and numerical aperture (0.26) [3], we calculated an effective area of 27 µm^2 at 1980 nm, assuming a fiber step-index profile. The nonlinear coefficient n_2 of the TDF is therefore evaluated in the range $(3.2-4.5)\cdot 10^{-20}\,\mathrm{m^2W^{-1}}$.

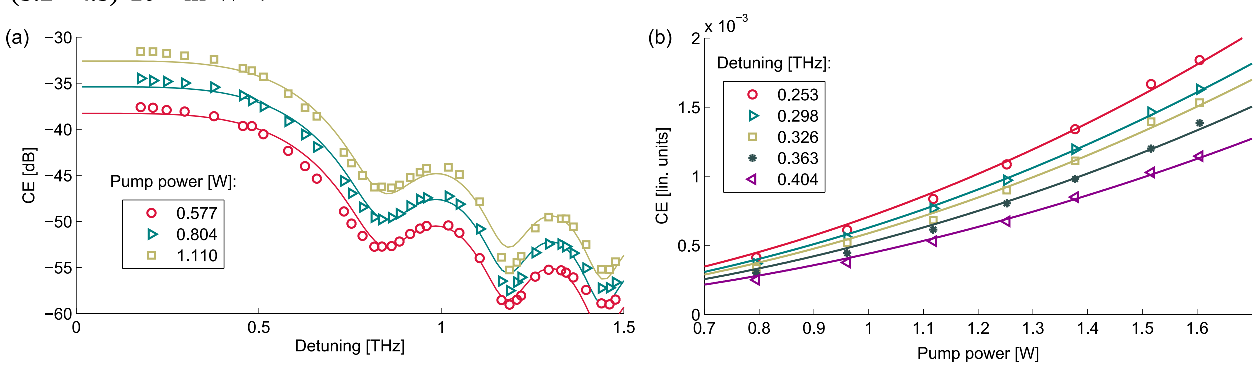

Fig. 3. (a) Experimental CE spectrum (markers) and fitting with the analytical model (solid lines) as a function of pump-signal detuning. (b) Experimental CE values versus launched parametric pump power (markers) and its fitting (solid lines).

We presented, to the best of our knowledge, the first measurement of nonlinearity at 2 µm for a commercially available TDF. Our measurements show a large value of γ compared to those of SMF (estimated γ_{SMF}=0.9 W^{-1}km^{-1} at 1980 nm) and also confirm the large anomalous dispersion at 2 µm. The combination of these two effects has the potential to initiate solitons generation directly in the gain medium of a fiber laser built with an OFS TmDF200, and could therefore enable the design of very compact mode-locked lasers architectures [6].

This work is supported in part by the European Research Council under grant agreement ERC-2012-StG 306630-MATISSE, and by the SNSF under grant agreement 200021_140816.

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