Unidirectional all-fiber thulium-doped laser based on theta cavity and fiber Bragg grating as filtering element

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Abstract: We present first all-fiber unidirectional ring thulium-doped laser, based on isolator-free theta cavity configuration and fiber Bragg mirror as filtering element. Laser provides 1W output power with 30% slope efficiency, and linewidth of about 0.2nm.

OCIS codes: (060.3510) Lasers, fiber; (060.2390) Fiber optics, infrared; (160.5690) Rare-earth-doped materials

1. Introduction

Thulium-doped fiber lasers (TDFL), emitting the light in a broad wavelength range from approximately 1800 nm to 2100 nm, gain a growing attention of research and industrial community, due to their numerous applications in spectroscopy, ranging, material and biological tissues processing as well as telecommunications [1]–[3]. Moreover, tunable narrow-linewidth lasers are used as pumping sources to drive nonlinear effects in optical fibers and waveguides, enabling a study of nonlinear processes at wavelengths that are not easily accessible with conventional semiconductor external cavity lasers [4], [5]. In most ring cavity TDFL implementations, grating-based filters [6], [7], Fabry-Pérot etalon [8], or combination of optical circulator with fiber Bragg grating (FBG) [5] are used as a wavelength selective element. While being packaged and interfaced with fiber pigtails, these filters remain inherently free-space optical components, which are sensitive to alignment fluctuations and have lower damage threshold, comparing to all-fiber elements. Additionally, optical isolator should be inserted into the cavity to ensure unidirectional lasing. The fibre isolator conventionally includes Faraday rotators and 45° cross polarizers with adjacent free-space optics [9] and suppresses backward propagating light within a given bandwidth, generally not exceeding several tens of nm. Therefore, isolator-free unidirectional ring fibre cavity (sometimes referred to "theta" or "yin-yang" resonators [10]) represents an attractive and cost-effective alternative solution. In theta cavities, non-reciprocal losses are introduced by providing an S-shape feedback within the main ring. We have already shown a core-pumped continuous wave TDFL that provides sub-Watt with a slope efficiency of 25%, 2 dB flat tuning range of 1900–2050 nm, and linewidth of 0.2 nm, and achieves the extinction ratio (ER) of 18–25 dB between the favored and suppressed lasing directions [11]. The TDFL wavelength was tuned by fiberized grating filter. A high power Q-switched theta cavity TDFL using carbon nanotube saturable absorber was also reported [12].

In this paper, we present truly all-fiber narrow linewidth unidirectional ring TDFL, relying on theta cavity and FBG as wavelength selective element. The need for a circulator is circumvented by leveraging the already existing architecture. The laser output power reaches 1 W, with 30% slope efficiency and spectral width less than 0.22 nm.

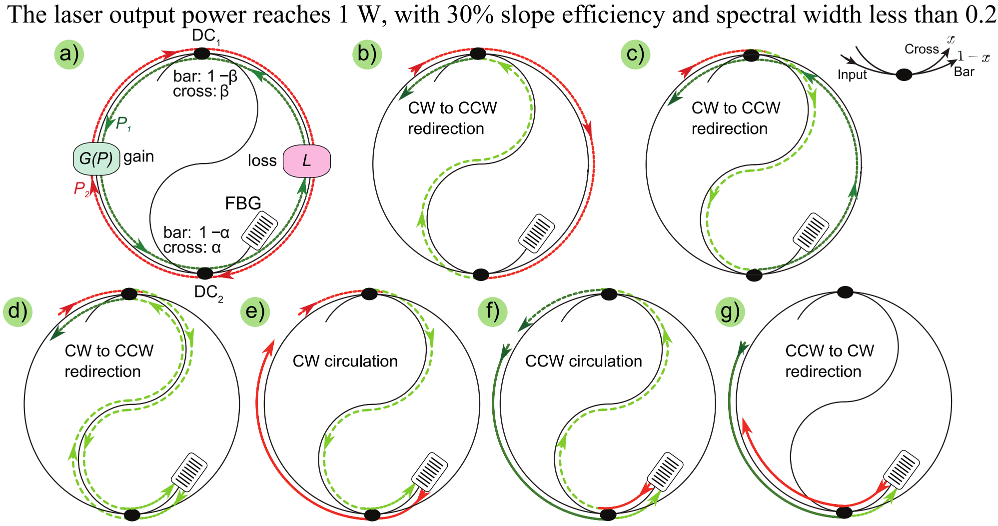

Fig. 1. Theta cavity with FBG layout. Optical path, not affected by FBG: a) Main paths for the clockwise (CW – red) and the counter –clockwise (CCW – green) propagating modes, corresponding to a ring; b-c) two possible rectifying path, redirecting the CW modes towards the CCW modes. Optical path, influenced by FBG: d) CW to CCW redirection; e) CW circulation; f) CCW circulation; g) CCW to CW redirection.

2. Principle of operation

The main idea behind theta resonator is a lasing direction rectification by introducing non-reciprocal cavity losses, described in details in [11]. We consider a ring resonator that consists of a lumped gain unit *G(P)*, and two directional couplers, which cross-outputs are connected together to form the S-shape feedback (Fig. 1). P_1 and P_2 are counter-clockwise (CCW) and clockwise signals entering the amplifying unit. The unused port of the directional couplers can be cleverly exploited by connecting a FBG. If no FBG is present in the design, only three possible paths are sustained: CCW and CW circulation in the main ring (Fig. 1a), and two rectifying paths from CW to CCW modes (Fig. 1b-c). If a FBG is connected to the free port of directional coupler 2 (DC_2), one obtains four extra paths, involving the grating: CW to CCW redirection, CW circulation, CCW circulation, and CCW to CW redirection (Fig. 1d-g). Therefore, the laser spectral line shape can be controlled by the FBG in reflection mode, which provides a wavelength selective feedback in the cavity, and that without the need for a circulator or any modification to the original cavity.

3. Fiber laser implementation and results

The experimental setup of the theta cavity TDFL with FBG is shown in Fig. 2a. The gain unit (GU) consists of 11.5 m of thulium doped fibre (TmDF200, OFS Fitel Denmark ApS) bi-directionally core pumped with a 1600 nm pump obtained from an amplified tunable laser source (TLS). The S-shape feedback is formed by two identical directional couplers ($DC_{1,2}$), connected in such a manner that cross-coupling ratios are 90% and 10% for DC_1 and DC_2, respectively. Different FBGs were attached to a free port of DC_2: chirped FBG with central wavelength of 1980 nm, and non-chirped FBGs at 2000, 2008, 2040 nm. The third monitoring 5% coupler (DC_3) is only included to evaluate the ER between CCW and CW modes. To extract the maximum possible power, a free port of DC_1 is used as output.

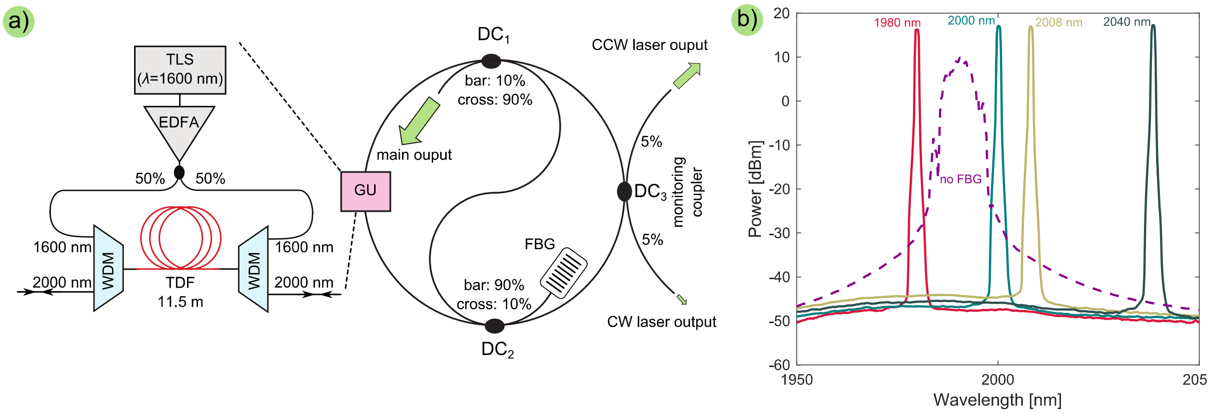

Fig. 2. Implementation of theta cavity TDFL. a) Experimental setup. Details of the gain unit (GU) are shown on the left. TLS: tunable laser source; EDFA: Erbium doped fibre amplifier; WDM: wavelength division multiplexer; TDF: Thulium doped fibre; FBG: fiber Bragg grating, DC: directional coupler. b) Attenuated emission spectra for different FBGs (pump power of 3W, 1 nm resolution).

Without a FBG, the cavity lases around the emission peak at 1990 nm, maintaining, however, unidirectional operation with 22 dB ER (Fig. 2b). Once a FBG is inserted, the TDFL generates a narrowband signal, tunable within entire emission bandwidth (Fig. 2b – low resolution, Fig. 3 – high resolution), with ER better than 21 dB.

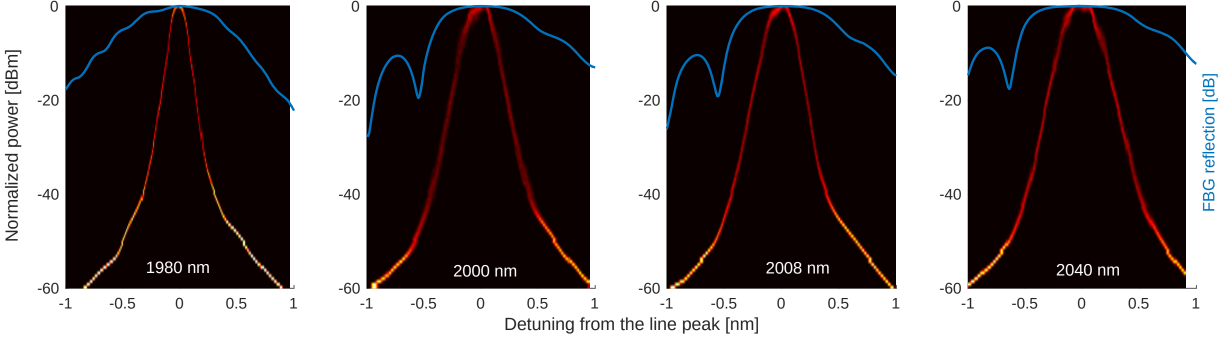

Fig. 3. Laser spectral line shapes for different FBGs, installed in the theta cavity. Every line shape is 2D histogram, based on 1000 traces. Pump power of 3W, 0.05 nm resolution. Blue lines – normalized reflection functions of FBGs.

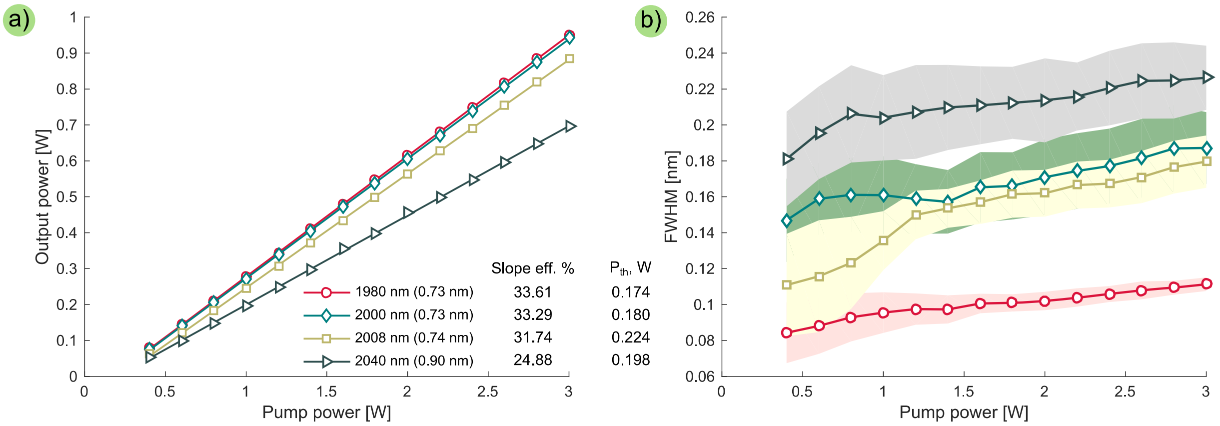

Fig. 4. Laser performance characteristics. A) output power vs. pump power. Inset table shows slope efficiency and pump lasing threshold. B) Laser linewidth (FWHM) vs. pump power. Shadowed regions indicate standard deviation of FWHM (linewidth jitter $\Delta\sigma_\lambda$)

As shown in Fig. 4a, all TDFLs can reach sub-Watt output power level with slope efficiencies of 25-34% and about 0.2 W threshold pump power. Overall, the laser performance of theta TDFL with FBGs is improved, comparing to previously reported theta cavity, which exploited a grating-based filter with 4 dB insertion losses. So, the slope efficiency at 2000 nm is increased from 25% (free-space grating) to 33% (FBG). A minimal slope efficiency of 24.9% is observed at 2040 nm due to operation at the edge of TDF gain spectrum. The linewidth at 3W pump ranges from 0.1 nm FWHM at 1980 nm to 0.22 nm FWHM at 2040 nm, with a slope of 0.008 nm/W for 1980 FBG and 0.013 nm/W for other FBGs (Fig. 4b). The FWHM is determined as $2\sqrt{2ln2}\sigma_\lambda$, where σ_λ is the standard deviation of the spectral line profiles in the wavelength domain. Possible fluctuations of FWHM (linewidth jitter $\Delta\sigma_\lambda$) are shown in Fig. 4b as well. The method of evaluation of $\Delta\sigma_\lambda$ has been described in the previous publication [11]. Remarkable point is that theta cavity TDFL, operating at 1980 nm, demonstrates a well-stabilized linewidth ($\Delta\sigma_\lambda$ of 4 pm at 0.1 nm FWHM). This behavior might be partially attributed to the operation close to the TDF gain peak. However, we believe that the chirping of the FBG strongly contributes to low linewidth jitter, because 2000 nm laser, exploiting regular FBG and emitting in the vicinity of maximum gain as well, exhibits much higher FWHM deviations (20 pm).

In conclusion, we demonstrate the first truly all-fiber unidirectional TDFL, based on theta cavity configuration with FBG as a filtering element. The laser provides up to 1 W output power with a slope efficiency of about 30%, preserving the linewidth smaller than 0.22 nm. Using the FBGs with narrower (~0.1 nm) reflection bandwidth can further reduce the emission linewidth, and improve the laser stability.

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