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High-Power and Narrow-Linewidth Er, Yb Fiber Laser Locked by a Volume Bragg Grating-Pair

Jun Liu, Deyuan Shen, Haitao Huang, Xiaoqi Zhang, Li Wang, and Dianyuan Fan

***Abstract*—A high-power and narrow-linewidth Er, Yb co-doped fiber laser is demonstrated by using two serially-paired volume Bragg gratings. A maximum output power of 19.4 W at 1545.3 nm with a full-width at half-maximum linewidth of <∼38 pm is obtained for 65.3 W of launched pump power, corresponding to a slope efficiency of 30.1% with respect to launched pump power.**

***Index Terms*—Er, Yb fiber laser, high-power, narrow-linewidth, volume Bragg grating.**

I. Introduction

High-power and narrow-linewidth fiber-based sources, especially those operating in the eye-safe wavelength regime at around 1.5-1.6 μm, have grown rapidly due to the numerous applications including range finding, laser radar and in the long-haul optical transmission systems. To enable access to narrow band operation in fiber lasers, effective spectral selection and narrowing components are therefore required. Fiber Bragg gratings (FBGs), which offer a narrow linewidth and good integrity with traditional single mode gain fibers, have been widely used for spectral control in fiber lasers [1]–[3]. However, they are not very effective in large mode area fibers for high-power generation and specialty fibers such as photonic crystal fibers. Volume Bragg gratings (VBGs), recorded in a bulk of photo-thermo-refractive (PTR) glass, have attracted great attention as appropriate external wavelength selection and spectral narrowing components in fiber lasers [4]–[8], due to their excellent performance including high diffraction efficiency, narrow spectral selectivity, low insertion loss and high damage threshold. Up to 103 W output power at 1552.6 nm with a linewidth of ∼0.4 nm (FWHM) was yielded for a launched pump power of 290 W at 976 nm [5].

More recently, some new laser resonator designs based on the novel use of VBGs have been demonstrated to achieve the narrow band operation in fiber lasers [9], [10]. Particularly, in Ref. [9], compared to the conventional configuration using a single VBG as spectral controlling component [7], further spectral narrowing with a FWHM linewidth of ∼2.2 pm was achieved in a cladding-pumped high-power Tm-doped fiber laser by serially pairing two specially designed VBGs. In this letter, we employ a similar dual-VBG-configured resonator for Er, Yb co-doped fiber laser (EYDFL) for spectral control and achieve a maximum output power of 19.4 W with <∼38 pm linewidth (FWHM) at the launched pump power of 65.3 W, corresponding to a slope efficiency of 30.1% with respect to the launched pump power. To the best of our knowledge, this is the narrowest laser linewidth in high-power Er, Yb co-doped fiber lasers based on VBG technique. In contrast to traditional narrow linewidth master-oscillator power amplifier (MOPA) configurations, this direct laser resonator design benefits from a simple structure and thus convenient maintenance.

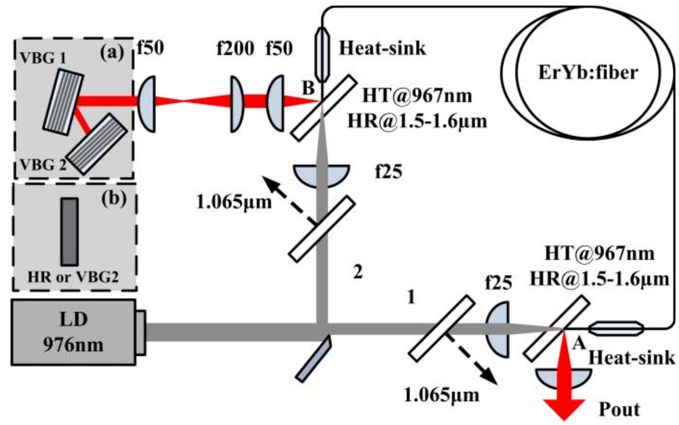

Fig. 1. Experimental schematic of the (a) dual-VBG narrowed Er, Yb co-doped fiber laser. A broadband HR mirror or a single VBG2 (b) substituting for configuration (a) was also performed for comparison.

II. Experiment and Results

The schematic diagram of the experimental setup for the EYDFL is shown in Fig. 1. Pump power was provided by a commercially available LD (LIMO) with a center wavelength of 976 nm and maximum output power of 650 W. The gain fiber (Nufern) employed in this experiment had an Er, Yb co-doped phospho-silicate core of 30 μm diameter and ∼0.2 NA, surrounded by a pure silica D-shaped inner-cladding of 400 μm diameter and ∼0.49 NA, with a low refractive index UV-cured polymer out-cladding. The nominal peak pump absorption at 976 nm of the fiber for the cladding-pumped regime was ∼5 dB/m. However, the measured effective pump absorption coefficient was somewhat lower due to the broad (∼5 nm) and power dependent output spectrum of the LD pump source. The spectral peak of the LD located at around ∼967 nm with output power controlled below 300 W. Therefore, a fiber length of 5.3 m was selected to guarantee sufficient pump absorption. The pump light was split into two beams of roughly equal power and then launched into opposite ends of the gain fiber through two dichroic mirrors by using two anti-reflection coated plano-convex lenses of 25 mm focal length. The pump launch efficiency into the inner-cladding of the gain fiber was estimated to be ∼80% relative to the power incident onto the fiber. Both end sections of the fiber were carefully embedded in water-cooled V-groove heat sinks to prevent possible

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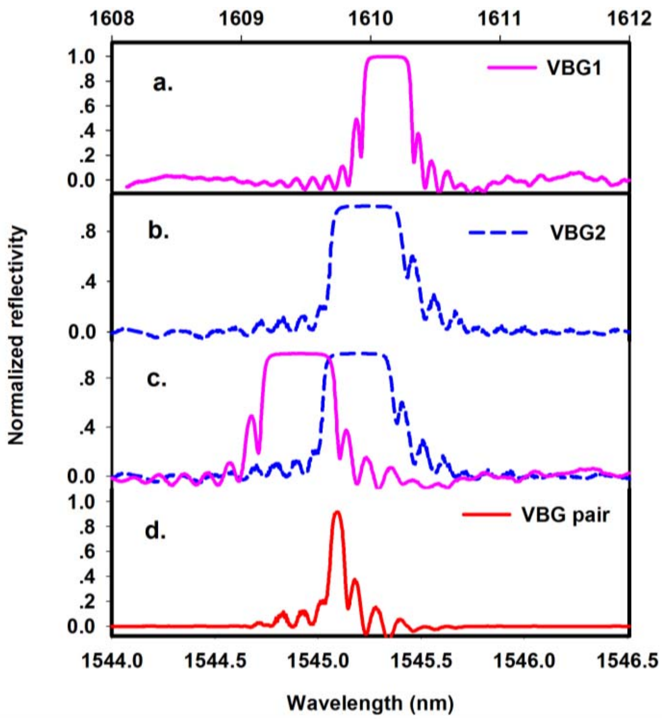

Fig. 2. Reflectivity spectra of VBG1 (a) and VBG2 (b) at normal incidence, and reflectivity spectra of both VBGs (c) in the case where VBG1 was tuned to overlap with reflectivity spectrum of VBG2; Effective reflectivity of the dual serially-paired VBGs (d) as a spectrum narrowing component.

thermal damage to the fiber coating caused by the unlaunched pump power and quantum defect heating, and the rest part of the fiber was coiled into a fan-cooled Al heat sink. The dichroic mirrors with high transmission at the pump wavelength and high reflectivity over the 1.5-1.6 μm band were positioned at 45° to steer the laser beam from the pump light, allowing efficient extraction of the EYDFL output. Another two dichroic mirrors with high reflectivity at ~1 μm and high transmission at the pump wavelength were inserted into the two pump arms to prevent any ~1 μm radiation, due to parasitic lasing on the Yb^{3+} transition, from being fed back to the diode pump source.

Lasing feedback for the narrow-linewidth EYDFL, was provided by the 3.6% Fresnel reflection from a perpendicularly-cleaved fiber end facet (A) and, at the opposite end (B), by a simple external cavity comprising a combination of 3 antireflection-coated lenses with the focal lengths of 50 mm, 200 mm and 50 mm, respectively, and a serially paired reflective VBGs (designated as VBG1 and VBG2). The corresponding focal lengths of these lenses in the external cavity were selected to obtain a comparable collimated laser spot with the clear aperture of the VBGs. The two VBGs (Optigrate corp.) both had a thickness of 7 mm with clear aperture of 6 mm×8 mm and were mounted in copper heat sinks with a layer of indium foil (0.1 mm in thickness) to ensure good heat dissipation. The fiber end (B) adjacent to the external cavity was angle cleaved at ~8° to suppress broadband feedback from the uncoated fiber facets. Spectrum of the laser output was recorded using an optical spectrum analyzer (AQ6370C, Yokogawa).

VBG1 and VBG2 used in our experiment were designed to have a central wavelength of 1610.1 nm and 1545.2 nm, with the same peak reflectivity of 99.9% and spectral selectivity of 0.38 nm, respectively. Both VBGs were anti-reflection coated for each surface (>99.6%) over the band from 1500 nm to 1700 nm to reduce cavity loss. The measured reflectivity spectra of these two VBGs at normal incidence were shown in Fig. 2. It can be seen that there will be no spectral overlap when both of them are aligned at normal incidence due to the large separation of as much as 65 nm between central diffraction wavelengths of these two VBGs. However, the Bragg wavelength λ_B of a VBG was determined by the incident angle θ (internal) of laser beam onto the VBG as in $\lambda_B = \lambda_0 cos\theta$, where λ_0 is the wavelength at normal incidence. Therefore, the reflecting Bragg wavelength for VBG1 could be tuned to fit the central wavelength of VBG2 by tilting it with an angle of about ~16°. This dual-VBG serially-paring alignment allows lasing at an effectively much narrower spectral bandwidth [see Fig. 2(d)] compared with that of a single grating and thus further narrowing of the laser output spectrum can be achieved [9].

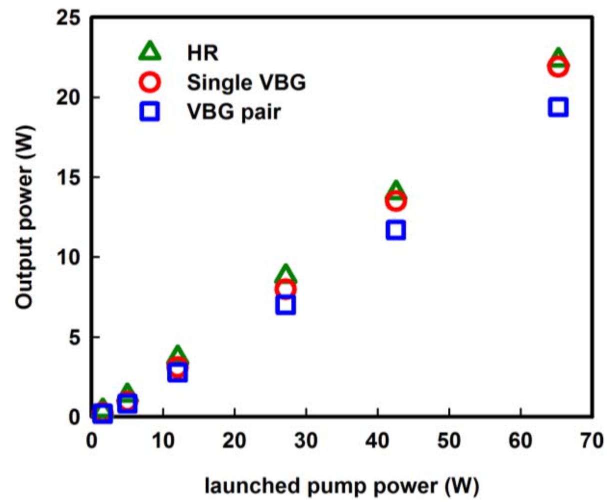

Fig. 3. Output powers as a function of launched pump power for the HR, single-VBG and dual-VBG narrowed configurations.

To construct the spectrum narrowing section with dual VBGs, depicted in configuration (a) (see Fig. 1), VBG1 was first aligned and positioned at a certain angle to acquire laser emission at around 1545 nm by the use of a high-reflection (HR) plane mirror at 1.5-1.6 μm as the terminal cavity reflector. Then VBG2 was substituted for the HR mirror and was carefully adjusted to maximize the output power. To achieve the laser output spectrum as narrow as possible without sacrificing the lasing efficiency, both VBGs were further finely adjusted in terms of the output power and spectral linewidth.

Lasing characteristics for the dual-VBG narrowed EYDFL is shown in Fig. 3. A maximum output power of 19.4 W was yielded for the launched pump power of 65.3 W, corresponding to a slope efficiency of 30.1% with respect to the launched pump power. Also, the laser output relations for the configuration (b) in Fig. 1, with serially-paired VBGs replaced by the HR plane mirror or VBG2, were also characterized for comparison. Output powers up to 22.3 W and 21.9 W were generated with slope efficiencies of 34.4% and 34.2%, respectively, for these two arrangements. The output power was very stable with fluctuations remained below 0.2% (RMS) over a time scale of 5 minutes and no intensive self-pulsation at the maximum output power was observed. The beam propagation factor (M^2) of the laser output at maximum output powers was measured to be around ~2.3 with a beam profiler (Nanoscan, Photon Inc). It can be seen that the dual-VBG locked EYDFL had somewhat poorer performance compared with the HR and single VBG2 arrangements, which is attributed to the reduced reflectivity of VBG1 aligned with a large incident angle [11]. Despite this, lasing output powers for the three different laser setups all showed a linear dependence with the launched pump power, indicating that there is considerable scope for

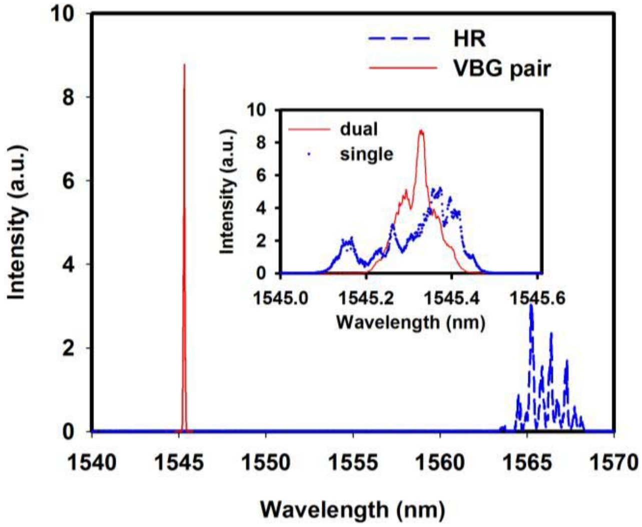

Fig. 4. Output spectra for the dual-VBG narrowed EYDFL and the free-running EYDFL (using HR mirror as terminal cavity reflector) recorded at a resolution of 0.5 nm. The inset in the figure shows the spectra of single-VBG and dual-VBG narrowed EYDFL recorded at a resolution of 20 pm.

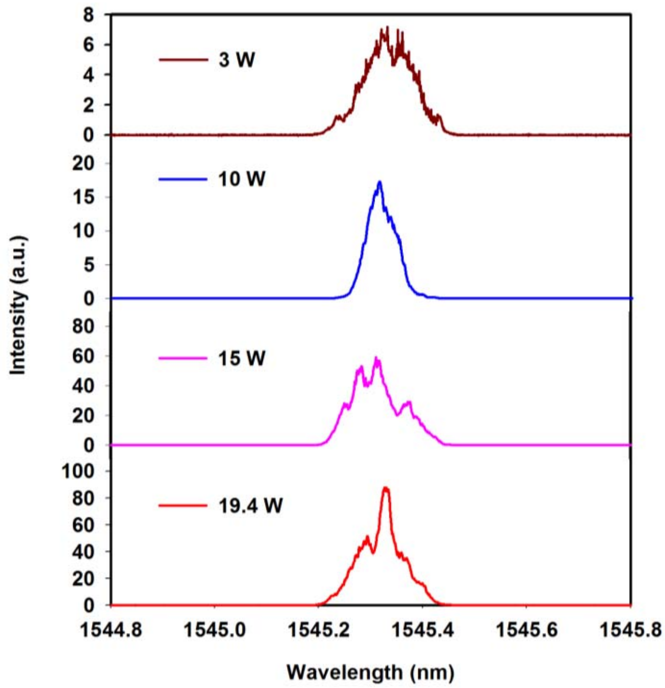

Fig. 5. Output spectra for the dual-VBG narrowed EYDFL recorded at different output power levels.

further power scaling by simply increasing the pump power. However, in our experiment, we limited the launched pump power to avoid any parasitic emission at ∼1 μm and the induced poorer lasing efficiency. No parasitic lasing of Yb^{3+} at ∼1 μm was observed even at the maximum launched pump power of ∼65 W, which demonstrates efficient energy transfer between Yb and Er ions in the gain fiber.

Fig. 4 shows the measured spectrum of the dual-VBG locked EYDFL in comparison with that using the broadband HR mirror as one cavity reflector recorded at the maximum output powers with a resolution of 0.5 nm. Also, the dual-VBG narrowed lasing spectrum recorded at maximum output powers with a higher resolution of 20 pm was compared with that of a single VBG2 arrangement (in the inset of Fig. 3). The EYDFL using the HR mirror for lasing feedback had a relatively broad spectrum spanning from 1564 nm to 1568 nm with primary spectral peak located at ∼1565 nm. In contrast, the dual-VBG narrowed laser spectrum at the maximum power was much narrower with a measured FWHM linewidth of ∼38 pm and 10 dB bandwidth of ∼0.2 nm, while the single VBG2-locked laser generated a broader spectrum with an exhibited FWHM bandwidth of ∼138 pm. It is worth noting that the measured laser linewidth for the dual-VBG narrowed EYDFL had a similar order of magnitude with the minimum resolution of the OSA used. Since we do not have an OSA with higher resolution or a scanned Fabry-Perot interferometer operated at the corresponding wavelength band to determine the actual laser linewidth, we have to characterize the actual resolution of the instrument and give a rough estimate of the real laser linewidth. Therefore, another OSA with the minimum resolution of 50 pm developed from the same corporation (Yokogawa, AQ6357) was employed to characterize the lasing linewidth in the Tm-doped laser system reported in Ref. [7]. The measured linewidth was 0.1 nm, an order larger than the actual value of ∼12 pm determined by the scanned Fabry-Perot interferometer. Therefore, we conclude the real laser linewidth for the dual-VBG narrowed EYDFL should be much smaller than the measured value of ∼38 pm.

The spectra at different output power levels for the dual-VBG narrowed EYDFL are illustrated in Fig. 5. We found that the spectral width (FWHM) at higher output power levels was somewhat narrower than that at lower power levels. We attributed this to a possible spectrum cleanup effect benefiting from more intense mode competition at high power levels. This mode competition effect should be more obvious in the Er-doped fiber due to its emission spectrum with multi-peaks than in the Tm-doped fiber with a relatively smooth emission spectrum. Variation of the laser center wavelength with output power increasing from 3 W to 19.4 W remained within ∼20 pm, which is comparable to the effective bandwidth of the flattop reflectivity window for the serially-paired VBGs. Therefore, the center wavelength is allowed to vary within this range. Improved control of center wavelength should be possible by finely adjusting the VBGs to achieve narrower reflectivity bandwidth, possibly at the expense of reduced reflectivity and thus the output power decline. Center wavelength fluctuations at the maximum output power remained below 10 pm while the FWHM linewidth varied within 15 pm over a time scale of 3 minutes, which demonstrates good stability.

Further experimental study will be conducted to obtain widely tunable, narrow bandwidth operation of an EYDFL by incorporating an additional HR plane mirror as end cavity reflector based on the VBG-serially-pairing configuration. The combination of two angularly configured VBGs will be acted as a wavelength tuning component and an ultra-narrow-band optical filter with linewidth limited by the overlap of their respective reflection bandwidth. Wavelength tuning is supposed to be realized by simultaneously adjusting the incident angles of these two VBGs. Furthermore, it is expectable that the output lasing spectrum in the dual-VBG narrowed tunable configuration will be much narrower than that reported in this paper due to additional wavelength discrimination resulting from the double reflections onto VBG2 for each transit of the external cavity.

III. Conclusion

We report on a high-power and narrow-linewidth Er, Yb co-doped fiber laser locked by a combination of two serially-paired VBGs. The laser yielded 19.4 W of output power at 1545.3 nm with a FWHM linewidth of <∼38 pm for 65.3 W of launched pump power, corresponding to a slope efficiency of 30.1% with respect to launched pump power. We believe the actual linewidth should be much narrower than the measured value of ∼38 pm due to lack of appropriate measuring instrument with sufficient spectral resolution. For comparison, output power relations and spectral characteristics were also evaluated for the broadband HR and single-VBG narrowed configurations, respectively. Narrower lasing linewidth operation without the lasing efficiency decline can be achieved by the use of two angularly configured VBGs as the spectrum narrowing component.

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