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A linearly-polarized tunable Yb-doped fiber laser using a polarization dependent fiber loop mirror

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ABSTRACT

A Ytterbium-doped linearly-polarized fiber laser is constructed with a polarization maintaining fiber Sagnac loop mirror. The fiber loop mirror made of polarization maintaining fiber coupler has a polarization dependent reflectivity, which provides the necessary polarization discrimination between the slow and fast axes. With a fiber Bragg grating written in normal polarization maintaining fiber as an output coupler, laser output of up to 5.6 W at 1070 nm is generated with a polarization extinction ratio of > 20 dB and an overall efficiency of 55%. The broadband polarization dependent reflection of the fiber loop mirror offers advantages of easy spectral tuning and simple linearly-polarized laser generation.

1. Introduction

Fiber lasers with linearly-polarized output are required in various applications, such as sensing, nonlinear frequency conversion, and laser beam combination. Many methods to achieve linearly-polarized fiber laser have been reported. Free space or in-fiber polarizer, such as polarization cube [1] and long-period fiber grating [2], have been inserted into fiber laser cavities to insure single polarization operation. Single polarization operation can also be obtained with single polarization gain fiber or fiber devices made of it [3, 4]. By coiling a highly birefringent large-mode-area fiber, Liu et al. achieved a 406 W linearly-polarized laser with a polarization extinction ratio (PER) of 19 dB [5]. However this method is not applicable to single mode fibers with a standard numerical aperture (NA). Using normal fiber and fiber devices are still favorable in most cases. Fiber Bragg gratings (FBG) written in polarization maintaining (PM) fiber naturally have two reflection peaks corresponding to slow and fast axes, respectively. Therefore, simultaneous laser action at the slow and fast axes will take place if two PM FBGs are used to form the fiber laser cavity. To obtain single polarization operation, Shirakawa et al. [6] spliced one of the FBGs perpendicularly and aligning the fast axis peak of one FBG to match the slow axis peak of the other FBG. Nevertheless, fine temperature or tension adjustment of the FBG were necessary for stable operation, which increased the complexity of the laser. Liu Chi et al. achieved a power of 43 W with a PER of 17.2 dB by amplifying a distributed feedback fiber laser with a PER of 20 dB [7].

In this letter, we report a simple linearly-polarized Yb-doped fiber laser design with a polarization maintaining fiber Sagnac loop mirror. The polarization dependent reflectivity of the fiber loop mirror provides the necessary polarization discrimination between the slow and fast axes. With a fiber Bragg grating written in normal polarization maintaining fiber as an output coupler, laser output of up to 5.6 W at 1070 nm is achieved with an overall efficiency of 55% and a polarization extinction ratio of > 20 dB without the need for complicate temperature or tension control of the FBG. The broadband reflection of the fiber loop mirror gives the laser an additional advantage of easy spectral tuning, which is demonstrated with about 6 nm tuning by straining the output FBG only. The whole construction is simple, compact and free from any adjustment.

2. Experimental setup

Our experimental setup is illustrated in Fig. 1. A piece of double-clad polarization-maintaining ytterbium-doped fiber (Nufern PM-YDF-5/130) is used as gain medium, which has a 5 μm core (NA 0.13), a 130 μm pumping cladding (NA 0.46), and nominal cladding absorption of 1.7 dB/m @ 975 nm. The pump source is a 10 W pigtailed laser diode (JDSU, 6398-L4i Series) with an NA of 0.22 and nominal emitting wavelength of 976 nm. However, the emitting wavelength drifts with temperature and power. A fiber length of 20 m is used in the experiments to insure adequate absorption of pump at room temperature and moderate power. The pump light is coupled into the active fiber with a fused pump combiner with a

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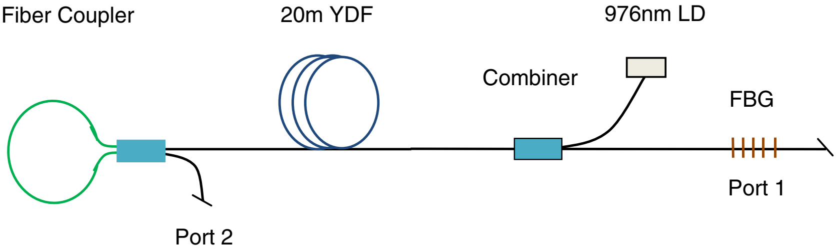

Fig. 1. Schematic of the linearly-polarized fiber laser.

transmission loss of 7%. The laser cavity is formed with a Sagnac fiber loop mirror as a high reflector and a PM FBG as an output coupler. The FBG has a peak reflectivity of 11%.

The fiber loop mirror is made by splicing together the two output ports of a fused PM fiber coupler. The total length of the fiber loop is less than 1.4 m and the laser power is less than 10 W. Therefore, no nonlinear response is expected. The reflectivity of a fiber loop mirror is given by [8]

$$R = 4\rho(1-\rho)T^2 \tag{1}$$

where T refers to the single pass total transmission through the fiber coupler, and ρ stands for the coupling ratio to one of the two ports. The fiber coupler was fabricated for other purpose at other wavelength on slow axis, and was utilized in the experiment for demonstration of the concept. The properties at 1070 nm were measured before the experiments. The total transmissions for the fast and slow axis of the fiber coupler are measured to be 51% and 99%, respectively. The coupling ratios are measured to be 53% and 70%, respectively. Such differences in coupling ratios between two axes are natural for PM fiber couplers, since PM fiber has a different index profile along two principle axes. The difference in transmissions between two axes might result from the manufacturing process. We see a favorable coupling ratio (closer to 50%) for the fast axis, but higher loss. According to Eq. (1), the reflectivity on the fast and slow axis is about 26% and 82%, respectively, which provides a polarization discrimination between two axes.

In this experiment, the polarization dependent reflectivity of the fiber loop mirror is obtained by polarization dependent loss of the coupler. A more elegant way is to obtain it by the polarization dependent branching ratio. The ideal fiber coupler should have a 50/50 coupling ratio at slow axis and near unity to zero at fast axis. However, we don't have such fiber coupler in the lab when carrying out the experiment.

The FBG was fabricated into the core of a panda PM fiber (Nufern PM980). A collimated KrF excimer laser beam was focused through a phase mask onto a horizontally positioned fiber. The typical energy density of the 248 nm pulses at the fiber was 0.05 J/mm^2 per pulse and the laser pulse rate was set to 30 Hz. The exposure time was changed according to the reflectivity needed. The FBG has a central wavelength of 1070 nm at slow axis and a -3 dB linewidth of 0.28 nm at room temperature. There is a Bragg wavelength for the fast axis as well about 0.26 nm away. However, the fiber loop mirror possesses a quite different reflectivity for light propagating on the fast and slow axis as shown in the previous paragraph. Therefore, laser action takes place only on the slow axis.

3. Experimental results

Fig. 2 shows the 1070 nm laser output from port 1 and the leaked power through port 2 as a function of the laser diode pump power. The lasing threshold is about 0.5 W. Maximum output power of 5.6 W at 1070 nm was obtained with a 10.3 W pump power, corresponding to an overall efficiency of 55%. The slope efficiency increases with the pump power, since laser diode drifted towards 976 nm at higher pump power, which matches better with the absorption peak of the ytterbium. As a result of the imperfect fiber loop mirror (82% reflectivity), there is always a leakage at 1070 nm through port 2, as high as 0.39 W when the pump power is 10.3 W. This can be solved by using a 50/50 fiber coupler at 1070 nm for the loop mirror, which will have a near unity reflectivity.

The polarization extinction ratio of the laser output is measured at different laser output powers. As shown in Fig. 3, the polarization extinction ratio of larger than 20 dB is achieved at all power level. The inset in Fig. 3 shows the measurement of the throughput power when rotating a polarizer after the laser. The result fits well with the Malus' Law.

We have also tried with the method proposed by Shirakawa et al. [6]. To effectively discriminate two polarizations, both the high and partial FBG reflectors have to be very narrow, less than or comparable to 0.26 nm, which is the separation between two Bragg wavelengths for the fast and slow axes. Because of this, fine controlling of the gratings by temperature or tension is necessary to wavelength matching, which complicates the laser design. In the laser configuration proposed in this letter, because one of the reflecting mirrors is broadband, no controlling of the output FBG is necessary at all.

Fig. 4 shows the slow axis reflectivity spectrum of the fiber loop mirror measured with an ASE source. A reflectivity of >70% is reached from a wavelength of 1060 nm to 1090 nm, which indicates a 30 nm broadband reflectivity. The broadband nature of the fiber loop mirror provides an additional advantage of easy wavelength tuning as well. Tuning of the output coupler FBG is sufficient as compared to the lasers with two FBGs as cavity mirrors, where simultaneous tuning of two FBGs is necessary. A 30 cm long fiber containing the output FBG is fixed at one end, and the other end is attached to a translation stage. When adjusting the translation stage, an axial strain is applied to the fiber, which changes the central reflectivity of the FBG.

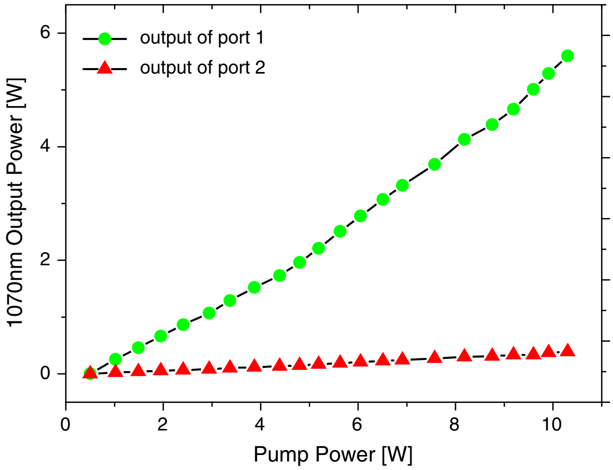

Fig. 2. 1070 nm laser output from port 1 (green) and leakage through port 2 (red) as a function of pump power.

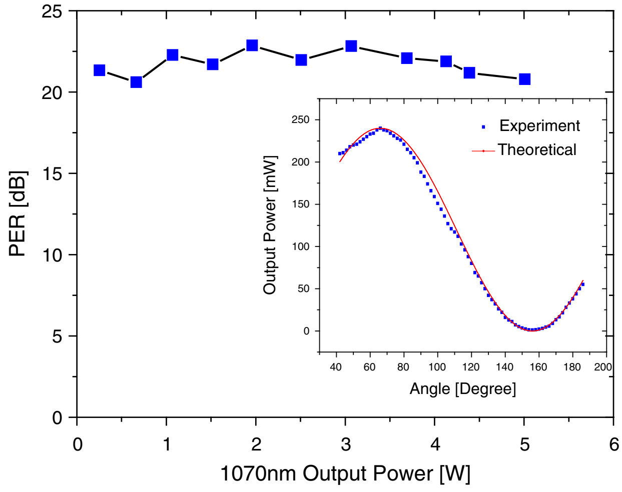

Fig. 3. Polarization extinction ratio as a function of the 1070 nm output power. Inset, throughput power as a function of polarizer rotation.

Although much wider tuning is possible [9], to avoid possible damage to the FBG, we have tuned the FBG over ~6 nm, as a demonstration of the tunability. The results are illustrated in Fig. 5(a). The six spectra shown in the graph have a stepwise increase of about 1 nm in peak wavelength from left to right, which correspond to a stepwise elongation of the 30 cm FBG fiber by about 0.5 mm. The output power shows a 30 mW variation only out of a total power of 500 mW. The PER is measured at each wavelength with no significant change observed.

The laser output spectra are measured with an optical spectrum analyzer (AQ6370, Yokagawa) with a wavelength resolution of 0.02 nm. Fig. 5(b) shows the laser linewidth as a function of pump power. The linewidth broadens with respect to pump power, up to about 0.4 nm.

The linearly-polarized laser showed excellent power stability as illustrated in Fig. 6. The output power was measured over a period of 70 min. The root mean square (RMS) of power fluctuation is 0.0158 W (0.4%) at output power of 4 W.

4. Conclusion

In summary, we have proposed and demonstrated an all-fiber, stable, highly linearly-polarized laser by employing a polarization dependent fiber loop mirror and a PM FBG for first time to the best of our knowledge. Maximum 5.6 W at 1070 nm was achieved with an optical efficiency of 55% and a PER of >20 dB. By stretching the output FBG only, the wavelength can be tuned from 1070 nm to 1076 nm, which is a demonstration of the additional advantage on wavelength tunability offered by the laser design. The laser shows an excellent power stability and does not require temperature and strain control of the FBG. The slope efficiency and the PER of the laser output can be improved with custom made fiber coupler which has 50/50

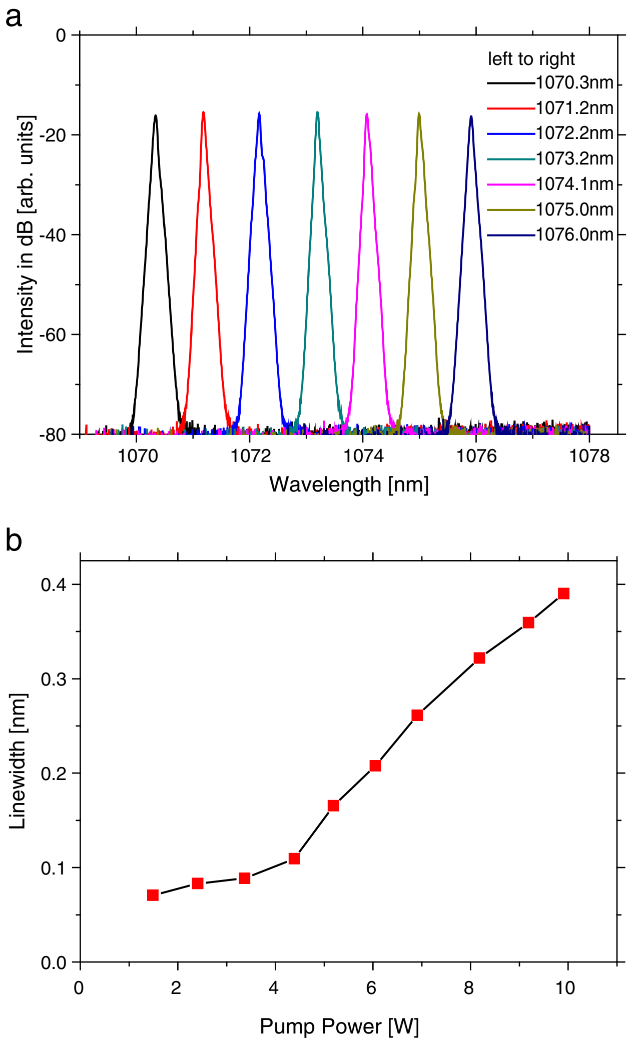

Fig. 5. (a) Spectral tuning of the laser.(b) Output linewidth at different pump powers.

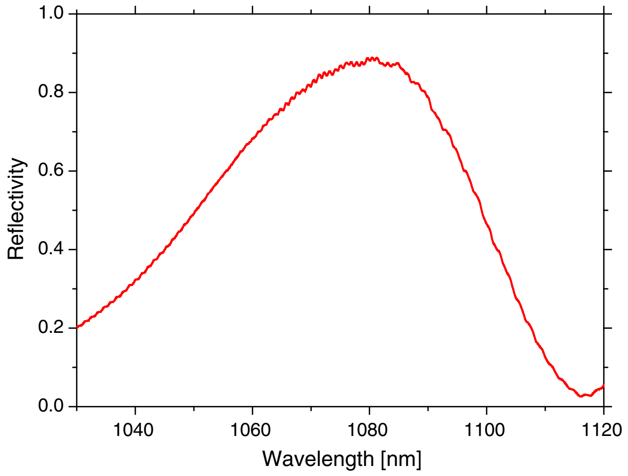

Fig. 4. Reflectivity spectrum of the fiber loop mirror.

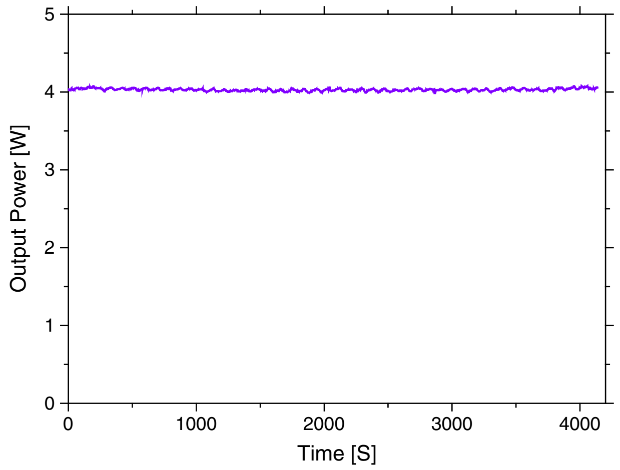

Fig. 6. Output power stability test at 4 W for more than 1 h.

coupling ratio at slow axis and near unity to zero at fast axis. The laser power can be scaled up by adding more pumping laser diodes. Up to hundred watts is feasible since fused fiber couplers had been shown to operating over 150 W [10].

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References

[1] E. Wikszak, J. Thomas, S. Klingebiel, B. Ortaç, J. Limpert, S. Nolte, A. Tünnermann, Optics Letters 32 (2007) 2756.

[2] S.A.V.e., A.S. Kurkov, I.G. Korolev, O.I. Medvedkov, E.M. Dianov, Quantum Electronics 31 (2001) 421.

[3] D. Xue, A.R. El-Damak, X. Gu, Optics Communications 283 (2010) 1059.

[4] M.J. Li, D.A. Nolan, G.E. Berkey, X. Chen, J. Koh, D.T. Walton, J. Wang, W.A. Wood, L.A. Zenteno, in: Y. Sun, S. Jian, S.B. Lee, K. Okamoto (Eds.), High-performance single-polarization optical fibers, SPIE, Beijing, China, 2005, p. 612.

[5] C.-H. Liu, A. Galvanauskas, V. Khitrov, B. Samson, U. Manyam, K. Tankala, D. Machewirth, S. Heinemann, Optics Letters 31 (2006) 17.

[6] A. Shirakawa, M. Kamijo, J. Ota, K.i. Ueda, K. Mizuuchi, H. Furuya, K. Yamamoto, IEEE Photonics Technology Letters 19 (2007) 1664.

[7] Y. Qi, C. Liu, J. Zhou, Q. Lou, W. Chen, J. Dong, Y. Wei, Applied Optics 48 (2009) 5514.

[8] N.J. Doran, D. Wood, Optics Letters 13 (1988) 56.

[9] C.S. Goh, M.R. Mokhtar, S.A. Butler, S.Y. Set, K. Kikuchi, M. Ibsen, IEEE Photonics Technology Letters 15 (2003) 557.

[10] Y. Feng, L.R. Taylor, D.B. Calia, Optics Express 17 (2009) 23678.