Dual-Frequency Operation in a Short-Cavity Ytterbium-Doped Fiber Laser

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Abstract—A dual-frequency 2-cm silica fiber laser with a wavelength spacing of 0.3 nm has been demonstrated using a polarization-maintaining (PM) fiber-Bragg-grating (FBG) reflector. The birefringence of the PM FBG was used to generate the two single-mode (SM) lasing frequencies of orthogonal polarizations. The SM operation in each wavelength has been verified. The output power reaches 43 mW with the optical signal-to-noise ratio of greater than 60 dB. The fiber laser shows stable dual-frequency output under pump variations.

Index Terms—Optical fiber lasers, laser modes.

I. INTRODUCTION

Fiber lasers have drawn much attention as alternatives to solid-state and semiconductor lasers because of their advantages of high reliability, thermal management, scalable output power, high beam quality, narrow bandwidth, and low noise floor [1]–[4]. Dual-frequency fiber lasers are attractive for applications in ranging, communications, and interferometers [5]–[7], and have been the focus of intensive research [8]–[13]. They have been demonstrated with a high-birefringence fiber Bragg grating (FBG) in a ring cavity [8], a high-birefringence FBG in a linear cavity [9], a multimode FBG in a linear cavity [10], self-seeded multimode Fabry–Pérot (FP) laser diodes [11], dual-FBGs with a circulator in a ring cavity [12], multiple bandpass filters in a ring cavity [13], and FBGs with multiple phase shifts in linear or ring cavities [14], [15]. Most of these demonstrated dual-wavelength lasers operate in a multimode regime at each of the dual-wavelengths [8]–[13].

In this letter, we demonstrate a room-temperature single-frequency linear-cavity silica fiber laser. A polarization-maintaining (PM) FBG and a single-mode (SM) FBG are used to generate two SMs at two frequencies with two orthogonal polarizations in a linear component. This configuration can be realized using standard commercial components.

II. ENABLING DUAL-FREQUENCY LASERS

In ytterbium-doped fiber lasers, the ytterbium can be treated as a spectral homogenous broadening medium and thus permits only a single lasing mode. In a linear cavity, however, a standing wave will be formed between the two reflectors and thus spatial-hole burning (SHB) occurs. Additionally, polarization-hole burning (PHB) is similar to SHB in the sense that different polarizations will extract different gains from the active medium [17] and, thus, affect lasers with birefringent components. Furthermore, gain saturation enhances the dual-frequency lasing through the modal competition process [15], [16]. Generally, the combined effects of SHB, PHB, gain saturation, thermal effects, and nonlinearities determine the modal behaviors of the fiber lasers.

III. EXPERIMENTS AND RESULTS

The proposed dual-single-frequency fiber laser is shown in Fig. 1. A section of 1.5-cm highly ytterbium-doped SM single clad silica glass fiber with an absorption rate of 1700 dB/m at 976 nm is spliced between two FBGs. Each of the FBGs has a grating section of about 3 mm. A wavelength-division multiplexer is used to couple the single-mode pump light at 976 nm into the active fiber core. The SM FBG has a center wavelength of 1029.3 nm and a 3-dB bandwidth of 0.46 nm with a peak reflectivity of 99%.

Fig. 2 shows the measured transmission spectrum of the PM FBG when seeded with an unpolarized amplified spontaneous emission (ASE) source. Because of the differential modal refractive index along the fast and slow axis, the grating exhibits two peak-reflection wavelengths, one for each polarization. The PM FBG (O-E Land) shows two reflection peaks at 1029.1 and 1029.4 nm, respectively. Both of the peak reflectivity wavelengths lie in the reflection band of the SM FBG under ambient-temperature conditions. Each of the reflection bands of the PM FBG has a 3-dB bandwidth of 0.06 nm and a 55% reflectivity for the corresponding polarizations. As discussed in Section II, the gain competition between polarizations at these two wavelengths determines the spectral properties of the laser.

The output power of the laser reaches 43 mW with 490 mW of pump power, with lasing threshold at 10 mW of pump power. The optical signal-to-noise ratio (OSNR) has been measured.
Fig. 2. Measured transmission spectrum of the PM FBG using an ASE source.

Fig. 3. Optical spectrum of the laser with 43-mW output power. When the output power is 43 mW, the OSNR is measured to be greater than 60 dB, as shown in Fig. 3. In the dual-frequency fiber laser shown in Fig. 1, the OSNR is limited by the residual ASE noise. No other lasing modes were observed over the entire ytterbium gain band. The wavelength spacing of the dual-wavelength laser is determined by the differential refractive index along the fast and slow axes of the PM FBG. Therefore, the wavelength spacing can be designed by writing the grating into PM fiber of proper birefringence.

The SM operation at each lasing wavelength is verified with an FP spectrometer. Fig. 4 shows the scanning spectrum of the laser modes when the output power is 43 mW. The free spectral range is 150 GHz. With a finesse of 150, the FP spectrometer has a resolution of 1 GHz. Since the fiber laser has a 2-cm cavity, corresponding to 5.1 GHz in modal frequency spacing, the multiple modes caused by the fiber laser cavity can be well resolved by the FP spectrometer. Although three FP modes can be supported in the 3-dB reflection band of the PM FBG, the curvature of the PM FBG reflection spectrum provides large longitudinal mode discrimination enabling only an SM operate at each polarization. In the measurement, no mode hopping is observed.

The relative intensity noise (RIN) has been measured by using an electrical spectrum analyzer. The measurement is limited by the bandwidth of the photodiode detector with the cutoff frequency of 1 GHz. The FP cavity is used to filter out each wavelength by applying a bias voltage but not a scanning signal. In this way, the RIN of each wavelength can be independently measured. Fig. 5 shows the RIN of each filtered lasing wavelength and the RIN of the total laser output with both wavelengths with the laser set to 43-mW output power. In the three cases, the RIN is limited by the shot noise beyond 60 MHz. The noise peak at the frequency of 10 MHz is caused by relaxation oscillations of the fiber laser. This is in agreement with the theoretical calculation using the measured upper state lifetime of 0.17 ms for this highly ytterbium-doped fiber. The RIN floor of the individual channels is higher than that of the total laser due to the optical power reduction caused by the FP that was used to separate the wavelengths.

The polarization of the fiber-laser output has been measured with a quarter wave plate and a polarizer. Each frequency
shows a single polarization with a polarization excitation ratio of >20 dB. The two polarizations at the dual-frequencies are orthogonal to each other, as expected from the PM FBG. Since the FBG spectra were aligned at room temperature, dual-wavelength operation with two orthogonal polarizations is achieved regardless of ambient temperature. This would not generally be true if a temperature controller was required to align the two FBG spectra. Differential output peak powers can be generated by tuning the temperature of the FBGs differently. As the overlapping of the FBG spectra is changed by the thermal tuning, the round-trip gain of the laser at two lasing frequencies will be changed and differential output peak power can be generated.

The dual-frequency operation of this laser is stable under perturbations of pump power. In the working regime, where the output power is close to 43 mW, the ratio of peak power at each wavelength changes with the pump current as 0.02 dB/mA. Therefore, a 1% change in pump power leads to 5% change in relative peak power. In practice, pump-power can be readily controlled with commercial diode laser drivers to better than 0.01%, which leads to less than a 0.05% relative peak-power variation between two fiber laser wavelengths This demonstrates that the laser has a highly stable dual-frequency output.

IV. DISCUSSION AND CONCLUSION

Dual-frequency lasers can be customized by appropriately designing the PM FBG. Different wavelength spacing can be achieved by controlling the birefringence of the PM FBG, while changing the period of the grating will make the laser work at different wavelengths. The output power of the dual-frequency laser can be scaled up by optimization of the PM FBG reflectivity and imposing higher pump power. The relaxation-oscillation peak can be reduced by using a negative-feedback circuit on the pump laser [18]. The orthogonal-output polarizations enable the fiber laser to work in a single-polarization single-frequency regime by using a polarization-filtering component.

In conclusion, a dual-frequency 2-cm silica-fiber laser with a wavelength spacing of 0.3 nm has been demonstrated using a PM FBG reflector. The birefringence of the PM FBG was used to generate the two SM lasing frequencies of orthogonal polarizations. The SM operation in each wavelength has been verified. The output power reaches 43 mW with the OSNR of greater than 60 dB. The fiber laser shows stable dual-frequency output under pump variations.

REFERENCES