Single-Frequency Fiber Laser From Linear Cavity With Loop Mirror Filter and Dual-Cascaded FBGs

Shenghong Huang, Guanshi Qin, Yan Feng, Akira Shirakawa, Mitsuru Musha, and Ken-Ichi Ueda

***Abstract*—A single-frequency ytterbium fiber laser was demonstrated by introducing a loop mirror filter, a polarization controller (PC), and dual-cascaded fiber Bragg gratings (FBGs) in linear laser cavity. The loop mirror with unpumped ytterbium fiber as a narrow bandwidth filter discriminated and selected laser longitudinal modes efficiently. The spatial hole burning effect was restrained by adjusting PC appropriately. Dual closely cascaded FBGs as the output coupler, acting as an etalon, expanded the operation range of single frequency. Output power up to 18 mW at 1064 nm were obtained under the launched pump power of 107 mW at 976 nm, the optical–optical conversion efficiency was about 16.8%; the slope efficiency was about 20%.**

***Index Terms*—Dynamic Bragg grating, loop mirror filter (LMF), single-frequency laser, spatial hole burning.**

I. INTRODUCTION

SINGLE-FREQUENCY lasers are of great importance in many applications, such as coherent communications, wavelength-division multiplexing (WDM), optical fiber sensors, and high-resolution spectroscopy. Fiber lasers are popular owing to their compactness, high efficiency, and simple operation. Therefore, recently, most work to generate a single-frequency laser focuses on fiber laser technology, for example, fiber ring laser [1], short linear cavity distributed Bragg reflector fiber lasers [2], [3] and fiber distributed feedback lasers [4]. Especially, single-frequency fiber laser can be achieved efficiently by using one section of unpumped gain fiber as the saturable absorber (SA) [5]–[8]. In these cases, the researchers used one section of gain fiber as the laser material, another section of unpumped fiber as the SA, in which counterpropagating waves can form very narrow dynamic absorption grating, such that to select single longitudinal mode. The gain and absorption of the fiber is very important for such configuration, because the gain coefficient determines the laser generation, and the absorption determines the dynamic grating in the SA. If the SA was placed in the fiber loop mirror, the total device was called loop mirror filter (LMF) because it acted as a very narrow filter. According to the references, they generated 1.5-μm single-frequency laser using erbium-doped fiber as the gain material and absorber, because the cross section of emission and absorption is large at this wavelength. In addition, they used complicated ring cavity with a fiber isolator or circulator.

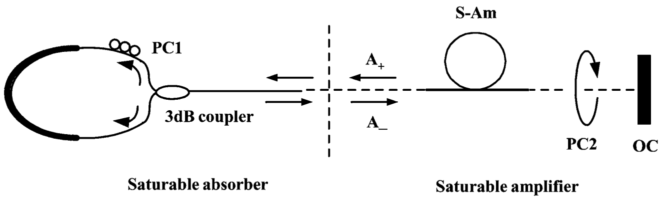

Fig. 1. Laser oscillator is composed of two sectins. The first one is the saturable amplifier section (the right section). In this one, PC2 is used to control the wave polarization and restrain the SHB effect. The second one is the SA section (the left section); it is an LMF (loop mirror with SA) acts as a very narrow filter.

In our experiment, based on simple linear cavity, we adopted ytterbium-doped fiber as the gain material and as the SA in the LMF in order to generate single-frequency 1064-nm laser. For Yb-doped fiber, the absorption cross section at 1064 nm is as weak as 5×10^{-27} m^2 [9]. So we must optimize the fiber length of SA in order to generate effective dynamic absorption grating at 1064 nm. We also restrained the spatical hole burning (SHB) effect in the linear cavity using the simple polarization controller (PC). From this fiber laser system, stable single-frequency 1064-nm laser with 18-mW output power was obtained. To our knowledge, this is first time single-frequency 1064-nm laser based on linear cavity with ytterbium fiber LMF has been generated.

II. PRINCIPLE OF SINGLE-FREQUENCY OPERATION

The experiment principle sketch is shown in Fig. 1; the left section is the LMF, which is a loop mirror with SA. The unpumped ytterbium fiber was used as the SA, which could not be used for passive mode locking because of its long time response. In the SA, the two counterpropagating waves formed an interference pattern, such that generated an absorption Bragg grating. This grating is a dynamic Bragg grating, more efficient than the normal fiber Bragg grating for discriminating and filtering laser longitudinal modes. The bandwidths of this absorption grating can cover the submegahertz to gigahertz range, which is approximately proportional to the inverse of the length of the SA. In addition, the length of the linear cavity was decreased remarkably when the loop mirror with the SA replaced the linear cavity with the SA, because the length of the LMF was not included in the total length of the linear cavity, which was advantageous to generate the single-frequency laser.

As we know, for linear laser cavity, it is easy to produce the SHB effect in the gain material, which can arouse multilongitudinal mode oscillation, and reduce the laser coherence [10]. The SHB effect is produced by the nonlinear wave mixing of

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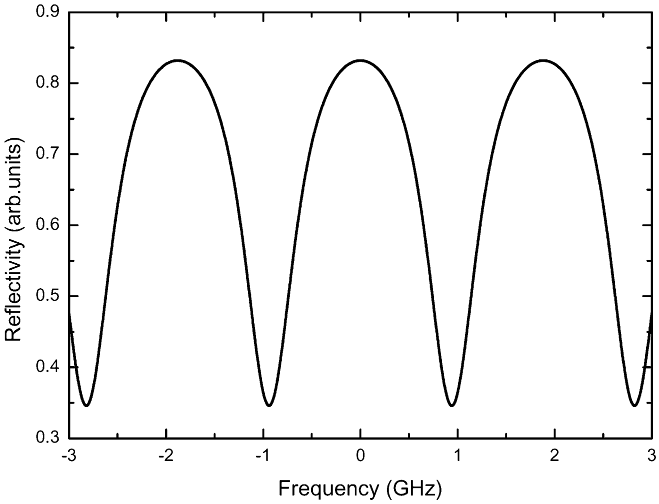

Fig. 2. Calculated reflection of the dual-cascaded FBGs. It acts as an etalon, has reflectivity of 83%, and bandwidth of 1.3 GHz.

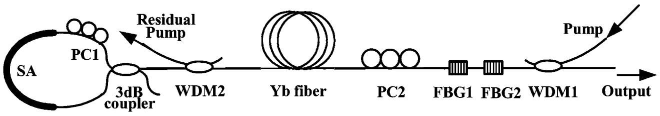

Fig. 3. Experiment setup of the single-frequency ytterbium fiber laser. The length of gain fiber is 15 cm, and the length of SA is 1.2 or 5 m; the reflectivity of cascaded GBDs is 64.5% and 16.6% at 1064 nm, repectively.

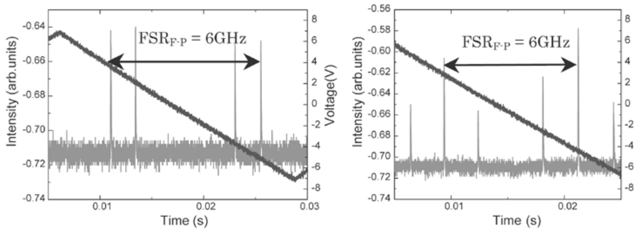

Fig. 4. Two-line and three-line laser oscillate when using 1.2-m SA.

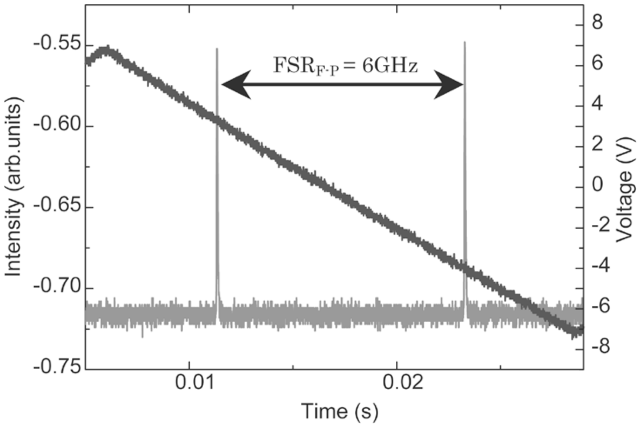

Fig. 5. Single-frequency laser oscillate when using 5-m SA.

the two counterpropagating waves in laser gain material. If we destroy the interference of the two waves, we can restrain SHB effects to some extent. In our experiment, we used simple PC (as shown PC2 in Fig. 1) to adjust the polarization state of the counterpropagating waves, to make the polarizations perpendicular and destroy the interference of them.

Dual-cascaded fiber Bragg gratings (FBGs) at 1064 nm were adopted as the output coupler. The reflectivity of FBG1 and FBG2 was 64.5% and 16.6%, respectively. The distance between the centers of the dual FBGs was about 55 mm. According to the theory of multimirror cavity [11], [12], such FBGs can be operated as an etalon; we calculated the reflection of it, as shown in Fig. 2. We found that the effective reflectivity of the FBGs was about 83% and the bandwidth of the reflection was about 1.3 GHz. Such narrow bandwidth can control and strengthen single-frequency oscillation to some extent.

III. EXPERIMENT PROCESS

The experimental setup is shown in Fig. 3. Because the absorption of Yb fiber at 1064 nm is very weak, in order to generate efficient absorption grating in the LMF, we used the fiber with 24 000-ppm ytterbium concentration. In addition, in the experiment, we optimized the fiber length of SA carefully. The gain fiber had a length of 15 cm and the length of SA in the LMF was selected as 1.2 and 5 m in the different experiments. The cavity was restricted by the LMF and the dual-cascaded FBGs at 1064-nm wavelength; the overall linear cavity length was about 1 m. PC2 was used in the laser gain section to adjust the wave polarization. WDM1 was used to input a 976-nm LD pump laser, and WDM2 to output the residual pump power. We measured and analyzed the laser frequency with a scanning Fabry–Pérot interferometer (Newport SuperCavity SR-150), which had a free spectral range (FSR) of 6 GHz and a resolution of 150 kHz.

At first we used 1.2-m ytterbium fiber as the SA. In the experiment process, first we generated 1064-nm laser by increasing pump power to appropriate value. We then rotated PC1 to maximize the loop mirror reflection and laser output power. Next we rotated PC2 to change the polarization of the counterpropagating waves. When adjusting the pump power, we observed the laser oscillation. During the adjusting process, pump power was less than 80 mW, stable two or three-line laser oscillation could be observed, as shown in Fig. 4, but the single-frequency laser did not appear. When the pump power was higher than 80 mW, multilongitudinal modes oscillation started.

Next, we used 5-m ytterbium fiber as the SA and repeated the same operation as above. As long as the pump power was increased up to the laser threshold, a single-frequency 1064-nm laser was generated. The oscillation was very stable at pump power up to 107 mW. Fig. 5 shows a scan over one FSR and confirms that only one longitudinal laser mode is present. The maximum laser power was 18 mW, the optical–optical conversion efficiency was about 16.8%, and the slope efficiency was about 20%, as shown in Fig. 6. When increasing the pump power more than 107 mW, multilongitudinal modes appeared, and the frequency was not stable. This happened because when the pump power was increased more, the laser power in the cavity became higher, which was easy to induce strong SHB, but the PC2, LMF with 5-m SA, and the cascaded FBGs could not suppress this strong effect in this condition.

From the two experiments, we can find that LMF with 5-m SA is more efficient than that with 1.2-m SA. It is because the absorption coefficient of ytterbium fiber at 1064-nm wavelength

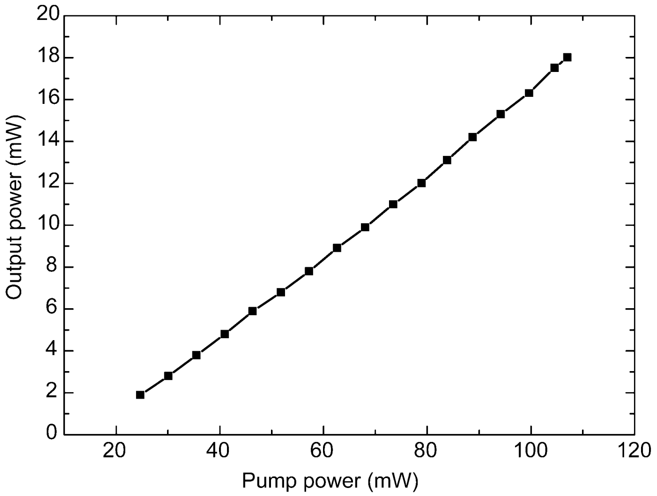

Fig. 6. Output power of 1064-nm single-frequency laser as a function of the pump power.

is very weak; 5-m Yb fiber as the SA can form efficient absorption grating to support single-frequency oscillation.

For comparison, the dual-cascaded FBGs were replaced with a single FBG. The reflectivity and bandwidth of the FBG was 80.1% and 0.47 nm, respectively. We repeated the same operation as before. When we adopted 5-m ytterbium fiber as the SA, we obtained single-frequency oscillation. When the pump power was increased from the threshold value to 68 mW, a stable single-frequency laser oscillated. The maximum laser output power was 11.7 mW, the optical–optical conversion efficiency was about 17.2%, and the slope efficiency was about 22%. Comparing the results under different output coupler conditions, we can find that the cascaded FBGs can strengthen the single-frequency oscillation accessorially. That is, using dual-cascaded FBGs as the output coupler, the operation range of single frequency is larger, and the maximum output power is higher than that using single FBG as the output coupler. But the slope efficiency is lower because of the slightly higher reflectivity of 83% than single FBG of 80.1%.

IV. CONCLUSION

We have demonstrated single-frequency 1064-nm fiber laser by introducing LMF, PC, and dual closely cascaded FBGs in linear laser cavity. LMF discriminated and filtered the laser longitudinal modes efficiently. The SHB effect was restrained by controlling the light polarization in the linear cavity. Dual-cascaded FBGs, acting as an etalon, expanded the operation range of single frequency. To our knowledge, this is the first time Yb fiber LMF in linear cavity has been adopted to generate a 1064-nm single-frequency laser. Such lasers can find applications in a wide range, such as signal detection, coherent communications, and high-resolution spectroscopy.

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