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Widely Wavelength-Tunable High Power Single-Longitudinal-Mode Fiber Laser in Mid-Infrared Waveband

Yi Lu \(^1,2\), Xiaogang Jiang \(^1,2\),*, Feihong Chen \(^1,2\), Chenlong Lu \(^1,2\) and Sailing He \(^1,2,\ast\)

\(^1\) Centre for Optical and Electromagnetic Research, National Engineering Research Center for Optical Instruments, Zhejiang University, Hangzhou 310058, Zhejiang, China; ldd140@zju.edu.cn (Y.L.); 0913450@zju.edu.cn (F.C.); 21960299@zju.edu.cn (C.L.)

\(^2\) Ningbo Research Institute, Zhejiang University, Ningbo 315100, Zhejiang, China

* Correspondence: xiaogang@zju.edu.cn (X.J.); sailing@zju.edu.cn (S.H.)

Abstract: We demonstrate a mid-infrared (MIR) wavelength-tunable high-power single-longitudinal-mode (SLM) fiber laser using a compound cavity structure. The compound cavity consists of an Er-doped ZBLAN fiber perpendicularly cleaved at two-ends and an external cavity formed by a fiber end-face and a narrow bandwidth ruled reflective diffraction grating. SLM operation is achieved through the combined effects of the narrow bandwidth grating and the compound cavity. By rotating the grating, the laser wavelength can be continuously tuned over 100 nm from 2705 nm to 2806 nm with the SLM operation maintained. High output power up to 450 mW is achieved under the SLM regime.

Keywords: mid-infrared; single-longitudinal-mode; wavelength tunable; high power; fiber laser

1. Introduction

In recent years, mid-infrared lasers have attracted increasing interest due to the growing applications in the areas of material processing [1], laser surgery [2], remote or trace spectroscopic sensing [3–8], and nonlinear mid-infrared photonics [9,10]. Some of these applications, such as spectroscopic sensing, would benefit from using MIR SLM laser sources, which have the excellent feature of long coherent length and narrow spectrum bandwidth.

So far, a number of techniques have been developed to achieve SLM lasers in the MIR region. Compared with SLM lasers based on traditional optical parametric oscillators (OPO) [11–15] and semiconductor-based quantum cascade lasers (QCLs) [16,17], MIR SLM fiber lasers based on ZBLAN fibers have some inherent merits such as good beam quality, high-conversion efficiency, excellent heat dissipation, and compact packing. Recently, SLM MIR fiber lasers have been demonstrated by using fiber Bragg grating (FBG) directly inscribed in a ZBLAN fiber [18,19]. However, although FBGs inscribed in silica fibers are well understood and developed, FBGs inscribed in a ZBLAN fiber are still challenging and expensive. Furthermore, the wavelength tuning of these lasers is limited, as is their output power.

In this paper, we demonstrate a widely wavelength-tunable high power SLM MIR ZBLAN fiber laser. We use a compound cavity, which consists of a ZBLAN fiber perpendicularly cleaved at two-ends and an external cavity formed by one fiber end-face and a narrow bandwidth ruled reflective diffraction grating. Owing to the combined effects of the narrow bandwidth grating and the compound cavity, SLM operation is achieved. The proposed fiber laser has the advantages of easy fabrication, low-cost, wide wavelength-tuning range and high output power.

2. Materials and Methods

The experimental setup of the present SLM Er\(^{3+}\)-doped ZBLAN fiber laser is shown in Figure 1. A commercially available 976 nm laser diode (LD) is used to pump the gain fiber.
The output fiber of the pump laser has a core diameter of 105 µm and a numerical aperture (NA) of 0.22, delivering an output power up to 6 W. The pump laser is firstly collimated and then focused into the inner-cladding of the active fiber by two CaF₂ plano-convex lenses, which have a focal length of 20 cm (L1 and L2) and a dichroic mirror (DM). The plano-convex lenses have an antireflection coating for both the 976 nm pump and the 2.8 µm laser. Thus, they have a high transmittance (>95%) at both wavelengths. The dichroic mirror has a transmittance of about 85% at 976 nm and high reflectance (~95%) at 2.8 µm for an incident angle of 45° on the dichroic mirror. The total pump coupling efficiency is measured to be about 70%. The active fiber is an octagonal-shaped double-clad 6 mol.% Er³⁺-doped ZBLAN fiber (ZDF-20/200-60E-O, Fabricated by FiberLabs, Inc.) with a length of 1.4 m, which has a core diameter of 18 µm, core NA of 0.12, an inner cladding diameter of 195 µm, inner cladding NA of 0.51, and an outer cladding diameter of 422 µm. The refractive index of the fiber is around 1.53 in the 3 µm region. The peak absorption coefficient at 980 nm is about 3–5 dB/m. Both ends of the gain fiber are perpendicularly cleaved (giving ~4% Fresnel reflection) and held by fiber-chunk holders with V-shaped grooves. Two types of cavity are formed depending on whether the grating is added or not in our experiment. In Case 1, the laser cavity is formed between the two fiber end-faces of the gain fiber. In Case 2, besides the cavity mentioned above, an external cavity is formed by the right fiber end-face and a ruled reflective diffraction grating (GR1325-45031, Thorlabs, NJ, USA). The laser emitted from the right fiber end-face is collimated by a plano-convex lens (L3) and then incident on the grating (GR) at a blazed angle (32°). The reflectance of the grating at the blazed angle is 85% in the 3 µm region. The laser output is divided into two beams by a CaF₂ plate beamsplitter (BSW501, Thorlabs, NJ, USA) so that we can measure the beating spectrum at RF by a photoelectric detector (PD) attached to the RF spectrum analyzer and the optical spectrum by a scanning monochromator at the same time.

Figure 1. Experimental setup of the laser cavity.

3. Results

In Case 1, most of the energy was transmitted out of the cavity due to the low reflection of the right fiber end-face, and consequently the cavity had a large loss and the lasing threshold for the pump light was as high as 2.7 W (measured from the pigtail fiber of the laser diode, the same as all of the pump power mentioned below). Once the pump power exceeded the threshold, the laser worked in the state of free operation. The spectrum of the output laser is shown in Figure 2 and the central wavelength could be tuned from 2766 nm towards a longer wavelength (2789 nm) when the pump power was increased to 3.6 W, which is mainly caused by the gain competition in the gain spectrum of the Er³⁺ ZBLAN fiber. Then, the central wavelength remained basically constant at 2789 nm when the pump power was further increased.
Figure 2. Output spectrum at different pump powers in Case 1.

The measured result of the output power in Case 1 is plotted in Figure 3 (gray line). In Case 2, the obvious improvement on the output power shown in Figure 3 (red line) is easy to understand. The laser transmitted out of the cavity through the right fiber end-face was collimated by L3, then incident on the grating at the blazed angle and finally reflected back into the fiber by the grating at the first order diffraction. As a result, the total output power was greatly improved and could reach 450 mW at the pump power of 5 W.

Figure 3. Output power in the two cases. Pump power is measured from the pigtail fiber of the laser diode.

When the pump power was fixed at 3.6 W, the beating RF spectra in both cases were determined and are shown in Figure 4. If the laser is operated in a multi-longitudinal-mode (MLM) state, different longitudinal modes will interfere with each other and generate beat frequency signals in the RF domain. It is worthwhile noting that in Case 1 the laser operates in an MLM state and the longitudinal mode interval is 69.3 MHz, which is matched well with the cavity length as shown in Figure 4a. In contrast, no beat frequency signal was observed in Case 2 as shown in Figure 4b. When a beam blocker (BT620, Thorlabs, NJ, USA) was inserted between L3 and the grating, beat frequency signals were observed again in the RF spectrum. However, once the beam blocker was removed, the beat frequency signals became undetectable immediately, indicating that the operation regime in Figure 4b could be rebuilt very quickly. Figure 4c shows the temporal dependence of the RF spectrum in Case 2 every 5 min. No beat frequency signal was observed during 30 min and the RF spectrum maintained a strong stability.

Figure 5a shows the detailed output spectra at the central wavelength of about 2784.5 nm in both cases when the pump power was fixed at 3.6 W. The bandwidth of the spectrum in Case 2 was obviously narrower than that in Case 1. Consequently, based on the variations in the beat frequency signal and the bandwidth of the spectrum, SLM
operation was achieved in Case 2. By rotating the grating, the lasing wavelength could be continuously tuned over 100 nm from 2705 nm to 2806 nm with SLM operation maintained, as shown in Figure 5b. It is worth noting that the SLM operation occurs only when the distance between the grating and the right fiber end-face is larger than 19 cm as shown in Figure 6. This is because when the distance is small, many different wavelength components reflected by the grating will be collected by the fiber and consequently beating frequency signals will be generated at the RF spectrum. When the distance is large, the fiber will collect only the reflected light of narrow bandwidth around one specific wavelength, which is crucial for the SLM operation in this laser.

![Figure 4](image1.png)

**Figure 4.** Beating spectra at RF with a 3.6 W pump. (a) Case 1 and (b) Case 2. (c) Stability of the RF spectrum in Case 2 during 30 min.

![Figure 5](image2.png)

**Figure 5.** (a) The output spectra around 2784.5 nm in Case 1 and Case 2. (b) Tuning the central lasing wavelength in Case 2 by rotating the angle of the grating.

![Figure 6](image3.png)

**Figure 6.** Beating spectra at RF when the distance between the grating and the right fiber end-face increases. The pump power is fixed at 4.5 W.
4. Discussion

Next, we discuss the mechanism of SLM operation in Case 2. To achieve SLM operation, the bandwidth of the grating needs to be narrow enough so that it can limit the number of longitudinal modes that can oscillate during the round-trip transmission. The bandwidth of the grating can be estimated by Equation (1) [20]:

$$\delta \lambda = \frac{\lambda}{|m|N} = \frac{\lambda d \cos \theta}{a}$$

where $\lambda$ represents the central wavelength, $m = 1$ is the first diffraction order, where most of the energy is concentrated, $N$ is the number of grating lines illuminated, $a$ is the diameter of the collimated laser beam, $\theta$ is the incident angle of the beam and $d$ is the interval between two grating lines. In our system, $\lambda = 2780 \text{ nm}$, $d = 2.2 \text{ µm}$, $a = 10 \text{ mm}$, and $\theta = 32^\circ$, and thus $\delta \lambda$ is calculated to be 0.52 nm (~21 GHz). As the longitudinal mode interval of the fiber FP cavity (consist of the two perpendicularly cleaved fiber facets) is roughly 1.8 pm (~71 MHz) and the interval of the external FP cavity (30 cm for example) is roughly 12.9 pm (~500 MHz), more than one longitudinal mode should be able to oscillate, as shown in Figure 7. Thus, other suppression mechanisms for longitudinal modes must exist. Due to the interference effect occurring between the longitudinal modes caused by the three-mirror cavity [21] and losses caused by the mirrors, lenses, coupling efficiency and the surrounding environment, longitudinal modes in the cavity will compete with each other and finally only those longitudinal modes which conform to the least common multiple of the frequency intervals for all individual FP cavities would survive. After this screening mechanism, some surviving longitudinal modes which are far away from the central longitudinal mode will suffer more losses and less gain due to the narrowband filter effect of the grating and finally are completely suppressed. As a result, only one longitudinal mode can be selected to oscillate in the composite cavity.

![Figure 7. Spectral responses centered at the same wavelength under the influence of all frequency tuning elements (fiber and external cavity modes and grating reflectance spectral characteristics).](image-url)

In order to verify the longitudinal mode suppression mechanism we have discussed above, another comparison experiment was designed. Here, the right fiber end-face was cleaved with an angle of 6° to decrease the Fresnel reflection greatly. In this situation, the laser structure without grating failed to oscillate when the pump power was below 5 W due to the extremely low reflection provided by the 6° fiber end-face. Once the grating was added, the laser started to oscillate with a threshold pump power of 1.2 W. However, since the compound cavity no longer existed due to the lack of reflection from the right fiber end-face, the beat frequency signals always exist at the RF spectrum, as shown in Figure 8a, no matter how the distance between the grating and the fiber end-face was adjusted. Furthermore, the measured optical spectrum bandwidth was also broader than
that in Case 2 at the same lasing wavelength as shown in Figure 8b. Since we kept all the other experimental conditions unchanged, it is obvious that the angle of the right fiber end-face plays a key role in the formation of the SLM operation. Hence, the compound cavity consisting of the external cavity and the cavity formed by the two perpendicularly cleaved fiber end-faces is a decisive factor in the formation of the SLM operation.

Figure 8. (a) Beating spectra at RF under different distances between the grating and the right fiber end-face. The fiber end-face is cleaved at 6°. (b) Optical spectra around 2784.5 nm when the fiber end-face is cleaved at 6° under different distances. The case of the perpendicularly cleaved fiber end-face is also shown for comparison.

5. Conclusions

In summary, we have demonstrated a widely wavelength-tunable MIR high-power fiber laser of SLM using a compound cavity structure. The mechanism of SLM operation has been discussed and verified. The SLM lasing wavelength can be continuously tuned over 100 nm from 2705 nm to 2806 nm by rotating the grating and a high output power up to 450 mW has been achieved. Our laser structure has the advantages of easy fabrication, low-cost, wide wavelength-tuning range and high output power. We believe that such a tunable MIR SLM fiber laser can be used in many applications, such as absorption spectroscopy for gas sensing (CO₂, SO₂, H₂S, etc.).

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