Wavelength combining with volume Bragg gratings in photo-thermo-refractive glasses

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Wavelength combining with a transmitting Volume Bragg Grating recorded in photo-thermo-refractive glasses is present. The combining condition is determined with theoretical simulation. The combining efficiency of 81.4% is obtained in the experiment, and it is influenced by the beam quality of the incident beam. The wavefront characteristics of combining beam are improved.

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High power fiber lasers[1,2] are necessary in numerous fields, such as industry, national defense and so on. However, the output power of single lasers is always limited by thermal distortion of active medium and beam quality degradation in solid-state lasers or optical damage in fiber lasers[3,4]. The wavelength combining, which is an incoherent beam combining, has been an important technique in modern high-power lasers systems[5]. Using this method, individual beams with different wavelengths can be combined into a single near-diffraction-limit output beam with using dispersive elements. Volume Bragg gratings (VBGs) recorded in the photo-thermo-refractive (PTR) glasses has been widely developed owing to the high diffraction efficiency[6], angular and wavelength selectivity[7]. Furthermore, the excellent thermo-mechanical properties and high damage thresholds[8] make them ideal elements for wavelength combining[9]. In 2002, Ciapurin *et al.*[10] demonstrated the use of PTR diffractive optical elements for the high-power laser beams and proposed the combining of two 100-W Yb-fiber lasers with the wavelength of 1085 and 1096 nm. In 2004, Ciapurin *et al.* combined two 100-W Yb-fiber lasers with the wavelength separation of 11 nm and diffraction efficiency of 92%, using a transmitting VBG to obtain a single beam with output power of 165 W[11]. In 2007, Andrusyak *et al.* used four reflecting VBGs to combine five beams with wavelength separation of 0.43 nm. The combining efficiency was 93.5% and M^2=1.11[12]. In 2008, the absolute combining efficiency and maximum output power increased respectively to 91.7% and 773 W with wavelength separation of 0.5nm and M^2=1.16[13]. In 2009, five beams with the wavelength separation of 0.25–0.5 nm around 1064 nm and 1550 nm have been combined into the output beam with combining efficiency of 92%–94%[3]. In 2010, five beams with wavelength separation of 0.25 nm have been combined into a single beam with output power of 750 W by Jain, *et al.*[14]. In 2011, Drachenberg *et al.* combined five beams with wavelength separation of 0.25 nm into a single beam with output power of 750 W as Ref. [14]. The combining efficiency was greater than 90% and M^2=1.65[15]. In 2012, Rawal *et al.* used two transmitting volume Bragg gratings (TBGs) to combined threes beams with the wavelength separation of 10 nm and power of 20 W into a single beam whose output power was 52 W. The combining efficiency was about 90%[16]. In 2013, Drachenberg *et al.* proposed a two-beams combining system[17], with the combined power of 301 W, wavelength separation of 0.25 nm, combining efficiency of 97%, M^2 of 1.18 and BCF of 0.77.

In this letter, two fiber lasers with the wavelength of 1053 and 1080 nm are combined into a single beam with output power of 232 mW, using a TBG recorded in PTR glasses. The requirements of angular and wavelength selectivity in TBGs for the wavelength combining are defined. The dependence of combining efficiency with near-field beam quality is discussed and analyzed by principle experiment.

According to the classical coupled wave theory[18], the diffraction efficiency of the TBGs is given by

$$\eta = \sin^2(\upsilon^2 + \zeta^2)/[1 + (\zeta/\upsilon)^2], \tag{1}$$

$$\begin{cases} \upsilon = \pi\Delta n d/\lambda(\cos\theta_{\mathrm{r}}\cos\theta_{\mathrm{s}})^{1/2} \\ \zeta = \delta d/2\cos\theta_{\mathrm{s}} \end{cases}, \tag{2}$$

where Δn is the refractive index modulation, d is the effective grating thickness, λ is the vacuum wavelength of the incident laser beam. θ_{s} and θ_{r} are the incident angles of the incident and diffraction beams respectively, and δ is the phase mismatch due to the incident laser beam off the Bragg condition.

The wavelength combining is based on the angular and wavelength selectivity of the TBGs. Two laser beams illuminate a TBG which has only two symmetric resonant angles providing total diffraction of a beam with a certain wavelength. Incidence angle for all transmitting beams should correspond to the Bragg angle for the diffracted beam. Transmitting beams are not diffracted by TBG if spectral shift corresponds to zeros in a spectral selectivity curve, and propagate in the same direction as a diffracted beam. Theoretically, many fiber laser beams can be combined with TBGs of the same structural parameters. To ensure the effective combining, the spectral selectivity width of TBGs should be narrower than the wavelength difference between two incident beams, and it must be greater than the spectral width of each incident beam. Simultaneously, the angular selectivity width of TBGs should be narrower than the divergence angle of each incident beam, and must be greater than the Bragg angle differential between two incident beams. The combining efficiency η is defined as

$$\eta = \frac{1+\eta_1+\eta_2+\cdots+\eta_n}{n+1}, \qquad (3)$$

where η_1 is diffraction efficiency of TBGs and n is the number of TBGs.

In this letter, the exposure to the interference pattern of He-Cd laser at 325 nm with average power of 50 mW and two-step thermal development of temperatures at 490 and 540 °C was used to record the TBGs in PTR glasses. Two fiber laser beams with wavelength of 1053 and 1080 nm are combined by the prepared TBG. The experimental setup is shown in Fig. 1. The collimated laser beam with wavelength of 1053 nm is incident on the TBG at Bragg angle, and another collimated laser beam with wavelength of 1080 nm is incident on the TBG with the same angle. The apertures are used to obtain apposite beam size to match the optical system. The two mirrors are used to precisely adjust the optical axis of the fiber laser beam of wavelength at 1080 nm. The power meter is used to measure the combining efficiency of the prepared TBG. The CCD, which measured the near field beam quality of laser beams, is used to analyze the factors affecting the combining efficiency. The wavefront of incident beams and combining beam are investigated by Shack-Hartmann. The average power of 1053 and 1080-nm laser beams are 145 and 140 mW, and the incident angles of 1053 nm and 1080 nm laser beams are 27.77° and –27.77°, respectively. Angular selectivity and wavelength selectivity of the prepared TBG with thicknesses of 2.8 mm, grating period of 1.13 μm and refractive index modulation of 138 ppm is shown in Fig. 2. The theoretical diffraction efficiency of the prepared TBG is 87.78%, and the FWFZs (Full Width at First Zero) of angular and wavelength selectivity are 1.15 mrad and 2.38 nm respectively.

The spectrum FWHMs (Full Width at Half Maximum) of 1053 and 1080 nm laser beams, which are 2.09 and 1.3 nm respectively, satisfy the combining condition

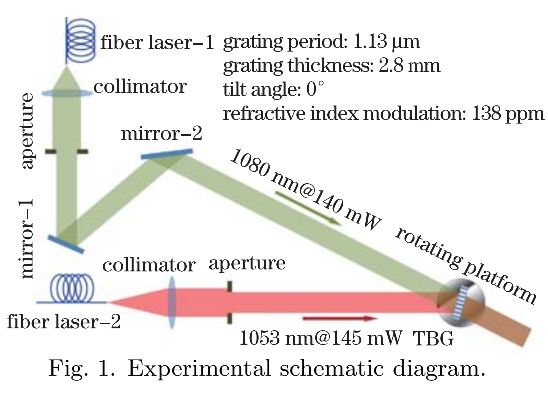


Fig. 1. Experimental schematic diagram.

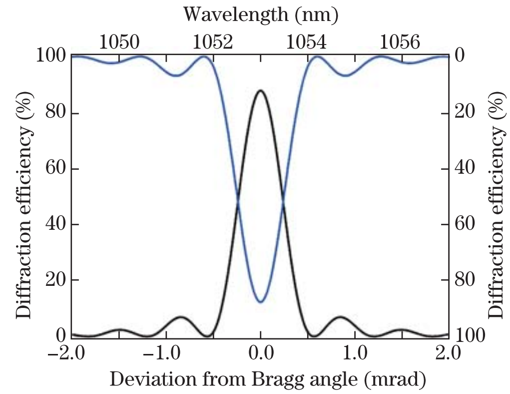


Fig. 2. Dependence of the diffraction efficiency of TBG with wavelength and incident angle.

proposed in preamble. Simultaneously the Bragg angle difference of 130 mrad (0.78°) also satisfy the combining condition. Thus, the two laser beams can be combined with the prepared TBG. As shown in Fig. 3, there are two visible characteristic wavelengths corresponding to 1053 and 1080 nm in spectrum of combining laser beam. The offset of two laser beams is less than 0.1 mm after transmitting three meters.

The measured average power of combining laser beam is 232 mW. Therefore, the experimental combining efficiency is 81.4%. According to Eq. (3), theoretical combining efficiency should be 93.89%. The combining efficiency difference of 12.94% is mainly caused by the following reasons. Firstly, there is no AR membrane on TBG surface. Thus, the combining efficiency is reduced about 8% by Fresnel reflection. Secondly, the beam size is controlled by the aperture. Thus, there are many spatial modulations in laser beam. When the laser beam is incident on the TBG at the Bragg angle, these spatial modulations in laser beams can be filtered out because of the angular selectivity of TBG[19]. The loss of combining efficiency caused by filtered spatial modulations is about 3%∼6%, which is not unacceptable in high power laser combining. Certainly, the higher diffraction efficiency of TBG by optimization preparation is an important method to improve combining efficiency.

Although the combining efficiency is influenced by filtered spatial modulations, it can improve the combining beam quality. As shown in Table 1, the near-field uniformity of combining beam is better than that of incident beam. The near-field modulation (M value) and near-field contrast (C value)[18] of the combining beam is respectively improved about 1.57 and 1.96 times. Meanwhile, the wavefront of laser beams is also improved by the wavelength combining with the TBG, as shown in Table 1. The wavefront of 1053-nm laser beam is much better than that of the 1080-nm laser beam. The wavefront of the combining beam is between the 1053-nm laser beam and 1080-nm laser beam. The measurement results show that the PV value and RMS value of combining beam are about the average of 1053-nm beam and 1080-nm beam, Moreover, the wavefront distribution of combining beam is similar to that of the 1080-nm beam. In actual wavelength combining laser system, we can use this feature to obtain better combining beam quality.

In conclusion, the wavelength combining with TBG recorded in PTR glasses is discussed. The combining

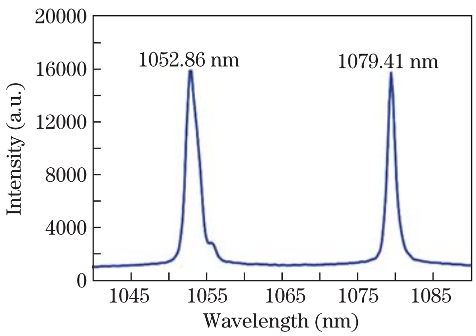
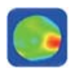


Fig. 3. Spectrum of combining laser beam.

Table 1. Beam Quality of Wavelength Combining

	1053-nm Beam	1080-nm Beam	Combining beam
Near field			
M Value	2.62	2.27	1.67
C Value	70.4%	75.2%	38.3%
Wavefront			
PV	0.289	0.858	0.531
RMS	0.053	0.149	0.105

condition is defined and verified by principle experiment. The two fiber lasers with wavelength of 1053 and 1080 nm are combined with the prepared TBG, and combining efficiency is 81.4%. The dependence of combining efficiency with near-field beam quality was analyzed. However, the angular selectivity of TBG also improves the combining beam quality.

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