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

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Received November 1, 2013; accepted January 15, 2013; posted online February 28, 2014

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.

OCIS codes: 090.7330, 140.3298.
doi: 10.3788/COL201412.030901.

High power fiber lasers1,2 are necessary in numerous fields, such as industry, national defense and so on. How-
ever, the output power of single lasers is always limited by thermal distortion of active medium and beam qual-
ity degradation in solid-state lasers or optical damage in fiber lasers3,4. The wavelength combining, which is
an incoherent beam combining, has been an important technique in modern high-power lasers systems5. Us-
ing 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 efficiency6, angular and wavelength selectivity7. Furthermore, the excellent thermo-mechanical properties and high damage thresholds8 make them ideal elements for wavelength combining9. 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.11 combined two 100-
W Yb-fiber lasers with the wavelength separation of 11
nm and diffraction efficiency of 92%, using a transmit-
ing VBG to obtain a single beam with output power
of 165 W11. In 2007, Andrusyak et al. used four re-
fecting VBGs to combine five beams with wavelength separation of 0.43 μm. The combining efficiency was
93.5% and M2=1.1112. In 2008, the absolute combining efficiency and maximum output power increased respec-
tively to 91.7% and 773 W with wavelength separation of 0.5 μm and M2=1.1613. In 2009, five beams with
the wavelength separation of 0.25–0.5 μm around 1064
nm and 1550 nm have been combined into the output beam with combining efficiency of 92%–94%14. 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.15 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 M2=1.65. In 2012, Rawal et al. used two transmitting volume Bragg gratings (TBGs) to com-
ined 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 system17, with the combined power of 301 W, wavelength separation of 0.25 nm, combining
efficiency of 97%, M2 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 prin-
ciple experiment.

According to the classical coupled wave theory18, the
diffraction efficiency of the TBGs is given by

\[ \eta = \sin^2(\theta^2 + \zeta^2)/[1 + (\zeta/\nu)^2], \quad (1) \]

\[ \begin{align*}
\nu &= \pi \Delta \eta / \lambda (\cos \theta_t \cos \theta_s)^{1/2} \\
\zeta &= \delta d/2 \cos \theta_s
\end{align*} \quad , \quad (2) \]

where \( \Delta \eta \) is the refractive index modulation, \( d \) is the effective grating thickness, \( \lambda \) is the vacuum wavelength of the incident laser beam, \( \theta_s \) and \( \theta_t \) are the incident angles of the incident and diffracted beams respectively, \( \delta \) 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 il-
minate 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 \( \eta \) is defined as

\[
\eta = \frac{1 + \eta_1 + \eta_2 + \cdots + \eta_n}{n + 1},
\]

where \( \eta_1 \) 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 the 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 appropriate 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 \( \mu \)m 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.](image_url)

![Fig. 2. Dependence of the diffraction efficiency of TBG with wavelength and incident angle.](image_url)
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.

This work was supported by the National Natural Science Foundation of China (Nos. 91023009 and 61275140), the Chinese Academy of Engineering (Nos. 11176021, 11076021 and 10876011), the Natural Science Foundation of Jiangsu Higher Education Institutions (No. 10KJA140045), a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), the National High-Tech “863” Program of China and the Graduate Research and Innovation Project of Jiangsu Province (No. CXZZ11_0095).

Table 1. Beam Quality of Wavelength Combining

<table>
<thead>
<tr>
<th>Near field</th>
<th>1053-nm Beam</th>
<th>1080-nm Beam</th>
<th>Combining beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Value</td>
<td>2.62</td>
<td>2.27</td>
<td>1.67</td>
</tr>
<tr>
<td>C Value</td>
<td>70.4%</td>
<td>75.2%</td>
<td>38.3%</td>
</tr>
<tr>
<td>Wavefront</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>0.289</td>
<td>0.858</td>
<td>0.531</td>
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<tr>
<td>RMS</td>
<td>0.053</td>
<td>0.149</td>
<td>0.105</td>
</tr>
</tbody>
</table>

References