Design and analysis of spectral beam combining system for fiber lasers based on a concave grating*

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A novel fiber laser spectral beam combining scheme based on a concave grating is presented. The principle of the presented system is analyzed, and a concave grating with blazed structure for spectral beam combining is designed. The combining potential of the system is analyzed, and the results show that 39 Yb-doped fiber laser can be spectrally beam combined via the designed system. By using scalar diffraction theory, the combining effect of the system is analyzed. The results show that the diffraction efficiency of the designed concave grating is higher than 72% over the whole gain bandwidth, and the combining efficiency is 73.4%. With output power of 1 kW for individual fiber laser, combined power of 28.6 kW can be achieved.

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In recent years, the output power of fiber lasers has increased rapidly with the emergence of large mode area (LMA) fiber and the development of pumping technology[1-3]. However, limited by thermal loading, nonlinear effect and fiber damage effect, scaling the output power of a single fiber laser to a higher level is difficult[4]. Spectral beam combining (SBC) of multiple fiber lasers is considered as an attractive and effective approach to break through the bottleneck in power scaling of fiber lasers[5-7]. In SBC systems, multiple beams with slightly different wavelengths can be spatially overlapped via dispersive elements into one beam. Planar diffraction gratings and volume Bragg gratings (VBGs) are popular dispersive elements for SBC. In the SBC system with a planar diffraction grating, a Fourier transform lens must be used to convert the position of each array element into the incidence angle of the grating and ensure the spatial overlap of the beams in the near field. Because most of the array elements are off-axis, the off-axis lens aberration affects the combining effect and limits the combining potential seriously[8,9]. In SBC system based on VBGs, the problem mentioned above is overcomed, and hence the combining efficiency is demonstrated to be high. However, with the increase of the elements, the system becomes more complicated and the volume becomes larger, which restricts its application[10,11].

In this paper, a novel SBC scheme based on a concave grating is proposed. Concave grating can serve simultaneously the functions of both diffraction and focusing. With a concave grating as the dispersive element, no other optical elements are needed. Therefore the problem of off-axis elements is solved, and the complexity of the SBC system is improved greatly, which is favorable for stable output.

Fig.1illustrates the schematic diagram of SBC system for fiber lasers based on a concave grating. The output end of each fiber laser element is fixed at a specified position determined by its operating wavelength through a V-groove array, and the central ray of each element directs to the grating pole (Point *O*).

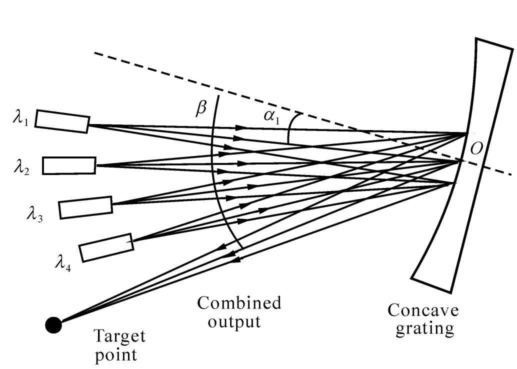

Fig.1 Schematic diagram of fiber laser SBC system based on a concave grating

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The *i*th element with operating wavelength λ_i has an incident angle of α_i, and the diffraction angles of all the elements are β. The diffraction process obeys the concave grating equation[12]

$$m\lambda = d\,(\sin\beta + \sin\alpha)\ , \tag{1}$$

where d represents the grating period, and m is the diffraction order. According to Eq.(1), the incident angle of the *i*th element is given by

$$\alpha_i = \arcsin\left(\frac{m\lambda_i}{d} - \sin\beta\right)\ . \tag{2}$$

All the diffracted beams focus on the same target point which is supposed to be at a distance S from the grating pole. According to the focusing equation of concave gratings[12], the incident radius, which is defined as the distance between the fiber output facet and the grating pole, is given by

$$r_i = \frac{\cos^2\alpha_i}{\dfrac{\cos\alpha_i + \cos\beta}{R} - \dfrac{\cos^2\beta}{S}}\ . \tag{3}$$

It follows the above equations that the concave grating acting as the beam combiner can combine multiple fiber laser beams and focus the combined beam on a given target without extra optical elements. As the target position changes, target tracking can be realized through adjusting the position and beam propagating direction of each element. It is beneficial for the applications in optical communication and laser weapon systems.

The key for achieving high combining efficiency is to design a concave grating with great diffraction performance. Here we design the grating on basis of blazed gating structure which is well known to have high diffraction efficiency. Fig.2 is the schematic diagram for grating design. The centers of all the triangular grooves locate on a circular arc with curvature radius R.

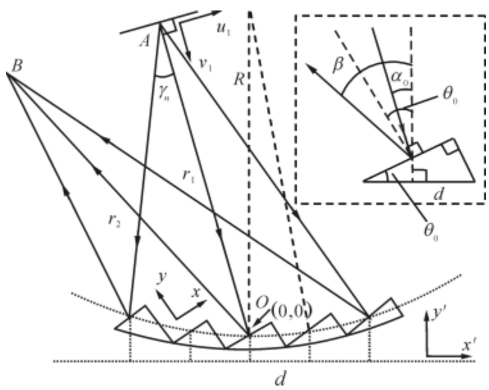

Fig.2 Design schematic diagram of concave grating

Firstly we calculate the coefficients of the central groove based on the path of the central ray incident on the grating pole, which is shown in the inserted figure. Assuming S=100 m, β= 60°, d = 1 mm and m = 1, for the central laser element with wavelength λ_0=1065 nm, the incident angle α_0 and the incident radius r_0 are calculated to be 11.5° and 129.8 mm, respectively. For a blazed grating with triangular grooves, the maximum diffraction efficiency is achieved when the direction of diffractive ray coincides with that of specular reflection from the groove facet with a blazed angle of θ_0, which means

$$\beta - \theta_0 = \theta_0 - \alpha_0\ . \tag{4}$$

According to Eq.(4), the blazed angle can be calculated as $\theta_0=(\alpha_0+\beta)/2=35.75°$. Under the assumption that the diffractive facet of the groove is orthogonal to the non-diffractive facet, the width of the diffractive facet is given by

$$d_0 = d\cos\theta_0 = 0.81\ \mu\text{m}\ , \tag{5}$$

and the diffractive facet depth is

$$h = d_0 \sin\theta_0 = 0.47\ \mu\text{m}\ . \tag{6}$$

The following step is to calculate the coefficients for arbitrary grooves. Two rectangular coordinate systems, *xOy* and *x*'*Oy*', are established, both of which make the grating pole as coordinate origin. *AO* represents the central ray emitted from the fiber facet, which is characterized by incident radius r_1, diffractive radius r_2, incident angle α and diffractive angle β.

The coordinate of the middle point of the *n*th groove is

$$\begin{cases} x'_n = nd \\ y'_n = R - \sqrt{R^2 - (nd)^2} \end{cases},\ n = 0, \pm1, \pm2 \cdots \pm \frac{N-1}{2}\ , \tag{7}$$

where N is the groove number. After coordinate transformation, the coordinate of the *n*th groove middle point in *xOy* system can also be expressed as

$$\begin{cases} x_n = x'_n \cos\theta_0 + y'_n \sin\theta_0 \\ y_n = y'_n \cos\theta_0 - x'_n \sin\theta_0 \end{cases}. \tag{8}$$

And the width of the *n*th groove is

$$d_n = 2(x_n - x_{n-1}) - d_{n-1}\ . \tag{9}$$

From Eqs.(8) and (9), we can obtain the position and facet width of arbitrary groove.

In this SBC system, the combining potential is determined by the dispersion power of the concave grating. Differentiating Eq.(1) yields the angle dispersion as

$$D_\alpha = \frac{\mathrm{d}\alpha}{\mathrm{d}\lambda} = \frac{m}{d\cos\alpha}\ . \tag{10}$$

Utilizing Eq.(3), the linear dispersion D_L is obtained as

$$D_L \equiv \frac{dl}{d\lambda} = rD_\alpha \approx \frac{m\cos\alpha}{d(\frac{\cos\alpha+\cos\beta}{R}-\frac{\cos^2\beta}{S})} . \quad (11)$$

Assuming that the space separation between adjacent elements is T and the gain bandwidth of the doped fiber is $\Delta\lambda$, thus the maximum allowable amount of fiber laser elements is

$$n = \frac{\Delta\lambda \cdot D_L}{T} \approx \frac{\Delta\lambda \cdot m\cos\alpha}{Td(\frac{\cos\alpha+\cos\beta}{R}-\frac{\cos^2\beta}{S})} . \quad (12)$$

Eq.(12) shows that the combining potential may be improved by increasing curvature radius R, diffraction order m, or decreasing space separation T and grating period d. However, the aberration becomes more serious with the increase of R, which can influence the combining effect, and T cannot be decreased arbitrarily, because it depends on the fiber size. Here supposing R=200 mm, T=200 μm and the gain bandwidth as 1020–1080 nm, the maximum number of elements is calculated as 39 according to Eq.(12).

According to Eqs.(2) and (3), the incident angle and incident radius of each element with given wavelength can be calculated, which determine the position distribution of 39 elements as shown in Fig.3.

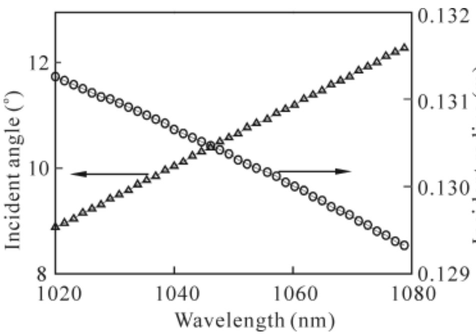

Fig.3 Position distribution of combining elements in the beam combining system

In this SBC system, the combining efficiency depends mainly on the grating diffraction efficiency. Since the curvature radius of the concave grating is much larger than the groove size and the beam spot size, it is feasible to consider each groove as a general straight groove, and the incident radius is constant approximately on each groove. The angle between the central ray AO and the incident ray on the nth groove can be approximately expressed as $\gamma_n \approx nd/r_1$.The angle between axis y and the incident ray on the nth groove is $\varphi_n=\varphi_0+\gamma_n$, where φ_0 represents the angle between AO and axis y, and can be calculated by $\varphi_0=\theta_0-\alpha_0$.

The diffraction efficiency is calculated on basis of the scalar diffraction theory. The electric field emitted from point A is supposed to be a Gaussian field expressed as

$$E(u_1) = E_0 \exp(-\frac{u_1^2}{\omega_0^2}) , \quad (13)$$

where ω_0 gives the waist radius of mode field.

According to the Kirchhoff-Huygence diffraction formula, the incident electric field at the middle point of the nth groove facet can be calculated as[13]

$$E_n = E_0 \frac{1+\cos\gamma_n}{2} \frac{\omega_0\sqrt{\pi}}{\sqrt{\lambda r_1}} \exp(ikr_1)\exp[-(\frac{\gamma_n}{\sigma})^2] , \quad (14)$$

where λ is the wavelength and $\sigma=\lambda/\pi\dot{u}_0$ is the beam divergence angle.

Assuming that the reflection coefficient of the grating facet is united and the losses resulting from scatting and shadowing between adjacent facets are zero, the diffraction efficiency defined as the ratio between the optical power reflected off the grating and the incident power is given by[13]

$$\eta = \frac{P}{P_0} = \frac{\sqrt{2}}{w_0\sqrt{\pi}} E_0^{-2} \sum_n d_n \cos(\varphi_n) |E_n|^2 . \quad (15)$$

By virtue of Eqs.(14) and (15), the diffraction efficiencies for different waist radii of mode field are calculated, as shown in Fig.4. The concave grating has higher diffraction efficiency with the increase of mode field radius. This is mainly due to that larger waist radius of mode field means smaller beam divergence, which makes for more optical energy participating in diffraction process. When the beam divergence is small enough to ensure that the great majority of the optical energy can be accommodated by the grating, the diffraction efficiency can reach a saturated value. As shown in Fig.4, the diffraction efficiency is nearly a constant 74% for mode field radius larger than 10 μm.

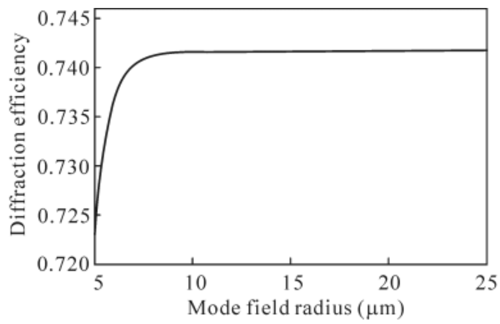

Fig.4 Curve of diffraction efficiency versus mode field radius of the fiber

Fig.5 gives the relation between the diffraction efficiency and the wavelength. In the whole gain bandwidth, the diffraction efficiency is greater than 72%. This is a great superiority over traditional SBC system in which several off-axis elements suffer from lower efficiency due to off-axis aberrations. Along with the increase of the wavelength, the diffraction efficiency rises. This is because when the wavelength increases, the corresponding incident radius decreases, but the incident angle becomes larger. The decrease of the incident radius can reduce the beam spot size incident on the grating, which can reduce the energy loss. The larger incident angle α_0 yields smaller φ_n, thus higher diffraction efficiency according to Eq.(15).

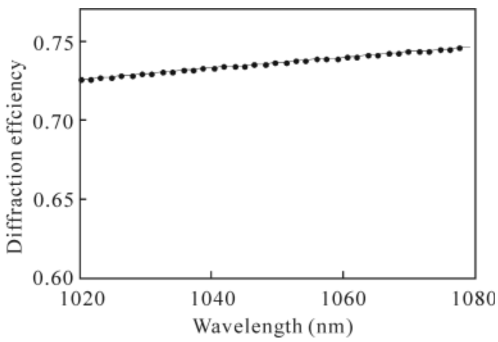

Fig.5 Curve of diffraction efficiency versus wavelength

Supposing all the laser elements with equal power, the combining efficiency of the SBC system is the average of the diffraction efficiencies for all the elements. Under the above coefficients of the designed system, the calculated combining efficiency is 73.4%. With the output power of 1 kW for a single fiber laser element, a combined power of 28.6 kW can be obtained with the SBC system.

In conclusion, a novel SBC scheme based on a concave grating is presented, and a concave grating with blazed grating structure is designed. The numerical simulation results show that 39 Yb-doped fiber lasers can be combined with the combining efficiency of 73.4%, and 28.6 kW combined power can be obtained with individual fiber laser having output power of 1 kW. Compared with the traditional SBC systems, the presented SBC scheme has simpler structure and more convenient trace-tracking performance, and the problem resulting from off-axis lens aberrations is overcomed. However, since the grooves of the concave grating are fabricated upon a circular arc, the diffraction effect is influenced inevitably by the aberrations. The future task is to further optimize the grating structure to reduce the aberrations in order to establish SBC systems with higher efficiency.

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