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SPECIALTY SECTION
This article was submitted to Optics and
Photonics,
a section of the journal
Frontiers in Physics

RECEIVED 18 November 2022
ACCEPTED 25 November 2022
PUBLISHED 08 December 2022

CITATION
Fan X, Zhang J, Li S, Li S, Wang Y, Du F,
Huang X, Li Y, Zhang L and Wang C
(2022), A method to achieve spectral
beam combining based on a novel
symmetric grating.
Front. Phys. 10:1102323.
doi: 10.3389/fphy.2022.1102323

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A method to achieve spectral beam combining based on a novel symmetric grating

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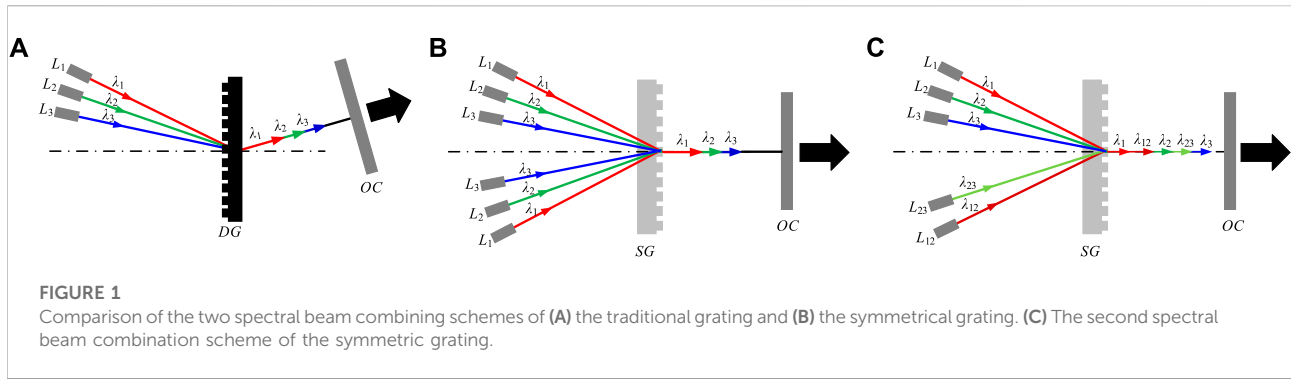
A symmetric grating is proposed to obtain higher output power in spectral beam combination by increasing the number of lasers and spectral utilization. The grating allows laser beams to be incident from both sides of the grating normal to achieve coaxial beam combining, so the number of beams and the combined output power are doubled compared with the traditional grating under the same spectral line-width. The grating is designed with the central wavelength of 4.65 μm , and the calculation results show that this grating is very advantageous for spectral beam combining, especially for the light waves in the range 4.55–4.71 μm , where their diffraction efficiencies are high (over 80%) and correspond to a wide and linear range of incidence angles. Meanwhile, based on the symmetric gratings we further propose a circular grating to achieve the same frequency spectral beam combining. This beam combining design will not increase the laser spectral line width while enhancing the laser power, reducing the requirements for the unit laser spectral line width, which is very meaningful in some application fields and will further enrich the research of spectral beam combining.

KEYWORDS

spectral beam combination, symmetrical grating, circular grating, same frequency spectral beam combination, coaxial beam combining

1 Introduction

The output power of a single laser beam is often difficult to meet scientific and industrial needs due to the gain saturation, non-linear effects and device damage. Combining multiple laser beams is an effective way to obtain higher output power to solve this problem [1]. In 1986, Wilfrid B. Veldkamp of Lincoln Laboratory first proposed a method for coherent beam combining of multi-channel lasers using binary phase gratings and achieved 6 GaAlAs laser beams combination [2, 3]. In 2011, Thales Research and Technology in France reported the coherent beam combining of 5 quantum-cascade lasers by a binary phase or Dammann grating [4]. All of the above solutions are coherent beam combining, which requires a high degree of coherence between different channel



lasers and is hard to accomplished experimentally, especially when the number of lasers is large [5–9]. The feasibility of a spectral beam combining (incoherent beam combining) scheme was proposed by Christopher C. Cook et al. at Lincoln Laboratory in 1999 [10] and was experimentally achieved for a semiconductor laser array in 2000, where the combined beam quality was almost identical to that of the single emitter [11], and in the same year, they have also successfully achieved spectral beam combining of 11-channel lasers [12]. Since then, the study of spectral beam combination has attracted extensive attention [13, 14].

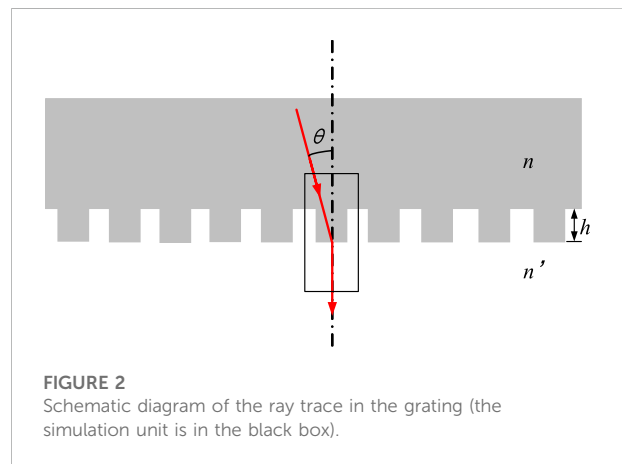
Theoretically, the more lasers, the higher the combined beam output power, but increasing the number of lasers will bring many problems, mainly in: 1) difficulty in optical path arrangement, because the existing spectral beam combination schemes require that all emitters (or laser arrays) can only be on the same side of the grating normal; 2) the spectral of each emitter must be broadband, and the more the emitters are, the wider their spectral must be, otherwise the efficiency of the spectral beam combination will be reduced.[15]

To overcome these above problems, we propose a symmetric grating for the spectral beam combining, and also develop a circular grating (two-dimensional grating) to achieve the same frequency spectral beam combining, which greatly enriches the study of spectral beam combining.

2 Novel spectral beam combining scheme

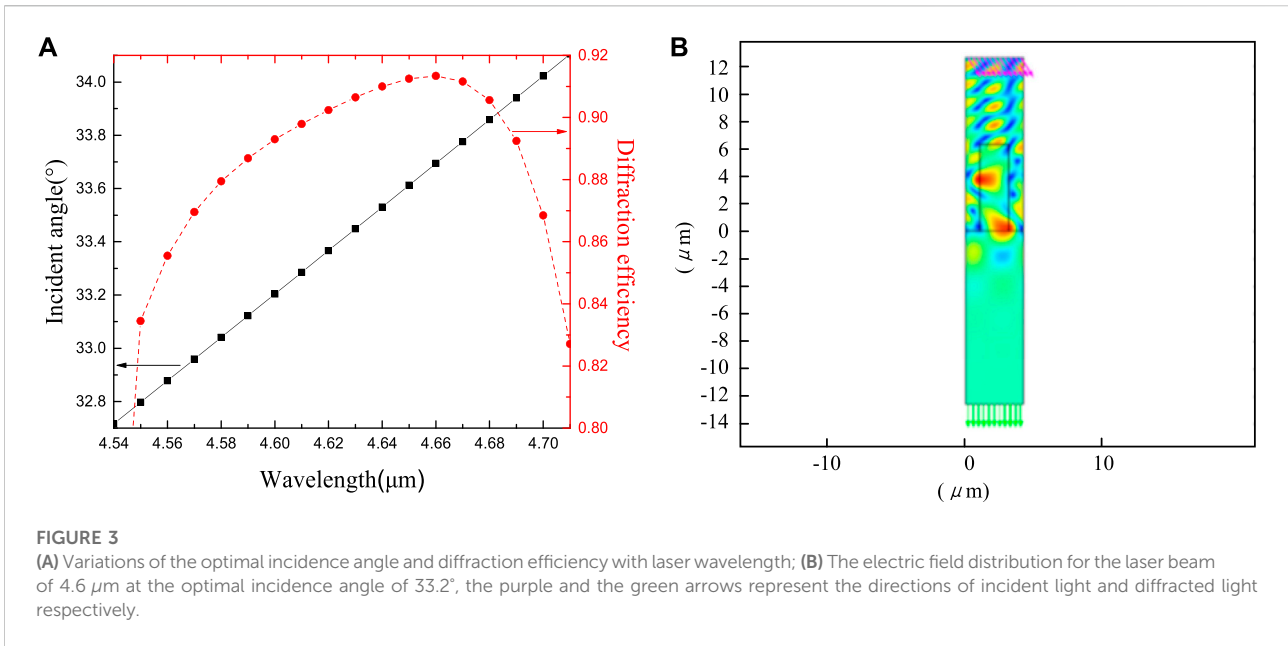
2.1 Symmetric grating and its spectral beam combining scheme

Compared with traditional grating, our symmetric grating has the following features: The diffracted light can be emitted perpendicular to the grating plane if the laser beam is incident on the grating at a suitable angle, so it can also be emitted perpendicular to the grating plane when the laser beam incident at the symmetrical position (or angle) on the other



side of the grating normal. This allows multiple laser beams to be incident from both sides of the grating normal to achieve spectral beam combining. Meanwhile, the incident light can only be on one side of the normal of the traditional grating for spectral beam combining. Take the example of the three-channel lasers L_1 , L_2 , and L_3 , the differences between the two spectral combining schemes of the traditional grating and the symmetrical grating are given in Figures 1A,B respectively. DG and SG are the traditional diffraction grating and the symmetric grating respectively, and OC is the coupling output mirror that partially reflects and partially transmits the spectral lines of the unit lasers L_1 , L_2 , and L_3 so that the three channels lasers are locked to the central wavelengths λ_1 , λ_2 and λ_3 respectively and are coaxially combined.

Compared with traditional gratings, it can be seen that the symmetrical grating has the advantages of a larger number of lasers, higher spectral utilisation, smaller space requirement and the ability to combine beam at the same frequency. As shown in Figure 1C, there is also another spectral beam combining scheme where the positions of the lasers on either side of the grating normal can be asymmetrical compared with Figure 1B, L_{12} and L_{23} are located between L_1 and L_2 , L_2 and L_3 respectively, which their corresponding wavelengths λ_{12} and λ_{23} are between λ_1 and λ_2 , λ_2 , and λ_3 respectively.

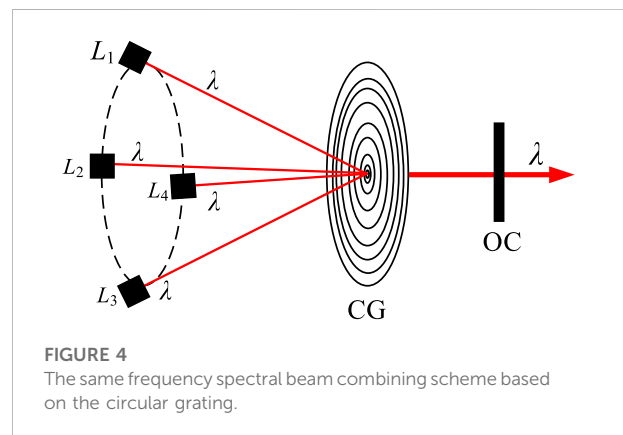


2.2 Parameter design and the spectral beam combining effect

A theoretical study and parametric design have been carried out for the new grating proposed above. In order to obtain high first-order diffraction efficiency, we have designed a sub-wavelength dielectric grating assuming the central wavelength of 4.56 μm [16]. As shown in Figure 2, the simulation unit is in the black box, and the refractive index of grating material n , air refractive index n' , grating period d , duty cycle η and ridge height h are respectively set at 2.0, 1.0, 4.2, 0.5 and 6.3 μm .

As shown in Figure 3A, calculations show that this grating is ideally suited for spectral beam combining, as it has a high diffraction efficiency (>80%) for the incident light in the range 4.55–4.71 μm , with a maximum diffraction efficiency of 91.4% at 4.66 μm , and a relatively significant difference in the incidence angle of these lights while their diffracted lights are emitted perpendicular to the grating plane. Figure 3B shows the electric field distribution of incident and diffracted light in the grating for the laser beam of 4.6 μm , the purple arrows represent the direction of incident light (33.2°) and the green arrows represent the direction of diffracted light, which is consistent with the initial assumptions and calculations made earlier. Due to the left-right symmetry of the grating structure (see Figure 2), the beam incident from the right side of the grating normal has the same direction of emission.

From the previous simulation and analysis, it is clear that the symmetrical grating is perfectly feasible for spectral beam combining, and has the advantages of high spectral utilisation and small space occupation compared with traditional grating combining scheme. But as shown in Figure 1B, this grating can only combine two beams of the same frequency (or same wavelength). If a grating could combine



multiple beams of light at the same frequency, the spectrum of each laser does not need to be broadband, and the combined laser beam is not broadband anymore which is very meaningful in some application fields [17]. To this end, we further develop a circular grating.

2.3 Circular grating and its spectral beam combining scheme

The so-called circular grating means that the grating grooves are not straight but circular, so that the same frequency beam is incident on the same solid angle to the center of the circular grating to achieve coaxial same frequency spectral beam combining. A schematic diagram of a 4-channel lasers spectral beam combining using the circular grating is given in Figure 4, CG is the circular

grating and OC is the coupling output mirror respectively. Obviously, the overall output power of the combined beam can be increased by increasing the number of the same frequency lasers at this solid angle, and further increased by increasing the number of different wavelength lasers at other solid angles.

3 Conclusion

To increase the number of lasers and spectral utilisation for greater output power of the combined beam, we propose a symmetric (one-dimensional) grating and a circular grating (two-dimensional). Compared with traditional spectral combining scheme, the symmetrical grating spectral beam combining scheme can double the total output power of the combined beam by doubling the number of lasers for the same spectral line-width. The grating was designed with a central wavelength of 4.65 μm , and the calculations show that this grating is ideally suited for spectral beam combining with a high diffraction efficiency (>80%) and a relatively significant difference in the incidence angle for the incident light in the range 4.55–4.71 μm . In addition, a circular grating is further proposed for the same frequency spectral beam combining. The ideas of symmetrical grating, circular grating and same frequency spectral beam combining proposed in this study will further enrich the study of spectral beam combination.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

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Author contributions

XF: Conceptualization, Original draft, Review and Editing JZ: Numerical simulation, Software SEL: Conceptualization SHL: Numerical simulation YW: Investigation FD: Review and Editing XH: Numerical simulation, Review and Editing YL: Review LZ: Writing, Review and Editing CW: Original draft, Review, Funding acquisition.

Funding

This work is supported by the Shandong Provincial Natural Science Foundation, China (No. ZR2020QA072).

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