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Theoretical analysis of beam quality degradation in spectral beam combining of fiber laser array with beam deviation

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ABSTRACT

Aimed to maintain excellent beam quality, the degradation of M^2 factor is theoretically studied in compact spectral beam combining (SBC) system of fiber laser array. Considering that the output beams from a laser array usually have axial translation and angular deflection, the correction of incident light field is built by the transformation of coordinates. Using the propagation model and the statistics, properties of the combined beam with perturbations of a single emitter or entire laser array are respectively discussed in detail. The degradation of M^2 factor is 0.14(±0.075) when the axial translation of entire laser array satisfies normal distribution with standard deviation of 100 μm. While the angular deflection is introduced with standard deviation of 10/3 mrad, the degradation increases to 3.57(±1.28). Owing to non-overlap ensemble of the incident beam on the grating, the deflection angle will translate the far-field beam spot after the diffraction, which causes a dramatic degradation of the beam quality. Considering the axial translation and the angular deflection simultaneously, the overall effect on the beam quality is dominated by the angular deflection. For applicable requirements of $M^2 < 2$, 3 mrad angular deflection is claimed with axial translation less than 300 μm in the compact SBC system. These analyses provide a valid basis for building the experimental system of SBC.

1. Introduction

High-brightness beam combining of fiber lasers provides a path for power scaling beyond the single fiber limit while maintaining many of the benefits of fiber lasers. Compared with coherent combining, incoherent spectral beam combining (SBC) have the advantages of permitting independent modulation of the lasers, not requiring phase control and interferometric alignment tolerances [1–3]. Beams with diverse wavelength in SBC are overlapped in both the near and far fields to achieve high concentration of power with near-diffraction limited output beam. In 2000, Daneu et al. proposed the SBC of a laser array in the external resonator configuration, achieving a SBC of 11-channel, wideband diode array, obtaining 20 times diffraction limit output [4]. This technique is also widely used in the fiber laser to increase laser brightness. The combined output power of SBC increases from 522 W to 8.2 kW with the beam quality degradation from 1.22 to 4.3 [5,6]. With the expansion of the laser array scale, Lockheed Martin Inc. has achieved a breakthrough in the total power of SBC from 3 kW to 30 kW with a beam quality of $M_x^2 = 1.6$ and $M_y^2 = 1.8$ [7,8].

The output power of SBC is determined by the number of emitters and power of a single laser, while the beam quality of the combined beam is theoretically identical to that of the individual beam from a single emitter. However, the beam quality is susceptible to the thermal distortion of diffraction grating, the optical aberration of transform lens, and beam deviation of laser arrays. According to a propagation model based on multilayer dielectric gratings (MDGs) [9–12], the combined beam quality degrades with the parameters and fabrication errors of MDGs [9,10] and aberration coefficient of the transform lens [11]. In these analyses, an ideal laser array is assumed, but the beam deviation of misaligned laser array also influences the properties of the combined beam,

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especially the beam quality, which has been a key performance index for evaluating the effect of the high-energy laser. For the wideband diode array, the non-ideal "smile" effect on the combined beam quality has been investigated using the ray-tracing method [12]. However, due to the different divergence angles in two orthogonal directions, diode laser arrays of SBC require complex beam shaping system with the output field of super-Gaussian distribution. The order of the super-Gaussian is hard to be determined precisely and the initial beam quality is unknown which reduces the usefulness and effectiveness of simulation. In contrast, the fiber laser array where the emitters release nearly diffraction-limited Gaussian beams is more applicable to establish SBC model for simulating and optimizing the beam quality. Most importantly, as the multiple beam combination with stochastic beam deviation, a systematical statistical analysis is critical for evaluating the beam quality precisely. For the numerical calculation, compared with the ray-tracing method, the approach using rigorous coupled wave analysis is stricter to consider phase modulation on the MDG in subwavelength structures (grating constant $d \approx \lambda$) [13]. To our best knowledge, the influence of beam deviation on the fiber SBC architecture is rarely analyzed in previous reports.

In this paper, the combined beam quality of SBC has been chosen as a universal standard to evaluate the changes caused by external disturbances that surround emitters, such as fabrication errors, mechanical vibration and temperature change. The paper is organized as follows. In Section 2, the incident light fields of beams with axial translation and angular deflection are derived by the transformation of coordinates and pass through the compact SBC system based on the beam propagation model. The intensity distributions and M^2 factor of the combined diffraction beams are numerically calculated and analyzed in mathematical statistics in Section 3. Conclusions are drawn in Section 4. We believe that this reliable analysis will play an important role in establishing SBC system of fiber lasers in practice.

2. Theoretical model

A schematic diagram for SBC system is shown in Fig. 1(a), consisting of fiber laser array, a transform lens, and a diffraction grating. The transform lens is located between the laser array and MDG to ensure that each individual beam is collimated and spatially overlapped on the MDG. All beams with different wavelengths whose incident angles specially satisfy the grating equation can be exported along the common aperture. Therefore, the emission wavelength of each beam is determined by both the MDG and the position of laser emitter. Compared with free propagation of

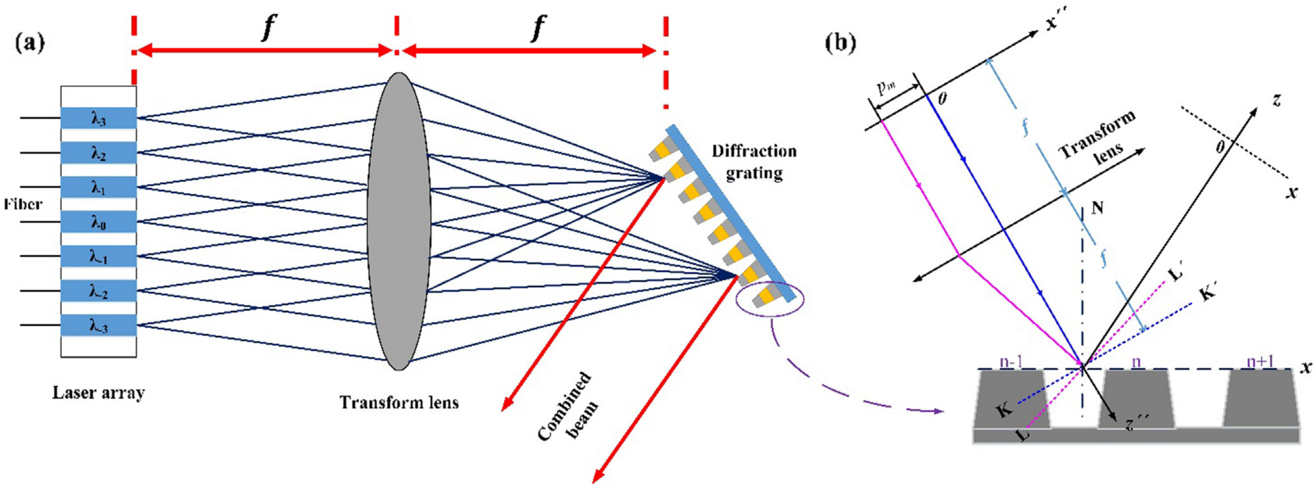

Fig. 1. (a) Schematic illustration and (b) simplified mathematical model of SBC system. LL' and KK' are equiphase surface for the different sub-beam; n, the numerical order of the relief.

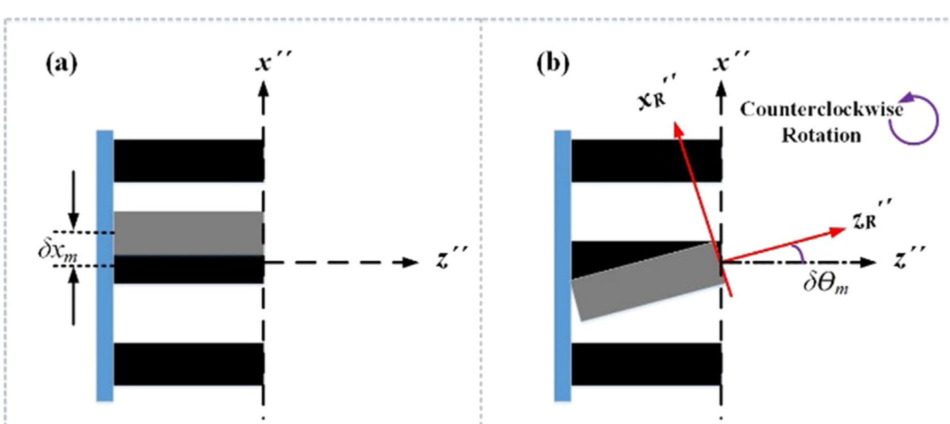

Fig. 2. Beam deviation of emitters including: (a) axial translation with δx_m; (b) angular deflection with $\delta\theta_m$.