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Investigation on ultimate efficiency of spectral beam combining based on an external cavity

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ABSTRACT

Based on the simplified model of spectral beam combining system with external cavity, the changes of the combined powers and efficiencies with different design parameters were analyzed in detail. We have presented an approach of determining single-mode output power for Large-mode-area fiber laser and further built the experimental setups including single fiber laser with an external cavity, tunable fiber laser, as well as spectral beam combining of two fiber emitters. The simulation gives the ultimate combining efficiency of the combining system of no more than 82%, and meanwhile the measured efficiency was about 64.3% according to the presented method.

1. Introduction

High-brightness lasers have significant applications in defense and manufacturing [1–4]. Spectral beam combining (SBC) is a promising alternative method to obtain high power fiber laser output beyond the power limit in a single fiber laser [5–8]. It can be accomplished with either spectrally-dispersive or spectrally-selective optical elements [9]. The former includes prisms or surface diffraction gratings, and the latter includes thin film filters or volume Bragg gratings [10–16]. In the late 1990s, an SBC setup based on a surface diffraction grating with spectral control of sources by optical feedback was proposed by Cook et al. [17], and it was later theoretically described and analyzed [18]. By means of the experimental system, Daneu et al. obtained the combined power of more than 50% from the outputs of an 11-element diode laser array [19], and August et al. achieved the combined power of 6W from a 5-element Yb^{3+} doped double-cladding fiber laser array [20]. To date, the experiment setup was reported to yield 100 W output power with central wavelengths offset of about 6.5 nm with $M^2 = 2.7$ [9,21]. The combined efficiency is generally concerned for the SBC setup, which is defined as the ratio of the combined power versus the sum of output powers of all emitters (without considering both the grating diffraction loss and the emitter-cavity coupling efficiency) [9]. This means that the output power of each laser in the combining system must be measured. The spectrum characteristics of large-mode-area (LMA) double-cladding fiber laser, however, are multimode, and the single-mode laser can not be obtained without tuning device. Previously, we adopted the ratio of the combined power to the sum of highest tunable output power to calculate the combined efficiency [22]. The method is not consistent with the combining definition, which may result in the calculated efficiency higher than the measured value due to the ignored various losses, such as transform lens, emitter cavity, and grating, etc.

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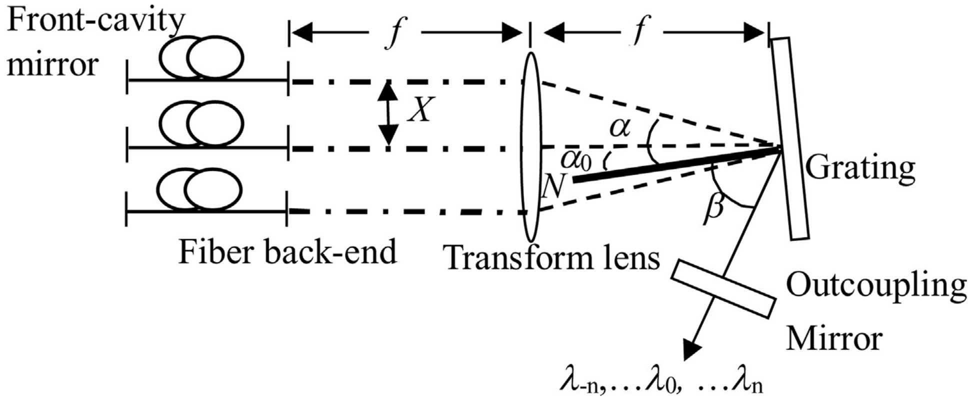

Fig. 1. Schematic diagram of spectral beam combining with an external cavity.

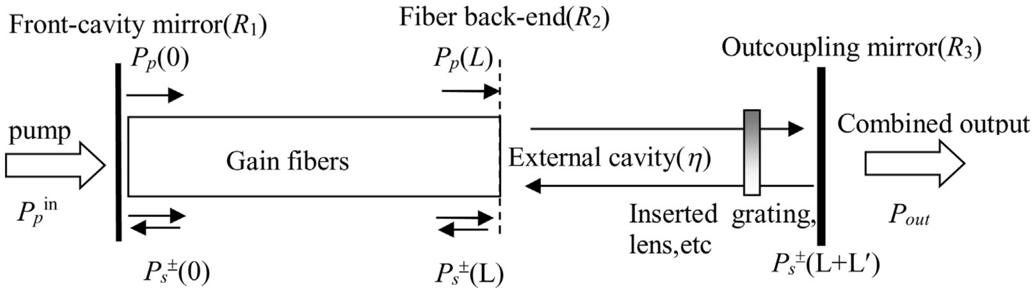

Fig. 2. Framework of simplified SBC system.

In this paper, the influences of design parameters (such as fiber length, cavity mirror, etc) on combining efficiency are firstly analyzed in Sections 2. Then, Section 3 gives an approach of determining single-mode output power for large-mode-area (LMA) double-cladding fiber laser. Finally, the measured results by means of the presented method show that the ultimate efficiency of the experimental system is about 64.3%.

2. Theoretical analyses

2.1. Simplification of SBC system with an external cavity

Fig. 1 gives a schematic diagram of SBC with an external cavity [18]. According to the principle of SBC of fiber lasers, the system can be simplified into Fig. 2 [22].

In Fig. 2, the length of the gain fiber is set to L, and that of the external cavity is set to L'. $P_p{}^{in}$ represents a launched pump power, and $P_s{}^{\pm}(0)$, $P_s{}^{\pm}(L)$ and $P_s{}^{\pm}(L+L')$ are the forward, backward signal powers at the front-cavity mirror, fiber back-end and outcoupling mirror respectively. P^{out} indicates the combined output power. The reflectivity of the front-cavity mirror, fiber back-end and outcoupling mirror on the signal light are R_1, R_2, and R_3, respectively, and the loss of the inserted objects (including transform lens, grating, etc.) on the signal light is R_4.

If the transmissivity of the front-cavity mirror on pump light equals to 1, then the following equations can be obtained according to Fig. 2 [22]:

$$P_p(0) = P_p^{in} \tag{1}$$

$$P_s^+(0) = R_1 P_s^-(0) \tag{2}$$

$$P_s^-(L) = R_2 P_s^+(L) + (1-R_2)^2(1-R_4)^2 \eta(\lambda) R_3 K(\lambda) P_s^+(L) \tag{3}$$

$$P^{out} = P_s^+(L)(1-R_2)(1-R_3)(1-R_4)K(\lambda) \tag{4}$$

where, $K(\lambda)$ is the diffraction efficiency of a blazed grating, η (λ) is the coupling efficiency that the signal light is coupled back into the fiber core for an emitter with off-axis distance X, transverse offset Y, and tilt angles θ_x and θ_y,

The $K(\lambda)$ above can be derived as:

$$K(\lambda) = K_0 \sin c^2 \{ \frac{bm}{d} - b \tan\theta \frac{\cos\alpha_j + \cos\beta]}{\lambda_j} \} \tag{5}$$