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High power signal combiner for fiber lasers

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Abstract: The 3 × 1 fused tapered fiber bundle (FTFB) signal combiner consisting of three signal fibers and a multi-mode output fiber was studied. The simulation results indicate that the transfer efficiency and output beam quality are getting better with longer taper length. Moreover, transfer efficiency for low-order mode launching is higher than that for high-order mode launching. A 3 × 1 signal combiner with taper length of 10 mm was fabricated in experiment. The input beam with high beam quality results in high transfer efficiency, which agrees with the simulation results. The transfer efficiency of 96.6%, total output power of 602 W and output beam quality of $M_x^2 = 10.5$, $M_y^2 = 9.7$ were achieved as two fiber lasers with 258 W and 365 W were combined by the FTFB signal combiner.

Key words: fiber optics, fiber lasers, lasers, general theory of combining
PACS: 42.81.-I, 42.55.Wd, 42.55.-f, 42.55.Ah

高功率光纤激光信号耦合器

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摘要：实验研究了由三根信号光纤锥形束和一根多模光纤组成的3×1信号耦合器. 通过仿真，发现锥形长度越长传输效率和输出光束质量越好，同时也验证了对于低阶模场的吸收要高于高阶模场. 实验中，制作了锥区长度为10 mm的3×1信号耦合器，在单纤注入信号功率分别为258 W和365 W的情况下获得转换效率为96.6%的信号输出，总输出功率602W，光束质量为$M_x^2 = 10.5$，$M_y^2 = 9.7$.

关　键　词：光纤光学；光纤激光器；激光；耦合理论

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Introduction

In recent years, fiber laser developers mainly target on high power output and high beam quality (BQ). However, limitations arise when entering the high power regime, such as the thermal effects[1-3] as well as nonlinearities[4-5]. One of the solutions for obtaining ultra high power output is beam combining, which includes coherent combining[6] and incoherent combining[7]. The output beam quality can be higher in coherent combining, but it has complex system difficult to realize. Incoherent beam combining has much simpler setup since it doesn't need precise phase control, making it easier to realize high output power. In all-fiber laser systems, the fused tapered fiber bundle (FTFB) combiners are the critical components to perform beam combining. The combiner combining near-single-mode laser beam is called signal combiner[8-9]. Y. Shamir *et al.* demonstrated the 3 × 1 TFB combiner with output delivery fibers which makes the device more practical[10]. They also demonstrated theoretically that delivery with no beam quality deteriora-

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tion can be achieved with proper fiber design[11]. They realized coherent combining using a simple FTFB[12]. The fiber tapered bundle with efficient brightness conservation composed of side-by-side addition of fiber lasers has been fabricated and performed. Two combiners were formed by cleaving a symmetric bi-conical tapered bundle at an optimal position[13-14]. M. H. Muendel *et al.* have reported a 7 × 1 signal-combiner. With seven lasers of 600 W as the inputs, through the 7 × 1 signal-combiner with <2% optical loss on every port and a output fiber with core diameter of 105 μm (NA = 0.22), 4 kW of output power with BPP = 2.5 mm × mrad has been realized[15]. An all-fiber 7 × 1 signal combiner for incoherent laser combining has been fabricated successfully by D. Noordegraaf and his co-workers, output power of 2.5 kW was achieved, and the beam parameter product of 2.22 mm × mrad (corresponding to $M^2 = 6.5$) was measured at a power level of 600 W[16].

In this paper, we report a 3 × 1 FTFB signal combiner. Three signal fibers were fused and tapered together, and then spliced to a multi-mode output fiber. The signal fibers were fused and tapered directly without low-index capillary tube, so the fabrication is relatively simple. Moreover, the output fiber makes this combiner compatible with an all-fiber laser system. Properties of the 3 × 1 FTFB signal combiner were studied theoretically and experimentally. In general, the transfer efficiency of signal light increases with the taper length. In the experiment, we compared the transfer efficiencies under different beam qualities. Higher transfer efficiency was obtained when input beam injected with higher quality. Experimental results agree with simulative results. Finally, the combined power was measured, when two fiber lasers with power of 258 W and 365 W were launched into two signal fibers simultaneously, the total output power of 602 W with transfer efficiency of 96.6% was achieved. The measured output beam quality factor was $M_x^2 = 10.5$, $M_y^2 = 9.7$.

1 Theoretical model and numerical results

1.1 Theoretical model

The schematic diagram of a 3 × 1 FTFB signal combiner is shown in Fig. 1. Three signal fibers are fused together gradually and then spliced with a multi-mode output fiber. The taper length of this FTFB combiner is L. The narrow end diameter of tapered bundle and the core diameter of output fiber are of the same value, both of which are expressed as D_2.

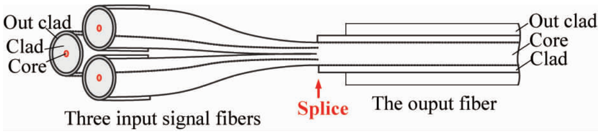

Fig. 1 The schematic diagram of a 3 × 1 fused tapered fiber bundle (FTFB) signal combiner
图 1 3 × 1 锥形光纤束示意图

In order to analyze the properties of FTFB signal combiner, a calculation model is established. The scalar Helmholtz equation is $\nabla^2 E + k_0^2 \varepsilon_r E = 0$. Under the slowly varying envelope approximation, the electric filed is written as,

$$E(x,y,z) = \sum_m \phi_m(x,y,z)\exp(-i\beta_m z)\,(m = 1, 2, 3) \quad , \qquad (1)$$

where $\phi_m(x,y,z)\exp(-i\beta_m z)$ is the propagation filed in the mth signal fiber of 3 × 1 FTFB signal combiner. Substituting Eq. 1 into scalar Helmholtz equation:

$$\frac{\partial^2 \phi_m}{\partial x^2} + \frac{\partial^2 \phi_m}{\partial y^2} + \frac{\partial^2 \phi_m}{\partial z^2} - 2ik_0 n_{ci} \cdot \frac{\partial \phi_m}{\partial z} + 2k_0^2 n_{ci} \Delta n \phi_m = 0 \quad . \qquad (2)$$

The propagation properties of signal beam are obtained by calculating Eq. 2 numerically using semi-vectorial Beam Propagation Method (BPM). The wide-angle beam propagation method based on Padé approximant operators was applied in the code we wrote.

The signal beams are three mutually incoherent lights. They are launched one by one into signal fiber and propagate separately through FTFB. Firstly, we simulated the propagation of signal beams one by one. Then we calculated all the data, such as intensity profile and the normalized power (P_{out}/P_{in}), which are saved at every position of Δz (Δz is the calculative step along longitudinal axis). After that, the output mode filed of three signal beams is incoherently superposed. The properties of the signal combiner were calculated based on the saved data.

1.2 Propagation properties of the signal combiner

With the foregoing model and the parameters in Table 1, we studied the propagation properties of FTFB signal combiner theoretically.

表 1 Parameters used in simulation
Table 1 仿真参数

Meaning	Value
NA of core of signal fiber	0.06
Wide diameter of FTFB (D1)	270 μm
Narrow diameter of FTFB (D2)	50 and 105 μm
Core diameter of output fiber (D2)	50 and 105 μm
NA of core of output fiber	0.12
Diameters of signal fiber (Dcore/Dclad)	20/125 μm

According to the parameters in Table 1, there are LP_{01} and LP_{11} modes existing in the core. LP_{11} mode has two polarized directions, LP_{11}x and LP_{11y}. Since the simulative results of LP_{11x} and LP_{11y} are very similar, we only show the results of LP_{11x} mode. Figures 2(a) and (b) show the intensity patterns of input signal beam of three LP_{01} and LP_{11x} modes, respectively. The white lines stand for the boundary of fiber core and inner cladding of signal fiber at the wide end of FTFB combiner. Corresponding to taper length of $L = 5$ mm, 8 mm and 10 mm, the intensity patterns of output beam with $D_2 = 105$ μm are depicted in Fig. 3. The total output intensity is the incoherent superposition of the intensity of three signal beams. Namely, $I = I_1 + I_2 + I_3$, where, I is the total output intensity, I_m ($m = 1, 2, 3$) is the output intensity of three signal beams, respectively.

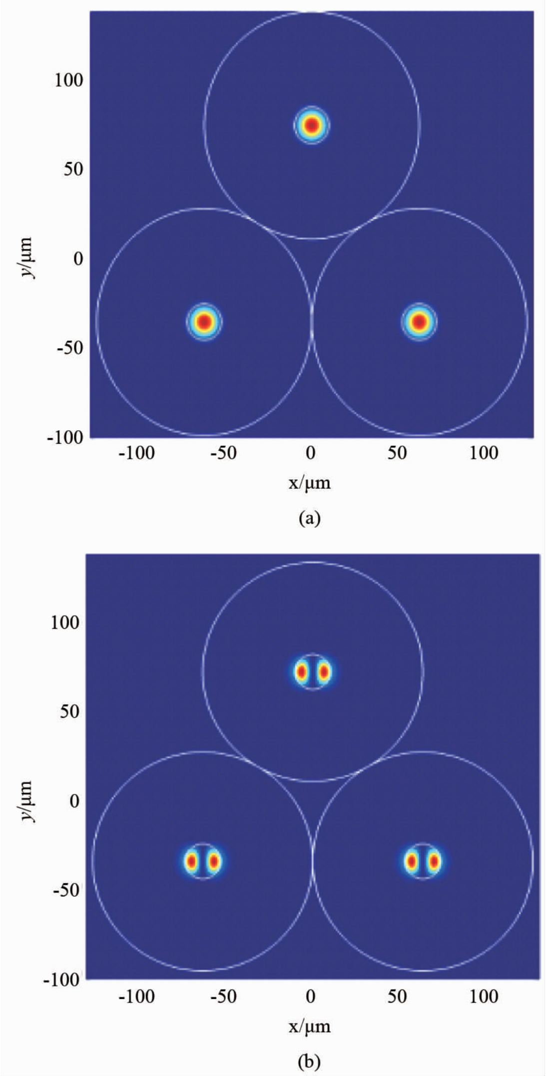

Fig. 2　The intensity patterns of input signal beams in the simulation for (a) LP_{01} mode launching and (b) LP_{11x} mode launching

图 2　输入信号光强度模拟(a)LP_{01}模信号强度图(b)LP_{11x}模信号强度图

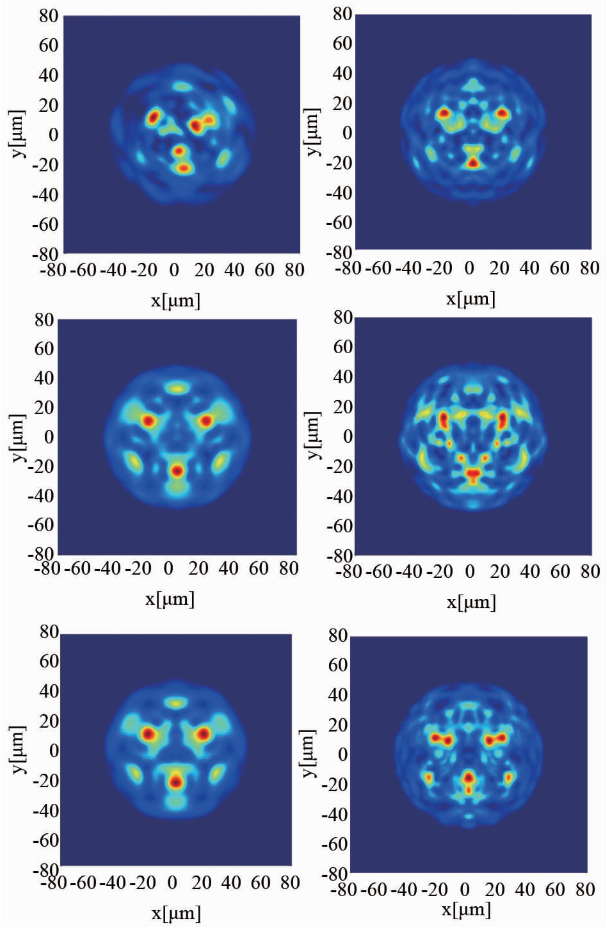

Fig. 3　The calculated intensity patterns of output beams with $D_2 = 105$ μm for LP_{01} mode launching (the first row) and LP_{11x} mode launching (the second row), respectively, with (a) $L = 5$ mm, (b) $L = 8$ mm, and (c) $L = 10$ mm

图 3　根据计算结果，$D_2 = 105$ μm 时信号光强度图案：第一排为 LP_{01}模信号强度图，第二排为 LP_{11x}模信号强度图.（a）$L = 5$ mm,（b）$L = 8$ mm, and（c）$L = 10$ mm

The signal power transfer efficiency of this FTFB combiner is described by the ratio of output signal power to the input signal power P_{out}/P_{in}. With signal beams of LP_{01} mode and LP_{11x} mode launched, transfer efficiency dependence on the taper length is shown in Figs. 4(a) and (b), respectively. It is seen that, under the same diameter D_2, the transfer efficiency increases with the taper length. For the same taper length, the larger diameter D_2 results in higher transfer efficiency. In addition, in the case that the diameter of D_2 and taper length of L are fixed, transfer efficiency with LP_{01} launched is higher than that with LP_{11} launched. For example, for $D_2 = 105$ μm and LP_{01} (or LP_{11}) mode launched, the signal power transfer efficiency is 99.54% (or 90.67%), 99.80% (or 94.75%) and 99.88% (or 95.54%) corresponding to taper length of $L = 5$ mm, 8 mm and 10 mm, respectively.

1.3　Output beam quality

To obtain the output beam quality, we firstly calculate the mode content of each mode in the output laser and the M^2 of each mode. Considering the orthogonality of fiber modes, the mode content of the ith mode ($i = 1, 2, \cdots$) in the output beam is calculated with complex overlap integral:

$$c_i = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \psi_{out}(x,y)\phi_i^*(x,y)\,\mathrm{d}x\mathrm{d}y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi_i(x,y)\phi_i^*(x,y)\,\mathrm{d}x\mathrm{d}y}, \quad (3)$$

where ψ_{out} is the electric field distribution at output end, $\phi_i(x,y)$ is the electric field of the ith mode. Furthermore, the beam quality factor (M_i^2) of the ith mode is computed by the method of second-order intensity moment[17-19]. Usually, beam quality is affected by relative phase of guided modes. However, the modes' group delay difference exceeds coherent time because they accu-

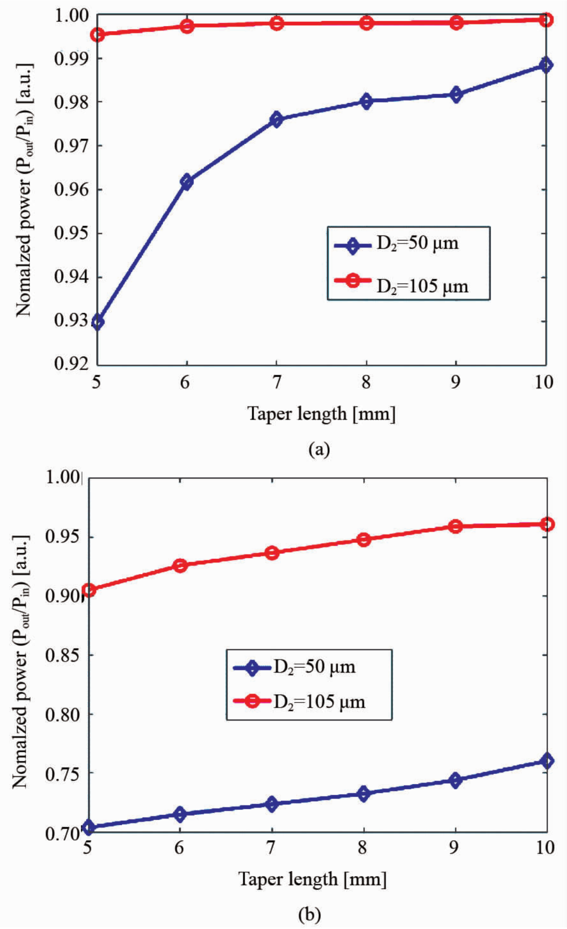

Fig. 4 The simulated signal power transfer efficiency versus the taper length L for (a) LP_{01} mode launching and (b) LP_{11x} mode launching

图4 通过仿真,信号光转换效率相对于锥区长度图(a) LP_{01}模(b)LP_{11x}模

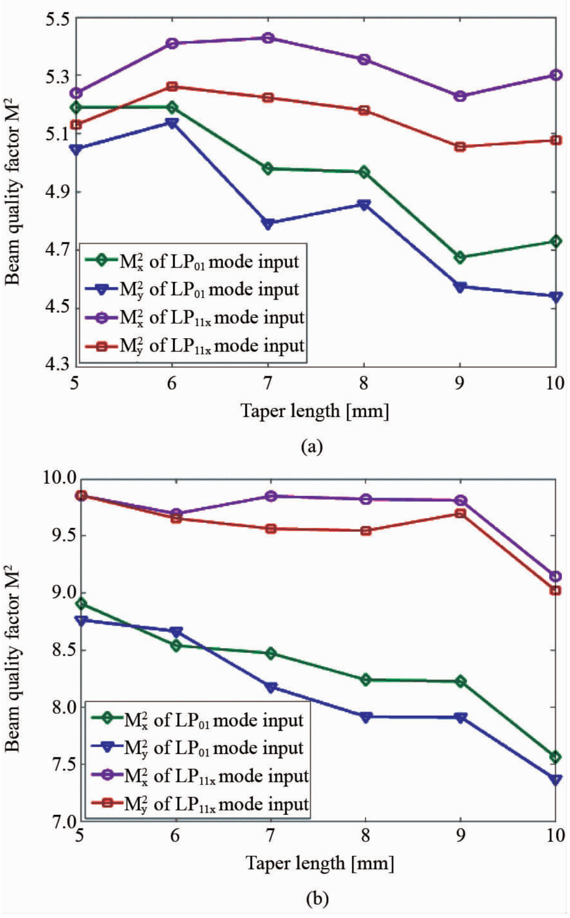

Fig. 5 The simulated beam quality factor of output beam versus the taper length for (a) D_2 = 50 μm and (b) D_2 = 105 μm

图5 通过仿真,光束质量相对于锥区长度图 (a) D_2 = 50 μm and (b) D_2 = 105 μm

mulated long enough through free-fiber section due to the signal source outputs with random polarization, its spectrum has a full width at half maximum (FWHM) of 1.5 nm, and it propagates incoherently through the FTFB. Meanwhile, for an input guided mode, such as the fundamental mode of LP_{01}, we express this source with three LP_{01} modes with signal wavelength and zero phase difference. In the simulation, these LP_{01} modes were launched and propagated through the FTFB separately. The total output intensity is the incoherent superposition of output intensities of three LP_{01} modes. So that the beam quality factor of output beam is obtained by the formula of $M^2 = \sum_i c_i M_i^2$, here, c_i is the relative mode content of the ith mode ($i = 1, 2, \cdots$) in the output beam.

There are 74 and 202 eigenmodes existing in the fiber core with core diameter of 50 μm and 105 μm (NA = 0.12), respectively. Therefore, the output beam of FTFB combiner could be expressed by the superposition of these 74 and 202 eigenmodes, respectively. The output beam quality factor versus the taper length for D_2 = 50 μm and 105 μm is represented in Figs. 5(a) and (b), respectively. We noticed that output beam quality factor gets better as the taper length increases. The output beam quality with three LP_{01} modes launching is better than that with three LP_{11x} modes launching. For instance, when taper length is L = 10 mm and D_2 = 105 μm, the output beam quality factor is $M_x^2 = M_y^2 = 7.5$ or $M_x^2 = M_y^2 = 9.2$ corresponding to LP_{01} or LP_{11x} mode launching, respectively.

2 Experiments and results

2.1 Fabrication of the FTFB signal combiner

The fabrication process of a signal combiner is similar to that of a fused-tapered pumping combiner[20], as shown in Fig. 6. It includes four steps, which are described as follows. Firstly, three signal fibers whose coatings were stripped are arranged in parallel (Fig. 6(a)). Secondly, based on the designed taper length, three signal fibers are fused and drawn together by a traveling oxygen-hydrogen torch on a three-axis motorized stage (Fig. 6(b)). Thirdly, the FTFB is cleaved at an appropriate position (Fig. 6(c)). In the end, the FTFB is spliced with the output fiber. The cleaved facet has the same diameter with the core of output fiber (Fig. 6 (d)).

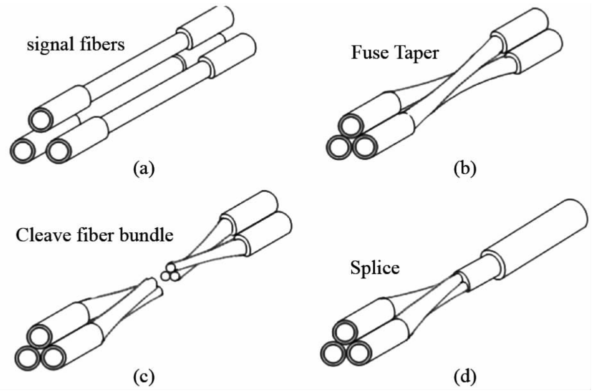

Fig. 6 Fabrication process of a 3 × 1 FTFB signal combiner in the experiment

图 6 3 × 1 信号耦合器制作过程示意图

A signal combiner was made by the above-mentioned fabrication process. For this signal combiner, the diameter of each signal fiber is 20/125 μm and NA of core is 0.06. Output fiber is a multi-mode fiber with core/cladding diameter of 105/125 μm (core NA of 0.12). Three signal fibers are closely packed (as shown in Fig. 6(b)), its original diameter is 270 μm, but the diameter becomes 105 μm after tapering. The length of tapered bundle is 10 mm. The side-view of the splice point and cross section of this bundle are shown in Figs. 7 (a) and (b), respectively. Some deformation at the splice joint can be seen, however, the deformation is too tiny to affect the transfer efficiency.

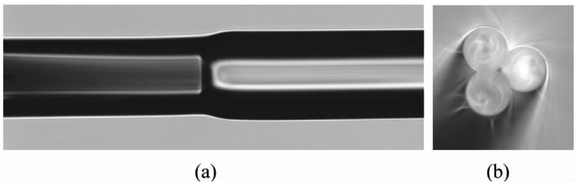

Fig. 7 Microscope pictures of a signal combiner, (a) side-view and (b) cross section

图 7 信号耦合器(a)显微镜侧视照片和(b)显微镜横截面照片

2.2 Measurement of transfer efficiency of the signal combiner

After finishing the fabrication of signal combiner, its transfer efficiency was measured by cut-off method. Transfer efficiency from input fiber to output fiber is described by P_{out}/P_{in} (P_{in} and P_{out} is the input and output power, respectively). We measured the power from output fiber as P_{out}. After that, we cut off the input signal fiber at the position from the splice point and measured the power as P_{in}.

Firstly, by cut-off method, the transfer efficiency of the combiner with input beam of high beam quality launching was measured. The input source is a fiber laser with output fiber of 20/125 μm (core NA of 0.06), output power is 2 W and output beam quality is $M_x^2 = 1.11$, $M_y^2 = 1.13$. The measured transfer efficiency of each signal fiber is 98.9%, 99.1% and 98.8% for port 1, 2 and 3, respectively. And then, the transfer efficiency of combiner with an input beam of poor beam quality launching was measured. The injected source was a fiber laser with output fiber of 20/125 μm (core NA of 0.06) as well, but the output beam quality is $M_x^2 = 1.65$ and $M_y^2 = 1.67$. By utilizing the cut-off method, the transfer efficiency of 95.5%, 95.9%, and 95.3% for port 1, 2 and 3 were realized, the average transfer efficiency is 95.7%. Due to the splice point or fiber deformation leads to power loss in the experiment, experimental result is a little bit smaller than the simulated result.

2.3 Two fiber lasers combination by the FTFB signal combiner

Fiber lasers combined by use of the FTFB signal combiner was tested as well. The schematic diagram of measurement setup is shown in Fig. 8. Two fiber lasers were used as input sources; the diameter of output fiber was 20/125 μm with core NA of 0.06. Here, due to the limitation of experiment condition, we only had two fiber lasers as seed sources, so we only measured the output beam combination of these two fiber lasers. The lasers were injected into the ports of 1 and 2 simultaneously during measurement, and the results are depicted in Fig. 9. The output power of each fiber laser (lines with marks ○ and □), the total input and output power of combiner (lines with marks Δ and ∇) increase with the electric current. The total input signal power was 623 W when the laser power of two fiber lasers were 258 W ($M_x^2 = 1.35$, $M_y^2 = 1.42$) and 365 W ($M_x^2 = 1.40$, $M_y^2 = 1.44$), respectively, and the total output power of 602 W was achieved at the output fiber of combiner. The transfer efficiency of the FTFB signal combiner was 96.6%.

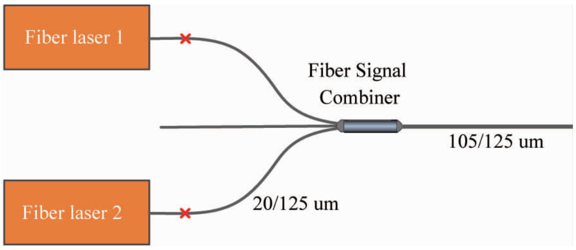

Fig. 8 The schematic diagram of experiment setup

图 8 耦合器测试实验搭建

The output beam quality factor of this signal combiner was measured with a Spiricon M^2-200 laser beam analyzer. The output beam quality factor were $M_x^2 = 10.5$ and $M_y^2 = 9.7$, which is a little bit worse than that predicted by theory. This is because that slight defects in the fabrication process, such as splice point, the slight deformation of fibers, and so on, could degrade the output beam quality of combiner.

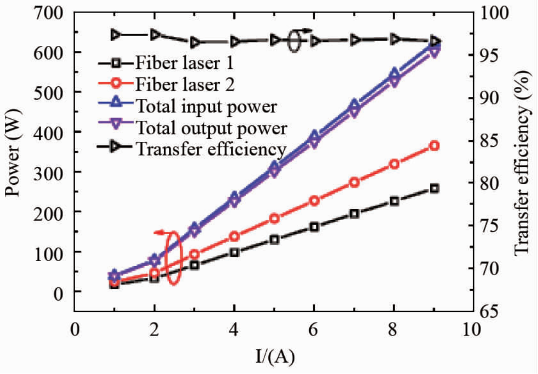

Fig. 9 The measured output power of fiber laser 1 and 2, the total input power and total output power of signal combiner, and the signal transfer efficiency of this combiner, respectively, as a function of electric current
图 9 根据测量结果,光纤激光器 1 和光纤激光器 2 的输出功率,耦合器总注入功率和总信号输出功率,分别对应的信号传输效率

3 Conclusion

The properties of 3 × 1 FTFB signal combiner composed of three signal fibers and a multi-mode output fiber were studied by theory and experiment. According to the calculated results, the longer taper length results in a higher transfer efficiency. Moreover, the input laser with higher beam quality leads to the higher transfer efficiency. In the experiment, a 3 × 1 signal combiner with taper length of 10 mm was fabricated. The transfer character of this combiner and the output beam quality were measured. We compared the transfer efficiency of each port when the input beam with different beam quality was injected. With the near fundamental mode source launched (beam quality is $M_x^2 = 1.11$, $M_y^2 = 1.13$), the transfer efficiency of combiner is 98.9%, 99.1%, and 98.8% for port of 1, 2, and 3. In the case of input beam with high-order mode launching (beam quality is $M_x^2 = 1.65$, $M_y^2 = 1.67$), the transfer efficiency corresponding to port of 1, 2, and 3 is 95.5%, 95.9% and 95.3%, respectively. At last, the power combination was measured. When two fiber lasers with power of 258 W and 365 W were launched into two signal fibers simultaneously, the total output power of 602 W with transfer efficiency of 96.6% and beam quality factor of $M_x^2 = 10.5$, $M_y^2 = 9.7$ were achieved.

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