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The pump arm numbers of (N + 1) × 1 couplers

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Abstract: The impact of (N + 1) × 1 coupler pump arm numbers on the pump coupling efficiency was numerically studied firstly. It is shown that pump coupling efficiency decreases with more pump arms built on the coupler, yet in a slightly decreasing manner. According to the simulation results, side-pumped (1 + 1) × 1 and (2 + 1) × 1 couplers were made. The total output power of the (2 + 1) × 1 coupler is about 681 W, almost two times that of the (1 + 1) × 1 coupler, enhancing the pump light injection capacity of the fiber laser system significantly.

Key words: fiber optics, fiber lasers, lasers, general theory of combining
PACS: 42. 81. -I, 42. 55. Wd, 42. 55. -f, 42. 55. Ah

光纤激光器侧面泵浦(N +1)×1耦合器泵浦臂数量

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摘要:利用仿真软件分析了侧面泵浦(N +1)×1耦合器不同泵浦臂数量对侧面泵浦耦合器效能的影响,并在实验中验证了分析结果,得到侧面泵浦耦合器中耦合效率随着泵浦臂数量增多呈下降趋势这一结论.根据这一结论制作了侧面泵浦(2 +1)×1耦合器,输出泵浦功率681 W,输出功率为同泵浦源(1 +1)×1耦合器的两倍,有效地减少了因泵浦臂数量影响造成的耦合器总功率缺失.

关　键　词:光纤光学;光纤激光器;激光;耦合理论

中图分类号:O43　　**文献标识码:**A

Introduction

High power all-fiber lasers and amplifiers play an important role in industry and gradually replace the traditional mechanical equipment. For high power laser systems, pump couplers are very important components that determine the pump light injection capacity. Currently there are mainly two pumping structures developed for fiber lasers and amplifiers, namely, the tapered fiber bundles (TFB) end pumped geometries[1] and the side pumped geometries.

For a TFB end pumped coupler, individual fibers are bundled together in a close-packed formation, heated to melting temperature, drawn into a taper and then fusion spliced to the cladding-pumped fiber. For a side pumped coupler, each pumping fiber is heated to melting temperature, drawn into a taper and then fusion spliced to the side of the cladding-pumped main fiber. Side pumped couplers are all (N + 1) × 1 couplers, which are particularly suitable for amplifier systems where N × 1 couplers cannot be directly used. Furthermore, with side-pumped configurations, not only longer fiber could be used to ensure relatively uniform distribution of popu-

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lation inversion, but also the thermal problem could be better managed as well than with TFB end configurations. A lot of side-pumped methods have been demonstrated. Non-all-fibered side-coupling configurations include the prim-fiber coupler[2], the V-groove side coupling technique[3], the enhanced evanescent field coupling method[4], and the embedded mirror method[5]. For the monolithic all-fibered coupling systems, there are the angle polished side coupler[6], the side grating coupler[7], the etched silicon capillary side coupler[8-9], the GT-Wave coupler[10], and the direct fusion side coupler[11-16]. The monolithic all-fibered systems are more stable and efficient than non-all-fibered configurations.

At present, commercial $(N+1)\times 1$ pump couplers can realize the coupling of more than 200 W pump power by one pump arm and a total pump power of 2.2 kW. International fiber laser company IPG has realized the 10 kW class laser output in an all-fiber configuration[17]. However, the manufacturing techniques of its pump couplers remain unknown to the outside. ITF Labs who provides a lot of fiber-coupled devices for the upstream fiber laser companies has achieved the total output power of 1.2 kW from a $(6+1)\times 1$ pump coupler[18]. Many arms were used to achieve kW-class power coupling in their couplers. Here we used only two arms to achieve this coupled power with very high efficiency.

$(N+1)\times 1$ couplers have N pump arms to provide pump power for laser systems. The number of pump arms N is limited by brightness conservation principle and fabrication technique. Obviously more pump arms allow more pump power to be injected into the pump coupler. However, the coupling efficiency of $(N+1)\times 1$ couplers with respect to N remains to be investigated. Optical design and analysis 3D-beam propagating method is used to simulate side-pumped $(1+1)\times 1$ and $(2+1)\times 1$ couplers. Other parameters are set the same except the pump arm numbers. It can be shown that pump coupling efficiency decreases with the number of pump arms built on the coupler increase, yet in a slightly decreasing manner. In experiment, a side-pumped $(1+1)\times 1$ and a side-pumped $(2+1)\times 1$ coupler were made. The former had a slight higher coupling efficiency than the latter in good agreement with the simulation results. The total output power of the $(2+1)\times 1$ coupler is about 681 W, almost two times that of the $(1+1)\times 1$ coupler, enhancing the pump light injection capacity of the fiber laser system significantly.

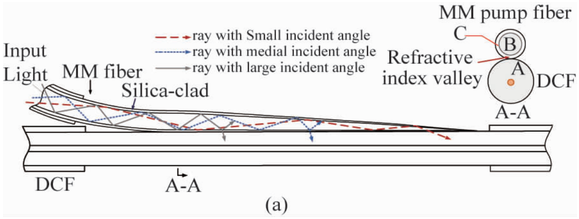

Fig. 1　Schematic side view of a side-pumped system composed of a DC fiber and a MM fiber with silica clad doped with fluorine.

图 1　双包层光纤耦合理论示意图

The schematic side view of a side-pumped coupler that consists of a double-clad (DC) fiber, a multi-mode (MM) pump fiber with silica clad doped with fluorine and a tapered section is shown in Fig. 1. The silica clad doped with fluorine (region C in Fig. 1) is between the core (region B in Fig. 1) of MM pump fiber and the inner-clad (region A in Fig. 1) of DC fiber. The indexes of A and B regions are 1.448. The index of silica clad doped with fluorine is slightly smaller than that of MM fiber core and DC fiber inner-clad. For example, the index of region C is 1.4402 when the MM pump fiber of 105/125 μm (NA = 0.15) is used. The index difference between region A (B) and region C is 0.0078, so the cladding of MM pump fiber forms a refractive index valley (RIV) between the core of MM pump fiber and the inner-clad of DC fiber. The tapered MM pump fiber gradually converges and fits on the inner-clad of DC fiber, forming the coupling region. For side-pumped $(N+1)\times 1$ couplers, all the tapered pump arms converge and fit on the main fiber at positions distributed symmetrically and periodically around the body of the main fiber.

In the following simulations, it is assumed that MM pump fibers are fused to a DC fiber perfectly. Pump light has a wavelength of 975 nm. Pump coupling efficiency is defined throughout this paper as the ratio of pump power coupled in the DC fiber to the total pump power provided by the MM pump fibers.

By 3D-beam propagating method, a side-pumped $(2+1)\times 1$ coupler model (pump arms: 220/242 μm and NA = 0.22; main fiber: 30/250 μm and NA = 0.46) was built. Without loss of generality and for computation time consideration, this side-pumped coupler was simulated in a 2D scalar model. The following aspects were investigated numerically: (1) The coupling efficiencies of $(1+1)\times 1$ and $(2+1)\times 1$ were studied and compared under the same tapered length and the same input mode field; (2) The coupling efficiencies of $(2+1)\times 1$ couplers were studied and compared under the same input mode field and the different tapered lengths; (3) The coupling efficiencies of $(2+1)\times 1$ couplers were studied and compared under the same tapered length and the different input mode fields.

1　Physical and mathematical model

The coupling efficiencies of $(1+1)\times 1$ and $(2+1)\times 1$ couplers were studied and compared under the same tapered length and the same input mode field. All the 220/242 μm pump arms have a tapered length of 8 cm. For the $(2+1)\times 1$ coupler, two tapered pump arms fit on the two sides of the 30/250 μm main fiber symmetrically. All the pump arms have a Gaussian mode field input. Simulation results show that the coupling efficiency is 90.35% for $(1+1)\times 1$ coupler and 89.66% for $(2+1)\times 1$ coupler under configurations mentioned above. Relative intensity distributions in the couplers are shown by color map in Fig. 2 (a) and (b). The correspondences between colors and relative intensities are given by the rightmost color bars. The white patterns on the relative intensity color maps are due to intensity saturation (relative intensity > 1). Green line and red line represent optical power evolutions in each pump arm, and light blue line represents optical power evolution in the main fiber along the longitudinal distance z. Deep

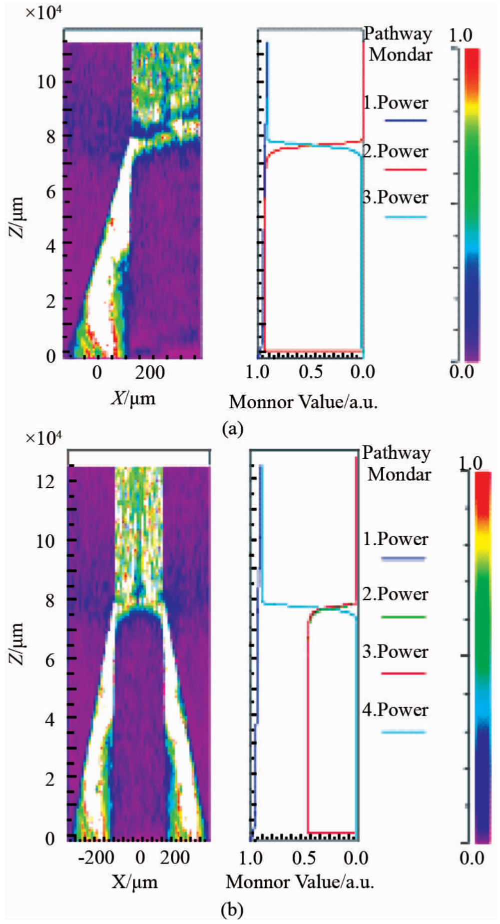

Fig. 2 Relative intensity distributions and power evolutions inside the couplers. For power evolutions along the longitudinal distance z, green and red lines represent the optical power in each pump arm, light blue line represents the optical power in the main fiber, and deep blue line represents the total optical power in the arms and main fiber. (a) (1 + 1) × 1 coupler with tapered length of 8 cm, resulting in a coupling efficiency of 90. 35%, (b) (2 + 1) × 1 coupler with tapered length of 8 cm, resulting in a coupling efficiency of 89.66%. The input mode fields are the same for both (1 + 1) × 1 and (2 + 1) × 1 couplers

图 2 耦合器内光强度分布、光功率演化过程. 光功率沿 Z 轴方向注入被耦合光纤内. 图中红色、绿色线代表耦合器内每个泵浦臂的功率,深蓝色线代表主光纤和泵浦臂总泵浦功率,淡蓝色线代表主光纤内的泵浦功率. (a)泵浦臂长度为 8 cm 的(1 + 1) × 1 耦合器泵浦耦合效率为 90. 35%,(b)泵浦臂长度为 8 cm 的(2 + 1) × 1 耦合器泵浦耦合效率为 89.66. 两次仿真均为相同的光场注入

blue line represents the evolution of the total optical power in the pump arms and main fiber. The simulation shows that the coupling efficiency of the (1 + 1) × 1 coupler is higher than that of the (2 + 1) × 1 coupler under the same tapered length and the same input mode field. It implies that large number of pump arms could have adverse impact on the total coupling efficiency. However, large number of pump arms will enhance power injection capacity significantly. Therefore, it is challenging but worthwhile to make a high-efficiency multi-pump-arm side-pumped coupler.

2 Experimental validation and discussion

According to the simulation results, number of pump arms, tapered lengths and input mode fields are key factors that determine the coupling efficiency of side-pumped (N + 1) × 1 couplers. Among them, a long tapered length is pretty crucial for fabricating a (1 + 1) × 1 coupler. In experiment, we made it to be approximately 8 cm realized by a homemade fused taper machine. The schematic diagram of the (1 + 1) × 1 coupler is shown in Fig. 3. It is composed of one Nufern 400/440 μm NA = 0. 22 fibers as its pump arms and one Nufern 20/400 μm NA = 0. 06/0. 46 fiber as the main fiber.

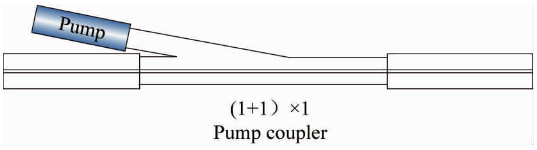

Fig. 3 The schematic diagram of a (1 + 1) × 1 coupler

图 3 (1 + 1) × 1 耦合器示意图

The coupling performance of the (1 + 1) × 1 coupler was tested. As shown in Fig. 4, one LD each with output power of about 350 W was spliced with the input arms of the (1 + 1) × 1 coupler with total splice loss less than 2%. A total output power of this (1 + 1) × 1 coupler is about 330 W, corresponding to a coupling efficiency as high as 96. 3%. Compared with the simulation results by 3D-beam propagating method, an impressively higher coupling efficiency was achieved thanks to a much longer tapered length fabricated, thus higher-order modes of pump light being coupled into the main fiber efficiently.

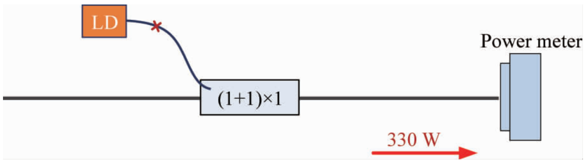

Fig. 4 Schematic diagram of the experimental setup for testing the pump light coupling performance of the (1 + 1) × 1 coupler

图 4 (1 + 1) × 1 耦合器通过搭建实验测试耦合效率示意图

The schematic diagram of the (2 + 1) × 1 coupler is shown in Fig. 5. The statement about (2 + 1) × 1 coupler is the same as (1 + 1) × 1 coupler (Fig. 3).

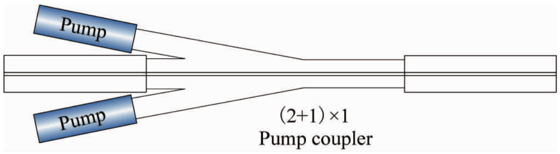

Fig. 5 The schematic diagram of a (2 + 1) × 1 coupler

图 5 (2 + 1) × 1 耦合器示意图

The coupling performance of the (2 + 1) × 1 coupler was tested. As shown in Fig. 6, a total output power of the (2 + 1) ×1 coupler is about 681 W, corresponding to a coupling efficiency as high as 95.7%.

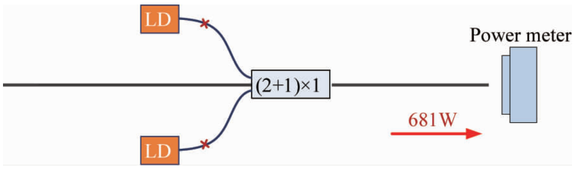

Fig. 6 Schematic diagram of the experimental setup for testing the pump light coupling performance of the (2 + 1) ×1 coupler
图 6 (2 + 1) ×1 耦合器通过搭建实验测试耦合效率示意图

The signal loss of this (2 + 1) ×1 coupler was tested. An all-fiber oscillator was used as the signal source as shown in Fig. 7. Yb-doped fiber was end pumped by 3 LDs through a 3 × 1 coupler. Laser oscillations formed via a pair of fiber Brag gratings. The laser output power from the oscillator was measured to be 395 W with optical-optical efficiency of 65.8%. The output end of the oscillator was then spliced with the input end of the (2 + 1) ×1 coupler. The measured signal power from the other end of the (2 + 1) ×1 coupler is about 390 W. In order to exclude the signal loss caused by the splicing point connecting the oscillator and the (2 + 1) × 1 coupler, just behind this splicing point the fiber was cut at a right angle and the output signal was measured again. The measured signal power is 391.5 W, corresponding to a signal loss of this (2 + 1) ×1 coupler less than 0.4%.

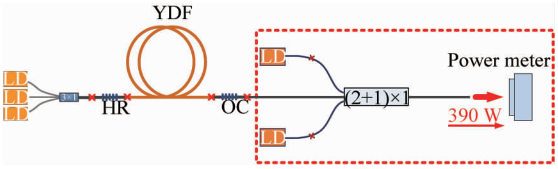

Fig. 7 Schematic diagram of the experimental setup for testing signal loss of the (2 + 1) ×1 coupler
图 7 (2 + 1) ×1 耦合器信号光损耗测试示意图

3 Conclusion

(N + 1) ×1 coupler model of two side-pumped (1 + 1) ×1 coupler and (2 + 1) ×1 were built by 3D-beam propagating method The influences of pump arms on the pump coupling efficiency were analyzed. It can be shown that pump coupling efficiency decreases with the number of pump arms built on the coupler, yet in a slightly decreasing manner. In experiment, side-pumped (1 + 1) ×1 and (2 + 1) ×1 couplers were made. The total coupled pump power of the (1 + 1) ×1 coupler is 330 W, corresponding to a coupling efficiency as high as 96.3%. The total coupled pump power of the (2 + 1) ×1 coupler is 681 W, corresponding to a coupling efficiency of 95.7%. The (2 + 1) ×1 coupler has almost two times pump injection power of the (1 + 1) ×1 coupler with only a little bit sacrificing of coupling efficiency. Fabricating more pump arms around the main fiber can further scale the coupler's power injection capacity while maintain acceptable coupling efficiency. Such high coupling efficiency and low signal light loss couplers are suitable and beneficial for fiber laser systems.

Acknowledgement

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