Efficient and Scalable Side Pumping Scheme for Short High-Power Optical Fiber Lasers and Amplifiers

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***Abstract*—A new and simple method of pumping short high-power optical fiber lasers and amplifiers is described. In our approach, several passive coreless optical fibers are brought into direct contact alongside a single rare-earth doped active fiber which constitutes the active medium of the laser (amplifier). Pump light is delivered through the passive coreless fibers and penetrates into the active fiber via evanescent field coupling. To enhance the pump absorption in the gain medium, high-order spatial modes are excited in the pump delivery fibers, and an active fiber with high concentration of the dopant ions is used. As a demonstration of the viability of our approach, test results are reported on a 12-cm-long $Er^{+3}-Yb^{+3}$ codoped phosphate glass fiber laser. The laser output reaches 5 W using 23-W pumping into six coreless fibers. Above threshold, the laser has ~24% optical-to-optical conversion efficiency (with ~64% being the theoretical maximum). The linearity of the input–output characteristic for the laser suggests that the output power can be scaled up by applying higher pump power.**

***Index Terms*—Amplifiers, high power, lasers, optical fiber, side pumping.**

I. Introduction

LOW MELTING temperature glasses have recently attracted attention as possible candidates for host media of doped optical fibers [1]–[3]. This interest is mainly due to the fact that such glasses allow for very high concentration of dopants, which can be as high as 20% by weight in some cases. The high dopant concentration can be instrumental as it allows for a short fiber laser cavity, making possible single longitudinal mode fiber lasers. In addition, short fiber lasers and amplifiers are free from the undesired nonlinear effects such as stimulated Brillouin and Raman scattering.

Optical pumping of a short, highly doped fiber is not straightforward: Commercially available pump diode sources are typically pigtailed with a multimode silica fiber. Although some advances have been made in fusion-splicing optical fibers made of dissimilar glasses [4], [5], a reliable mating of the mechanically different fibers is still challenging, especially when dealing with high optical power. Several efficient side-pumping schemes suitable for short fiber lasers and amplifiers have been proposed and implemented that either make use of elaborate microoptics [6], [7], or require machining of the active fiber [8]; both approaches may be problematic in the high-power designs.

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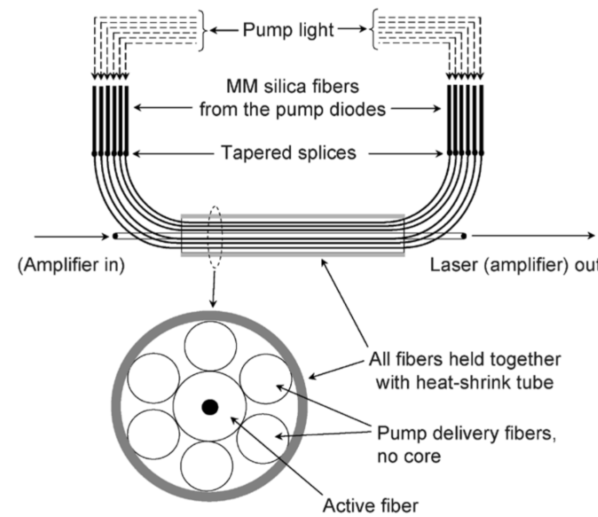

Fig. 1. Schematic diagram of the contact side-pumping scheme. The lower figure shows the cross section of the assembly.

In this letter, we describe an efficient and scalable method of optically pumping short fiber lasers and amplifiers. Our method utilizes an enhanced evanescent-field coupling scheme between several passive fibers that deliver the pump light and a single active fiber. The idea to use this mechanism of pump delivery was originally proposed for optically pumping solid-state laser rods [9]. We have adopted this scheme to pumping short doped optical fibers. Similar methods of side pumping active fibers have been used before [10]–[13], but they required either a substantial pump coupling length of a few meters, or relied on fusion of the fibers delivering the pump light to the active doped fiber, which is not readily feasible with dissimilar fibers.

II. New Side-Pumping Scheme for Short Fiber Lasers and Amplifiers

The setup for scalable side-pumping of a short highly doped optical fiber is shown in Fig. 1. In this scheme, the active fiber is surrounded by several passive pump delivery fibers, the whole bundle being held together by a heat-shrink tube made of polytetra-fluorinated ethylene (PTFE). The reason for choosing this particular polymer is twofold: First, its refractive index in the infrared is ~1.35, which is lower than that of fused silica (~1.45), preventing the pump light from escaping into the tube. Second, commercially available heat-shrink tubes made of PTFE, have walls as thin as 35 μm. In operation, the assembly will inevitably

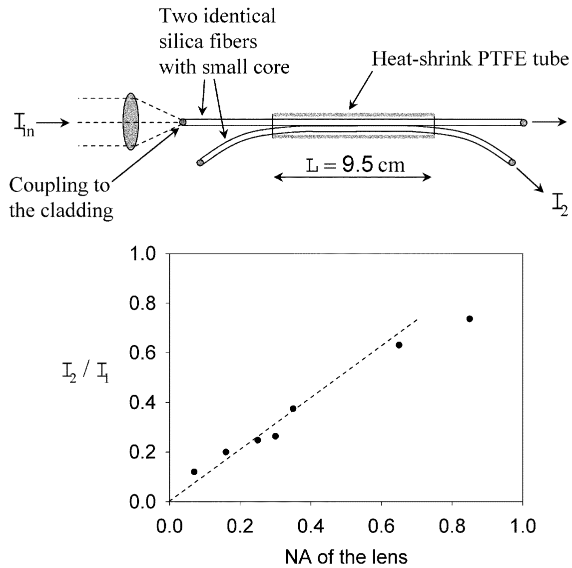

Fig. 2. Setup for measuring the dependence of evanescent coupling strength on the modal content of the propagating lightwave. The lower figure shows the measured ratio of the two outputs from the fibers as the NA of the coupling lens is varied.

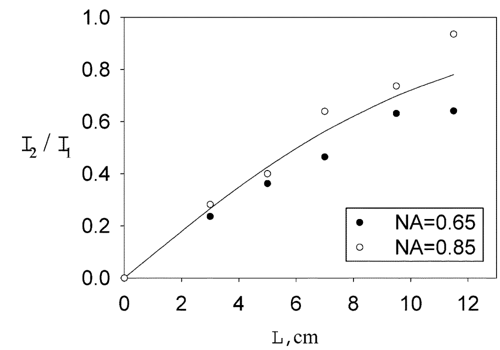

Fig. 3. Dependence of the coupling strength on the interaction length for two different NA values of the pump light source. The data is fit $I_2/I_1 = \tanh(L/L_0)$, with $L_0 = 11$ cm (solid line). The measurement setup is the same as that in Fig. 2.

heat up, and the small wall thickness of the tube allows for efficient heat dissipation from the hot fiber bundle. Ideally, the delivery fibers should have no core at all. However, commercially available single-mode fibers for ultraviolet light can also be used as they have very small core size (~2 to 3 μm), and the pump light propagating in the cladding of such fibers is virtually undisturbed by the presence of the small core.

Two processes determine the pumping efficiency in our scheme: The first is the absorption of the pump light in the doped fiber itself, with a rate depending mainly on the concentration of the dopant in the core glass material of the active fiber as well as the geometry of the fiber cross section. The second process is the evanescent-field cladding-to-cladding coupling between the coreless delivery fibers and the active fiber. The rate of the latter is roughly proportional to the ratio of the numerical aperture (NA) of the pump lightwave in the coreless delivery fiber to the fiber diameter. This ratio approximately equals the number of reflections at the interface between the fibers per unit length, experienced by the guided pump beam as it propagates in the delivery fiber. Therefore, to maximize the pump absorption in the active fiber, one should decrease the diameter of the delivery fibers and also inject the pump light into the delivery fibers in such a way as to excite high-NA spatial modes.

To gain a qualitative understanding of the dependence of the evanescent-field coupling strength on the NA of the guided pump light, we conducted a simple experiment shown schematically in Fig. 2. Two identical passive single-mode silica fibers with the cladding diameter of 125 μm are held together with the PTFE tube over a fixed length of 9.5 cm. The free-space collimated pump light is coupled into the cladding of one of the fibers with objective lenses of different NA. The measured power splitting ratio at the output of this multimode two-by-two combiner as a function of the NA is plotted in Fig. 2, together with a linear fit. From the figure, the splitting ratio for this particular combiner length is about one fifth of its maximum value of one, if the NA of the coupling lens is 0.2, a typical value for the multimode fiber used for pigtailing pump laser diodes. The splitting ratio grows approximately in proportion with the NA of the guided lightwave in the input fiber. Since total internal reflection of the pump light at the interface between the silica fibers and the PTFE tube occurs for NA < 0.53, this value should not be exceeded in designing a practical device, to prevent rapid loss of the pump light into the heat-shrink tube.

Using a similar setup, we further measured the effective length of evanescent coupling for the case of two identical silica fibers and two high-NA coupling lenses. The output coupling ratio was separately measured for five combiners of different length. The data is shown in Fig. 3. Assuming that the coupling along the combiner is proportional to the intensity difference between the two fibers, with a proportionality constant equal to the inverse of the effective coupling length, the coupling length can be estimated from Fig. 3 as ~10 cm. In reality, the coupling between silica delivery fibers and low-melting temperature doped fiber can be somewhat higher because of the negative difference between the refractive indexes for the two materials (The indexes are ~1.45 and ~1.55 for silica and a typical phosphate glass, respectively.) In addition, the pump coupling can be enhanced by using pump delivery fibers of smaller size than that of the active fiber.

To excite the high-NA spatial modes in the pump delivery fibers, the multimode fiber pigtails from the pump laser diodes can be tapered and spliced to the delivery fibers. Since the pigtails and the pump delivery fibers are made of silica, both tapering and splicing are straightforward with standard fusion splicing equipment. The highest degree of tapering is determined by the ratio of the maximum "safe" NA of ~0.53, to that of the pigtails. Typically, high-power pump laser diodes are pigtailed with a multimode silica fiber with NA $\simeq 0.2$, which determines the optimum tapering ratio to be ~2.5.

It is important to point out that the above-described dependence of the pump coupling efficiency on the NA of the pump light in the delivery fibers, as well as the pump intensity distribution between the fibers along the bundle, have to be understood as only qualitative design guidelines. These measurements basically show that a substantial fraction of the pump light can be coupled into the active fiber in the ~10-cm-long structure, and that the coupling can be considerably enhanced by modifying the modal content of the pump light in the delivery fibers. Both pump coupling between the fibers and its absorption in the active fiber will vary along the interaction region, because the high-order spatial modes in the pump delivery fibers are

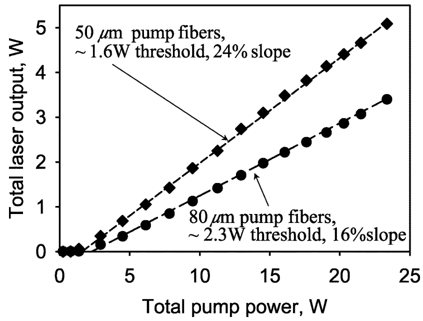

Fig. 4. Total power output of the laser at around 1535 nm, versus total pump power, for two different pump delivery fiber sizes. The data is shown with symbols, the linear fits with lines.

transferred into the active fiber first and the low-order modes last, and the pump absorption in the active fiber core is different for modes of different geometry. Modeling this system deserves more thorough treatment and will be presented elsewhere.

III. 12-cm-Long Side-Pumped Fiber Laser With ~5 W of Total Output Power

To demonstrate the viability of our pumping method, we built a simple short multimode fiber laser operating in the telecom wavelength range around 1535 nm. The set-up is essentially identical to the one shown in Fig. 1. A single 12-cm-long strand of a doped phosphate–glass fiber acts as an active medium of the laser. The diameters of the core and the cladding of the active fiber are 18 and 125 μm, respectively, and the core is codoped with 1% of Er^{+3} and 8% of Yb^{+3} (by weight). The active fiber has NA ~0.2, and thus, supports multiple spatial modes for the laser light. The active fiber is surrounded by six coreless silica fibers creating 12 independent possible entrance points for the pump light. The heat-shrink PTFE tube with the wall thickness of ~35 μm holds the bundle together. A single multimode laser diode source operating at a wavelength of 975 nm with maximum output power of ~25 W is used as a pump source. The output of the pump source is evenly split between six multimode fibers with 105-μm-diameter core and 125-μm-diameter cladding, and these fibers are tapered and fusion-spliced to six out of the 12 coreless fiber inputs of the bundle, leaving six inputs unused. The two cleaved ends of the active phosphate fiber form a 12-cm-long multimode resonator cavity for the laser light. The pump light, after penetrating into the active fiber from the delivery fibers is predominantly absorbed by the Yb^{+3} ions that transfer the excitation to the Er^{+3}. The effective inverse absorption length in the active fiber alone, measured independently for the end-coupled pump light, is ~0.29 cm^{-1}. We tried two different delivery fibers, with diameters of 80 and 50 μm. As expected, out of the two lasers, the second one yielded higher optical-to-optical slope efficiency and lower threshold. Fig. 4 shows the total output intensity at ~1535 nm, from both ends of the laser. With 50-μm delivery fibers, the laser output reaches 5 W. The laser threshold in this case occurs at ~1.6 W of the combined pump power, and the optical-to-optical conversion efficiency is ~24%, with ~64% being the theoretical maximum for the $Er^{+3} - Yb^{+3}$ system pumped at 975 nm. This slope efficiency is not quite as high as the highest reported figure of ~40% obtainable with high-power end-pumped Er–Yb fiber lasers [14]. We have measured that the fraction of the pump power left in the delivery fibers after passing through the bundle, in the two cases of 80 and 50 μm fibers, was ~30% and ~15%, respectively. We have also experimentally confirmed that at the fixed diameter of the delivery fibers, the slope efficiency was roughly proportional to the tapering ratio of the pump inputs. The linearity of the laser output versus the pump power suggests that the output power can be scaled up both by pumping more inputs of the bundle and by applying higher pump power. For example, if each input of the bundle is pumped by 4 W, a somewhat typical value for the contemporary laser diode bars, the maximum possible fiber laser output can be as high as 11 W.

In the experiment, the heat generated in the active fiber was dissipated by placing the bundle into a groove cut in a massive aluminum heatsink, and no degradation in the laser performance resulted from a prolonged operation (a few hours). In case the output laser power is scaled up and this cooling method is no longer sufficient, water cooling by placing the outer surface of the PTFE tube in direct contact with cold running water may be considered.

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