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Fluoride-fiber-based side-pump coupler for high-power fiber lasers at 2.8 μm

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A side-pump coupler made of fluoride fibers was fabricated and tested. The tested device had a coupling efficiency of 83% and was driven with an incident pump power of up to 83.5 W, demonstrating high-power operation. Stable laser output of 15 W at a wavelength of around 2.8 μm was achieved over 1 h when using an erbium-doped double-clad fiber as the active medium. To the best of our knowledge, this is the first time a fluoride–glass-fiber-based side-pump coupler has been developed. A test with two devices demonstrated further power scalability.

OCIS codes: (140.3500) Lasers, erbium; (140.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (140.3480) Lasers, diode-pumped.

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Because of their specific absorption properties, high-power mid-infrared (mid-IR) fiber lasers are in demand for applications in medicine, defense, and remote sensing [1] and also for industrial applications, such as the processing of glass and plastic materials. In glass, e.g., unlike for industrial lasers with wavelengths in the usual ranges, the output of a mid-IR laser is absorbed between 2.7 μm and 5 μm over a few hundred micrometers to several millimeters [2], which favors cutting and other processes [3].

Over recent decades, erbium-doped (ED) fluoride fibers (FFs) have been used to build watt-class lasers in the mid-IR regime around 2.8 μm. As foreseen from earlier theoretical considerations [4], the energy recycling through energy-transfer upconversion processes provides a relatively high efficiency in highly doped FFs. For this reason, numerous watt-level fiber lasers of this type have been reported [5–7], with the present record being an output power of 30 W at a wavelength of 2.94 μm using an all-fiber design [8].

Recently, some amplifier designs have been reported with picosecond [9] and femtosecond [10] seed pulses. However, although side pumping would benefit such applications, the active fiber was still end pumped by a laser diode (LD), and the seed light was injected via a dichroic mirror into the amplifying fiber.

In this Letter, we fabricate an FF-based side-pump coupler (SPC) by splicing the power-delivering multimode fiber onto the first cladding of a double-clad (DC) fiber. As the splicing method for the pump coupler, we chose a method similar to that reported in Ref. [11], wherein a transmittance of >90% was achieved using silica-based fibers. However, the fabrication in the present case is more difficult because FFs are so fragile, requiring very soft polishing and an extremely narrow range of working temperature for ZBLAN-like glasses [12] during the splicing process.

The polishing process was conducted using a tape-polishing machine (SM-25; Matsuda-Seiki, Japan), with the fiber held in a specially designed holder. The fiber tip to be polished protruded from the holder so that the oscillating diamond tape could polish the fiber at an angle of 10° (see Fig. 1). Pressure was applied by pushing the polishing tape onto the fiber at speed v_1, which was on the order of a few micrometers per minute. The polishing tape was oscillated in the horizontal direction perpendicular to the direction of tape advancement with a frequency $f_1 \sim 30$ Hz and amplitude of 2 mm to abrade the fiber's material. The tape advancement speed $v_2 \sim 20$ mm/ min ensured a supply of previously unused tape with sufficient roughness.

Figure 2 introduces the polished FF. The surface roughness due to the roughness of the polishing material is typically below 0.2 μm. Although grooves from this polishing process have a size that is only a fraction of the wavelength of the injected pump light, they are still assumed to cause slight amounts of Rayleigh scattering even after the splicing process.

After the polymer coating had been stripped off the DC fiber, the polished fiber was placed onto its glass cladding. Similar to [11], a homemade optical setup was used to focus a CO_2 laser beam onto the interface between the two fibers with a spot size of roughly 200 μm. A scan was performed by moving the two fibers horizontally. The fluoride glass

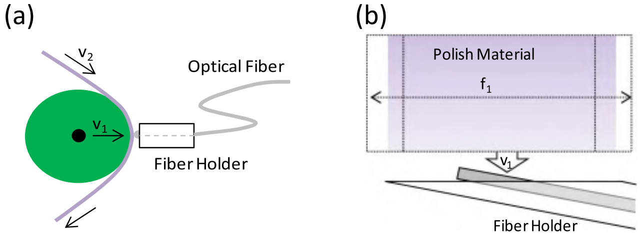

Fig. 1. Details of the polishing process: (a) side view, (b) top view. f_1 is the oscillation frequency, v_1 is the speed at which the fiber is pressed onto the polishing tape, and v_2 is the speed at which the tape is advanced.

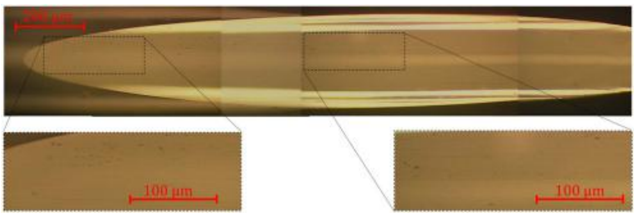

Fig. 2. Surface of inclined polished fiber.

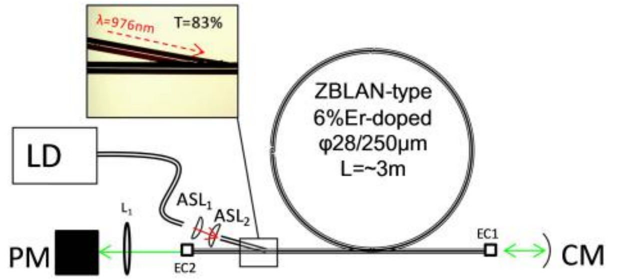

Fig. 3. Experimental setup for testing one single-pump coupler. PM, power meter; LD, wavelength-stabilized laser diode; CM, concave mirror; EC1, EC2, end caps; ASL1, ASL2, aspheric lenses.

was melted sufficiently for splicing by applying 200 mW of CO_2 laser output power and a scan speed of 1 mm/s. This indicates that with these process parameters, the glass reached a working temperature of 300–350°C [12].

We fabricated the pump coupler using an ED DC fiber as the active medium and tested it in a simple optical setup to generate laser oscillations at a wavelength of 2.8 μm. Besides the intended application in glass processing, this choice for the setup is also based on the fact that this type of laser is currently receiving the most attention among all fluoride-based fiber lasers because of its power record in this wavelength range [8] in which silica-based fibers are not applicable. However, in principle, such a coupler could be used in any FF-based laser setup (e.g., [13,14]).

The coupling efficiency of the fabricated coupler was evaluated with probe light at 700 nm because this wavelength does not experience absorption in the ED DC fiber. During the process development, a sample with a record coupling efficiency of 94% (loss <0.27 dB) was achieved. A process with the preliminary parameter settings led to stable coupling efficiencies of 80–85%. Because Rayleigh scattering is one source of the losses, the coupling efficiency at 976 nm is assumed to be slightly higher.

The experimental setup for evaluating the one-pump coupler under laser operation is shown in Fig. 3. A fiber-coupled LD (K976AG1RN; BWT, China) was used as the pump source that is wavelength stabilized at 976 nm. This wavelength was selected because of its availability and efficient absorption by the erbium ions. The fiber output [105 μm core diameter, numerical aperture (NA) 0.22] was coupled over a free-space optical system with magnification of roughly 1.4 into a non-doped ZBLAN fiber of core and cladding sizes of 170 μm and 240 μm, respectively, and a core NA of 0.155.

An ED DC fiber (FiberLabs Inc., Japan) of roughly 3 m in length was employed as the active medium. The 6-mol. % doped core had a diameter of 28 μm and an NA of 0.12, therefore being a few-mode fiber at 2.8 μm (i.e., supporting LP_{01} and LP_{11} modes). The first cladding size is truncated and possesses a nearly flat plane with a width of 240 μm necessary for splicing. The polymer coating of 390 μm diameter includes the second cladding of low-refractive-index resin that creates an NA of 0.52 for the first cladding. Only ~3% residual pump power was measured, indicating a pump absorption in the first cladding of roughly 5 dB/m. Coreless end caps made of humidity-resistant CaF_2 were spliced onto fiber tips [15,16] under heating at about 300°C to prevent potential damage due to thermal runaway caused by chemical interaction of the fiber's material with ambient OH molecules [17].

The coupler was spliced about 100 mm in front of the output end of the DC fiber. The coupling efficiency from the multimode fiber into the first cladding of the ED DC fiber of this coupler was 83% (loss ~0.8 dB). A representative image of the coupler is shown in Fig. 3.

The laser cavity is formed by a concave mirror (CM) that is placed at the fiber's other end and the spliced surface of the end cap at the fiber tip near the pump coupler. The CM is high-reflection coated for 2.8 μm and possesses a radius of curvature of 30 mm. Although the end cap at the CM end of the fiber gives some reflection, it was assumed that the well-aligned high-reflective-coated CM provides the strongest feedback with a high power-damage threshold. The laser output is collimated by an anti-reflective-coated CaF_2 lens with a focal length of 50 mm before incidence with a thermopile-type power meter (L-50; Ophir Optronics, Israel).

In this experiment, the pump coupler was held between coupler heat sinks, and the fiber was placed on a platform made of aluminum and both were liquid-cooled.

Figure 4 shows the laser output power as a function of the launched pump power. A maximum mid-IR laser power of 15 W was achieved with a pump power of 83.5 W. The lasing threshold was roughly 1 W and the slope efficiency was roughly 24% up to a pump power of roughly 20 W. This corresponds to a slope efficiency of 29.3% with respect to the absorbed pump power. The slope efficiency then decreased to approximately 18% and finally saturated to less than 15% at pump powers above 70 W. The reason for this decrease is not well understood but is likely some kind of thermal effect in the pump coupler. The beam profile was found to be elliptical, which indicates the influence of the multimode oscillation of the ED core.

Figure 5 shows a 1 h log at the maximum pump power of 83.5 W. An average stable output power of 15.6 W was

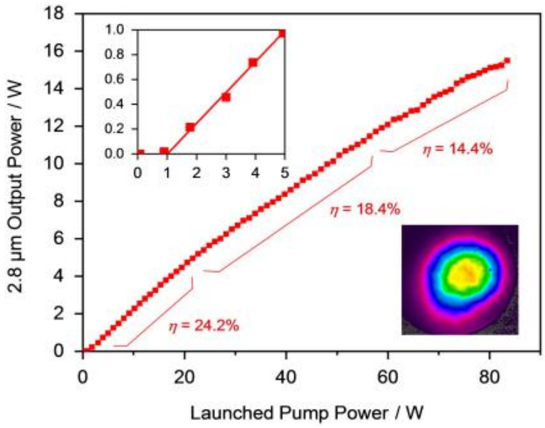

Fig. 4. Laser output power at 2.8 μm as a function of the launched pump power.

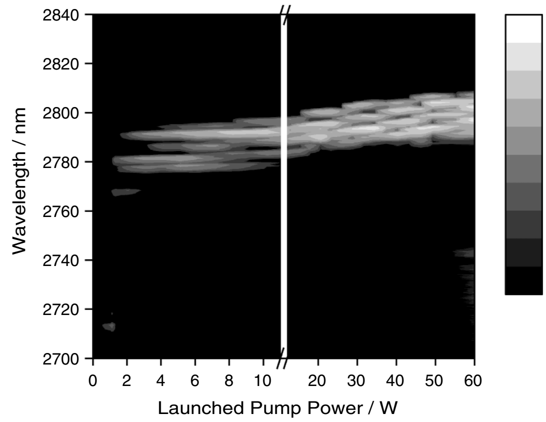

Fig. 6. Laser output wavelength spectra at various pump powers.

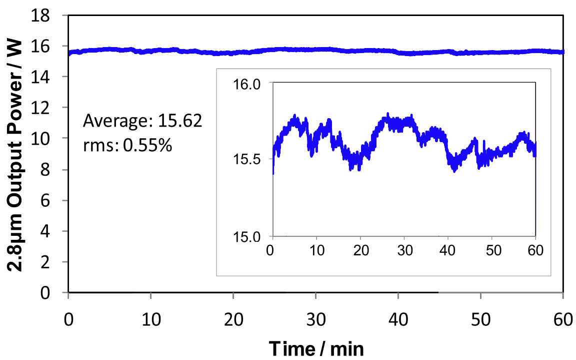

Fig. 5. Laser output power log at a launched pump power of 83.5 W.

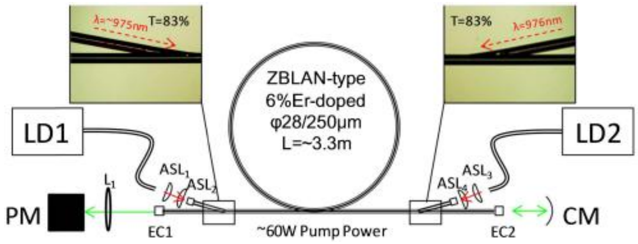

Fig. 7. Optical setup employing two pump couplers.

measured with a root-mean-square fluctuation of 0.55%. No degeneration [8,17] was observed in this power range. With this design, the ED core temperature near the fiber tips remains low because they are essentially not pumped because of the extinct pump power at the mirror's end and no direct incident pump power prior to the coupler at the output end. This is an inherent advantage over the usually used fiber-end pump schemes with ZBLAN-based fiber lasers, resulting in superior power stability and reliability.

Additionally, the spectrum of the laser light was measured by a scanning spectrometer with a focal length of 110 mm (CM110; Spectral Products, USA) and is shown in Fig. 6.

A red shift is observed from 2713 nm to 2800 nm at pump powers of 1–60 W. Similar characteristics have been found previously with end-pumped setups [5]. It is presumed that the observed multiple peaks originate from the multimode behavior of the ED fiber.

An additional experiment was performed using two couplers spliced near each tip of the fiber. The setup is shown in Fig. 7. The center wavelength of the first LD (LD1) used in this setup was not stabilized (nLight element e12), and the second (LD2) was the same as that used in the earlier experiment (Fig. 3). The peak emission wavelength of LD1 was about 964 nm at 1 W and shifted nearly linearly to 970 nm at 60 W (977 nm at 100 W) output power and had a linewidth of about 5 nm. The power-delivering fiber of the two LDs and the subsequent optics do have similar specifications.

The pump light counter-propagates through the DC fiber in this setup, which is therefore similar to the setup in Ref. [6]. Although theoretically this configuration provides less gain than co-propagating pumps in which the second coupler is spliced near the center of the fiber, this configuration was chosen because of easier fiber handling and reduced core temperatures.

The configuration with two SPCs does have advantages over the double end-pumping configuration described in Ref. [6] because it reduces the fraction of pump light propagating into the opposite pump diode. We measured only 5.4% of light propagating from LD1 into the multimode fiber's core of LD2 using the 700 nm probe light.

By increasing the pump power of both LDs in similar steps, we could achieve an output power of 20 W at a pump power of 60 W delivered by each LD (Fig. 8). Compared to one coupler, we could achieve a more linear power increase. The slope efficiency corresponds to roughly 18%, which is similar to the average slope efficiency observed using one coupler.

Figure 9 shows the power log over 20 min. In this initial test, no power drop was observed, and the statistics indicate even better stability than that in the earlier experiment, potentially resulting from the reduced core temperature of the fiber because less pump power was injected per coupler. The data were measured over this short time span only because one coupler burned shortly afterward. An insufficiently cooled part of the recoated polymer cladding at the coupler was identified as the reason.

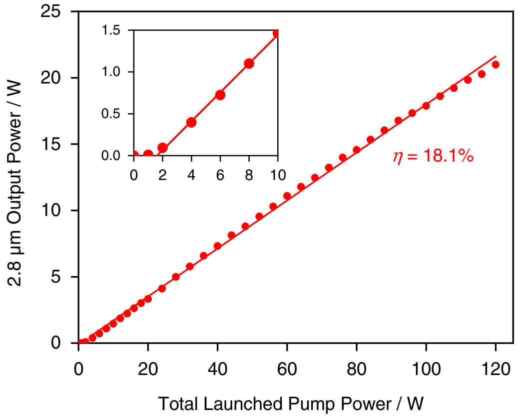

Fig. 8. Output power as a function of pump power per LD using two pump couplers.

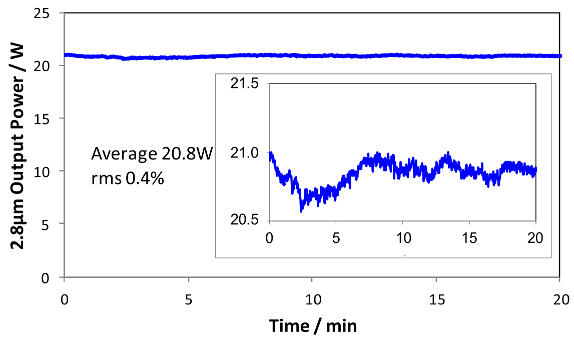

Fig. 9. Time dependent behavior of the twin pump combiner setup shown in Fig. 7.

In summary, an FF-based SPC has been fabricated for the first time and used to inject pump power into an ED DC fiber. With a pump power of 83.5 W, a stable mid-IR output power of 15 W at 2.8 μm was generated over an hour. Using two couplers, an output power of more than 20 W was achieved with a pump power of 60 W each.

The developed pump coupler is a significant step forward in FF technology and paves the way for further power scaling of FF-based lasers. Applied strategies will rely on increasing the applicable pump power injected per pump coupler using more couplers per fiber, as well as increasing the slope efficiency of the laser.

To increase the amount of applicable pump power, the active fiber must be redesigned for less heat load. One approach would be a smaller core diameter, meaning that it would be a single-mode fiber. At some point, the pump coupler should be improved to support to a larger core and NA of the multimode fiber so that light can be coupled efficiently from a high-power LD-connected fiber with a core diameter of 200 μm and an NA of 0.22 into the active fiber.

Increasing the slope efficiency involves a more fundamental redesign of the active fiber. A potential candidate for power scaling is cascade lasing, which may lead to not only considerably less heat load in the fiber but also higher slope efficiency [18], even without using fiber Bragg gratings [19].

As well as power scaling, the developed coupler is suited for use as an amplifier in a master-oscillator power fiber amplifier (MOPFA) setup. As an oscillator, a tunable laser source will be used [20] to completely characterize the fiber in amplifier mode.

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