Single Mode Laser Oscillation in an Nd-Doped Large Core Double Clad Fiber Cavity with Concatenated Adiabatic Tapers

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ABSTRACT— We created a new design for an Nd-doped clad-pumped silica fiber laser to enhance the pump absorption and lasing efficiency for a butt-coupled, end-pumped scheme. Two concatenated adiabatic tapers formed within the laser cavity simultaneously removed higher order modes and were spliced to conventional single mode fibers. We theoretically analyzed mode propagation along the composite cavity and experimentally achieved continuous wave oscillation in the LP_{01} mode at 1.06 μm and a laser output power of over 820 mW with a slope efficiency of 27%.

I. INTRODUCTION

The rapid development of arrayed semiconductor laser diodes (LDs) with high output power has influenced many applications in optical communications, especially high power fiber amplifiers and fiber lasers. The beam quality parameters of the arrayed LDs, however, are not compatible with those of conventional single mode fiber (SMF). To overcome this mode mismatch and increase power delivery, some researchers have developed laser cavities based on double clad fiber (DCF), in which the pump and signal beams have different optical paths interacting with each other over the length of the cavities [1], [2]. The pump is launched in the silica cladding waveguide with a large area and a high numerical aperture supported by a low refractive index polymer jacket. Various pump schemes and fiber designs using this technique have been reported. Po et al. obtained a 5-W single mode laser with a slope efficiency of 52% in an Nd-doped rectangular inner cladding DCF [2]. Weber et al. obtained a slope efficiency of 66% in an Nd-doped DCF using a side-pumping scheme [3]. Zellmer et al. reported an output of 9.2 W at a slope efficiency of 26% in an Nd-doped DCF with a 400 μm clad diameter [4]. The DCF has a special structure which enhances slope efficiency, but in turn increases the splicing loss that occurs with conventional single mode fiber.

Recently, Fermann [5] researched single mode radiation in a multimode active core, and Alvarez-Chavez et al. [6] applied the results to the double clad fiber laser. They obtained an almost single mode output by tapering the middle of the double clad fiber with a multimode active core. Minelly et al. fabricated a multimode core fiber composed of Yb multicomponent silicate glass with a tapered-end section. They obtained a single mode output of 450 mW for a pumping power of 1.7 W [7].

In this work, we demonstrate a new high power end-pumped laser cavity based on a double clad fiber embedding a multimode core doped with Nd to obtain LP_{01} mode output concatenating tapers. Our proposed butt-coupled, end-pump scheme, which uses pump–signal overlap in a large core along a concatenated adiabatic taper structure, shows advantages over prior designs: a low-loss splicing with SMF and enhanced pump absorption and slope efficiency. This fiber laser can be applied as a good pumping source for a Tm-doped fluoride fiber amplifier or a Pr-doped selenide fiber amplifier [8].

Manuscript received Dec. 12, 2001; revised May 8, 2002.

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II. EXPERIMENT AND RESULT

To enhance the absorption of the pump power passing through the cladding into the core area, it is important to keep the rare-earth doped core region as large as possible. The maximum core, however, is defined by the refractive index of the core for a single mode condition, which limits the concentration of aluminum oxide needed to dope rare earth material into the silica core, because aluminum oxide increases the refractive index in silica glass. A greater concentration of aluminum oxide decreases the core diameter for the single mode condition so that the core-coupling efficiency of the pump beams decreases. However, depending on the launching condition, the single mode operation is possible even in a large core with many modes when the fiber length is short [5]. Using a mode-filtering technique, a single mode operation can be even more precisely controlled without the excitation of higher order modes. A mode filtering technique is a method to remove unnecessary modes. Various methods have been proposed using fiber bending, grating, and tapering. A single mode operation can be easily achieved by tapering the large core fiber into a single mode core fiber. Using this method, we constructed a high power Nd-doped double clad fiber laser with a single mode operation in a large core.

We fabricated a cylindrical optical fiber preform with an Nd-doped core using modified chemical vapor deposition with an aerosol delivery technique. The refractive index of the Nd-doped core was 0.003 higher than that of the silica cladding (see Fig. 1, N.A. = 0.1). The preform was drawn into the fiber with a cladding diameter of 600 μm compatible with the power delivery optical cable of an arrayed laser diode system (SDL: Diode Laser System FD25). The fiber was coated with a UV-

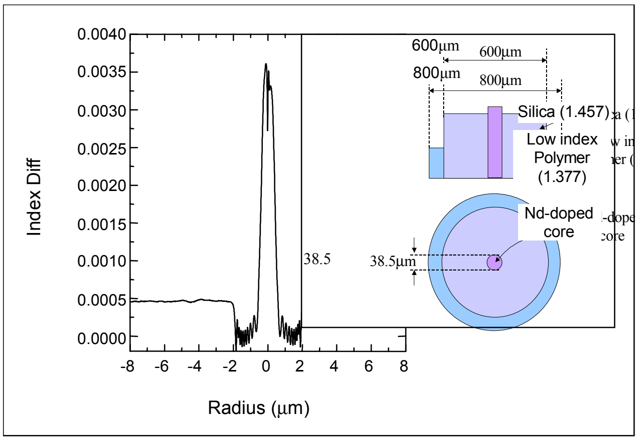

Fig. 1. The refractive index profile of the perform of Nd-doped double clad fiber, and the drawn fiber structures.

curable low refractive index polymer with an index of 1.377 to result in a DCF structure (Fig. 1). The numerical aperture between the silica and UV polymer was about 0.47, the coating thickness about 100 μm, and the core diameter of the double clad fiber about 38.5 μm, which can hold many modes in the core. We designed the fiber to filter out higher-order modes in the double clad fiber when its diameter was reduced from 600 μm to 125 μm. In this way, by tapering the fiber down to 125 μm, only a single mode LP_{01} remained in the reduced core, and it became the dominant lasing mode through competition of the modes in the large-core-fiber laser cavity with a tapered section at both ends.

Figure 2 schematically shows the proposed fiber laser cavity. The polymer jacket was removed near the ends and the bare fiber segments were tapered using a micro-torch in a translation system. The waist diameter of the tapers was precisely con-

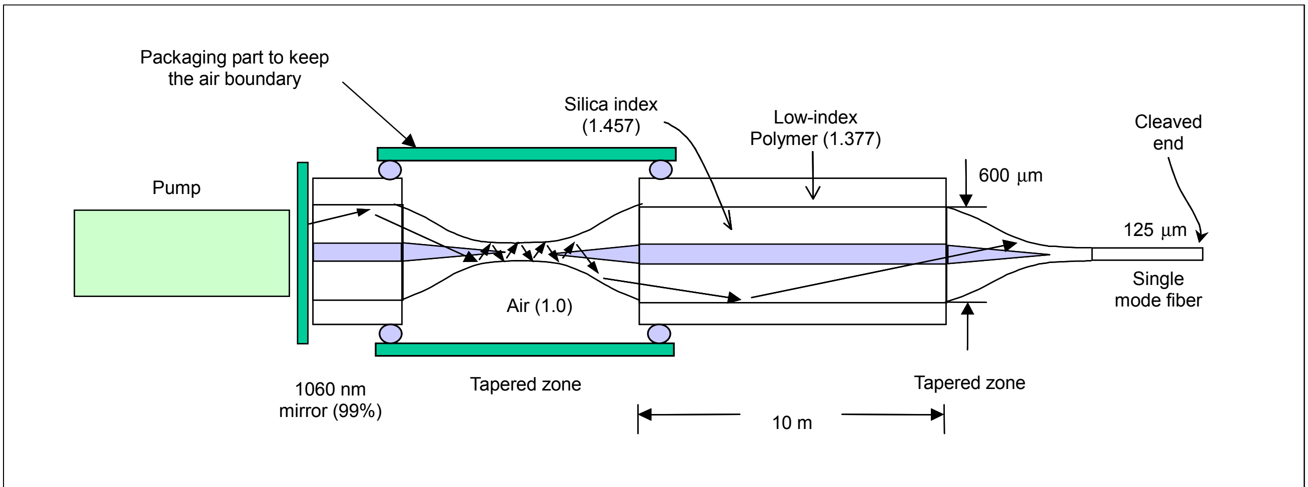

Fig. 2 Experimental setup of Nd-doped double-clad fiber which has large core and both tapered ends. In the left tapered zone, pump beam survives with low loss due to the large numerical aperture formed at the interface between silica clad and air. The lasing signals with higher modes excited in scattering centers are filtered out in the both tapered zones.

trolled at 125 μm where only the LP_{01} mode was guided through the core at 1.06 μm. The pump power at 0.8 μm was delivered through an SMA type patch-code with a diameter of 600 μm. The patch code was butt-coupled to the cavity through a bulk input-end mirror. The dichroic mirror with a 1 mm thickness had a reflection of 99% in the range of 1.04 to 1.12 μm and a transmission of 95% at 0.8 μm. The mirror was mechanically attached to the polished end surface of the DCF using an index matching oil in a holder. The pump was launched into the 600 μm silica cladding and had a low power leakage in the input taper because of the high numerical aperture formed by the interface between the air and the silica cladding whose indices of refraction were 1.0 and 1.457, respectively. After the tapered zone, the pump was absorbed in the Nd-doped core along the 10 m long fiber providing population inversion in Nd ions. The output taper was formed at the end of the DCF, which was spliced to a conventional SMF with a diameter of 125 μm. The end of the SMF was cleaved at 90° providing a 4% Fresnel reflection serving as an output-coupler of the laser cavity. The loss for the pump light at the first taper was about 0.8 dB, which was due to the pump beam's scattering by tiny particles on the tapered fiber and oil spots on its surface. The loss of the pump laser through the high reflecting mirror was about 3.5 dB, which contributed to the main loss of this fiber laser. When pumped, emission from Nd ions propagated through the large core along the composite cavity. Only the fundamental mode survived after the optical feedback through the two concatenated tapers where only the LP_{01} mode was allowed into the core. Results of the analysis of the beam propagation method for the waveguide between the two concatenated tapers are shown in Fig. 3. The initial weak light escaped from the spontaneous emission propagated through the Nd-doped core. The field profile of the light consisted of a linear combination of many modes in the cavity. Only the fundamental mode among the modes, however, survived in the two tapered zones and propagated along the large core of the Nd-doped fiber with a dominant power back and forth. Even though other modes were excited by the scattering centers in the large core, the tapered zones filtered out the excited modes. In addition, the higher order modes over-coupled from the fundamental mode in the section of the bulk mirror were removed in the first tapered zone so they would not be amplified in the cavity before the modes reached the end tapered section. These modes were induced from the tilt of the bulk mirror or the surface imperfection of the multimode fiber attached to the bulk mirror. Note that in the middle section the fundamental mode had a significant increase in the overlap integral with the pump modes guided along the cladding to enhance pump efficiency.

The far field pattern of the laser output coupled from the cavity was captured with an infrared CCD camera (Fig. 4). The captured intensity pattern showed the LP_{01} mode output at a high pump power over the threshold. Figure 4 also shows the output power characteristic of the proposed fiber laser. The maximum output power was 820 mW for the pump with 5.8 W. The slope efficiency was about 27%, which was lower than that of conventional Nd-doped DCFs. This is due to the cross-section area of the silica inner cladding and its geometry, because the efficiency is closely related to the number of cladding modes coupled into the doped core.

Experimentally, the loss of pump power launch was about 4 dB measured right after the input taper, which was attributed to the reflection loss at the input end mirror assembly and core misalignment. We are pursuing further optimization

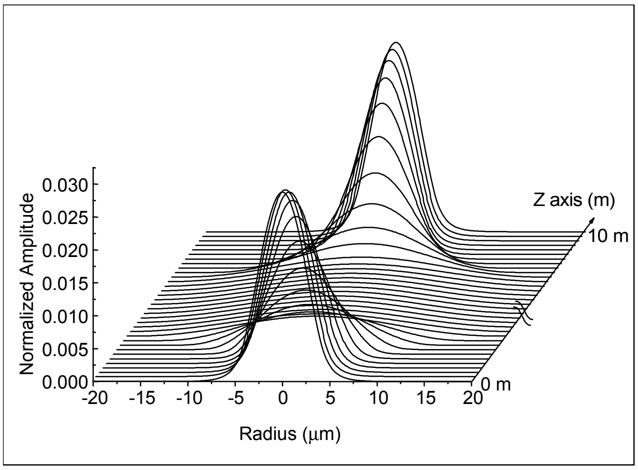

Fig. 3. Beam propagation of the fundamental LP_{01} mode through the core in a composite waveguide terminated by tapers at both ends.

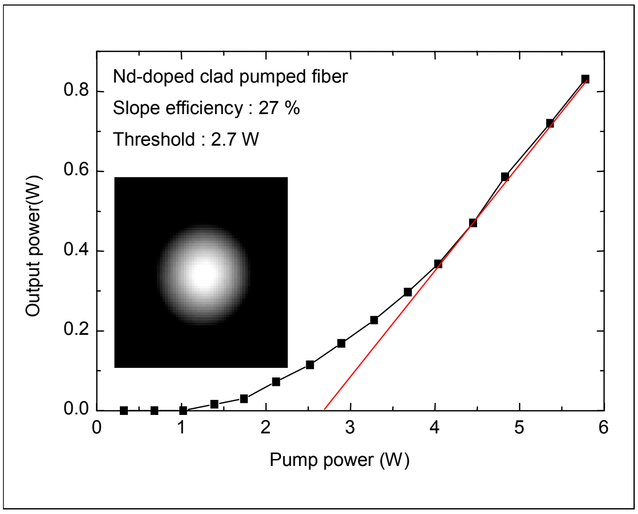

Fig. 4. Output power characteristic of the proposed fiber. The farfield pattern of output is also shown.

of the cladding diameter, cavity length, Nd concentration in the core, and butt-coupled losses to improve laser performance.

III. CONCLUSION

We demonstrated a new Nd-doped clad-pumped fiber laser in which two concatenated tapers served as a higher order mode rejection filter. We obtained a laser output power of over 820 mW with a slope efficiency of 27% and a threshold of 2.7 W. We are aiming for further reduction of the threshold, closing the cavity with a fiber Bragg grating inscribed at the output single mode fiber with an optimal reflectivity.

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