Efficient Low-Threshold Lasers Based on an Erbium-Doped Holey Fiber

K. Furusawa, T. Kogure, J. K. Sahu, J. H. Lee, T. M. Monro, and D. J. Richardson

***Abstract*—We report experimental results on the continuous-wave lasers based on a small core erbium-doped holey fiber. In a simple Fabry–Pérot-type cavity with high output coupling, we demonstrate low-threshold (0.55 mw) high slope-efficiency (57.3%) operation confirming both the quality and exceptionally high gain efficiency of the fiber. In an all-fiber ring cavity where the cavity loss is reduced, we show that it is possible to achieve a low-threshold laser with extremely wide tunability (>100 nm around 1550 nm). Our results illustrate some of the unique opportunities provided by active small core holey fibers.**

***Index Terms*—Fiber laser, holey optical fiber, laser tuning, microstructured optical fiber, optical fiber fabrication, photonic crystal fiber, rare-earth doped fiber.**

I. Introduction

RESEARCH into the field of holey optical fibers (HFs) has attracted a great deal of interest in recent years due to the novel and extended range of waveguide properties that are possible in this new class of optical fiber [1]. These properties include: endlessly single-mode operation, anomalous dispersion down to visible wavelengths, and high or low nonlinearities—all of which can be achieved by appropriate design of the holey cladding and rely upon the large index contrast between air and silica. To date, most work has focused on demonstrating or using these properties in passive HFs, however, many of these novel features are highly attractive for a variety of rare-earth-doped fibers and devices [2]–[5]. Of particular importance in our opinion, as previously considered theoretically in [6], is the fact that HF technology can be used to provide greater control of the overlap between pump-mode, signal-mode, and rare-earth dopant than can be achieved using conventional fiber technology. Moreover, control of the modal properties can be achieved in a way that is largely independent of the rare-earth host glass composition for many HF designs since the modal properties are determined primarily by the distribution of air holes within the structure rather than the material properties of the core glass itself. By contrast, in conventional fibers, both the spectroscopic characteristics of the gain medium and the fiber waveguide properties are defined by the core glass composition and which can be restrictive. For example, it is difficult to achieve high numerical aperture (NA) fibers using an aluminosilicate glass host which represents the best host glass choice for broad-band silica-based erbium (Er^{3+})-doped fiber amplifiers—this can readily be achieved using HF technology. The above features can lead to important benefits for fiber laser operation, for example, to provide efficient operation of fiber lasers at very low pump powers as we show herein.

To obtain high-efficiency operation of a fiber laser, it is necessary to ensure a low laser threshold and high slope efficiency. To realize this, two strategies can be taken in terms of waveguide design: one is to minimize the effective mode area of the fiber, and the other is to maximize the intensity of the pump and signal beams in the vicinity of the doped section of the fiber [7]. This can be readily achieved in HFs. First, due to the large refractive index difference between silica and air it is possible to achieve high NAs and, hence, very small mode areas. Second, due to the property of endlessly single-mode guidance, it is possible to ensure fundamental mode propagation for both signal and pump beams, even when the wavelength difference is large, e.g., for upconversion lasers and, albeit to a more limited extent, for Er^{3+}-doped fiber (EDF) lasers pumped at 980 nm. Finally, by virtue of the stacking procedure used to fabricate such fibers, the rare-earth dopant can be accurately confined to the central region of the fiber so that it lies at the position of peak intensity for the pump and signal modes propagating within the structure.

In this letter, we report the fabrication of a small-core Er^{3+}-doped aluminosilicate holey fiber (EDHF) and present results from two separate device experiments that highlight some of the benefits of HF technology. First, we report a simple Fabry–Pérot laser with a slope efficiency of 57.3% and a threshold as low as 0.55 mW. Second, we incorporate our EDHF within an all-fiber ring cavity by fusion splicing the EDHF to standard single-mode fiber components and demonstrate broad-band tuning (104 nm centered around 1550 nm) with laser thresholds as low as 0.48 mW.

II. Fabrication and Characterization

We first fabricated a high concentration (~1000 ppm by weight) Er^{3+}-doped aluminosilicate-based modified chemical vapour deposition preform with an NA of 0.14. Conventional EDFs drawn from this preform were found to show good optical power conversion efficiency (>40%) in simple fiber laser experiments despite the relatively high dopant concentration. The core of this preform was then extracted by ultrasonic drilling

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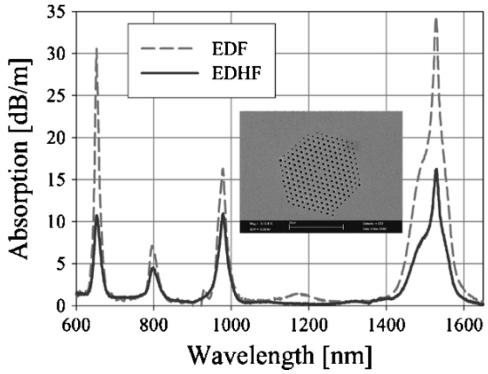

Fig. 1. Absorption spectra of EDF and EDHF. Inset: Scanning electron microscope picture of the EDHF.

and carefully polished to form a hexagonal rod with an excellent surface quality. This rod was then inserted into a capillary bundle HF preform comprising eight rings of capillaries and an external jacket tube. The preform was subsequently dehydrated using a small amount of chlorine gas in order to prevent excess incorporation of OH content within the fiber, and was then drawn into a fiber using a two step drawing approach.

The hole diameter d and pitch Λ in the final fiber were measured to be 1.0 and 2.0 μm, respectively, corresponding to $d/\Lambda \sim 0.5$ [see inset Fig. 1(a)]. The fiber outer diameter is 130 μm. The Er^{3+} ions were confined to a region of diameter $\sim$1 μm at the center of the fiber by virtue of the preform stacking process. From the structural/refractive-index profile of the fiber, the core should theoretically be multimoded; however, with good bulk optic and spliced cavity interconnection, the fiber was effectively single-mode in practice at both the pump and signal wavelengths. The confined dopant, thus, sits at the peak of the pump and signal mode-field distributions maximizing the pump and signal intensities, thereby facilitating high gain efficiency operation. Note that the on-axis confinement of the dopant also ensures that the fundamental mode experiences preferential gain which in principle serves to further discriminate against multitransverse mode laser operation.

The absorption characteristics of the fabricated EDHF were measured by a cut-back technique using a white light source. Fig. 1 shows a comparison of absorption spectra between the EDHF and the conventional fiber (EDF) drawn from the original preform. Note that the presence of modal cutoffs clearly affects the absorption spectrum of the EDF around 1.2 μm. No such effects are seen for the EDHF since, as previously explained, the EDHF is effectively single-mode over this wavelength range when properly excited. Due to the reduced ratio of doped area to mode area for the guided mode in the EDHF, the absorption of this fiber is seen to be smaller than that of the conventional fiber. However, it can be clearly seen that the absorption at 980 nm is relatively stronger for a given absorption around 1530 nm. This is due to the strong wavelength dependence of the mode area within HFs, where the modal confinement is considerably tighter at shorter wavelengths and leads to enhanced modal overlap with the doped section at the pump wavelength. This is favorable from a device perspective since it compensates for the smaller doped area in this HF allowing a shorter fiber length to be used than might otherwise be expected. The available fiber length ($\sim$30 m) was too short to accurately characterize the background losses, however, we estimated the background loss to be well below 100 dB/km (estimated at a wavelength of 1.2 μm) and, thus, to have had a negligible effect in the lasers described herein which all incorporated fiber lengths of order 3–4 m.

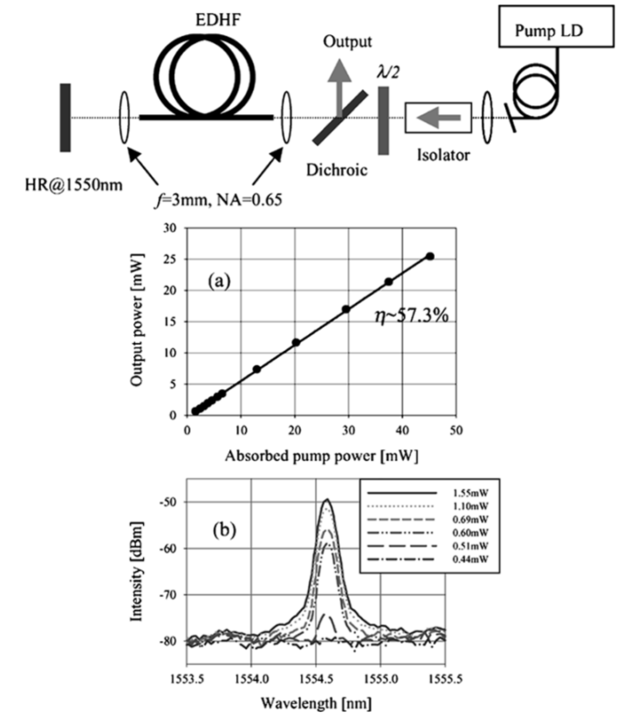

Fig. 2. (Top) Schematic of experimental setup for Fabry–Pérot laser, (a) laser output, and (b) the lasing spectra near the threshold.

III. Fabry–Pérot Laser

Continuous-wave laser operation was first investigated using a Fabry–Pérot cavity. The setup is shown in Fig. 2. A fiber pigtailed single-mode laser diode operating at a wavelength of 976 nm served as a pump source and was coupled into the EDHF via an aspheric lens. A 980-nm optical isolator was used to isolate the laser from the pump and a 45° angled dichroic mirror was placed between the lens and isolator to extract the laser signal. The laser cavity was defined by a high reflector at 1550 nm and the $\sim$4% Fresnel reflection at the pump launch end of the fiber. The maximum pump coupling efficiency was $\sim$50%. The slope efficiency was optimized by changing the fiber length.

Fig. 2(a) shows the laser output obtained from a 3.4-m length of the EDHF, through which $\sim$90% of the pump power was absorbed. The laser wavelength was 1535 nm and the quantum efficiency at this wavelength is $\sim$63.8%. A slope efficiency of 57.3% with respect to the absorbed pump power and a threshold of 0.55 mW were estimated from this data. (Note that the accuracy of the laser output power measurement close to threshold was compromised by the stability of the laser diode when operated at such low powers). It was found that a slope efficiency of more than 40% could be readily obtained using EDHF lengths of between 3 and 4.5 m. The very low laser threshold was also confirmed by examining the laser output spectrum close to threshold, as shown in Fig. 2(b), where a 4.5-m length of the fiber is used. It is clear that the lasing peak quickly grows for absorbed pump powers of 0.5 mW and

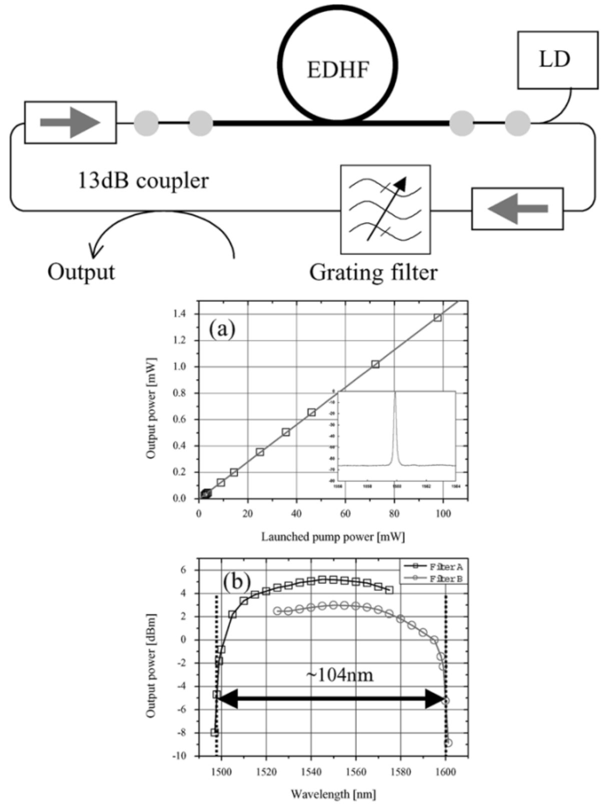

Fig. 3. Schematic of a tunable all-fiber ring laser based on EDHF. (a) Laser characteristic near threshold. (b) Tuning curve.

above. By contrast typical laser thresholds for erbium fiber lasers based on conventional fiber types are of the order of several milliwatts or more [8].

IV. All-Fiber Ring Laser

To realize more useful and practical devices, it is essential to be able to integrate EDHF into all-fiber cavities. To allow this, we developed a low-loss splicing approach to allow connection of the EDHF to standard single-mode fibers. Our technique requires controlled collapse of the EDHF air holes to allow mode expansion and the use of an intermediary buffer fiber to minimize the combined effective mode mismatch through the interconnection. Note that use of the intermediary buffer fiber is essential since control over both the mode area and the collapse of the structure becomes very sensitive when the collapsed air holes are small $(d/\Lambda \sim 0.2)$ and this sets a limit to the amount of mode expansion that can be achieved in the EDHF alone. Using a conventional high NA fiber intermediary fiber $(\mathrm{NA} = 0.22)$, it was possible during these experiments to reduce the total splice loss between a single-mode fiber and our EDHF to <1.6 dB while the return loss at the spliced point was estimated to be more than 47 dB. (Note that we have subsequently further improved the process by moving to a higher NA buffer fiber and are now able to achieve less than 1-dB loss for interconnection to this fiber.)

Having developed a splicing approach, we constructed a tunable all-fiber ring laser cavity using 4.5 m of the EDHF, as shown in Fig. 3. The pump was coupled via a wavelength-division multiplexing and a tunable grating filter was incorporated into the cavity. The laser output was extracted from the 5% port of a 13-dB coupler. In order to explore the full laser tuning range, we needed to use two tunable filters, both of which had a 3-dB bandwidth of 0.6 nm. Filter 1 had a tuning range from 1525 to 1620 nm and a minimum loss of 3 dB. Filter 2 had a tuning range from 1470 to 1575 nm and a lower minimum loss of 1.5 dB. The loss of both filters rose steadily to >5 dB at the extremes of their tuning ranges.

The output power versus pump power was first measured at a wavelength of 1550 nm (using Filter 2 within the cavity). The result is shown in Fig. 3(a). We obtained a laser threshold of 0.48 mW of pump (measured at the EDHF input). The optical spectrum under maximum pump power conditions is shown in the inset of Fig. 3(a). where it is seen that an extremely clean narrow-band spectrum is achieved. Fig. 3(b) shows the results of our experiments on wavelength tuning of our laser. We obtained a tuning range of more than 104 nm which is comparable to the best ever achieved with conventional EDFs [8], and which was limited by the increased losses of the filters at the edges of their tuning ranges. Further improvements should be expected with improved filter performance and further optimization of the fiber length.

V. Conclusion

We have developed a low background loss small core ($\Lambda \sim 2\ \mu$m, $d/\Lambda \sim 0.5$) aluminosilicate EDHF. As a result of the small mode area and tight pump and signal mode confinement, we have been able to demonstrate a Fabry–Pérot-type laser with very high slope efficiency (57.3%) and low pump threshold (0.55 mW). Furthermore, by incorporating the EDHF within an all-fiber ring cavity using fusion splicing, we have demonstrated a laser with a wide ($\sim$104 nm) tuning range with a low threshold ($\sim$0.48 mW). These results illustrate some of the interesting active device opportunities opened up by HF technology and point to the possibility of ever more efficient EDF-based devices suited to applications requiring/using low pump and signal powers.

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