Effect of Helical Bending on Gain Beyond 1650-nm of an Er-Doped Optical Fiber Amplifier

Pramod R. Watekar, Aoxiang Lin and Won-Taek Han

Department of Information and Communications, School of Photon Science and Technology, Gwangju Institute of Science and Technology, Gwangju 500-712

Seongmin Ju

Optonest Corporation, Gwangju 500-712

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An Er-doped optical fiber amplifier sensitized with Yb ions was developed with a two-cores three-claddings layer structure. Extended L-band amplification over 1650-nm was achieved upon 980-nm pumping with helical bending. The gain after helical bending was about 12 dB at 1700-nm.

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I. INTRODUCTION

The Er-doped amplifier (EDFA) is already an established device in the field of optical fiber communication links. It operates in the range of 1500-nm to 1600-nm, which is also a low-loss band for single-mode optical fibers. Recently, thanks to the surge of broadband usage due to the internet, there has been an increasing demand for other wavelength bands to be utilized for wavelength-division multiplexed systems. Reports have already been published for new 800-nm and 1470-nm band amplifiers using Tm-doped optical fibers [1-4]. However, a main problem with such uncommon bands of wavelengths for optical communication is the very low gain efficiency (<0.05 %), which requires a very large power (in several Watts), thereby increasing the cost of amplifying the output of the device and restricting its commercial use to the laboratory. Tm-doped fluoride fibers that show great gains have been developed, but they are incompatible with the existing network of silica glass optical fibers [5]. Thus, another option to increase the bandwidth of optical communication is extending the existing EDFA bands beyond the usual bands of 1530-nm to 1570-nm (C-band) and 1570-nm to 1650-nm (L-band). Keeping this motivation in mind, we report the realization of an EDFA operating beyond the L-band. The optical fiber was developed using the MCVD (modified chemical vapor deposition) process. A special refractive index structure with two cores and three claddings was utilized and Er ions, along with Yb ions, were doped in the inner core of the fiber. In general, the amplifiers behave as other EDFAs, with emission around 1550-nm upon pumping with a 980-nm LD. However, after application of optimized helical bending, a significant decrease in the emission around 1550-nm and an enhanced emission beyond 1650-nm were observed.

II. EXPERIMENTS

An optical fiber preform codoped with Yb/Er ions was fabricated using the MCVD technique. It had two cores inside a silica glass tube and both the cores were basically silica and GeO₂. Additionally, an inner core was doped with Al₂O₃, together with Yb ions and Er ions by using a modified solution doping process. The cores were separated by a low-index layer made of fluorine-doped silica and the outer core was surrounded by silica cladding. A cross-section of the preform is illustrated in Figure 1. The optical fibers with outer diameters of 125 µm were drawn from these preforms by using a drawing tower at 2000 °C. A low-index cladding polymer was used as the outer coating. The refractive indices of the inner core, the outer core and the inner cladding were 1.460, 1.447 and 1.441, respectively. The radial widths of the inner core, the outer core and the inner cladding were 7 µm, 3.7 µm and 2.7 µm, respectively. The Yb ions, the Er ions and the Al ions concentrations were estimated to be 9 × 10²⁴ ions/m³, 9 × 10²⁵ ions/m³ and 1.8 × 10²⁶ ions/m³, respectively. The concentrations of GeO₂ were around 11 mole% and 2 mole% in the inner and the outer cores, respectively.

The attenuation spectrum of the Yb/Er-doped optical fiber with a double-cores triple-cladding structure
(YEDFA) was measured using the cutback method. A white light broadband source was used as the input source and output powers with long- and short-length fibers were measured using an optical spectrum analyzer. The difference between these two power levels gave the attenuation for the length difference between the long and the short fibers. To measure the gain of the YEDFA, we used an amplified spontaneous emission (ASE) source emitting at 1450-nm to 1700-nm as the signal source and a laser diode emitting at 980-nm with a maximum power of 300 mW was used as the pump source. The signal and the pump were coupled to the YEDFA by using an optical fiber coupler and the output power was measured by using the optical spectrum analyzer. All measurements were performed at room temperature.

III. THEORY

The YEDFA fiber structure can be modeled as three fibers coupled one another. To understand the physics behind the coupling of these three fiber structures, one has to solve the complicated coupled-mode equations related to these three fiber structures [6-9]. We have adopted the method of an equivalent planar model for the optical fiber [6], as shown in Figure 2, where the device has been divided into three sections. The input and the output fibers are represented by single-mode planar waveguides in the input and the output sections. The device section represents the YEDFA fiber. The solutions in the different layers of a multilayered structure can be written as:

\[
\Psi_{n} = A_{n} \exp(\gamma_{n}x) \quad \text{for} \quad x \leq (x_{n} - x_{n-1}) \quad \text{or} \quad x_{n-1} \leq x \leq x_{n+1},
\]

where \(\Psi_{n}\) represents the electric field in the \(n\)th layer, \(A_{n}\) and \(B_{n}\) are the constants, \(\gamma_{n} = k_{0} \left( n_{n}^{2} - n_{eff}^{2} \right)^{1/2}\), \(x_{n-1}\) is the thickness of the \(n\)th layer with refractive index \(n_{n}\), \(n_{1}\) is the refractive index of the cladding region, \(n_{eff}\) is the effective index of the core, \(k_{0} = 2\pi/\lambda_{0}\) and \(\lambda_{0}\) is the operating wavelength.

Applying boundary conditions at each interface leads to \(A_{n}\) and \(B_{n}\) being represented in terms of a single arbitrary constant \(A_{1}\). As the diameter of the inner core of the YEDFA fiber (7 \(\mu\)m) is almost equal to the diameter of the core of the single mode optical fiber, we can assume that most of the input power is propagating in the inner core of the YEDFA. Under this assumption, the total propagating electric field at any distance \(z\) can be expressed as

\[
\Psi_{total} = \sum_{l} a_{l} \Psi_{l} \exp(-i\beta_{l}z) \quad \text{with}
\]

\[
a_{l} = \frac{1}{2} (\varepsilon_{0}/\mu_{0})^{1/2} n_{eff} \int_{-\infty}^{\infty} \Psi_{in} \Psi_{l} \, dx
\]

where \(l\) is the mode number and \(a_{l}\) is the excitation coefficient between the input section (SMF) and the device (YEDFA), \(\varepsilon_{0}\) and \(\mu_{0}\) are the permittivity and the permeability of vacuum, respectively and \(n_{eff}\) is the effective index at mode number \(l\).

The excitation coefficient between the device (YEDFA) and the output section (SMF) is expressed as

\[
b = n_{eff} \sum_{l} a_{l}^{2} \Psi_{l} \exp(-i\beta_{l}L),
\]

where \(L\) is the length of the YEDFA and \(l\) is the mode number. The output power is then equal to \(|b|^{2}\). Thus, the output power depends on the input excitation coefficient \(a_{l}\), which, in turn, depends on the overlapping of the input and the device electric fields. The excitation coefficient \(a_{l}\) can be varied using various techniques such as an overlay waveguide, a bending technique, etc., which will result in a filter-like property of optical fiber. We
The attenuation spectrum of the YEDFA measured with the cutback method is shown in Figure 3, where different absorption peaks related to Yb ions (918-nm, 981-nm) and Er ions (530-nm, 652-nm, 981-nm, 1533-nm) can be noticed. To measure the amplification spectra of the YEDFA, we chose a 1-m-long fiber and we simultaneously launched the ASE signal (1450-nm to 1700-nm) and the pump (100 mW at 980-nm) powers into the fiber by using a 1500/980-nm coupler. The peak gain was about 11.5 dB at 1540-nm, as illustrated in Figure 4. It is worth noting that all the gains mentioned in the manuscript are the gains in the saturation region, unless otherwise stated.

To enhance the emission beyond 1650-nm, we started to provide helical bendings to the YEDFA. Several diameters of bends were tried and an optimum bending radius of about 3 cm with a minimum 4 bend helix was found to provide the required filtering property, thereby providing maximum output power at 1650-nm. The measured gain spectrum is illustrated in Figure 5. It is observed that the peak gain at 1540-nm with bending is now reduced to about 5.4 dB from 11.5 dB (without bending). However, the amplification band centered at 1540-nm was not altered in either of the cases. The most interesting fact is that the reduction in gain at 1540-nm after bending has been compensated for by having another band of gain around 1650-nm to 1700-nm. The gain at 1700-nm is about 12 dB, which is much beyond the error range of measurements. Probably, the gain band would have been widened, may be up to 1710-nm to 1720-nm, unfortunately, the gain measurements could not be done due to the lack of a signal source at that wavelength. The obvious question is the origin of such behavior of the gain in the YEDFA, which has never been observed in Er-doped optical fibers.

The reasons for such behavior of the YEDFA can be inferred from the results that we obtained by taking the four things together: (a) a special refractive index structure of the YEDFA, (b) rare-earth-ion doping in the cores of the optical fiber, (c) the multimode nature of the optical fiber and (d) the low-index outer coating. As shown in Figure 1, there are two cores and three cladding layers (including an outer most layer of the low-index polymer) in the YEDFA. Rare-earth ions were doped only in the inner core while the outer core was undoped. Thus, when the pump power was launched into the straight YEDFA, the signal power propagated in the form of a fundamental mode and some higher order modes (because the sig-
nal was launched from a single-mode fiber). This power propagated in the inner core and its behavior was like that of the usual Er-doped amplifier, i.e., a strong emission at the 1540-nm band and a weak emission at other longer wavelengths. However, upon bending, some of the strong emission (signal) was coupled to the outer core, which was undoped (so no amplification) and some of this power was coupled to the cladding, thus reducing the signal power in the doped inner core and thereby reducing the amplification at 1540-nm. In other words, the excitation coefficient $a_l$ (in Eq. (3)) was reduced due to helical bending, thereby providing a partial stop-band type phenomenon at the band around 1540-nm.

As shown in Figure 5, the emission beyond 1650-nm band became strong upon bending, which means that weak emissions got amplified strongly. Previously, helical bending has been used in double-clad Yb-lasers as a means to enhance pump-to-signal coupling [9]. In our case, the helical bending enhanced the power-to-signal coupling. Also, after helical bending, a few higher-order modes were cutoff, thereby increasing the power to the lower-order modes. Thus, the increased pump-to-signal coupling, the decreased main emission, the increased strength of modes due to the higher-order mode cutoff result in a strong amplification of an otherwise weak emission to enhance the gain, as shown in Figure 5. With regards to the pump efficiency, as we introduced the loss in the band at 1540-nm, the pump efficiency for amplification at 1540-nm was reduced by 3 times. However, it was compensated for by an increase in the gain at the band beyond 1650-nm.

V. CONCLUSION

We fabricated a Yb/Er-doped optical fiber with a two-core three-cladding layer structure for amplifier applications at wavelengths beyond 1650-nm. A extended L-band amplification of about 12 dB at 1700-nm was achieved after 980-nm pumping with helical bending. The significant increase in the gain after a helical bending of about 3 cm in radius of the fiber was found to be due to the decrease in the gain at 1540-nm.

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