Differential Modal Gain Reduction using a Void Inscribed in a Two-Mode-Erbium Doped Fiber

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Abstract: Differential modal gain (DMG) reduction technique that uses laser-inscribed void is proposed. We reveal that DMG can be successfully controlled by introducing one void into two-mode-EDF while keeping the initial gain, NF and flatness. © 2020 Author(s).

1. Introduction

Mode division multiplexing (MDM) transmission is a candidate for realizing transmission capacities above 100 Tb/s/fiber. In an MDM system, differential modal gain (DMG) among transmission modes in a few-mode optical amplifier severely degrades system performance [1]. There are three major techniques for controlling DMG in a few-mode amplifier. First technique controls the mode content of the pump light [2]. Second technique manages the electric field distribution of each transmission mode by means of the refractive index profile (e.g. ring core Erbium doped fiber (EDF) [3]). Final one tailors the spatial distribution of Erbium dopant [4]. DMG values of less than 1 dB have been achieved with these techniques. However, the first approach needs additional optical components and the other two methods require complex design and precise fabrication of the EDF. Femto-second laser inscription is now attracting much attention as a technique for realizing a smooth refractive index change [5], birefringent refractive index modification [6], and empty void [7] within glass. It has been also reported that laser inscription enabled to attenuate a particular core in a multi-core fiber [8].

In this paper we propose a DMG reduction technique based on laser inscription. We show that the DMG in a two-mode-EDF (TM-EDF) can be controlled by means of changing void diameter. Experiments demonstrate the 1.2 dB reduction of DMG at a wavelength of 1555 nm by imposing one void with a 6.8 μm diameter into a TM-EDF while maintaining the original amplification property, gain, noise figure (NF) and their wavelength dependence.

2. Discussion model

Figure 1 shows the conceptual diagram of our proposed laser inscription based DMG reduction technique. We consider one void is formed at the core center of a TM-EDF. Laser inscription enables laser processing at arbitrary positions along a fiber from an arbitrary direction. However, in this study, we considered a void formed at the end face of a TM-EDF which is inscribed from the longitudinal axis of the fiber as shown in Fig. 1. This is because we can directly confirm the void condition at the end face, and we can reduce the influence of non-circularity and positioning error compared when we consider the laser inscription from cross sectional direction of the fiber. Figure 1 also shows the calculated electric field distribution of LP_{01} and LP_{11} modes at 1550 nm. Here, we simply assumed a sphere (non-elliptical) void with diameter of 5.0 μm. The plots confirm that the electric field of LP_{01} mode is strongly affected by a void, as its intensity at core center is greatly reduced. On the contrary, LP_{11} mode has limited influence of the void on its electric field. This implies one laser inscribed void can selectively attenuate just the LP_{01} mode in a TM-EDF.

In the following experiments, we used a step-index type TM-EDF. We fabricated a void at one end face of a 15 cm long TM-EDF by using a femtosecond laser with a wavelength, pulse duration and repetition rate of 515 nm, 300 fs and 200 kHz, respectively. Here, the laser beam was converged by an objective lens (Mitsutoyo, ×100, 0.5NA). Void diameter was controlled by means of the pulse energy. The 15 cm long laser inscribed TM-EDF was inserted into our experimental setup to evaluate the optical property by using conventional fusion splicing. Here, it should be noted that we reduced the arc fusion level as much as possible so that the inscribed void can be remained after fusion splicing.

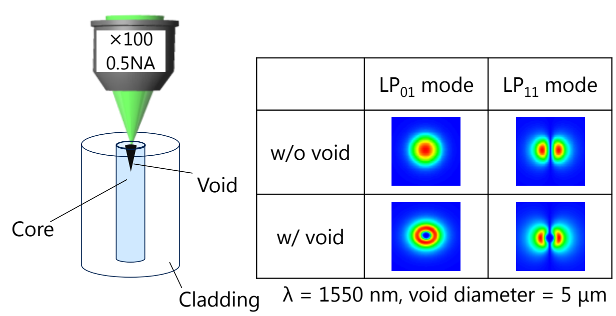
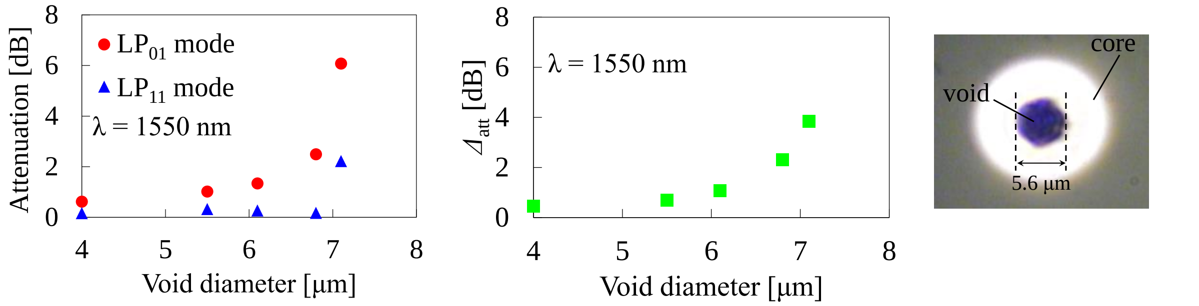


Fig. 1 Conceptual diagram of laser inscription based DMG reduction technique



(a) Attenuation of LP_{01} and LP_{11} modes (b) Δ_{att} (c) end face view of void

Fig. 2 Void diameter dependence of (a) attenuation of LP_{01} and LP_{11} mode, (b) attenuation difference between LP_{01} and LP_{11} modes Δ_{Att} measured at λ = 1550 nm, and (c) end face view of EDF with 5.6 μm diameter void.

3. Experiments and discussion

Figure 2 shows the void diameter dependence of (a) attenuation of LP_{01} and LP_{11} modes, (b) attenuation difference between LP_{01} and LP_{11} modes (Δ_{Att}) measured at λ = 1550 nm, and (c) end face view of EDF with 5.6 μm diameter void. Figure 2(a) confirms that LP_{01} mode attenuation monotonically increased from 0.6 dB to 6.1 dB with an increase of void diameter from 4 to 7 μm. It is also seen that LP_{11} mode attenuation was under 0.5 dB for void diameters of less than 7 μm, and there is no remarkable void diameter dependence. However, void diameters above 7 μm rapidly increased LP_{11} mode attenuation, which would degrade the gain performance. Figure 2(b) revealed that Δ_{Att} varies from 0.5 dB to 4 dB over the void diameters examined. Here, the variation in Δ_{Att} and return loss were less than 0.8 dB and −41 dB in the full C-band at the void diameter of 6.8 μm. We also confirmed that the accuracy of setting void diameter was about 0.4 μm in our setup. These results show that we can expect to reduce the DMG of 1~4 dB effectively by using the proposed model.

We next evaluate the gain and NF characteristics of the TM-EDFA. Figure 3 shows the experimental setup. We input the saturated signals at 1530, 1540, 1550, and 1560 nm to lock the population inversion state of Er^{3+}. Their input power were set as –12 dBm per wavelength. A signal light from a tunable wavelength laser diode (TWLD) was modulated into QPSK format to suppress the modal interference induced intensity fluctuation, and guided into a commercially available mode-multiplexer (MUX) based on 3D-inscribed waveguide by Modular Photonics with the four laser lights by using a 1:4 splitter. The mode multiplexed signals were injected into the TM-EDF through isolators and pump combiner. The input power was set as –25 dBm per each mode by utilizing variable optical attenuators (ATTs) inserted before the mode MUX. The pump light source was operating at λ = 980 nm and launched the pump light with the LP_{01} mode. A 21m length of TM-EDF was used to obtain acceptable gain flatness within the-C-band. The amplified MDM signal was demultiplexed and we used an optical spectral analyzer (OSA) to characterize each mode separately by switching the output port of the mode-demultiplexer (DEMUX.) When we evaluated the amplification property with void, we added a 15 cm long TM-EDF with a 6.8 μm diameter void at 9 m from the input end of the TM-EDF. This is because setting the additional attenuation at the beginning or end of the EDF would cause gain or NF degradation [9].

Figure 4 shows the pump power dependence of gain, $\Delta G_{01\text{-}11}$, and NF measured at λ =1555 nm. Here $\Delta G_{01\text{-}11}$ denotes the gain difference between LP_{01} and LP_{11} modes. Figure 4(a) shows the gain and NF measured when we

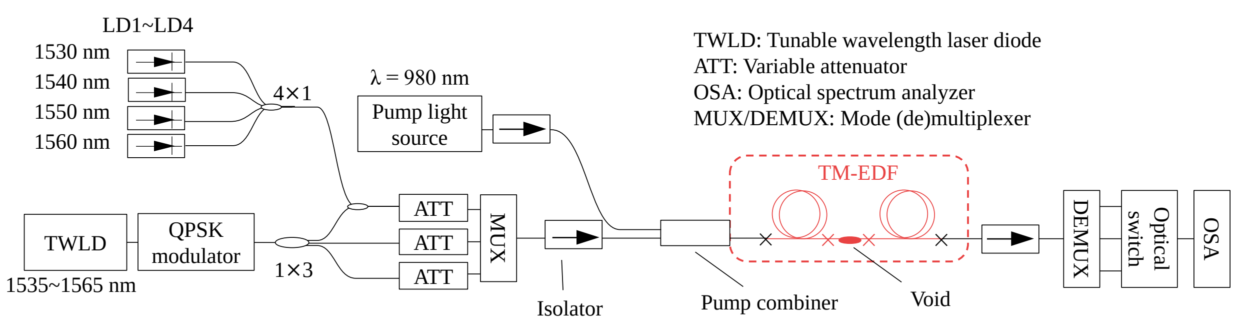


Fig. 3 Experimental setup to characterize TM-EDFA

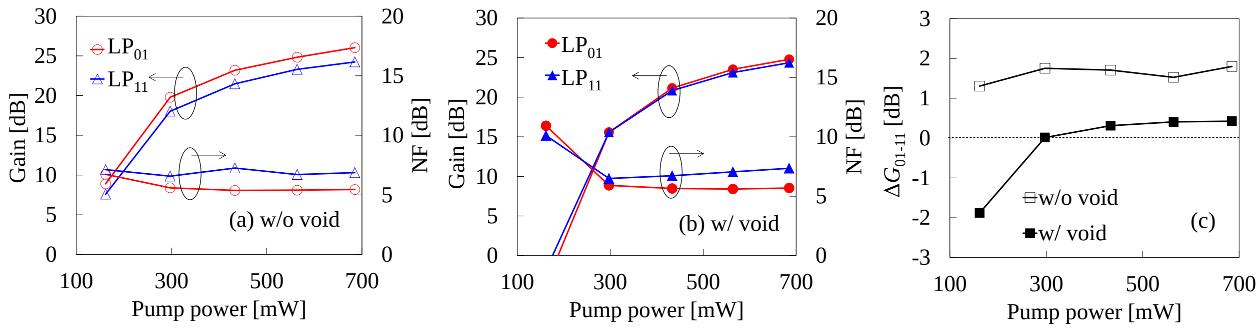


Fig. 4 Pump power dependence of gain and NF measured at 1555 nm (a) without and (b) with a 6.8 μm diameter void. (c) shows the gain difference between LP_{01} and LP_{11} modes obtained without and with a 6.8 μm diameter void.

did not introduce the void. This result shows that the TM-EDF can realize gain of more than 20 dB with a 5~7 dB NF when the pump power is 400 mW or more. But it is also confirmed that the TM-EDF intrinsically exhibits $\Delta G_{01\text{-}11}$ of about 1.7 dB. Figure 4(b) shows the amplification properties obtained with the void. It can be seen that $\Delta G_{01\text{-}11}$ was successfully reduced while keeping the similar gain and NF characteristics over 400 mW pump power. Figure 4(c) shows the gain difference between LP_{01} and LP_{11} modes obtained with and without a 6.8 μm diameter void. From Fig. 4(c), it is seen that $\Delta G_{01\text{-}11}$ was successfully reduced from 1.7 dB to 0.5 dB by adding void induced EDF. However gain and NF at pump powers under 200 mW were also degraded by introducing the void. It may be considered that attenuation in pump light caused the degradation in gain and NF particularly at lower pump power, but additional examination is needed.

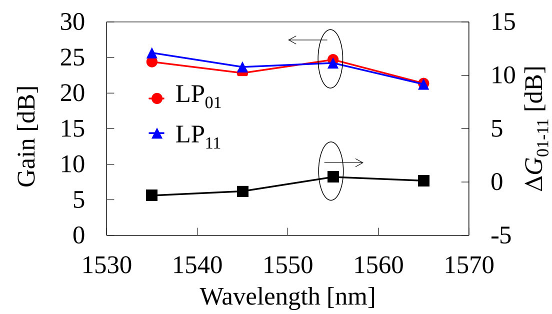


Fig. 5 Wavelength dependence of gain and ΔG measured when void diameter and pump power were at 6.8 μm and 685 mW, respectively.

Figure 5 shows the wavelength dependence of gain (red and blue symbols) and $\Delta G_{01\text{-}11}$ (black symbols) when pump power and void diameter were 685 mW and 6.8 μm, respectively. Circles and triangles correspond to the gain of LP_{01} and LP_{11} modes, respectively. Figure 5 confirms that $\Delta G_{01\text{-}11}$ was −1.2~0.5 dB over the C-band with no noticeable degradation in gain or gain flatness. These results reveal that DMG in TM-EDF can be effectively reduced by simply using the laser inscription technique and splicing to set one void into the EDF.

4. Conclusion

We proposed laser inscription based DMG control technique, and revealed the validity of the proposed technique by test on a step index type TM-EDF. DMG reduction of 1.2 dB was achieved while keeping sufficient gain, NF and flatness in the entire C-band by simply introducing one 6.8 μm diameter void into the TM-EDF. Proposed technique is beneficial for realizing DMG managed amplifiers and/or transmission lines.

5. Reference

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