## Article

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# Differential mode-gain equalization via femtosecond laser micromachining-induced refractive index tailoring

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## Abstract

The mode-division multiplexing technique combined with a few-mode erbium-doped fiber amplifier (FM-EDFA) demonstrates significant potential for solving the capacity limitation of standard single-mode fiber (SSMF) transmission systems. However, the differential mode gain (DMG) arising in the FM-EDFA fundamentally limits its transmission capacity and length. Herein, an innovative DMG equalization strategy using femtosecond laser micromachining to adjust the refractive index (RI) is presented. Variable mode-dependent attenuations can be achieved according to the DMG profile of the FM-EDFA, enabling DMG equalization. To validate the proposed strategy, DMG equalization of the commonly used FM-EDFA configuration was investigated. Simulation results revealed that by optimizing both the length and RI modulation depth of the femtosecond laser-tailoring area, the maximum DMG (DMG<sub>max</sub>) among the 3 linear-polarized (LP) mode-group was mitigated from 10 dB to 1.52 dB, whereas the average DMG (DMG<sub>ave</sub>) over the C-band was reduced from 8.95 dB to 0.78 dB. Finally, a 2-LP mode-group DMG equalizer was experimentally demonstrated, resulting in a reduction of the DMG<sub>max</sub> from 2.09 dB to 0.46 dB, and a reduction of DMG<sub>ave</sub> over the C band from 1.64 dB to 0.26 dB, with only a 1.8 dB insertion loss. Moreover, a maximum range of variable DMG equalization was achieved with 5.4 dB, satisfying the requirements of the most commonly used 2-LP mode-group amplification scenarios.

**Keywords:** Mode-division multiplexing, Few-mode Erbium-doped fiber amplifier, Differential mode gain, Femtosecond laser micromachining

## Introduction

Recently, various network applications such as artificial intelligence, the Internet of Things, virtual reality, and

cloud computing are expected to rapidly deplete the transmission capacity based on standard single-mode fibers (SSMF). By extending the operation wavelength to the S-band, the SSMF-based transmission system has reached a capacity record of 206.1 Tb/s<sup>1</sup>. However, owing to the limitations originating from the fiber nonlinearity, further extending the transmission band to increase the capacity is not sustainable<sup>2</sup>. The mode-division multiplexing (MDM) technique, either by utilizing linear-polarized (LP) or the orbital angular momentum (OAM) mode as an independent

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transmission channel, has been regarded as a promising solution to mitigate the capacity limitations of traditional SSMF-based transmission systems<sup>3,4</sup>. To deploy a long-haul MDM transmission system, a few-mode Erbium-doped fiber amplifier (FM-EDFA) with the ability to wavelength simultaneously amplify the division multiplexing (WDM) signals within all the guided modes is indispensable because the transmission attenuation of the few-mode fiber (FMF) needs to be compensated. Nevertheless, the differential modal gain (DMG) arising in the FM-EDFA owing to the different overlapping integrals among the pump mode profile, erbium doping, and signal mode profile, limits both the capacity and reach of the MDM transmission<sup>5,6</sup>. Numerical results indicate that to achieve a 2000-km long-haul MDM transmission, an FMF link with a power variation of less than 1 dB is preferred<sup>7</sup>.

Several strategies have been proposed to minimize DMG, which can be divided into two categories. First, manipulation of the pump mode profile was implemented to achieve mode-selective Erbium-doped fiber (EDF) pumping<sup>8,9</sup>. Alternatively, a cladding pumping scheme was proposed to homogenize the pump intensity within the core region<sup>10,11</sup>. Second, the doping profile of the EDF was tailored to approach the optimal erbium ion distribution<sup>12-14</sup>. These methods offer a DMG of less than 2 dB, but either a complicated pump configuration or a precise refractive index (RI) design of the FM-EDF is compulsory, increasing the deployment cost and inconvenience. Because the DMG indicates the gain difference among all the guided modes, cascading a DMG equalizer with a variable mode-dependent attenuation after the FM-EDFA can significantly simplify the implementation of FM-EDFA. These DMG equalizers can be categorized into the following two types of configurations: free-space and allfiber. Free-space DMG equalizers include spatial light modulators (SLM) and silica-based planar light-wave circuit (PLC). By utilizing the spatial attenuation of the SLM, a range of variable DMG equalizations of 10 dB and an insertion loss (IL) of 5 dB can be achieved within the  $LP_{01}$  and  $LP_{11}$  mode-group<sup>15</sup>. However, 68% of the pumped power is expected to be dissipated. Meanwhile, a DMG equalizer based on a silica-based PLC with a 1.5 dB equalization range and 4 dB IL was demonstrated<sup>16</sup>. Again, only 40% of the pumped power was efficiently used for optical amplification. Therefore, both free-space DMG equalizers suffer from high manufacturing costs and severe ILs. The high IL of this type of DMG equalizer reduces the minimum gain of the FM-EDFA over the C-band. Alternatively, the all-fiber configuration offers the benefits of a low IL, easy maintenance, and excellent compatibility. By splicing a short-segment, small-core, single-mode fiber between two FMFs, a DMG equalizer with an 8 dB equalization range and 2 dB IL was reported<sup>17</sup>. A simulation study recently demonstrated that an all-fiber DMG equalizer based on cascaded long-period fiber gratings (LPFGs) can reduce the DMG to lower than 0.6 dB. However, this requires both, specially designed fibers and several LPFGs<sup>18</sup>. Given the persistent need for an efficient approach to provide concise and effective DMG equalization, it is imperative to explore viable methods to fulfill this objective.

Femtosecond laser micromachining has gained research interest worldwide owing to its ability to achieve both localized and permanent RI tailoring in various transparent media<sup>19-21</sup>. By manipulating the fabrication parameters, such as the pulse energy, laser repetition rate, and fabrication velocity, several functional optical devices have been successfully demonstrated, including Fabry-Perot interferometers<sup>22,23</sup>, fiber gratings<sup>24–27</sup>, light manipulators<sup>28–30</sup>, and mode converters<sup>31,32</sup>. These devices have been widely applied communication and to optical sensing technologies.

In this study, a novel DMG equalization strategy based on in-line femtosecond laser micromachining that tailors the RI was proposed and experimentally demonstrated. Variable mode-dependent attenuation can be applied to each guided mode group by introducing an RI tailoring area into the FMF core, leading to successful DMG equalization. To verify the flexibility of the proposed DMG equalization strategy, a commonly used FM-EDFA with uniform erbium doping and fundamental-mode corepumping was examined. First, when we numerically investigated the DMG increasing in the 3-LP mode-group FM-EDFA under variable pumping powers and EDF lengths, a detrimental DMG was identified. Subsequently, by optimizing the parameters of the DMG equalizer, including the femtosecond laser scanning length and width, and RI modification depth ( $\Delta n$ ) induced by varying the femtosecond laser scanning times, a 3-LP mode-group DMG equalizer with a variable range of DMG equalization was obtained, which can be used to mitigate the DMG by cascading the all-fiber DMG equalizer after the FM-EDFA. Finally, a 2-LP mode-group DMG equalizer was femtosecond experimentally fabricated via laser micromachining, which can significantly reduce the DMG with a minimal IL, and efficiently utilize the pumping power. Moreover, by modifying the scanning times of the femtosecond laser, the equalization range of the DMG equalizer can be efficiently adjusted to satisfy the requirements of the commonly used 2-LP mode-group FM-EDFA pumping configuration.

## Results

## DMG equalization strategy

Fig. 1 presents a schematic of the proposed DMG equalization scheme. Various guided modes with the same launch power were transmitted over the FMF, and all the guided modes experienced nearly the same attenuation. However, when the FM-EDFA was used to compensate for the transmission attenuation, a DMG occurred, which is defined as the maximum gain difference between the guided modes at a specific wavelength, as shown in Eq. 1

$$DMG(\lambda) = \max_{\substack{m \neq n}} |G(m,\lambda) - G(n,\lambda)|$$
(1)

where *G* is the gain value at the specific guide mode,  $\lambda$  is the operational wavelength, and *m* and *n* are the indices of the guided mode. Two metrics were defined to evaluate the performance of the DMG equalizer: DMG<sub>max</sub> and DMG<sub>ave</sub>.

The DMG<sub>max</sub> indicates the maximum DMG and DMG<sub>ave</sub> is the average DMG in Eq. 1. Subsequently, to minimize the DMG, an in-line DMG equalizer with different mode attenuations (DMA) is cascaded after the FM-EDFA, and the DMA is defined as follows:

$$DMA(\lambda) = A_{LP_{01}}(\lambda) - A_{HOM}(\lambda)$$
<sup>(2)</sup>

where  $A_{LP_{01}}$  is the attenuation of the LP<sub>01</sub> mode and  $A_{HOM}$  is the attenuation of the high-order modes (HOMs). By modifying the RI of the FMF core via femtosecond laser micromachining, a higher attenuation is applied to the LP<sub>01</sub> mode while minimizing its impact on the HOMs. Finally, the higher gain of the LP<sub>01</sub> mode can be effectively reduced by cascading the fabricated DMG equalizer, consequently achieving the DMG equalization of the FM-EDFA.

## Design of femtosecond laser micromachiningenabled DMG equalizer

Fig. 2a presents a schematic diagram of the proposed DMG equalizer. The femtosecond laser was focused on the core of the FMF to generate RI modulation. The modified RI region induced by the femtosecond laser was then modeled as a cuboid, whose width W, height H, length L, and RI modulation depth  $\Delta n$  can be flexibly manipulated by adjusting the femtosecond laser micromachining parameters, as shown in Fig. 2b, c. A simulation based on the beam propagation method was implemented to theoretically investigate the performance of the DMG, as shown in Fig. 2d. Various guided modes are expected owing to leakage of the fiber cladding, consequently suffering different attenuations. The  $LP_{01}$  mode, whose profile is mainly concentrated at the center, experiences a larger attenuation than that of the HOMs. As shown in Fig. 2d, different attenuations of the  $LP_{01}$ ,  $LP_{11}$  and  $LP_{21}$ modes were achieved by modeling a DMG equalizer in the FMF core. Because the degenerate modes are continuously and randomly coupled along the FMF, only the attenuation of the mode-group is considered. Therefore, by optimizing the DMG equalizer parameters, the variable-modedependent attenuation among the various mode-group can be obtained. Finally, an all-fiber DMG equalizer with a variable range was anticipated.

## Simulation results of 3-LP mode-group DMG equalizer

To verify the feasibility and advantages of the proposed DMG equalization strategy, a simple-structured and costeffective 3-LP mode group EDFA with uniform Erbium doping and fundamental mode core-pumping was numerically investigated to introduce a larger DMG and





identify the relationship between the DMG and pumping parameters, including the pumping power and EDF length, as shown in Fig. 3a.

## Discussion

As shown in Fig. 3a, when the pumping power and EDF length were varied from 200 to 600 mW and 1 to 7 m, respectively, the DMG between the 3-LP mode-group fluctuated from 4.8 dB to 16.2 dB. Subsequently, an FM-EDFA configuration with a 4.5 m EDF and 600 mW fundamental mode pump power was selected to verify the DMG equalization process, where the DMG<sub>max</sub> and DMG<sub>ave</sub> over the C-band were 10 dB and 8.95 dB, respectively, as shown in Fig. 3b.

The DMA of a 3-LP mode group DMG equalizer based on femtosecond laser micromachining to induce RI tailoring was numerically investigated. As shown in Fig. 4a, when the Land  $\Delta$ n values vary from 0 to 400  $\mu$ m and from 0 to -0.05, respectively, the DMA changes from 0 to 27.8 dB, which is sufficient to cover the entire DMG range of the 3-LP mode-group EDFA. Subsequently, the capability of the DMG equalization was numerically evaluated, as shown in Fig. 4b.

Before DMG equalization, a 4.5 m EDF was corepumped with a 600 mW, 980 nm laser in the fundamental mode, and the DMG<sub>max</sub> and DMG<sub>ave</sub> over the C-band were 10 dB and 8.95 dB, respectively. When a DMG equalizer with a length of 120  $\mu$ m and  $\Delta$ n of -0.02 was cascaded after the designated FM-EDFA, the DMG<sub>max</sub> decreased from 10 dB to 1.52 dB, and the average DMG<sub>ave</sub> over the C-band decreased from 8.95 dB to 0.78 dB.

As shown in Fig. 5a, the mode-dependent gain and DMG over the C-band of the 2-LP mode-group before the DMG equalization was initially characterized owing to the lack of the 3-LP mode-group EDF. The maximum gains of the  $LP_{01}$  and  $LP_{11}$  mode-group were greater than 21 dB and 20 dB, whereas the DMG<sub>max</sub> and DMG<sub>ave</sub> values over the C-band were 2.09 dB and 1.68 dB, respectively. The variations in the DMG with the scanning length L were investigated, as shown in Fig. 5b. When the length L of the DMG equalizer gradually increased with an interval of 20  $\mu$ m, the corresponding DMG<sub>max</sub> and DMG<sub>ave</sub> values after equalization were recorded under the different device lengths. When L increased from 0 to 300  $\mu$ m, DMG<sub>max</sub> gradually decreased from 2.09 dB to 0.46 dB, and DMG<sub>ave</sub> decreased from 1.68 dB to 0.26 dB. Thus, the optimal length L was fixed at 300 µm. Subsequently, the scanning time N was optimized, as shown in Fig. 5c. By increasing the femtosecond laser scanning time N, both DMG<sub>max</sub> and DMG<sub>ave</sub> increased, as a larger DMA occurred within the LP<sub>01</sub> and LP<sub>11</sub> mode-group. Therefore, the optimal value of both the length L and scanning times N were set to 300 µm and 1, respectively. Fig. 5d presents the gain profile and DMG after equalization of the DMG with the optimal fabrication parameters. The values of DMG<sub>max</sub> and  $DMG_{ave}$  decreased from 2.09 dB to 0.46 dB and from 1.64 dB to 0.26 dB, respectively. The maximum IL of the LP<sub>11</sub> mode-group after using the DMG equalizer was less than 1.9 dB over the C-band, ensuring 64% utilization of







the pump power.

A supercontinuum source (YSL Photonics) with an operational wavelength ranging from 450 to 2400 nm was launched into the FMF to obtain an intuitive vision of the inline DMG equalizer. Fig. 6a presents the top view of the DMG equalizer with a length of 300  $\mu$ m after a single femtosecond laser scan captured by a camera. The fabricated DMG equalizer was then cleaved to obtain a cross-sectional view of the DMG equalizer, as shown in Fig. 6b.

Because the theoretical DMG of the 2-LP mode-group reached up to 6 dB, the range of the in-line DMG equalizer was investigated by changing the scanning times N, as shown in Fig. 7. When N=1, the average attenuation of the DMG equalizer applied to the LP<sub>01</sub> mode was approximately 3.14 dB, whereas the LP<sub>11</sub> mode underwent an attenuation of 1.45 dB attenuation, leading to a 1.69 dB DMG equalization range. When N=2, the average attenuation values of the LP<sub>01</sub> and LP<sub>11</sub> mode-group are approximately 5.61 dB and 2.32 dB, respectively, resulting in a 3.29 dB range of DMG equalization. When N=3, the average attenuation value applied to the  $LP_{01}$  mode can reach 8.44 dB, introducing an additional attenuation of 3.05 dB to the  $LP_{11}$  mode. Therefore, the maximum range of DMG equalization was obtained at 5.39 dB. By introducing the geometric parameters of the DMG equalizer into the simulation, the variation of  $\Delta n$  induced by a single scan was approximately -0.01. Further increasing the scanning time can extend the range of DMG equalization, but it also presents a severe IL to the  $LP_{11}$ mode-group. In addition, the DMG equalizer introduced mode-crosstalk within the LP<sub>11</sub> mode-group, resulting in power oscillations. Both the IL and mode crosstalk of the  $LP_{11}$  mode can be reduced with a more precise physical



**Fig. 5** Characterization of the DMG equalization process. **a** Modal gain and DMG over the C-band before DMG-equalization obtained from the experimental measurements. Variations in the measured  $DMG_{max}$  and  $DMG_{ave}$  with respect to: **b** L, and **c** the scanning times N. **d** Experimentally measured modal gain and DMG over the C-band after DMG equalization.



size control of the femtosecond laser-induced RI tailoring area.

In summary, we demonstrated an inline DMG equalizer based on femtosecond laser micromachining-induced RI tailoring. The Simulation results revealed that the optimizing parameters of the femtosecond laser micromachining, including both the length L and RI modulation depth  $\Delta n$ , can change the range of DMG equalization. To verify the correct function of our proposed equalization strategy, a commonly used FM-EDFA with both a uniform doping FM-EDF and fundamental-mode core pumping was used in both the simulation and experiment. The simulation results demonstrate that when the pump power and EDF length varied from 200 to 600 mW and from 1 to 7 m, the DMG within the LP<sub>01</sub>, LP<sub>11</sub>, and LP<sub>21</sub> mode-group varied from 4.8 dB to 16.2 dB. By cascading the DMG equalizer with optimal values of the length L and  $\Delta n$ , the values of DMG<sub>max</sub> and DMG<sub>ave</sub> over the C-band decreased from 10 dB to 1.52 dB and from 8.95 dB to 0.78 dB, respectively. Finally, a proof-of-concept experiment demonstrated that the DMG<sub>max</sub> decreased from 2.09 dB to 0.46 dB, and the DMG<sub>ave</sub> values



over the C-band decreased from 1.64 dB to 0.26 dB. More importantly, the IL induced by the DMG equalization was less than 1.9 dB, indicating that 64% of the pumping power was efficiently utilized. The proposed DMG has a maximum equalization range of 5.4 dB, which satisfies the flexible application of the current FM-EDFA. A higher-order mode-group DMG equalization can be achieved with a more complicated RI modification pattern and higher-resolution femtosecond laser micromachining technology, which is ideally desirable for future long-haul MDM transmissions.

## **Materials and Methods**

### **Experimental setup**

The proposed DMG equalizer was fabricated using an ytterbium-doped femtosecond laser (Satsuma, Amplitude), which operated at a wavelength of 1030 nm, pulse width of 270 fs, and variable repetition frequency of 0-250 kHz. The laser was attenuated using a half-wave plate and a Glan prism before being focused onto the core of the FMF by a 20X objective (numerical aperture = 0.5). The FMF was positioned on a 3D motion stage (XMS-50, Newport) with a motion resolution of 50 nm. Real-time monitoring of the fabrication process and position reference of the laser focus plane were achieved when two CCDs were provided for the top and side views, respectively.

In addition, a real-time FM-EDFA mode-gain profile monitoring system was developed. The signal light from a multichannel tunable laser (TSP-1000, OVLINK) was fixed to -10 dBm for each mode-group and co-propagated with a 980 nm pump light at a fundamental mode via a few-mode wavelength division multiplexer (FMSIWDM-15-900-1-FA, YX). Subsequently, the signal and pump light were introduced into a 5 m uniformly-doped FM-EDF with a doping concentration of  $10^{25}$  m<sup>-3</sup>. Two selffabricated 2-LP mode-group (LP<sub>01</sub> and LP<sub>11</sub>) photonic lantern (PL) were used for mode-division multiplexing and demultiplexing. The state of polarization (SOP) of the light at the input port of  $PL_1$  was carefully adjusted using a polarization controller (PC) to achieve the maximum output power at the same output port of  $PL_2$ , and then fixed during fabrication and characterization. By conducting a measurement of the power transmission matrix of a pair of PLs, the mode crosstalk between the  $LP_{01}$  and  $LP_{11}$  modegroup was determined to be less than -13 dB. Finally, the spectra of the amplified signals were measured using an optical spectrum analyzer (OSA, AQ6370D, Yokogawa). Because the PL is mode-group-selective, the powers of the two  $LP_{11}$  output ports were summed as the power of the  $LP_{11}$  mode-group. This real-time DMG monitoring ensures that the fabrication process achieves optimal DMG equalization.

#### Numerical simulation

Numerical computations of the DMG equalizer were performed using the beam-propagation method (BPM). The relationship between the parameters of the DMG equalizer and DMA was investigated. As shown in Fig. 2d, the FMF used in the simulation had a step RI index with the same core/cladding diameter, the core RI was 1.4498 at 1550 nm. The white dotted area in Fig. 2d represents the DMG equalizer with a width of 4 µm, height of 13  $\mu$ m, length of 120  $\mu$ m, and  $\Delta$ n of -0.02. A cylinder with a bottom circular radius of 30 µm and height of 600 µm was set as the simulation region, which includes the DMG equalizer and corresponding input and output. The injection mode was the fiber mode of  $LP_{01}$ ,  $LP_{11}$ , and LP<sub>21</sub> respectively. Two degenerate modes (LP<sub>11a</sub> and  $LP_{11b}$ ) were individually injected into the simulation region and summed at the simulation output as one mode-group.

The DMG of the 3-LP mode-group FM-EDFA was simulated based on the two energy levels of the EDFA model<sup>33</sup>. The influence of the pump power and FM-EDF length on the DMG was investigated, as shown in Fig. 3a. The most commonly used pumping configurations of the

fundamental-mode core pumping and FM-EDF with a stepindex profile were used for the simulation. The FM-EDF used in the simulation had a step-index profile with a core/cladding diameter of 19/125  $\mu$ m. The RI of the FMF core was 1.4507 at 1550 nm, and the erbium ions were uniformly doped at a concentration of 10<sup>25</sup> m<sup>-3</sup>. The passive FMF used in the simulation had a step RI index with the same core/cladding diameter; the core RI was 1.4498 at 1550 nm. To obtain the gain profile and DMG between the LP<sub>01</sub>, LP<sub>11</sub>, and LP<sub>21</sub> mode-group under variable pumping powers and EDF lengths, the input signal power was fixed to -10 dBm for each mode-group.

As shown in Fig. 4a, the DMG equalizer used in the simulation had a width D and height H of 9  $\mu$ m and 10  $\mu$ m, respectively. The influence of the RI modulation depth  $\Delta n$  and length L on the DMA of DMG equalizer were investigated. To select the device parameters, the individual mode-group spectrum and DMG<sub>ave</sub> over the C-band were first obtained. Subsequently, an equalizer with different parameters would introduce various mode-group attenuations. By subtracting the DMA spectrum from the un-equalized mode gain spectrum, the DMG over the C-band and corresponding device parameters can be obtained, as shown in Fig. 4b.

#### **Device fabrication**

The DMG was fabricated using femtosecond laser micromachining. The pulse energy and repetition frequency of the femtosecond laser were set to  $1.8 \mu$ J and 30 kHz, respectively. The 3D motion stage was programmed to scan along the FMF core axis with a speed of 10  $\mu$ m/s to fabricate the DMG equalizer.

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#### Author contributions

C. Zhang conceived the idea and prepared the manuscript. S. Y. Zhang conducted the femtosecond laser micromachining process. Y. Zen prepared the FM-EDFA simulation results. Y. Wang conceived the

schematic image. M. Xiang and Di Lin participated in the manuscript discussion. S. N. Fu and Y. W. Qin supervised and managed the entire project. All authors participated in the data analysis and contributed to writing the manuscript.

#### Conflict of interest

Yuwen Qin is an Editor for the journal, and no other author has reported any competing interests.

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