Broadband Mode Scramblers for Few-Mode Fibers based on 3D Printed Mechanically Induced Long-Period Fiber Gratings

Xin Huang, Yongmin Jung, Yaping Liu, Kerrianne Harrington, and David J. Richardson

***Abstract*— We present simple, low loss and broadband mode scramblers for mode division multiplexed (MDM) transmission based on few-mode fibers. By simply shortening the length of the long-period fiber grating (LPFG), the optical bandwidth is significantly enhanced and >260 nm bandwidth is predicted in our simulations with a grating length of 0.613 cm. In an experimental demonstration we fabricate a mechanically induced LPFGs using a commercially available 3-dimentional (3D) printing technique and wideband operation is confirmed over the C band with a low loss (0.2 dB) and low mode dependent loss (0.1 dB).**

***Index Terms*—Few mode fibers; mode division multiplexing; 3D printing; mode scramblers**

I. Introduction

MODE Division Multiplexing (MDM) technology [1-3] has been shown to be a promising approach to increase the transmission capacity of optical fiber with substantial theoretical and experimental work on few-mode fiber (FMF) and multimode fiber systems conducted over the past decade or so. Mode dependent loss (MDL) and differential group delay (DGD) are two parameters in MDM transmission systems and ensuring low net values of both is critical in order to prevent capacity loss/outage and to reduce the computational complexity of the Multiple Input Multiple Output (MIMO) digital signal processing required at the receiver [4].

Recently, it has been reported that strong mode coupling [5, 6] is highly effective in reducing both the impact of MDL and accumulated DGD and various fiber optic mode scramblers (i.e. devices for inducing effective mode coupling amongst all the guided modes in an optical fiber) have been considered including those based on long-period fiber gratings [7-9], phase plates [10], microbends [11] and offset fiber splices/launches [12]. Long-period fiber grating (LPFG) solutions are particularly attractive, representing one of the most effective ways of promoting strong mode coupling with low loss in optical fibers. There have been several attempts to apply LPFGs in MDM transmission systems (both step-index and graded-index FMFs) [7-9]. However, it remains a challenge to simultaneously meet all of the performance requirements of a practical mode scrambler in terms of wide bandwidth operation, low insertion loss (IL) and a low MDL. It should be noted that LPFGs generally offer a limited optical bandwidth (typically ~10 nm) due to the strict phase matching conditions between modes and multiple LPFGs with different grating pitches are usually required to obtain sufficiently wide bandwidth mode mixing in FMFs. It is to be appreciated that the narrow bandwidths (or strict phase matching conditions) of LPFGs are essentially due to constructive interference from multiple beams diffracted by the periodic refractive index modulation and that greatly increased bandwidths can be achieved simply by reducing the number of these modulation periods (i.e. by shortening the length of the grating). This comes though at a cost in terms of coupling strength. Fortunately though, for mode scrambler applications, only moderate coupling between modes is required i.e. ~50-60% (not >99% as required for many other LPFG devices such a mode converters), providing considerable opportunity to design gratings to enable low loss mode coupling devices with appreciable optical bandwidth (~100's nm).

Here we systematically analyze how the optical bandwidth of the LPFG varies with design and propose a short grating device for low loss, low MDL and wideband mode scrambler for MDM transmission system based on FMFs. With a commercially available 3D printing technology, any corrugated structures can be readily fabricated in a low cost and highly flexible manner and 3D printed mechanically induced fiber gratings are examined in our experiment as a convenient means for creating various lengths of gratings in a FMF. As an exemplary demonstration, we experimentally demonstrate a mode scrambler for two mode group fiber supporting LP_{01} and LP_{11} modes and wideband mode coupling was confirmed with a low IL and a low MDL.

II. Design and simulations

In principle, energy transfer between guided modes in a FMF occurs only if the resonant condition of the LPFG is satisfied. The associated phase matching condition is given by:

$$\delta(\lambda) = \frac{1}{2}\left[\frac{2\pi}{\Lambda} - \Delta\beta(\lambda)\right] \quad (1)$$

Manuscript received December 13, 2021; accepted January 10, 2022. Date of publication January 18, 2022. This work was supported by the Engineering and Physical Science Research Council through grants EP/N00762X/1 and EP/P030181/1. Data contained in this paper is openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D2091.

X. Huang, Y. Jung, K. Harrington and D. J. Richardson are with the Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK. (email: x.huang@soton.ac.uk; ymj@orc.soton.ac.uk;k.harrington@soton.ac.uk; djr@orc.soton.ac.uk).

Y. Liu is with the Key Laboratory of Opto-electronics Information Technology of Ministry of Education, School of Precise Instrument and Opto-electronics Engineering, Tianjin University, Tianjin, China (email: liuyp@tju.edu.cn).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier

Copyright (c) 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

where $\delta(\lambda)$ is the detuning parameter, Λ is the grating period and $\Delta\beta(\lambda)$ is the difference between the propagation constants of the modes. For mode coupling between the LP_{01} and LP_{11} modes in a two-mode fiber (TMF), the resonant wavelength λ_{res} and bandwidth $\Delta\lambda$ [13] can be further expressed by:

$$\lambda_{res} = \left(n_{eff}^{01} - n_{eff}^{11}\right) \cdot \Lambda \quad (2)$$

$$\Delta\lambda \propto \lambda_{res}^2 / \left[L \cdot \left(n_{eff}^{01} - n_{eff}^{11}\right)\right] \quad (3)$$

where $L = N \cdot \Lambda$ is the grating length and N is the number of grating periods. n_{eff}^{01} and n_{eff}^{11} are the effective refractive indices of the LP_{01} and LP_{11} modes, respectively. Therefore, from this general analytic expression, it is clear that the optical bandwidth ($\Delta\lambda$) of the LPFG is inversely proportional to the grating length and the effective index difference between the two spatial modes.

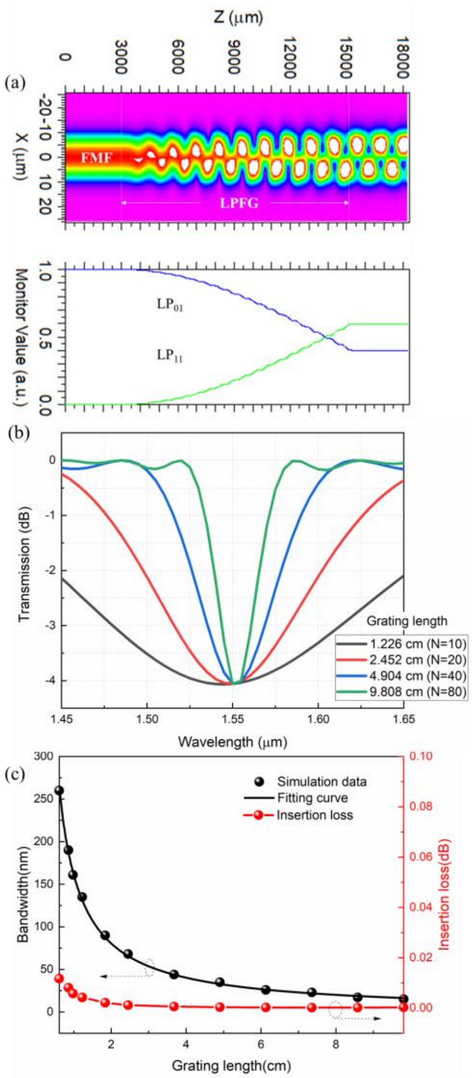

Fig. 1. (a) Beam propagation simulation of broadband TMF mode scrambler and (b) calculated transmission spectra and (c) 3 dB-bandwidths of the LPFGs with different grating lengths (for a fixed coupling strength of 60% at 1550 nm).

In order to quantitatively investigate the mode coupling and bandwidth change with grating length, we modelled the impact of a periodic refractive index (RI) modulation in a FMF using a finite difference beam propagation method (RSoft BeamPROP). According to ref. [14-16], two physical effects (i.e. geometrical deformation and the photo-elastic effect) are considered in our simulations. The geometrical deformation describes the physical deformation of the fiber cross-section when an external load is applied to an optical fiber and the photo-elastic effect represents the refractive index change resulting from strain-induced glass density changes. In Fig. 1(a), therefore, the coupling efficiency is related to both the RI variation and lateral core offset by the deformation and its amplitude depends on the load applied to the fiber. A simple step-index TMF (core diameter of 19.8 µm and a relative refractive index difference of 0.005) was used and the grating period (Λ) was selected to be 1226 µm to match the phase matching condition between the LP_{01} and LP_{11} modes at 1550 nm. Under initial pure LP_{01} mode excitation, the power in the fundamental mode is gradually transferred on propagation along the grating to the LP_{11} mode. Around 60% mode coupling efficiency is observed after propagation through 1.226 cm of fiber grating with an effective RI modulation of 1×10^{-4}. Under LP_{11} mode excitation, the same coupling efficiency can be obtained from the LP_{11} to the LP_{01} mode and that is why the LPFGs can be used as an effective mode scrambler for FMFs. We investigated how the optical bandwidth varies according to the grating length while maintaining the overall coupling efficiency at 60% (i.e. 4 dB coupling) at 1550 nm. Fig. 1(b, c) shows the calculated transmission spectra and 3 dB-bandwidths (i.e. >50% coupling efficiency) of the LPFGs with various grating lengths. In the case of a 9.808 cm LPFG, the 3-dB bandwidth was only 15 nm but it increased gradually with a decrease in grating lengths. Notably the increase in bandwidth increases exponentially with reduced grating length for gratings with lengths in the few centimeters regime and the 3-dB bandwidths of the 1.226 cm and 0.618 cm LPFGs were 135 nm and 260 nm, respectively. In Fig. 1(c), the black line follows the analytical prediction of Eq. (3) from simulated results (black dots). The red line is the IL of the LPFGs and it decreases with an increase in grating length. The maximum IL is found to be less than 0.02 dB and 0.06 dB for LP_{01} and LP_{11} mode excitation, respectively. This result indicates that short LPFGs represent a very effective way to realize broadband mode scramblers for FMFs.

III. Fabrication and Characterization

By taking advantage of affordable and highly flexible 3D printing technology, different lengths of LPFGs were designed using an OpenSCAD software and fabricated by the Stereolithography (SLA) process [17]. In SLA, an object is created by selectively curing a polymer resin in a layer-by-layer fashion using an ultraviolet laser. In our sample fabrication, a Formlabs Grey Pro Resin is used, which is a photosensitive polymer resin that offers high precision, fine details, moderate elongation and low creep at a minimum layer height of 50 µm. Fig. 2(a) shows an example of CAD designs with a periodic triangular corrugated surface. The dimensions of the sample are 50 mm (length)×16 mm (width)×3 mm (height). Fig. 2(b) shows a cross-sectional microscope image of the fabricated grating sample. Although there is a slight smoothening effect, a clear periodic triangular shape is observed. The individual layer lines are also visible from the side view of the 3D printed part. The measured_average grating pitch was ~1173 µm with ±10

Copyright (c) 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

µm variations (maximum-minimum value) and the average height of the vertices was ~230 ±10 µm.

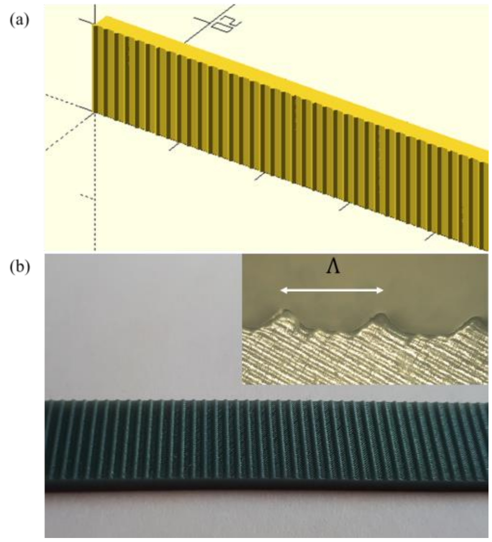

Fig.2. 3D printed grating device: (a) CAD design using an OpenSCAD software and (b) fabricated sample images (inset: microscope image).

First of all, the transmission spectra of the 3D-printed gratings was measured using a superluminescent diode (Thorlabs, S5FC1550P-A2) and optical spectrum analyzer. In order to make sure of pure LP_{01} mode excitation and detection, the TMF (having the same specifications as our simulation) was spliced with conventional single-mode fibers (SMFs) at both input and output ends. The TMF was sandwiched between a flat metal plate and the 3D printed LPFG and a compressive force was applied by adding a static load to the top plate. Fig. 3(a) shows the transmission spectra of the LPFGs with different grating lengths (10 cm, 5 cm, 2.5 cm, 1.25 cm). For the 10 cm long LPFG, the 3dB-bandwidth was only ~ 11 nm at 2.78 N total load. Notably more and stronger side lobes were observed with increased grating length, which is due to the fact that a longer grating has a narrow bandwidth and stronger sidelobes due to the Fourier transformation of the uniform grating distribution. As the grating length is decreased, however, we see a significant increase in optical bandwidth, which is in good agreement with our simulations. The 3dB-bandwidth of the 1.25 cm long LPFG was ~ 100 nm (from 1494 nm to 1594 nm), covering the whole C-band. The polarization dependence of 1.25 cm LPFG was also characterized by changing the input polarization via a fiber-loop polarization controller at the input SMF and just a minor transmission shift (2 nm) was observed.

In order to further confirm the 3-dB energy transfer between the LP_{01} and LP_{11} mode, a time-of-flight (or impulse response) measurement of the 1.25 cm-long LPFG was carried out. A mode-locked femtosecond pulsed fiber laser was launched into our mode scrambler and the output signal was detected by a digital sampling scope after propagating through a 10 km-length of the TMF. As each mode of interest possesses a distinct group velocity and the light in different modes will arrive at the end of the fiber at different times and we can readily distinguish different spatial modes with their DGDs (DGDs) and identify the relative power distribution excited by the LPFG. As shown in Fig. 3(b), an almost equal power distribution was observed between the LP_{01} and LP_{11} modes with the LPFG under a load of 1.5 N load and the mode coupling efficiency remains relatively constant over the C-band from 1535 nm to 1560 nm, which is in good agreement with the transmission spectra in Fig.3(a).

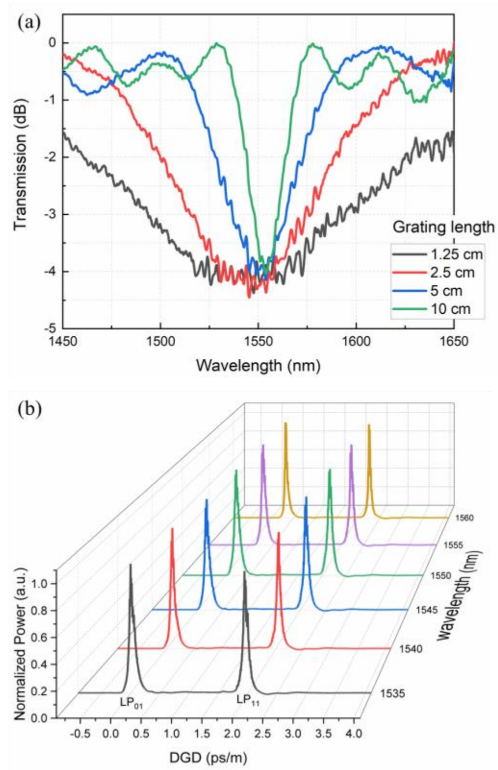

Fig.3. (a) Measured LPFG transmission spectra with different grating lengths and (b) the impulse response of 1.25 cm-long LPFG.

To further characterize the mode mixing properties of the device, a time-of-flight measurement was carried out in conjunction with mode selective excitation using a mode multiplexer based on phase plates [18]. Under LP_{01} mode excitation, as shown in Fig. 4(a), most of the light power was in the LP_{01} mode but the power in LP_{01} is gradually coupled to LP_{11} mode with applied load. The coupling efficiency reaches ~50% when the load is 1.5 N and a periodic power oscillation was found between two spatial modes as the load is further increased. The IL was less than 0.2 dB at loads under 2.25 N. Under LP_{11} mode excitation, interestingly, the mode conversion efficiency strongly depends on the lobe orientation of the LP_{11} mode (i.e. whether the LP_{11a} or LP_{11b} mode is excited). For LP_{11a} mode excitation (i.e. vertical orientation which is the same direction as the external force), as shown in Fig. 4(b), optical power gradually shifted from the LP_{11} to LP_{01} mode and the coupling efficiency can reach to ~50% at 1.5 N and ~80% at 3 N, which is consistent with the LP_{01} excitation case. The IL for LP_{11a} mode excitation was less than 0.2 dB for loads under 2.25 N. Under LP_{11b} excitation (i.e. horizontal orientation), however, there is barely any mode coupling from the LP_{11b} to LP_{01}, as shown in Fig. 4(c). This phenomenon arises from the asymmetry of the LPFG, where the load is applied vertically at the top of the fiber and the fiber experiences unidirectional

Copyright (c) 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

lateral offset or deformation [14]. Therefore, the efficiency of mode coupling is maximized when the direction of the local deformation matches the lobe direction of the LP_{11} mode. We believe that this aspect can be addressed by creating a more symmetric grating using other fabrication techniques such as ultraviolet light inscription, CO_2 laser irradiation, arc discharge or periodic tapering but this topic is beyond the scope of this paper.

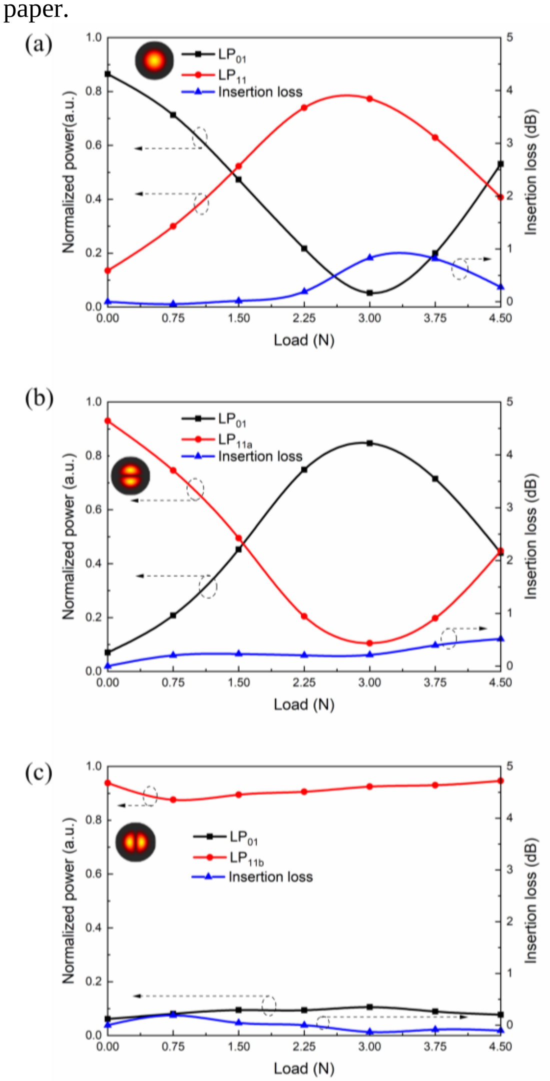

Fig. 4. Mode coupling properties of the mode scrambler under pure (a) LP_{01}, (b) LP_{11a} and (c) LP_{11b} mode excitation at different loads.

IV. Conclusion

In conclusion, low-loss and broadband FMF based mode scramblers have been successfully demonstrated using 3D-printed LPFGs. The optical bandwidth of the LPFGs was substantially improved by shortening the device length (i.e. number of periods of index modulation) and >260 nm bandwidth was predicted in our simulation with a 0.613-cm long LPFG. In our experiment, a 1.25-cm long LPFG was successfully fabricated using a commercial 3D printing technique and 100 nm bandwidth was confirmed over the C band with a low insertion loss (0.2 dB) and low mode dependent loss (0.1 dB). This short fiber grating approach can be further applicable to optical fibers with a larger number of spatial modes (both step-index and graded-index profiles) and should be able to provide an efficient way of mode scrambling for successful MDM transmission.

References

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson, “Space-division multiplexing in optical fibres,” *Nat. Photon.*, vol. 7, no. 5, pp. 354–362, Apr. 2013.

[2] P. J. Winzer, “Energy-efficient optical transport capacity scaling through spatial multiplexing,” *IEEE Photon. Technol. Lett*., vol. 23, pp. 851-853, July 2011.

[3] V.A.J.M. Sleiffer, Y. Jung, V. Veljanovski, R.G.H. van Uden, M. Kuschnerov, H. Chen, B. Inan, L. Grüner-Nielsen, Y. Sun, D.J. Richardson, S.U. Alam, F. Poletti, J.K. Sahu, A. Dhar, A.M.J. Koonen, B. Corbett, R. Winfield, A.D. Ellis, and H. de Waardt, “73.7Tb/s (96x3x256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA,” *Opt. Express*, vol. 20, pp. B428-438, 2012.

[4] Randel, Sebastian, Roland Ryf, Alberto Sierra, Peter J. Winzer, Alan H. Gnauck, Cristian A. Bolle, René-Jean Essiambre, David W. Peckham, Alan McCurdy, and Robert Lingle. "6× 56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6× 6 MIMO equalization." *Opt. Express*, vol.19, no. 17, pp. 16697-16707, 2011.

[5] K. -P. Ho and J. M. Kahn, “Mode-dependent loss and gain: statistics and effect on mode-division multiplexing,” *Opt. Express*, vol. 19, no. 17, pp. 16612-16635, 2011.

[6] K. -P. Ho and J. M. Kahn, “Statistics of group delays in multimode fiber with strong mode coupling,” *J. Lightwave Technol.*, vol. 29, no. 21, pp. 3119–3128, 2011.

[7] Huiyuan Liu, He Wen, Bin Huang, Rodrigo Amezcua Correa, Pierre Sillard, Haoshuo Chen, Zhihong Li and Guifang Li, “Reduced group delay spread using uniform long-period gratings,” *Sci. Rep.*, vol. 8, 3882, 2018.

[8] Jian Fang, An Li, and William Shieh, "Low-DMD few-mode fiber with distributed long-period grating," *Opt. Lett.*, vol. 40, pp. 3937-3940, Sep. 2015.

[9] Haoshuo Chen, Nicholas K. Fontaine, Bin Huang, Roland Ryf, and Ian Giles, „Demonstration of mode scramblers supporting 6 spatial modes to reduce differential group delays,” Proc. of ECOC’17, pp. W2F3, 2017.

[10] J. Li, N. K. Fontaine, H. Chen, R. Ryf, M. Cappuzzo, R. Kopf, Al Tate, H. Safar, C. Bolle, D. T. Neilson, E. Burrows, K.W. Kim, P. Sillard, F. Achten, J. Du, Z. He, M. Bigot, A. Amezcua-Correa, R. Amezcua Correa, and J. Carpen “Design and Demonstration of Mode Scrambler Supporting 10 Modes Using Multiplane Light Conversion,” Proc. of ECOC’18, pp. 1-3, 2018.

[11] Lei Su, Kin Seng Chiang, and Chao Lu, “Microbend-induced mode coupling in a graded-index multimode fiber,” *Appl. Opt.*, vol. 44, pp. 7394-7402, 2005.

[12] Stefan Warm and Klaus Petermann, “Capacity increase in spliced mode-multiplexed transmission systems by using mode mixers,” IEEE Summer Topical, TuC3.3, Jul. 2012.

[13] A. M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, J. E. Sipe, and T. E. Ergodan, “Long-period fiber gratings as band-rejection filters,” *J. Lightwave Tech.*, vol. 14, no. 1, pp. 58-65, Jan. 1996.

[14] R. C. Youngquist, J. L. Brooks and H. J. Shaw, “Two-mode fiber modal coupler,” Opt. Lett., vol. 9, no. 5, pp. 177-179, May 1984.

[15] S. J. Garth, “Intermodal coupling in an optical fiber using periodic stress,” Appl. Opt., vol. 28, no. 3, pp. 581-587, Feb. 1989.

[16] Peter D. Gianino and Bernard Bendow, “Calculations of stress-induced changes in the transverse refractive-index profile of optical fibers, Appl. Opt., vol. 20, no. 3, pp. 430-434, Feb. 1981.

[17] Ferry P. W. Melchels, Jan Feijen and Dirk W. Grijpma, “A review on stereolithography and its applications in biomedical engineering,” *Biomaterials*, vol. 31, no. 24, pp. 6121-6130, Aug. 2010.

[18] Y. Jung, Q. Kang, J. Sahu, B. Corbett, J. O’Callagham, F. Poletti, S. Alam, and D. J. Richardson, “Reconfigurable modal gain control of a few-mode EDFA supporting six spatial modes,” *IEEE Photon. Tech. Lett.*, vol. 26, no. 11, pp. 1100-1103, Jun. 2014.

Copyright (c) 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.