Femtosecond laser inscribed parallel long-period fiber gratings for multi-channel core mode conversion

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Abstract: We propose and demonstrate the inscription of parallel long-period gratings (LPGs) in a few-mode fiber (FMF) using femtosecond lasers. Mode conversion from the fundamental mode LP_{01} mode to high order core modes including LP_{11}, LP_{21}, LP_{31}, LP_{02}, and LP_{12} modes is achieved by controlling the inscription period of the gratings. Taking advantage of the highly focused femtosecond laser, LPGs with different off-axis offsets were fabricated, and the resonance wavelength and the inscription efficiency of the gratings versus the offset were investigated. Based on the off-axis writing technique and using the femtosecond laser source, we wrote parallel LPGs that contain multi-gratings in a single FMF and achieved a multi-channel core mode converter in a single FMF with flexibility in terms of the resonant wavelength and mode conversion among different modes. This approach offers a new option for implementing with high integration, and a multi-channel mode converter, which could find potential applications in the FMF multi-wavelength laser system, and wavelength/mode division multiplex communication system. Furthermore, this microstructured LPGs integrated into an optical fiber can be used as a multifunctional sensor.

1. Introduction

Mode-division multiplexing (MDM) communication system based on few-mode fiber (FMF) can effectively solve the problem of the single-mode fiber (SMF) communication capacity bottleneck [1-2]. The flexible generation and conversion of high-order modes are highly desired in the MDM system. A variety of mode converters are considered, e.g., spatial light modulator (SLM), phase plate, and fiber devices [3-6]. Although both SLM and phase plate possess the extraordinary ability to generate high-order spatial modes of high purity, the bulk-optic components are susceptible to external environments, exacerbated by the very demanding collimation of light for the all-fiber system. This not only affects the compactness of the all-fiber system but also induces extra cost. In recent years, all-fiber mode converters like mode selective coupler, photonic lantern, fiber Bragg grating (FBG), and long-period grating (LPG) have attracted extensive attention due to their high performance, low insertion loss, robustness, and compact structure [5-8].

LPG-based mode converters have been widely studied due to their flexible fabrication. The usual approach to the fabrication of LPG in an FMF is using CO_2-laser techniques, including point-to-point writing technology and laser heating technology [5, 9]. As an alternative, oxygen flame heating technology and arc discharge technology are also demonstrated to write LPGs in FMFs [10-11]. These techniques allow achieving high-order modes conversion but with the obvious disadvantages. The heated region using these techniques cannot be made small due to the laser beam size or the arc area, which is usually larger than 50 μm, and the duty cycle of the grating is fixed. As a result, the conversion among higher-order modes, in particular, simultaneous conversion to multiple higher-order modes in a single fiber is challenging since the conversion between higher-order modes often requires a smaller grating period and a more precise modulation to the refractive index [12-13]. Although the simultaneous generation of two high order modes using CO_2-laser inscribed LPGs were reported, e.g., cascaded helical LPGs, high diffraction order helical LPG [9, 14], the cascaded helical LPGs often require longer grating lengths, which cause the difficulty integrating the gratings [14]. For a high diffraction order helical LPG, the resonance wavelengths of different high order modes have interdependence, which is hard to control [9]. Owing to the large spot diameter (tens of microns) of the heating region again, the above methods are difficult to inscribe microstructures locally in the fiber to achieve mode manipulation.

By contrast, the femtosecond laser has the ability to precisely process materials and it has been thoroughly researched for many years, it can break the chemical bond and precisely modify the refractive index of the fiber material. The focused laser can modify the refractive index in a very localized and tiny region for the absorption of the femtosecond laser is nonlinear and its cross-section can break the diffraction limit [15]. Femtosecond laser-based inscription of optical fiber microstructure devices has been widely reported, including helical LPG [16], parallel-integrated FBGs inscribed in the core and cladding of SMF [17-18], and off-axis LPGs with different off-axis offsets [19], and so on. These works pave the way for a completely new class of integrated fiber mode converters. Mode conversion between different core modes based on LPG inscribed by a femtosecond laser has been demonstrated [20, 21], but only mode conversion between LP_{01} and LP_{11} mode has been achieved. Moreover, the problem of high grating insertion loss in Ref. [20] (more than 12 dB). Since the duty cycle of the LPG is too small, longer grating lengths are required in Ref. [21] (more than 6 cm). The simultaneous realization of mode conversion among different high-order modes at different wavelengths with a single device is still a challenge.

In this letter, we demonstrate a highly integrated mode converter for simultaneous mode conversion among different modes. Inscribed in an FMF by the femtosecond laser, the converter consists of multiple parallelled LPGs, each facilitating the conversion between the LP_{01} mode and a distinct higher-order core mode.

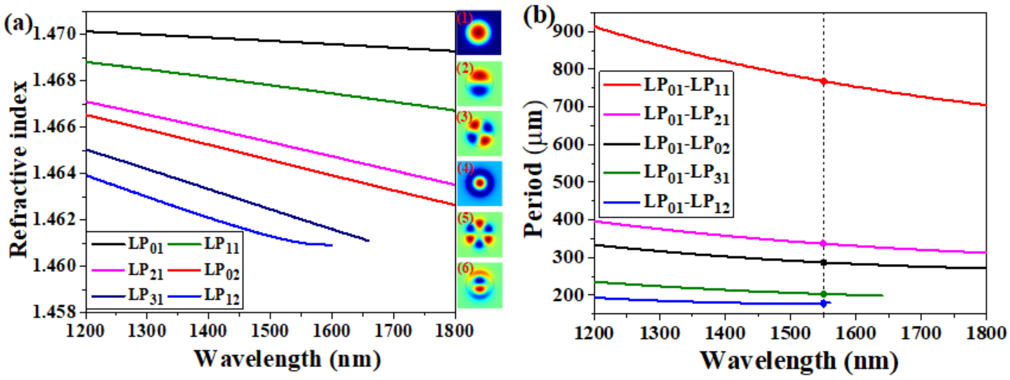

Fig. 1. (a) The simulated six-core modes effective refractive index of the FMF. (b) The calculated phase-matching curve for mode conversion between the fundamental and high-order core modes..

The fiber we used is a step-index FMF (YOCF, Six-mode fiber) with a core diameter of 16 μm and a cladding diameter of 125 μm. The refractive index of the core and the cladding is 1.454 and 1.444, respectively [12]. Analyzed with the finite element method using COMSOL MUTLIPHYSICS software, the fiber is found to support six core modes in wavelength of 1550 nm, including LP_{01}, LP_{11}, LP_{21}, LP_{02}, LP_{31}, and LP_{12}, respectively. Figure 1(a) shows their calculated effective refractive index versus wavelength, with the corresponding electric fields displayed to the right.

The mode conversion among different modes of a LPG is determined by the phase-matching condition: $\lambda = (n_{fundamental} - n_{high-order})\Lambda$, where $n_{fundamental}$ and $n_{high-order}$ are the effective refractive index of core fundamental and high order modes, respectively. λ is the resonance wavelength and Λ is the period of the LPG. Figure 1(b) shows the phase-matching curve for the realization of the mode conversion from the fundamental mode to different high-order core modes at different wavelengths. For example, the required grating period for mode conversion from LP_{01} to LP_{11} at a resonant wavelength of 1550 nm is 759 μm. Due to the larger difference in the equivalent refractive index between the higher-order modes and the fundamental mode, smaller grating periods are needed for the conversion from LP_{01} to higher-order modes. The femtosecond laser can be focused to a smaller spot size than that of a CO_2-laser and enables the inscription of an LPG of a smaller step size for the realization of the mode conversion from LP_{01} to higher-order core modes.

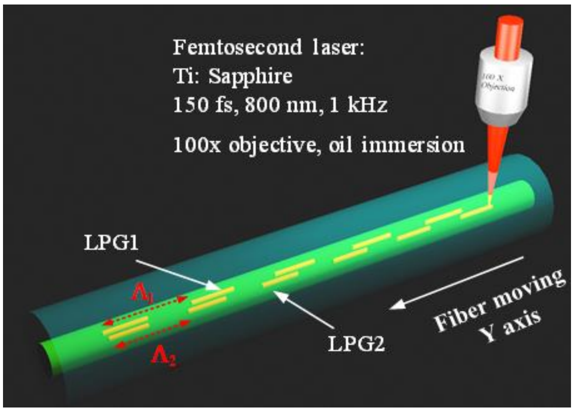

Fig. 2. Schematic diagram of the parallel LPG includes two grating with different periods. The two LPGs have different distances off the center in the fiber core.

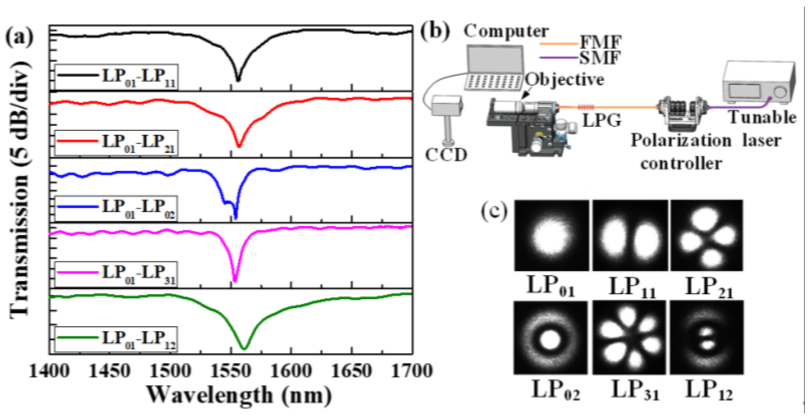

Fig. 3. (a) The measured transmission spectra of the FMF-LPGs for different high-order core modes conversion. (b) Schematic diagram of the measurement setup for observation of the mode pattern. (c) The observed near-field intensity distribution of the fundamental mode and the converted high-order core modes.

The femtosecond laser used in our experiment is an amplified Ti: Sapphire laser system (Spectra-Physics) operating at 800 nm, with a pulse duration of 150 fs and a repetition rate of 1 kHz. The fiber is immersed in a glass bath containing an index matching oil (RI: 1.518) and the oil is used to eliminate astigmatic aberrations induced by cylindrical fibers. The laser is focused into the fiber core by a 100x microscopic objective with a NA of 0.55 and a working distance of 13 mm. The fiber is fixed by two fiber clamps and a slight tension is applied to the fiber to keep the fiber straight. During the inscription of the LPG, the fiber is axially moved by a high precision air bearing translation stage (A3200, Aerotech), and by controlling the switching time of the shutter, a series of line-by-line refractive index modulation can be introduced in the fiber core. Figure 2 shows the schematic diagram of the line-by-line inscription of parallel LPG includes two gratings with different positions in the core region, each to achieve a different high order mode conversion.

We firstly inscribed five individual LPGs to achieve mode conversion between LP_{01} and LP_{11}, LP_{21}, LP_{02}, LP_{31}, LP_{12} modes at the 1550 nm waveband, and according to the simulation results in Fig. 1(b), the selected periods are 760 μm, 336 μm, 285 μm, 200 μm, and 170 μm, respectively. It should be noted that the peak loss of the LP_{01} mode of the LPG is given by $cos^2(kL)$, where k is the coupling coefficient proportional to the perturbation of the refractive index and L is the grating length. This provides the opportunity to control the conversion efficiency by varying k or L. With the grating length designed of about 1~2 cm, the number of periods for the five gratings are 15, 31, 50, 100, and 80, respectively and their duty cycles are 50%. To achieve similar conversion efficiency, variation of k is also taken into account, achieved by adjusting the moving speed and the energy of the femtosecond laser. After rounds of trial and error, the movement speeds of the fiber for the five mode converters were 0.08, 0.1, 0.06, 0.06, and 0.06 mm/s, respectively. And the femtosecond laser energies for writing gratings were measured at the entrance of the objective lens to be 1.7, 1.5, 1.85, 1.85, and 1.7 μJ, respectively. We find that the spectrum of the grating is strongly polarization-dependent and this is due to local asymmetric refractive index modulation introduced by the femtosecond laser. The transmission spectra of the gratings were measured with a polarized light source that is a broadband light source (Agilent 83437) followed by a polarizer and a polarization controller and recorded by an optical spectrum analyzer (AQ6370B, YOKOGAWA) with a resolution of 1.0 nm. Figure 3(a) shows the measured transmission spectra of the five mode converters. The central wavelengths of these LPGs are located around 1550 nm and the mode conversion efficiencies are higher than 99%. We investigated the polarization characteristics of the LPGs experimentally, and the results are given in Fig. S1 in Supplement 1. To confirm the mode conversion, the near-field intensity distributions of the converted high order modes are measured by a CCD camera (Digital CamIR1550 463125, Scintacor Ltd) with an objective lens placed at the fiber end, as shown in Fig. 3(b). A tunable laser acts as the probe light source. A polarization controller is placed behind the laser to optimize the polarization states for later measurements. By changing the wavelength of the laser source and fine-tuning the polarization controller, the fundamental mode and high-quality high-order mode patterns were observed, indicating that high-efficiency polarized mode conversion between LP_{01}-LP_{11}, LP_{01}-LP_{21}, LP_{01}-LP_{02}, LP_{01}-LP_{31}, and LP_{01}-LP_{12} modes can be achieved at the resonance wavelengths of LPGs. The insertion loss of these LPGs is below 2 dB.

For fabrication of multiple parallel LPGs in a single FMF, we then studied the spectrum characteristics of the LPG of different off-axis offsets from the fiber core. Figure 4(a) shows the transmission spectrum of a LPG without offset from the fiber center (black curve), which can convert the fundamental mode to a higher-order mode LP_{31}. The writing conditions are 0.05 mm/s for the scan velocity and 1.8 μJ for the pulse energy. The image on the top in Fig. 4(b) shows the microscope images of LPG without an offset viewed along the X-direction. When the LPG is inscribed at a position of a non-zero offset, for instance, 3 μm or 5 μm from the center as shown by the other two images of Fig.4(b), the resonant wavelength is found blue-shifted with an extent positively associated with the offset (See Fig. 4(a)). The femtosecond laser inscription can effectively increase the refractive index of the modified region. When the inscription is in the middle, the increase is maximal to the fundamental mode as its field is highest there. The effectiveness is less for other modes, especially for those that have a zero field in the middle. For offset inscription, increasing of refractive index to the core is less for the fundamental mode, while it increases for higher-order core modes, particularly for LP_{31}. As a result, $n_{fundamental} - n_{high-order}$ will be reduced, giving rise to a blueshift of the resonant peak of the LPG.

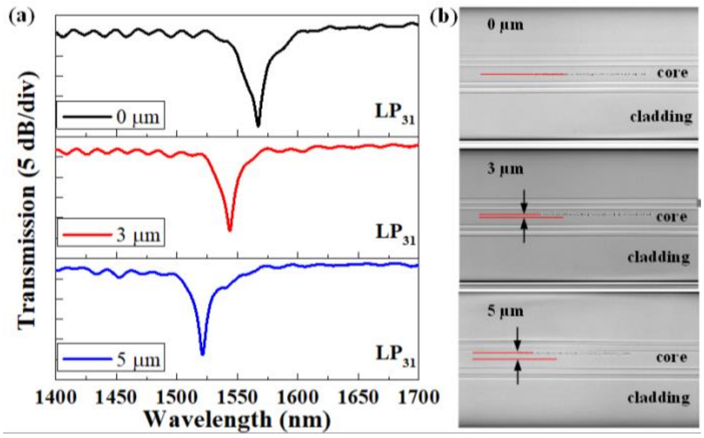

Fig. 4. (a) The measured transmission spectra of the off-axis LPG with different distances off the center in the core. (b) Microscope images of the refractive index modulation regions of the off-axis LPGs viewed in X-direction.

The writing efficiency of the gratings is noted to decrease significantly along with increasing of the offset. The coupling coefficient $\kappa \propto \int \delta n\, E_1 E_2^* dxdy$ will be integrated for the region where $\delta n \neq 0$, where E_1 and E_2 are the transverse electric field of fundamental and high order mode respectively. For the symmetric inscription, it happens in the middle where $\int_{\delta n \neq 0} E_1 E_2^* dxdy$ should be maximal, where for offset inscription, the integration could be reduced. This problem can be overcome by adding more periods. For instance, to realize the mode conversion from LP_{01} to LP_{31}, with an efficiency of ~20 dB, the period number is 65 for nill offset, while it needs to increase to 79/120 for an offset of 3/5 μm, respectively.

The parallel LPG is then fabricated by writing multiple LPGs with different off-axis offsets in the core of FMF. The core diameter of the FMF is 16 μm, which is several times larger than the height of the focused spot of the laser, by optimizing the grating arrangement and inscription parameters, the LPG arrays can be written in fiber core (both X- and Z- directions). Therefore the cross-coupling among LPGs in the core can be effectively avoided. Writing of the parallel LPG is a simple repetitive process: we first wrote one LPG, and then shift the focused spot from the axis and repeat the writing process, with the same start for all LPG. To achieve the mode conversion among specific modes for different LPGs, the writing speed and energy should be adjusted according to the offset and the grating period. Figure 5(a-1) shows the transmission spectrum of a parallel LPG of two-component gratings with offsets of 4 μm along the Z+ and Z- directions, respectively. Both gratings realize the LP_{01}-LP_{31} mode conversion and their periods are 206 and 199 μm, respectively, giving correspondent central wavelengths of 1479.2 and 1553 nm, respectively. The intensity distributions of the converted modes are shown on the top in Fig. 5(b). We noticed that the resonant wavelength of the first grating experiences a red-shift when the second grating is writing, it is proving that the refractive index perturbation is positive. When the femtosecond laser inscribes the second grating, the refractive index modulation would change the effective refractive index of the core mode, causing an increase in the refractive index difference between the fundamental mode and high order modes, and resulting in a resonance wavelength shift of the first grating.

Parallel LPGs that realize the mode conversion from the fundamental mode to different higher-order modes can also be fabricated. By setting the offset distance to 4/0 μm as well as choosing a grating period of 207/330 μm, we achieved the mode conversion between the LP_{01} mode to LP_{31} and LP_{21} modes in the parallel LPGs simultaneously (See the spectrum in Fig. 5(a-2) and the mode distribution in the mid of Fig. 5(b)).

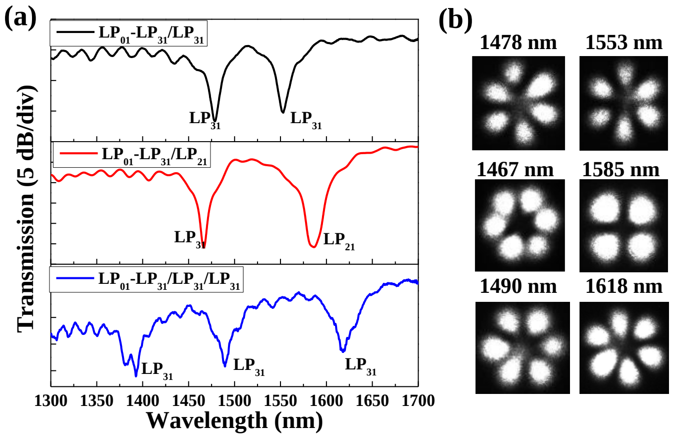

Fig. 5. (a) The measured transmission spectra of parallel LPGs with different parameters. (b) The measured mode pattern of the parallel LPGs at their resonance wavelengths.

The offset distance from the gratings to the fiber core provides the degree of freedom to write multi gratings in a single FMF, realizing the simultaneous mode conversion among modes in parallel LPGs. Figure 5(a-3) shows the transmission spectrum of the parallel LPGs including three gratings with the offset of +4 μm, -4 μm, and 0 μm from the core. The grating periods are 214, 207, and 197 μm, respectively. Three-channel LP_{01}-LP_{31} mode conversion is simultaneously realized at wavelengths of 1392.4, 1489.6, and 1619.8 nm, respectively. The bottom of Fig. 5(b) shows the measured mode pattern at 1489.6/1619.8 nm, confirming the mode conversion. The mode distribution at 1392.4 nm is not observed due to the wavelength limit of the tunable laser for measurement. The microscope image of part of the refractive index modulation regions of the parallel LPGs include three gratings is give in Fig. S2 in Supplement 1. Furthermore, by adjusting the grating period, it can realize the conversion of the fundamental mode to the same/different higher-order modes at different wavelengths. These integrated parallel LPGs can be used as a multi-channel mode converter. It should be point out, in Fig. 5(a), the insertion losses of the three types of parallel LPGs are measured to be 2.7, 6.1, and 8.1 dB. Moreover, the insertion loss is relatively high in short wavelength, which results from the Mie scattering [22]. The insertion loss can be reduced with decreased pulse energy, but for practical application, it is necessary to optimize the inscription parameters and balance the insertion loss.

In conclusion, we have demonstrated the inscription of parallel LPGs in a single FMF using a line-by-line femtosecond laser. Mode conversion between the fundamental core mode and higher-order core modes has been achieved experimentally. Furthermore, using the highly focused femtosecond laser, off-axis LPGs with different offsets from the fiber core were fabricated. Parallel LPGs were achieved by multi-grating with different offsets from the center in the core, the multi-channel mode converter experimentally demonstrated the conversion of the fundamental mode to the same/different high order modes at different wavelengths, respectively. The temperature sensitivity of the FMF-LPG based mode converter is much lower than that of conventional LPG [23]. Thus, the parallel LPGs show high potential as the high integration, temperature-insensitive multi-channel mode converter for applications in wavelength/mode division multiplex communication system.

Supplemental document.

The polarization-dependent loss (PDL) of the gratings for mode conversion between LP_{01}-LP_{11} modes, LP_{01}-LP_{21} modes, LP_{01}-LP_{02} modes, LP_{01}-LP_{31} modes, and LP_{01}-LP_{12} modes were measured by using an optical vector analyzer (OVA 5000, Luna) with a resolution of 0.15 pm. The PDL of the five mode converters is measured to be 23.1, 39.3, 22.1, 23.9, and 34.2 dB, respectively. Figure S1 (a) shows the measured PDL, maximum, and minimum loss spectra of the LPG with mode conversion between LP_{01} and LP_{31}. The high PDL could be attributed to the local asymmetric refractive index modulation in the fiber core. Figure S1 (b) shows the schematic diagram of a fiber cross-section of the LPG illustrating the refractive index modulation of the fiber core. The X+ is the laser irradiation direction, and Z-axis is perpendicular to the refractive index modulation plane. Figure S1(c) are the microscope images of the refractive index modulation in the X-Y and X-Z planes observed via microscope with a 40x oil objective. We can observe a significant refractive index modulation region along with the Y-direction of the fiber core. The height of the refractive index region is about 3.0 μm (See in the bottom image in Fig. S1 (c)), and the depth of the refractive index region is about 8.7 μm (See in the top image in Fig. S1 (c)), suggesting that the cross-section of the modulation region induced by the laser in the fiber core resembles an ellipse shape. This explains the high PDL of the gratings. The depth of the refractive index region can be reduced with decreased pulse energy, and reduce the asymmetry of the modulation area.

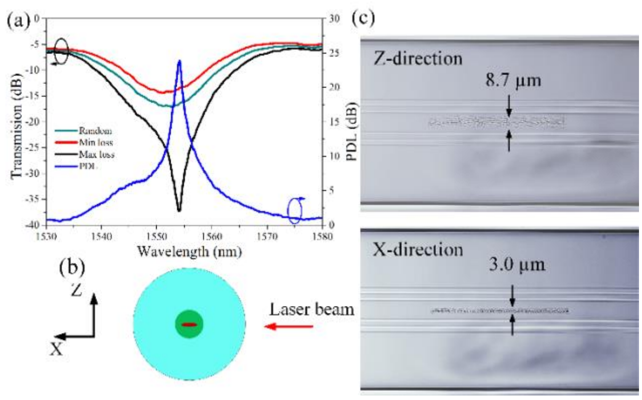

Figure S1 (a) The measured transmission spectrum and PDL spectrum of the LPG with mode conversion between LP_{01} and LP_{31} modes. (b) Schematic diagram of the refractive index modulation of the fiber grating cross-section. (c) Microscope images of the refractive index modulation regions were viewed in X- and Z- directions.

Figure S2 shows the microscope image of part of the refractive index modulation regions of the parallel LPG includes three gratings viewed in the X-direction.

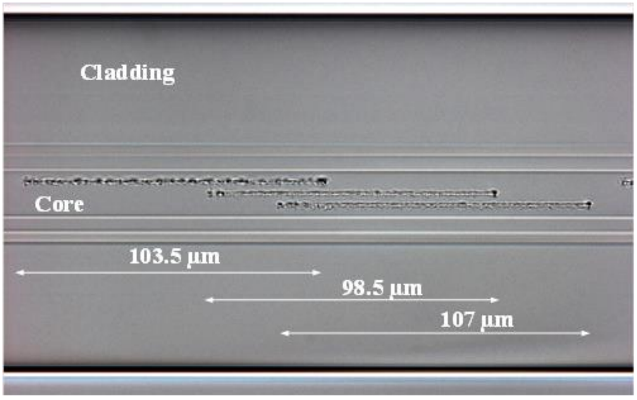

Figure S2 Microscope images of the modified regions by the femtosecond laser for the three parallel LPGs with different periods viewed in X-direction.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See Supplement 1 for supporting content.

Full References

1. N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A.E. Willner, and S. Ramachandran, “Terabit-scale orbital angular momentum mode division multiplexing in fibers,” science, **340**(6140), pp.1545-1548 (2013).
2. P. Gregg, P. Kristensen, A. Rubano, S. Golowich, L. Marrucci, and S. Ramachandran, “Enhanced spin orbit interaction of light in highly confining optical fibers for mode division multiplexing,” Nature Communications, **10**(1), pp.1-8 (2019).
3. Y. Ohtake, T. Ando, N. Fukuchi, N. Matsumoto, H. Ito, and T. Hara, “Universal generation of higher-order multiringed Laguerre-Gaussian beams by using a spatial light modulator,” Optics Letters, **32**(11), pp.1411-1413 (2007).
4. G. Ruffato, M. Massari, and F. Romanato, “Generation of high-order Laguerre–Gaussian modes by means of spiral phase plates,” Optics Letters, **39**(17), pp.5094-5097 (2014).
5. Y. Zhao, Y. Liu, C. Zhang, L. Zhang, G. Zheng, C. Mou, J. Wen, and T. Wang, “All-fiber mode converter based on long-period fiber gratings written in few-mode fiber,” Optics Letters, **42**(22), pp.4708-4711 (2017).
6. S.G. Leon-Saval, N.K. Fontaine, J.R. Salazar-Gil, B. Ercan, R. Ryf, and J. Bland-Hawthorn, “Mode-selective photonic lanterns for space-division multiplexing,” Optics Express, **22**(1), pp.1036-1044 (2014).
7. S. Pidishety, S. Pachava, P. Gregg, S. Ramachandran, G. Brambilla, and B. Srinivasan, “Orbital angular momentum beam excitation using an all-fiber weakly fused mode selective coupler,” Optics Letters, **42**(21), pp.4347-4350 (2017).

8. M.M. Ali, Y. Jung, K.S. Lim, M.R. Islam, S.U. Alam, D.J. Richardson, and H. Ahmad, "Characterization of mode coupling in few-mode FBG with selective mode excitation," IEEE Photonics Technology Letters, **27**(16), pp.1713-1716 (2015).
9. T. Detani, H. Zhao, P. Wang, T. Suzuki, and H. Li, "Simultaneous generation of the second-and third-order OAM modes by using a high-order helical long-period fiber grating," Optics Letters, **46**(5), pp.949-952 (2021).
10. L. Shao, S. Liu, M. Zhou, Z. Huang, W. Bao, Z. Bai, Z. Liu, G. Zhu, Z. Sun, J. Zhong, and Y. Wang, "High-order OAM mode generation in a helical long-period fiber grating inscribed by an oxyhydrogen-flame," Optics Express, **29**(26), pp.43371-43378 (2021).
11. B. Li, X. Zhan, M. Tang, L. Gan, L. Shen, L. Huo, S. Fu, W. Tong, and D. Li, "Long-period fiber gratings inscribed in few-mode fibers for discriminative determination," Optics Express, **27**(19), pp.26307-26316 (2019).
12. X. Zhao, Y. Zhao, Y. Liu, Z. Liu, C. Mou, L. Shen, L. Zhang, and J. Luo, "High-order mode conversion in a few-mode fiber via laser-inscribed long-period gratings at 1.55 μm and 2 μm wavebands," Applied Optics, **59**(34), pp.10688-10694 (2020).
13. X. He, J. Tu, X. Wu, S. Gao, L. Shen, C. Hao, Y. Feng, W. Liu, and Z. Li, "All-fiber third-order orbital angular momentum mode generation employing an asymmetric long-period fiber grating," Optics Letters, **45**(13), pp.3621-3624 (2020).
14. P. Wang, H. Zhao, T. Detani, and H. Li, "Simultaneous generation of the first-and second-order OAM using the cascaded HLPGs," IEEE Photonics Technology Letters, **32(**12), pp.685-688 (2020).
15. K. Zhou, F. Shen, G. Yin, and L. Zhang, "Optical fiber micro-devices made with femtosecond laser," In Optical Sensors 2016 (pp. SeW3D-1), Optical Society of America.
16. J. Chen, Z. Bai, G. Zhu, R. Liu, C. Huang, Z. Huang, L. Wu, C. Liao, and Y. Wang, "Femtosecond laser inscribed helical long period fiber grating for exciting orbital angular momentum," Optics Express, **30**(3), pp.4402-4411 (2022).
17. F. Chen, X. Li, R. Wang, and X. Qiao, "Multiple cladding fiber bragg gratings inscribed by femtosecond laser point-by-point technology" Journal of Lightwave Technology **39**(23), pp.7539-7544 (2021).
18. Y. Wang, Z. Li, S. Liu, C. Fu, Z. Li, Z. Zhang, Y. Wang, J. He, Z. Bai, and C. Liao, "Parallel-integrated fiber Bragg gratings inscribed by femtosecond laser point-by-point technology," Journal of Lightwave Technology, **37**(10), pp.2185-2193 (2019).
19. M. Heck, G. Schwartz, R.G. Krämer, D. Richter, T.A. Goebel, C. Matzdorf, A. Tünnermann, and S. Nolte, "Control of higher-order cladding mode excitation with tailored femtosecond-written long period fiber gratings," Optics Express, **27**(4), pp.4292-4303. (2019).
20. Y. Zhao, Y. Liu, C. Mou, N. Gordon, K. Zhou, L. Zhang, and T. Wang, "Femtosecond laser inscribed axial long-period fiber gratings in two-mode fiber for efficient optical angular momentum generation," In Optical Fiber Communication Conference 2017 (pp. W2A-14), Optical Society of America.
21. C. Yang, C. Zhang, S. Fu, L. Shen, Y. Wang, and Y. Qin, "Mode converter with C+L band coverage based on the femtosecond laser inscribed long period fiber grating," Optics Letters, **46**(14), pp.3340-3343 (2021).
22. M. L. Åslund, N. Nemanja, N. Groothoff, J. Canning, G. D. Marshall, S. D. Jackson, A. Fuerbach, and M. J. Withford, "Optical loss mechanisms in femtosecond laser-written point-by-point fibre Bragg gratings," Opt. Express **16**(18), pp. 14248–14254 (2008).
23. J. Dong, and K.S. Chiang, "Temperature-insensitive mode converters with CO_2-laser written long-period fiber gratings," IEEE Photon. Technol. Lett. 27(9), pp.1006-1009 (2008).