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Superior ultrafast laser inscribed photonic-lantern mode (de)multiplexer using trajectory-asymmetry with uniform waveguides

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Abstract: Femtosecond laser fabrication technology has been applied to photonic-lantern mode (de)multiplexer for recent years, which is popular for its advantage of three-dimensional fabrication capability. The current designs of photonic-lantern mode (de)multiplexer based on femtosecond laser fabrication technology mostly follow the fiber-type photonic-lantern design, which use trajectory-symmetry structures with nonuniform waveguides for selective mode excitation. However, the nonuniform waveguides could lead to inconsistent waveguide transmission losses and coupling losses. The trajectory-symmetry designs are also inefficient for selective mode excitation. Hence, we optimize the design by using trajectory-asymmetry with uniform waveguides and fabricate superior ultrafast laser inscribed photonic-lantern mode (de)multiplexers. The consistent waveguide transmission losses of 0.1 dB/cm and coupling losses of 0.2 dB/facet at 1550 nm are obtained on the uniform single-mode waveguides. Based on the trajectory-asymmetry design for photonic-lantern mode (de)multiplexer, efficient modes excitation (LP_{11}^{a}, LP_{11}^{b}, and LP_{01}) with average insertion losses as low as 1 dB at 1550 nm are achieved with the mode dependent losses less than 0.3 dB. The photonic lantern design is polarization insensitive with the polarization determined losses are less than 0.2 dB. Along with polarization multiplexing realized by fiber-type polarization beam splitters, six signal channels (LP_{11x}^{a}, LP_{11y}^{a}, LP_{11x}^{b}, LP_{11y}^{b}, LP_{01x}, and LP_{01y}), each of which carries 42 Gaud/s quadrature phase shift keying signal, are transmitted through the few-mode fiber for optical transmission. The average insertion losses of the system are less than 5 dB. The maximum crosstalk of the system with few-mode fiber is less than -12 dB, leading to a power penalty of 4 dB. This work paves the way for the practical application of 3D integrated photonic chip in high-capacity optical transmission systems.

1. Introduction

During the last decades, the explosive demand for communication traffic has significantly pushed the capacity growth of optical communication systems, thereby causing the rapid development of modern communication technology [1]. The demand for higher communication capacity is unstoppable. However, the data capacity in a single-mode fiber is limited because of the Shannon limit caused by optical nonlinearities [2]. A promising technology to break through the limit is space-division multiplexing (SDM) [3]. SDM technology includes multi-core division multiplexing in which multiple single-mode cores are placed into a common cladding, and mode division multiplexing (MDM) in which different orthogonal modes transmitted in one few-mode fiber (FMF) are used as individual data channels [4–6]. Furthermore, SDM brings significant improvements in the spectral efficiency as well as energy efficiency, reducing the cost per transmitted bit compared to individual single-mode fibers. Spatial multiplexers, including mode (de)multiplexers and multi-core fan-in/fan-out (FIFO) devices, are the most critical configuration for SDM technology. Recently, MDM (de)multiplexers have rapidly developed as the on-chip MDM systems have received a lot of attentions. The commonly used free-space mode multiplexers, such as phase-plate [10] and liquid crystal spatial light modulators (SLMs) [11], are elaborate and typically lossy. Compared with the free space optical system with huge size, integrated optics realizes more efficient, faster, and higher dimensional multi-functional information processing with the advantages of small size, low loss, high integration, and high scalability [12].

Traditional optical waveguide fabrication techniques, such as ion implantation [13], proton exchange [14], thin film deposition, metal ion diffusion [15], and so on, limit the optical waveguide to one-dimensional planar structure. Although two-dimensional optical waveguides can also be fabricated by lithography technology, it is far from meeting the needs of the development of modern integrated optics. Fortunately, with the continuous development of high-performance ultrafast laser technology, femtosecond laser fabrication technology has developed rapidly since 1990s [16]. Femtosecond laser fabrication technology is widely used in basic and application research in many fields, especially providing a flexible and efficient true three-dimensional fabrication method for the manufacture of monolithic components in integrated optics [17,18]. Especially, femtosecond laser fabrication technology has the unique advantages of three-dimensional fabrication, arbitrary structure design, high fabrication resolution and wide range of applicable materials, which makes it an ideal technology for fabricating photonic lantern mode (de)multiplexer [19–23]. Ideally, a mode (de)multiplexer based on femtosecond laser fabrication technology can be compact, entirely passive, and compatible with few-mode fibers.

At present, there are many researches on photonic-lantern mode-division multiplexed transmission through ultrafast laser inscribed mode-multiplexers. If there is no special design, simply using consistent waveguides to form photon-lantern structures will result in the inability to achieve selective mode excitation [22]. To achieve selective mode excitation, B. Guan et al. use dissimilar waveguides along symmetry trajectories in coupling region to form three-channel mode-group-selective photonic lantern by ultrafast laser inscription with 4 dB loss [23]. In 2017, S. Gross et al. report ultrafast laser inscribed mode-group-selective 6-mode photonic lanterns by similar design with 4.7 dB insertion loss [24]. Although these designs follow the principles of fiber-type photonic-lantern mode (de)multiplexers, there are such problems as inconsistent waveguide transmission losses, inconsistent coupled losses, and inefficient selective mode excitation. The insertion losses and mode quality of these devices are relatively poor, making it impractical for application.

In this paper, we demonstrate superior ultrafast laser inscribed photonic-lantern mode (de)multiplexers

using trajectory-asymmetry with uniform waveguides. Nonuniform waveguides with different sizes could lead to inconsistent waveguide transmission losses and coupling losses. The uniform optical waveguides with ultra-low transmission loss of 0.1 dB/cm and coupling loss of 0.2 dB/facet are obtained. With trajectory-asymmetry structure, the femtosecond laser inscribed photonic lantern mode (de)multiplexer can efficiently selectively excite three modes (LP_{11}^{a}, LP_{11}^{b}, and LP_{01}) with high purity. The intensity profiles of transmitted beams are captured and the insertion losses are measured. The devices are test to be polarization insensitive. Furthermore, we demonstrate a six-channel (LP_{11x}^{a}, LP_{11y}^{a}, LP_{11x}^{b}, LP_{11y}^{b}, LP_{01x}, and LP_{01y}) mode- and polarization-division multiplexing and demultiplexing system. The crosstalk of the system is measured. Finally, we demonstrate the high-speed communication experiment with 42 Gaud/s QPSK signals based on the six-channel mode- and polarization-division multiplexing and demultiplexing system. The bit error rate (BER) performances are also measured.

2. Design and fabrication

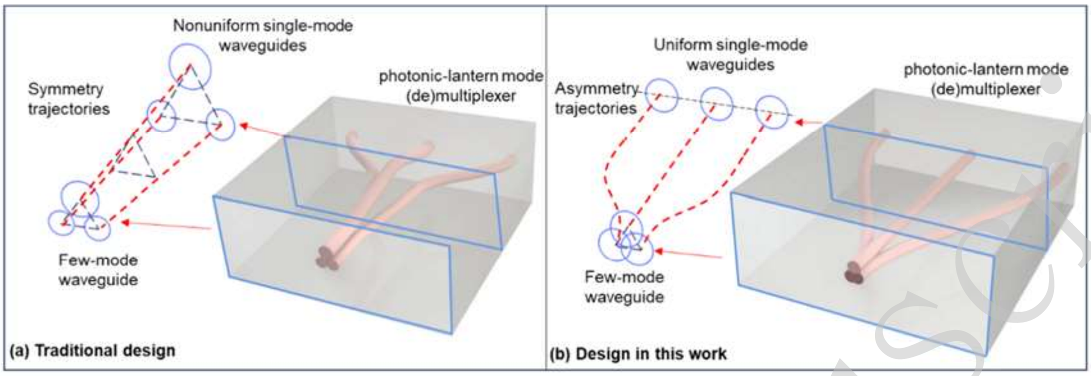

Fig. 1. Schematic of photonic-lantern mode (de)multiplexers. (a) traditional design using trajectory-symmetry with nonuniform single-mode waveguides, (b) design in this work using trajectory-asymmetry with uniform single-mode waveguides.

Photonic lanterns are 3D waveguide devices that convert N single-mode waveguides into one few-mode waveguide that supports N modes. Mode selective excitation is the key principle of photonic-lantern mode (de)multiplexers, which allows for selective excitation and multiplexing of diverse LP modes. It is challenging to fabricate a mode multiplexer that excites each mode of a few-mode fiber without loss since the spatial modes of the fiber are spatially overlapping and cannot be simply separated. Mode selectivity in a mode multiplexer is useful to equalize the mode-dependent such as mode dependent loss. By breaking the symmetry between the modes and avoiding mode coupling, the mode-selectivity can be introduced into the photonic-lantern mode multiplexer. Photonic lanterns are originally fabricated by fiber-tapering technique, which tapering multiple single-mode fibers along symmetry trajectories. By using dissimilar single-mode fibers, asymmetry is introduced to achieve mode selectivity. Traditional photonic-lantern design by femtosecond laser fabrication technology follows the fiber-type design, as shown in Fig 1. (a). The nonuniform single-mode waveguides are placed in symmetric positions across the vertical symmetry axis of the arrangement and positioned along the vertical axis of the preform. The nonuniform waveguides are fabricated through different fabricating laser power. At the end side, the few-mode waveguide is composed of strongly coupled single-mode waveguides.

In contrast, design in this work uses uniform single-mode waveguides along asymmetry trajectories to form the few-mode waveguide, as shown in Fig 1. (b). All single-mode waveguides are fabricated by same fabrication parameter with same properties. The middle waveguide is a straight waveguide while the two sides are bending waveguides, forming the asymmetric trajectory. The design can yield different coupling conditions among all the waveguides along the coupled region, which ensuring different propagation constants for each supported mode in the final few-mode waveguide. Thus, the mode-selectivity is achieved by the asymmetry trajectory. Meanwhile, femtosecond laser fabrication technology can achieve overlap between waveguides, which can better adjust the size of the few-mode waveguides.

Next, the details of femtosecond laser fabrication will be discussed. As shown in Fig. 2. (a), it is the femtosecond laser fabrication system with a high repetition rate Ytterbium-based laser (double

frequency 515 nm wavelength, 100 kHz repetition rate, 234 fs pulse duration). The ultraviolet optical quartz glass (JGS2) sample is placed on a high precision XYZ air-bearing stage. The linear polarization femtosecond laser is vertically focused ~70 μm below the top surface of a glass sample through a 50X0.42 objective (M Plan Apo NIR, Mitutoyo). Through the light emitting diode (LED) lighting system, the femtosecond laser direct writing process is monitored in real time by the charged coupled device (CCD). A 300-nm linear slit is used to modify the laser beam profile, as shown in Fig. 2. (b). The laser beam diameter before the slit is about 1.5 mm. The pulse energy is measured as 9 μJ/0.75 μJ before or after the slit. In general, the cross-section of femtosecond laser inscribed waveguide in glass appears as an elongated ellipse along the femtosecond laser propagation direction with a large aspect ratio due to the conventional spherical focusing optics [25]. The strong core asymmetry, which corresponds to complicated refractive index distribution, can cause significant path loss. By inserting a slit before the focusing lens with the slit oriented parallel to the laser scanning direction, the aspect ratio in the cross-section of waveguide could
be greatly reduced, producing low loss, circular waveguides in glass [26–28]. Besides, the circular waveguides have better mode field matching with fibers. The femtosecond laser inscribed photonic lantern mode (de)multiplexer in glass chip is shown in Fig. 2. (c). The image of the cross-section of the output side of the mode multiplexer is shown in Fig. 2. (d). The enlarged picture of the three input ports of the mode multiplexer is shown in Fig. 2. (e).

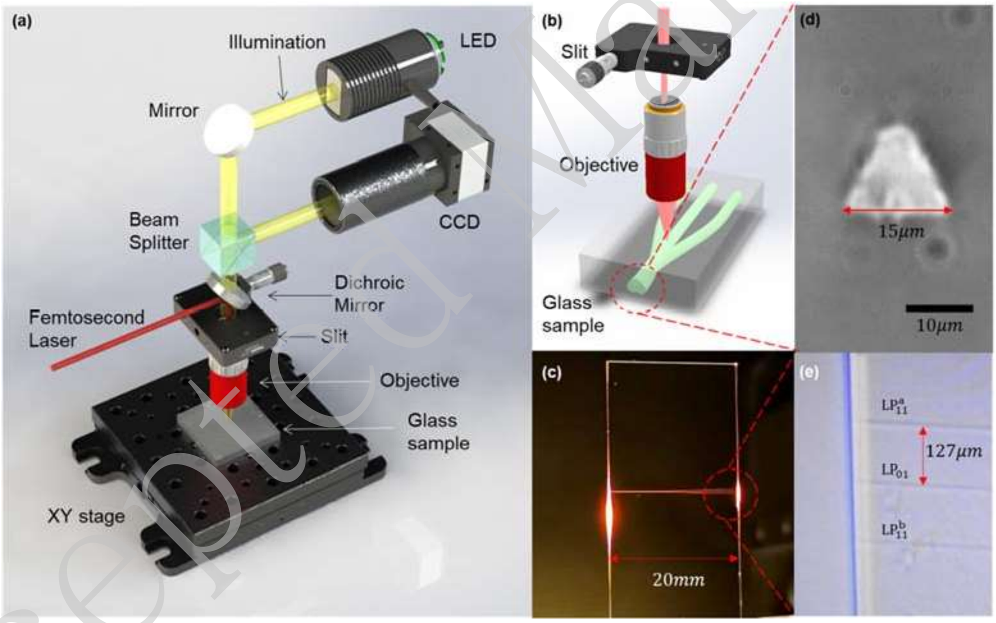

Fig. 2. Femtosecond laser 3D fabrication system and fabricated devices. (a) Femtosecond laser 3D fabrication system. (b) Femtosecond laser direct writing the structure of 3-port photonic lantern mode (de)multiplexer. (c) The photo of 3-port photonic lantern mode (de)multiplexer in glass chip. (d) The image of the cross-section of the output side of the mode multiplexer. (e) The enlarged picture of the three input ports of the mode multiplexer.

The properties of optical waveguides fabricated by femtosecond laser are affected by various fabrication parameters. In traditional design, the sizes of optical waveguides are controlled by changing the power of the femtosecond laser or by changing the number of scans, which is essentially influencing the energy magnitude deposited in the material to modify the range and degree of material modification. Variations in optical waveguide's properties also affect the transmission loss of optical waveguides and the coupling loss with optical fibers. To study the optimal waveguide fabrication parameters, a series of optical waveguides are inscribed by femtosecond laser in a 2 cm long quartz glass by changing the femtosecond laser power from 54 mW to 87 mW. Both ends of the waveguides were pigtailed by commercial single-mode fibers (waveguide diameter 9 μm). One side of the fiber is connected to the 1550 nm laser, while the other side is connected to the optical power meter. The transmission losses of the 2 cm waveguides are measured, as shown by the black line in Fig. 3. The coupling losses on one side are measured by using the truncation method, as shown by the red line in Fig. 3. The transmission losses of the waveguides are calculated and shown by the blue line in Fig. 3. The waveguide cross-sections at 54 mW, 75 mW, and 87 mW are marked in Fig. 3, with waveguide sizes of 6.3 μm, 9.0 μm, and 10.5 μm, respectively. The higher the laser power, the larger the waveguide size. When the laser power is 75 mW, the minimum insertion loss is 0.63 dB, with the 0.21 dB/facet coupling loss, and the 0.1 dB/cm waveguide transmission loss. When the laser power is lower, the refractive index difference is lower, which leads to the waveguides not being able to effectively constrain the beams, causing greater transmission losses of the waveguides. When the laser power is higher, defects will be introduced into the waveguide during fabrication, causing a decrease in waveguide smoothness and resulting in higher transmission losses. Meanwhile, the size of a single-mode fiber is between 9 and 10 microns. Therefore, the size of single-mode waveguides needs to be matched with the corresponding optical fibers to achieve the lowest coupling loss. The mismatch of waveguide sizes and fiber sizes can also increase the coupling losses. Hence, the nonuniform waveguides could lead to inconsistent waveguide transmission losses and coupled losses. By using uniform single-mode waveguides, ultra-low waveguide transmission losses of 0.1 dB/cm and coupled losses of 0.2 dB/cm at 1550 nm are obtained. According to the data in the figure, when the laser power is between 69 mW and 81 mW, the insertion loss of the waveguide can be maintained below 1 dB, and the corresponding mode multiplexers devices can achieve excellent performance.

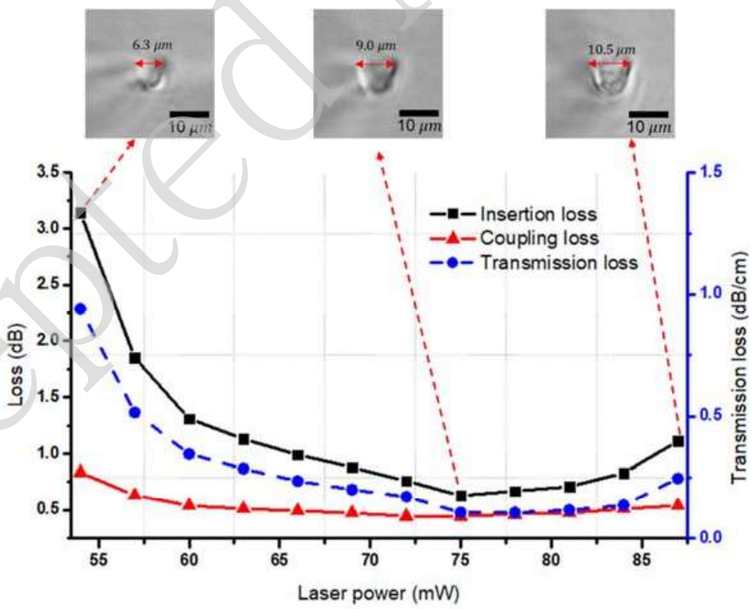

Fig. 3. The insertion losses, coupling losses and transmission losses of femtosecond laser inscribed 2 cm waveguides under different laser power.

The photonic lantern mode (de)multiplexer is inscribed into a 20 mm×40 mm×1 mm JGS2 glass substrate at a constant speed of 0.4 mm/s. The waveguides are scanned four times repeatedly to improve the refractive index and smooth the waveguide. The fabricated waveguides have a cross-section of 9.0 μm × 9.0 μm diameter with a refractive index contrast of approximately 0.3%. The RI contrast is estimated by measuring numerical aperture. Through infrared CCD camera and high-precision moving stages, the divergence angle of the light from the femtosecond laser inscribed waveguide can be measured. The refractive index of the waveguide can be calculated by the formation: $n\sin\theta = \sqrt{n_1^2 - n_2^2}$. n is air refractive index n_1 is the waveguide refractive index n_2 is the glass refractive index. θ is the measured divergence angle.

As shown in Fig 1. (b), the mode multiplexer consists of three waveguides of 20 mm. The middle waveguide W_2 is set as a 20 mm straight waveguide to generate LP_{01}mode. The waveguide W_1 of LP_{11}^a mode channel and waveguide W_3 of LP_{11}^b mode channel are both composed of a straight waveguide and a bending waveguide. The 3 single-mode waveguides are arranged at the input in a linear array to match a 127 μm pitch fiber array. Through the 3D bending waveguides, the 3 cores are brought together gradually to form an equilateral triangle few-mode waveguide at the output. When the waveguide size is 9.0 μm and the spacing between the three waveguides is 6.0 μm, it exactly forms a small mode waveguide with a size of 15.0 μm, which matches the small mode fiber with a size of 14.8 μm. In the case where both ends of the waveguide are fixed, waveguide W_1 and waveguide W_3 are contained in the inclined planes with the angle of $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_3}$ to the horizontal plane, respectively.

The low-loss trajectories of the bending waveguides are designed to obey the following formation:

$$y = \frac{6h}{L^5}x^5 - \frac{15h}{L^4}x^4 + \frac{10h}{L^3}x^3 \quad (1)$$

By rotating the 2D trajectories along the transmission direction axis at an angle θ, a 3D waveguide can be obtained. The formula for this 3D waveguide is as follows

$$y = \frac{6h}{L^5}(x^2+z^2)^{5/2} - \frac{15h}{L^4}(x^2+z^2)^2 + \frac{10h}{L^3}(x^2+z^2)^{3/2} \quad (2)$$

$$\tan\theta = \frac{z}{x} \quad (3)$$

where L denotes the horizonal length of the track, h corresponds to the vertical length of the track, x indicates the horizonal coordinate.

Next, all the design parameters of the mode multiplexer can be determined by formula by determining the length of the bending waveguides on both sides. According to the information in the section 2 of supplementary file. The waveguide corresponding to LP_{11}^b mode is composed of a 10.3 mm straight waveguide and a 9.7 mm bending waveguide. The waveguide corresponding to LP_{11}^a mode is composed of a 11.1 mm straight waveguide and an 8.9 mm bending waveguide. The fabrication time of each photonic lantern mode (de)multiplexer is only about 20 minutes, which means that multiple iterative processing can be carried out in a short time.

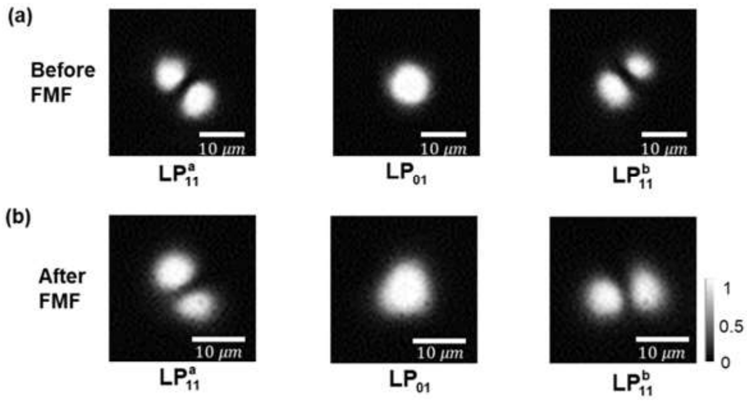

Fig. 4. The intensity profiles of 3-port photonic lantern mode (de)multiplexer outputs. (a) the intensity profiles of LP_{11}^{a}, LP_{11}^{b}, and LP_{01} modes, which are captured before the FMF; (b). the intensity profiles of LP_{11}^{a}, LP_{11}^{b}, and LP_{01} modes, which are captured after the FMF.

The 3D laser inscribed photonic lantern mode (de)multiplexer can remap the one-dimensional single-mode waveguide array into two-dimensional few-mode distribution, based on which selective excitation of specific modes can be achieved. By launching into the single-mode waveguide array with single mode beams, the beam from few-mode waveguide side of the photonic lantern is coupled into a 14.8 μm core diameter step-index few-mode fiber. Refractive index matching fluid are used on both interfaces to reduce the Fresnel reflection. The single-mode beam is injected into the input ports of the multiplexer in turns to get the intensity profiles of the output. As shown in Fig. 4. (a), the modes LP_{11}^{a}, LP_{11}^{b}, and LP_{01} with high purity can be clearly seen. Figure 4. (b) shows the intensity profiles from the output end of the FMF. The patterns from the FMF becomes slightly worse due to the crosstalk of the FMF. But they still maintain relatively good shapes. The high mode-selectivity can reduce the electronic single processing complexity. The insertion loss (including coupling losses) for LP_{11}^{a}, LP_{11}^{b}, and LP_{01} modes are 1.14 dB, 1.19 dB, and 0.84 dB, respectively. The polarization dependent losses are test to be less of 0.2 dB. Hence, the photonic-lantern mode (de)multiplexers are polarization insensitive, which makes polarization-division multiplexing applicable. Compared with the femtosecond laser inscribed photonic-lantern mode (de)multiplexers with traditional design, the performances of the devices with design in this work are greatly improved [23, 24].

Further, the spectrum characteristics of the femtosecond laser inscribed mode multiplexer with the wavelength range from 1480 nm to 1640 nm are measured. A tunable laser is applied to supply light source with the wavelength range from 1480 nm to 1640nm. A power meter is used to record the output power after the laser beam transmitting through the mode multiplexer. The wavelength interval of adjacent measurements is 1nm. As shown in Fig. 5, each measurement curve is formed of 161 points. The insertion losses ranged between 0.5–2.4 dB over the S + C + L bands with an average of 1.4 dB, for all modes. The fluctuation of the insertion losses of all channels are less than 1.4 dB. The low insertion losses can increase the transmission length without the need for optical amplification. The broad bandwidth enables the device to be scalable to ultra-wide wavelength division multiplexing (WDM) applications.

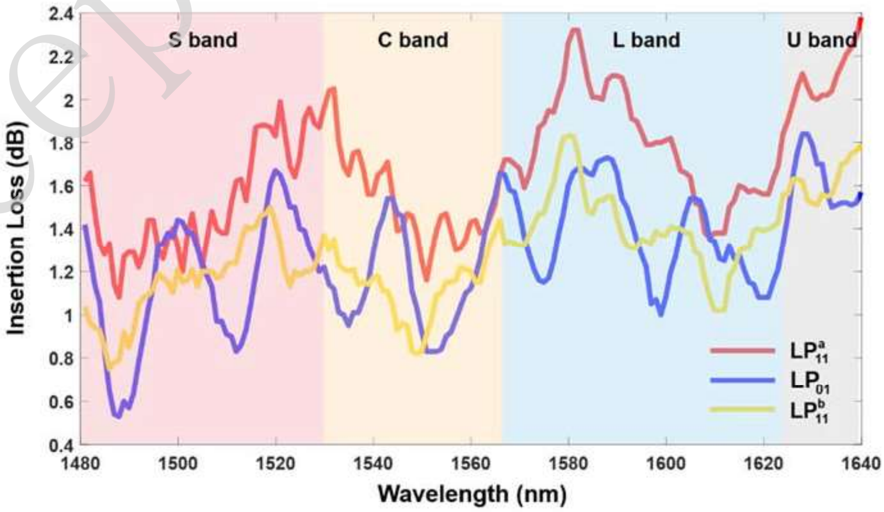

Fig. 5. The spectrum characteristics of the femtosecond laser inscribed mode multiplexer. The three input ports can excite LP_{11}^{a}, LP_{11}^{b}, and LP_{01} modes, respectively. Each curve represents the insertion losses between the corresponding input channel and output channel over the wavelength range from 1480nm to 1640nm.

3. Experimental setup

As shown in Fig. 6. We generated a 42-Gbaud/s QPSK signal by modulating the 1550 nm laser using an optical I/Q modulator. The signal was amplified using a C band erbium doped fiber amplifier (EDFA) after modulation. The signal was divided by a 50:50 coupler and then two 33:33:33 couplers into six equal parts, each of which is delayed using a different length of fiber to decorrelate the data sequence. These signals were transmitted through single mode fibers of 2 km, 1 km, 1 km,1 km, 1 km, 0.5 km respectively as sub networks. Polarization controllers (PCs) were used to adjust the polarization of signals alternately as x-polarization and y-polarization to meet the requirement of PBS. Three PBSs, each of which coupled a x-polarization signal and a y-polarization signal together, were applied to realized polarization multiplexing. The insertion loss of the PBS is about 0.8 dB. The three polarization multiplexed signals are injected into a 127-μm pitch fiber array. The fiber array is placed on a high precision 6-aixs stage, aiming at the input ports of the photonic lantern mode multiplexer, which is fixed on the chip placement stage. Three single-mode beams with polarization multiplexed signals are transformed into three LP modes respectively, which are output simultaneously at the few-mode waveguide side as mode multiplexing. One side of 860-m few-mode fiber is fixed on another 6-aixs stage to receive the output beam from the glass chip. The 6 multiplexed signals (LP_{11x}^{a}, LP_{11y}^{a}, LP_{11x}^{b}, LP_{11y}^{b}, LP_{01x}, and LP_{01y}) are then transmitted through the 860-m few-mode fiber. One PC is used here to compensate the polarization state variation originated from the transmission of 860-m few-mode fiber. The output side of the few-mode fiber is fixed on the third 6-axis stage, aiming at the few-mode waveguide input side of the demultiplexer inside the second glass chip. The mode multiplexed signals are demultiplexed and separated into specific single-mode output waveguides. Another fiber array placed on the fourth 6-axis adjuster is used to receive the 3 single mode outputs, which are polarization demultiplexed by three other reverse PBSs. Refractive index matching liquid is used between the fibers and glass chips to eliminate the Fresnel reflection and promote the mode field matching.

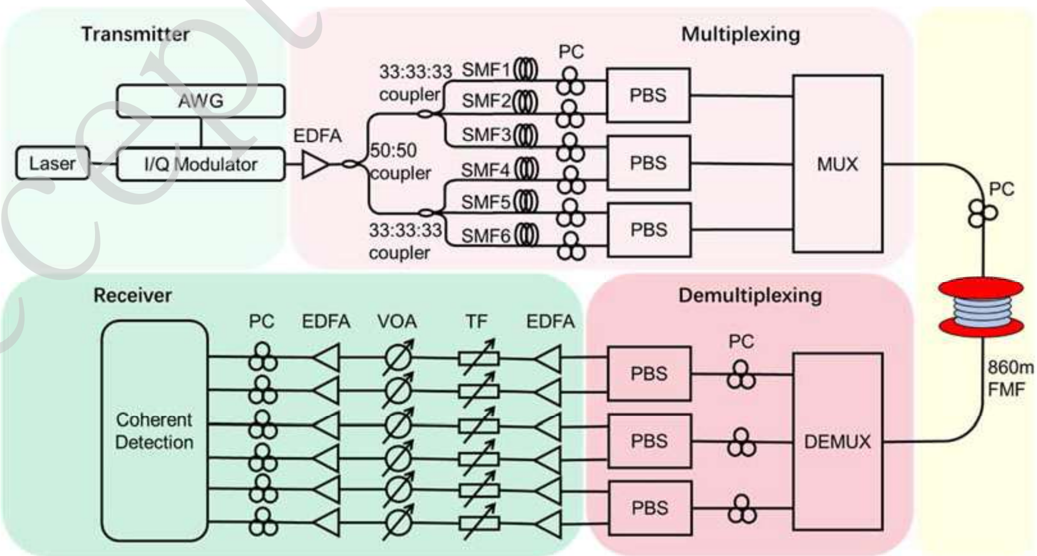

Fig. 6. The experimental setup of 6×6 mode- and polarization-division multiplexing optical transmission based on ultra-fast laser inscribed on-chip mode (de)multiplexer.

After demultiplexing, 6 single-mode beams with signals are sent to the receiver. The EDFAs are used to amplify the received signals. The amplified signals are then filtered by tunable filters (TFs) to filter out the selected wavelength. The groups of variable optical attenuator (VOA) and EDFA are used to adjust the optical signal-to-noise ratio (OSNR) performance. The signals are coherently detected with the local oscillator light at the receiving end to obtain the QPSK electrical signals of two polarizations. After sampled by the oscilloscope, the signals go through off-line digital signal processing, including I/Q orthogonalization, polarization demultiplexing equalization, frequency offset compensation, and phase offset compensation. Then, the recovered QPSK baseband signal is remapped into binary bits. Finally, the decoded binary pseudo-random sequence is used to calculate the BER.

4. Experiment results

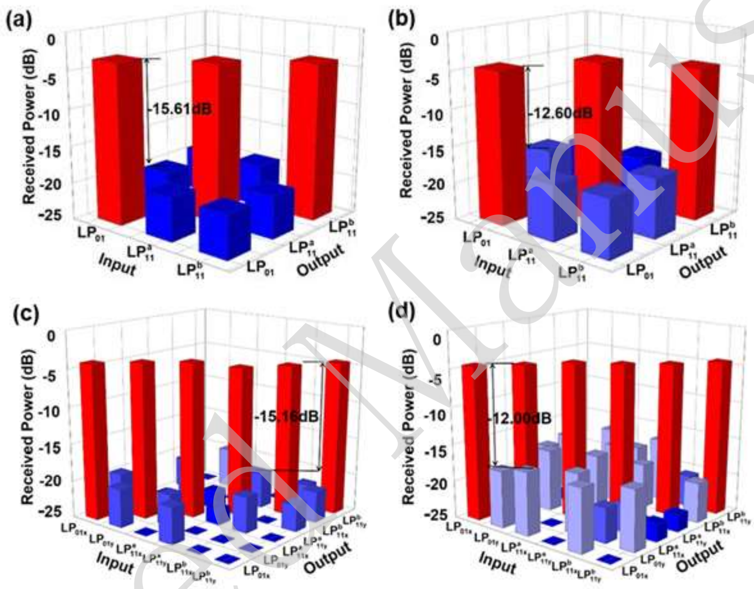

Fig. 7. The crosstalk of 3×3 mode-division multiplexing and demultiplexing system with 2-m FMF in (a) and 860-m FMF in (b); The crosstalk of 6×6 mode- and polarization-division multiplexing and demultiplexing system with 2-m FMF in (c) and 860-m FMF in (d).

The simplified 3×3 mode-division multiplexing and demultiplexing system with only two photonic lantern mode (de)multiplexers and FMFs is first build. As shown in Fig. 7. (a), the crosstalk of 3×3 mode-division multiplexing and demultiplexing system with 2m FMF is -15.61 dB. When the system is applied with 860-m FMF, Fig. 7. (b) shows that the crosstalk enlarges to -12.60 dB. The increasement of crosstalk is because of the lengthened FMF, which limits the high-speed and long-distance signal transmission in FMF system. Thus, the 860-m FMF is chosen to realize high-speed optical communication. Then the 6×6 mode- and polarization-division multiplexing and demultiplexing system is built. As shown in Fig. 7. (c)-(d), the crosstalk with 2-m FMF and 860-m FMF are -15.16 dB and -12.00 dB respectively. The two systems have similar crosstalk, which means that the polarization-division multiplexing does not introduce serious crosstalk and that polarization-division multiplexing and mode-division multiplexing in the system are well combined.

The polarization controllers are used to adjust the polarization to ensure the light of the LP_{11}^{a} and LP_{11}^{b} emerge at the output end. When the length of the optical fiber is 2 m, the disturbance from the optical fiber can be ignored, and the optical fiber transmission system can remain stable for a long time. When the fiber length increases to 860 m, the modes mix with each other, which increases crosstalk. After adjusting the polarization of the light by polarization controllers to get the required mode output, the measured crosstalk increases from –15 dB to –12 dB. The result indicates that the fiber disturbance is not very serious, which allows us to complete the demonstration in a stable period. For longer optical fiber transmission experiments with severe crosstalk and disturbance, multiple-input multiple-output digital signal processing (MIMO-DSP) technology is generally used.

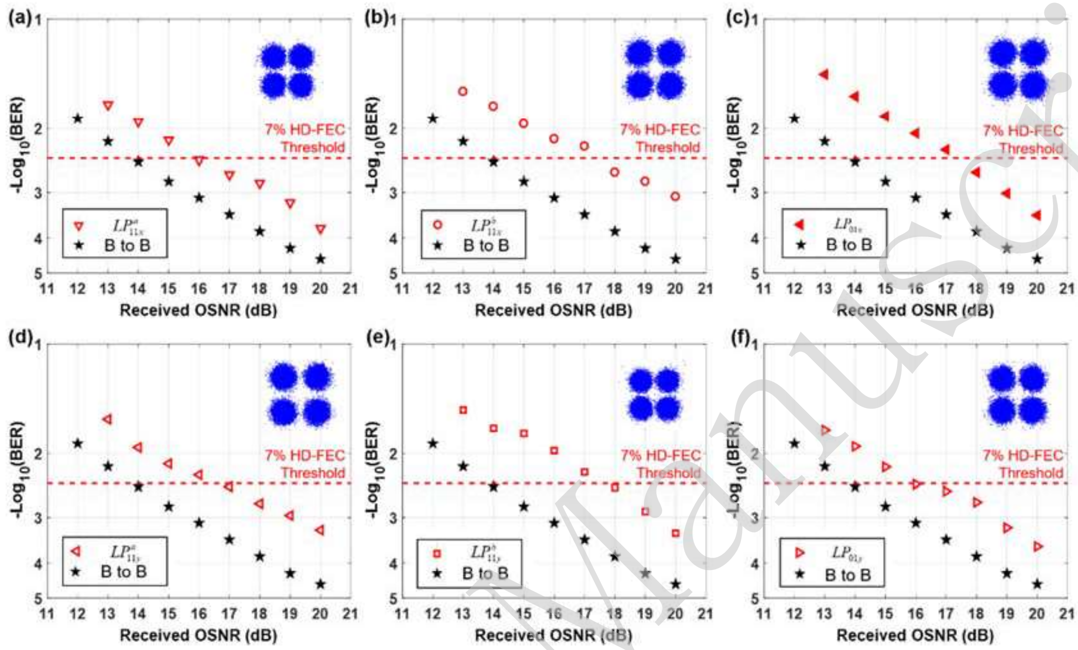

Fig. 8. Measured BER performance of 6×6 mode- and polarization-division multiplexing and demultiplexing transmission with 860m FMF. The BER curves of different modes (LP_{11x}^{a}, LP_{11x}^{b}, LP_{01x}, LP_{11y}^{a}, LP_{11y}^{b}, and LP_{01y}) are shown in (a)-(f), respectively.

Finally, we measured the BER performance as a function of the received OSNR for 6×6 mode- and polarization-division multiplexing transmission. The BER curves of different modes (LP_{11x}^{a}, LP_{11y}^{a}, LP_{11x}^{b}, LP_{11y}^{b}, LP_{01x}, and LP_{01y}) are shown in Fig. 8. (a)-(f), respectively. Each figure also contains a BER curve of the back-to-back system as reference. The difference between the two curves at the same BER value is the OSNR penalty, which represents the deterioration degree of the signal. The observed OSNR penalties of different polarizations with the same LP mode are similar, which means that the difference of polarization does not affect the quality of the signal. While the observed OSNR penalties of LP_{11}^{b} mode is 1.5 dB larger than that of LP_{11}^{a} mode and LP_{01} mode at the BER of 3.8×10^{-3} (7% hard-decision forward-error correction (FEC) threshold), which means that the quality of LP_{11}^{b} mode is worse, leading higher insertion loss. The uneven performance of different modes is caused by the asymmetry of the structure during processing. Although compensation has been achieved by introducing coupling regions of different lengths, resulting in both exhibiting better LP modes. However, the distribution of the two lobes of LP11a is more uniform than that of LP11b, resulting in better performance of LP11a. At the output end, the three waveguides that make up the few-mode waveguide have a standard equilateral triangle distribution, which limits their flexibility. In theory, compensatory optimization can be achieved by adopting a more flexible waveguide distribution, which can achieve higher quality LP mode excitation and solve the problem of mode imbalance. The BER of all channels can reach below 3.8×10^{-3} easily, which means the 6×6 mode- and polarization-division multiplexing and demultiplexing transmission in 860-m FMF with 42Gaud/s is reliable.

5. Conclusions

In summary, we have comprehensively optimized the design of the ultra-fast laser inscribed photonic-lantern mode (de)multiplexer by using trajectory-asymmetry with uniform waveguides for superior performances and utilized it to achieve mode- and polarization-division multiplexing and demultiplexing optical transmission. First, optimized design by using trajectory-asymmetry with uniform waveguides is proposed. Based on uniform single-mode waveguides, the consistent waveguide transmission losses of 0.1 dB/cm and coupling losses of 0.2 dB/facet at 1550 nm are obtained. Efficient modes excitation (LP_{11}^{a}, LP_{11}^{b}, and LP_{01}) with average insertion losses as low as 1 dB at 1550 nm are achieved with the mode dependent losses less than 0.3 dB by the trajectory-asymmetry design. By comparison, it can be concluded that the design in this paper performs better. Afterwards, we build the 3×3 mode-division multiplexing and demultiplexing system and 6×6 mode- and polarization-division multiplexing and demultiplexing system. Both systems feature low insertion losses and low crosstalk. Finally, we have demonstrated a 6×6 mode- and polarization-division multiplexing and demultiplexing system for high-speed optical communication in 860-m FMF. The results of BER measurement shows that the high-speed optical communication is reliable, which could play an important role in building the optical interconnection links based on spatial multiplexing with ultra-large communication capacity. Furthermore, larger communication capacity could be realized with added mode channels, even by utilizing more other multiplexed resources of light in the future.

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Availability of data and materials

The data that support the findings of this study are available from the corresponding author on request.

Declaration

Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Supplementary information

See supplementary file for supporting content.

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