Radial high-order OAM mode multiplexing

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***Abstract*—We demonstrate a two-dimension mode multiplexer consisting of spatially discrete multi-phase planes by inverse design for radial high-order orbital angular momentum (OAM). 10 OAM modes with the topological charge of *l*=0, -1, -2, -3, -4 and the radial indices of *p*=0, 1 were generated and characterized experimentally.**

Keywords—mode multiplexing, radial high-order OAM, multi-phase planes

I. Introduction

Orbital angular momentum (OAM) beams are widely used in a number of applications, such as optical communications [1], particle manipulation [2] and imaging [3]. In the application of optical communication, mode division multiplexing (MDM) technology based on OAM beams is a promising approach to significantly increase the communication capacity due to the orthogonal properties between OAM beams with different topological charge *l*. In the last few years, various multiplexed techniques for OAM modes with different topological charges have proposed and demonstrated, such as mode-selective couplers [4], phase diffraction grating [5], meta-surface [6] and optical geometric transformations [7]. All reported multiplexers (MUXs) are considered only one dimension of topological charge *l* on the basis of radial zero-order OAM modes. However, the maximum value of *l* is restricted by the finite apertures of optical systems. Therefore, there is an urgent development of additional dimensions to increase the number of multiplexed channels.

The transverse structure of most optical photonic functions carrying OAM contains only angular dimensions. Although these OAM modes provide a basis set for the azimuthal structure of the representative photon, they do not fully span the entire transverse state space. Further extensions are therefore limited. The Laguerre-Gaussian (LG) mode function provides an additional radial degree of freedom, which can more adequately represent the spatial structure of the transverse field. The intensity profile of LG mode is determined by the azimuthal mode index *l* and the radial mode index *p*. Simultaneous multiplexing of radial and angular indices of OAM beams is promising to extend the number of transmission channels. However, most of the mode multiplexing methods can only achieve one-dimensional multiplexing, which is challenging for two-dimensional (2D) mode multiplexing with the modulation of complex optical field. Recently, multi-plane light conversion (MPLC) technology has shown unique advantages in terms of mode control and has great potential for the 2D sorting of modes optical field modes [8].

Here, we show a 10-mode multiplexer (MUX) of radial high-order OAM modes based on MPLC for fiber communication at the wavelength of 1310 nm. The results demonstrate the feasibility of the approach in extending of multiplexing channels.

II. Experimental Sestup and Results

MPLC implements any spatial mode transformation by a sequence of transverse phase profiles separated by the spatial optical Fourier transform. The MUX is composed of 5-layer phase planes. Phase planes were calculated by inverse design based on wavefront matching. The phase planes were fabricated using four cycles of photolithography and dry etching on a silicon substrate. As shown in Fig.1(a), the microscopic images of the fabricated phase planes are consistent with the phase distributions of the design.

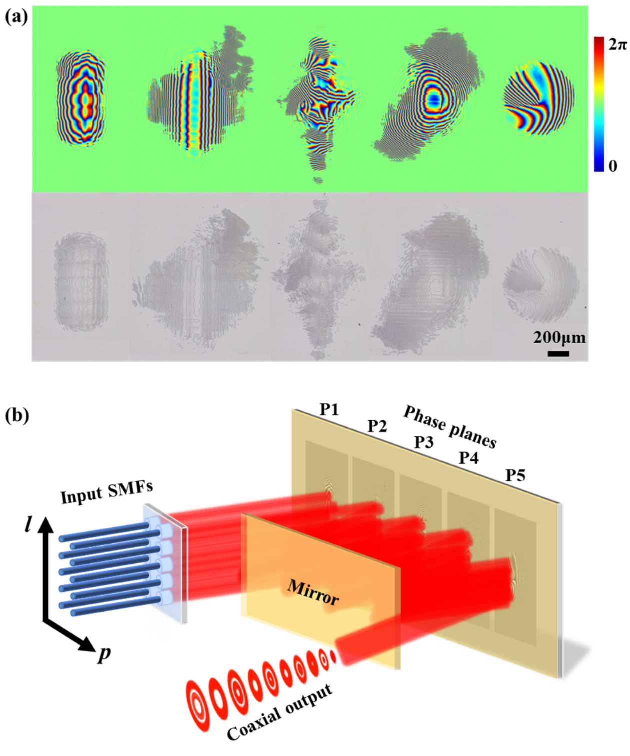

Fig.1. (a) Caculated phase and fabricated surface structure distributions of the five phase planes. (b) Schematic of the radial high-order OAM MUX.

As illustrated in Fig.1(b), the entire system for multiplexing consists of 2×5 fiber-microlens array source, five gold-coated phase planes and a gold-coated mirror. The Gaussian spots input from the 2D fiber-microlens array and are converted into the coaxial OAM modes with different parameters of radial *p* and angular *l* after 9 times reflections back and forth between the phase planes and the mirror. The inputs of 2×5 corresponding to the generation of OAM modes with the radial index p = 1, 2 and the azimuthal index l = 0, -1, -2, -3, -4.

Fig.2(a) and Fig.2(b) shows simulation results of the intensity and phase distributions of OAM modes generated by the MUX. We calculated an average loss induced by mode conversion of 0.66 dB, an average mode purity of 84 % and the maximum crosstalk of -15 dB.

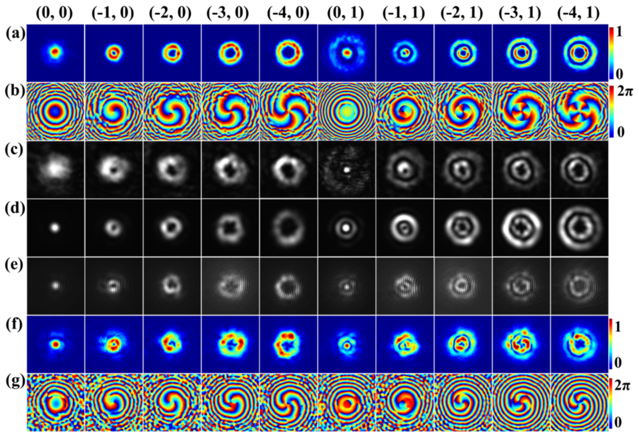

Fig.2. (a) Intensity and (b) phase distributions of the simulated OAM modes with the indices (l, p) of the MUX. Measured intensity distributions of the output modes with the indices (l, p) (c) in free-space and (d) after coupling into 1.5 m fiber. (e) Measured interference intensity profiles based on Fourier transform interferometry after coupling into fiber. (f) Intensity and (g) phase distributions of the reconstructed modes after coupling into fiber.

In our experiments, a tunable distributed feedback laser was used as the input light source. The intensity distributions of the generated coaxial OAM modes were captured by a near-infrared camera with Indium Gallium Arsenide sensor. Fig.2(c) shows the output modes in free-space. These results demonstrate that the experimentally generated modes are consistent with the simulated modes. The insertion losses (ILs) of the generated OAM modes measured are less than 5.4 dB. Except for the loss of mode conversion, The ILs are caused by the reflection, the coupling of fiber-microlens and the errors of processing and experiment.

The intensity distributions of the OAM modes generated by the MUX after coupling into a ring-core fiber are shown in fig.2(d). Off-axis digital holography technology was employed to reconstruct the intensity and phase distributions of modes. The measured interference intensity profiles are illustrated in fig.2(e). Fig.2(f) and Fig.2(g) demonstrate that the OAM modes generated experimentally by our MUX can be coupled into the fiber with the correct number of rings and helical phase profiles.

The MUX used in the inverse direction enables the demultiplexing of the OAM modes. A back-to-back multiplexing/demultiplexing system comprising a MUX, 3 meters of the ring-core fiber and a DEMUX was characterized. The experimental setup diagram is shown in Fig.3(a). When the laser light source was input from the single channel of the MUX, the optical power of all output channels of the DEMUX was detected.

The crosstalk is defined as the power in desired output channel related to the total power in other output channels. Fig.3(b) shows the crosstalk matrix calculated from the power measured by the system. There is an anomalous channel with non-negative crosstalk values due to the fiber coupling mismatch of the OAM mode with l = 0 and p = 1 generated by the channel of ch6. The crosstalk of other channels are all below -6 dB.

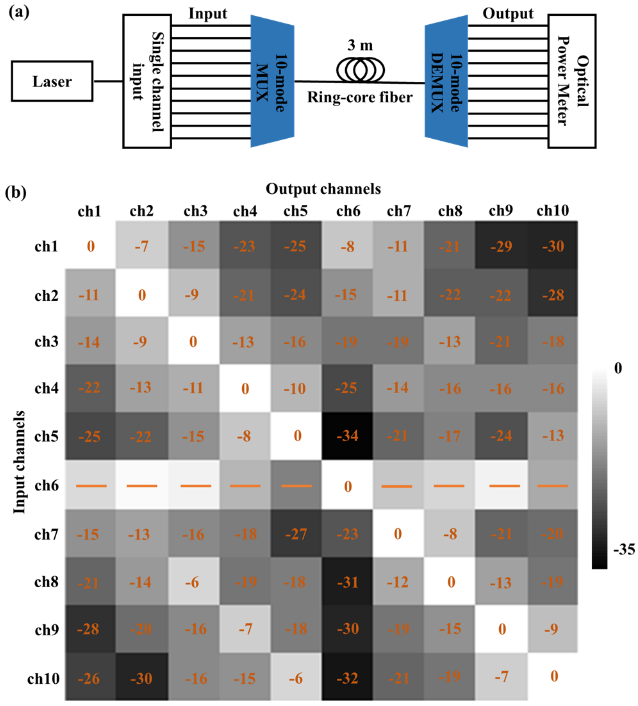

Fig.3. (a) Diagram of the back-to-back multiplexing/demultiplexing system. (b) Crosstalk matrix of the system.

III. Conclusions

In conclusion, we demonstrated experimentally a 10-mode MUX of radial high-order OAM consisting of five phase planes designed by inverse design. The mode conversion performed high-quality multiplexing of radial high-order OAM modes by experimental characterization. Coupling multiplexed OAM modes into specially designed ring-core fiber can keep the correct intensity and phase distributions of the modes. The measurement of the MUX-DEMUX system show great potential for implementing further communication transmissions.

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