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All-fiber orbital angular momentum mode generation and transmission system

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A B S T R A C T

We proposed and demonstrated an all-fiber system for generating and transmitting orbital angular momentum (OAM) mode light. A specially designed multi-core fiber (MCF) was used to endow with guide modes different phase change and two tapered transition regions were used for providing low-loss interfaces between different fiber structures. By arranging the refractive index distribution among the multi-cores and controlling the length of MCF, which essentially change the phase difference between the neighboring cores, OAM modes with different topological charge l can be generated selectively. Through two tapered transition regions, the non-OAM mode light can be effectively injected into the MCF and the generated OAM mode light can be easily launched into OAM mode supporting fiber for long distance and high purity transmission. Such an all-fiber OAM mode generation and transmission system owns the merits of flexibility, compactness, portability, and would have practical application value in OAM optical fiber communication systems.

1. Introduction

Vortex beams carrying orbital angular momentum (OAM) have attracted immense research attentions due to its helical phase front comprising an azimuthal phase term $\exp(il\Phi)$, where l is the topological charge that determines the number of phase discontinuities (abrupt phase jumps from $-\pi$ to π) within a 2π range, and Φ is the azimuthal angle [1]. Different integer l stands for different OAM light, and the OAM light with different l values are mutually orthogonal. This property suggests that the OAM could be a new degree of freedom for increasing the capacity of optical communication systems. It has been confirmed that the capacity and spectral efficiency of optical communication systems are significantly enhanced either by encoding information as OAM states of the beam [2] or by using OAM beams as information carriers for multiplexing [3,4].

Due to its unique characteristics and extensive applications, many approaches for generating OAM modes have been proposed and demonstrated. In free space, OAM modes can be generated by spiral phase plate [5], diffractive phase holograms [6], metamaterials-based phase plates [7], cylindrical lens pairs [8], q-plates [9], silicon integrated devices [10] and so on. However, these methods usually require a lot of bulk free space optical devices, which causing the non-compact and inefficient communication application. Besides, compared with the short distance free-space optical communications, most of the long-distance high-capacity communication occurs in optical fiber. Therefore, it is extremely valuable to develop the feasibility and practicality of employing OAM as an additional degree of freedom for data multiplexing in optical fiber communication system [11]. Fiber-based OAM transmission has been studied by A. N. Alexeyev since the 1990s [12]. Recently, specially designed fibers, which possess a high refractive index ring in fiber core region, are demonstrated for the transmission of OAM modes [4,13–15]. In addition, proposed schemes related with the generation of OAM modes in fibers include twisted special fibers [16–18], micro-bend fiber gratings [19], novel compact OAM couplers [20], helical gratings [21], and the OAM mode converter [22]. However, the overall solution for all-fiber OAM mode generation and transmission system still remains incomplete and ambiguous, which could not be simply realized by cascading the fiber-based OAM generation and transmission techniques together.

In this work, firstly, the OAM mode generation fiber is designed as shown in Fig. 1, which has a multi-core structure with a circular graded core refractive index distribution. Each core with fine refractive

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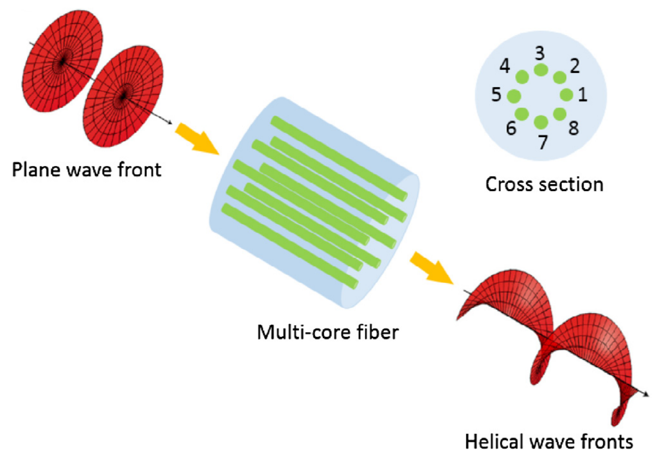

Fig. 1. Schematic of a multi-core optical fiber that induces wavefront shaping.

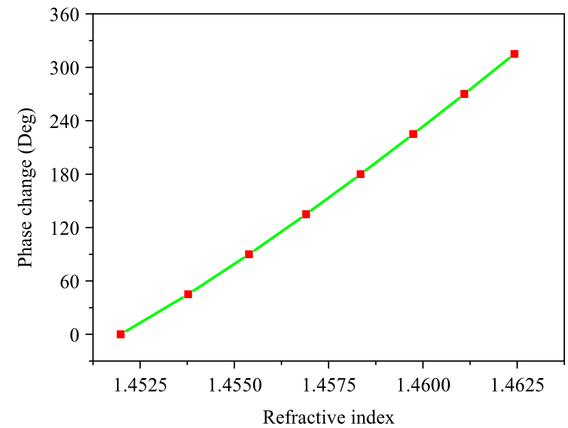

Fig. 2. Phase change as a function of the core refractive index. Solid green curve corresponds to theoretical predictions using Eq. (2), square red dots are the designed phase change points.

index setting could introduce a specific phase, a total phase change of 2π or its integer multiple can be imposed on the wave front of the beam through such a fiber. As a result, after propagate through the MCF, a conventional (Gaussian) laser beam can be transformed into a vortex beam. Secondly, two tapered transition regions is proposed as the low-loss interfaces between different fiber structures. By using the two tapered transition regions, the non-OAM mode light can be effectively injected into the MCF, and then the generated OAM mode light can be easily launched into OAM mode supporting fiber. Finally, a graded index multi-mode fiber (GI-MMF) structure has been proposed for OAM mode propagation with low loss and high purity transmission [23]. Based on the OAM mode generation fiber, two tapered transition regions and OAM mode propagation fiber, the all-fiber OAM mode generation and transmission system is proposed and illustrated. This system owns the merits of flexibility, compactness, portability, and would have practical application value in OAM optical fiber communication systems.

2. Operation principle and structure design

The waveguide modes in cylindrical optical fibers for electric and magnetic fields can be written as

$$\Psi(r,\theta,z,t) = \Psi_n(r,\theta)\, exp\,[i\,(\beta z - \omega t)]\,, \tag{1}$$

where ω and β are the angular frequency in vacuum and the propagation constant inside the fiber, respectively. From the requirement of the continuity of the tangential components of the electric field E and the magnetic field H at the core–cladding interface $r = a$, the eigenvalue equation for the optical fiber is

$$\beta^2 m^2 \left(\frac{1}{U^2} + \frac{1}{W^2}\right)^2 = \left[\frac{J_m'(U)}{UJ_m(U)} + \frac{K_m'(W)}{WK_m(W)}\right] \times \left[\frac{k^2 n_{co}^2 J_m'(U)}{UJ_m(U)} + \frac{k^2 n_{cl}^2 K_m'(W)}{WK_m(W)}\right], \tag{2}$$

where $U = ka\left(n_{co}^2 - n_{eff}^2\right)^{1/2}$ and $W = ka\left(n_{eff}^2 - n_{cl}^2\right)^{1/2}$ are the normalized transverse phase parameter and attenuation parameter, respectively, $J_m(U)$ and $K_m(W)$ are the mth-order first kind Bessel function and Hankel function, respectively, $k = 2\pi/\lambda$ is the wavenumber in vacuum, λ is the wavelength, n_{co} and n_{cl} are the refractive index of the core and cladding, respectively. By solving the transcendental Eq. (2), we obtain the phase change βL, where L is the fiber length, as a function of the refractive index of the core n_{co}. The parameters λ = 1.55 μm, n_{cl} = 1.444 and L = 180 μm have been used for phase change calculation as shown in Fig. 2, where the green curve gives the phase change as a function of the core refractive index. Here, the phase change at $n_{co} = 1.4520$ has been selected as the zero calibration.

Fig. 2 indicates that the phase change in the fiber increases along with its core refractive index. Therefore, by arranging the refractive index distribution among the multi-cores of MCF (as schematically shown in Fig. 1), the phase of each core is $\varphi_n = 2\pi ln/N$ and the phase differences of the adjacent core exactly equal $2\pi l/N$, where l is an integer, N is the total number of cores, $n = 0, 1, \ldots, N-1$. Such a phase difference distribution matches the spatial sampling of the azimuth phase of OAM state l. When the spatial-phase-modulated multi-beams converge in a section of ring core fiber (RCF), OAM mode with topological charge l can be effectively generated [24,25]. Note that the incident light beam must have the identical initial phase and amplitude.

In order to increase the practicability of the MCF, a tapered MCF transition region is used to guide incident light into the each core. It is a low-loss optical waveguide device that connects one multimode core (MMC) to several single-mode cores (SMCs). Light passing through the device will follow the transition if it is gradual enough, that is, if the transformation between the different waveguide systems occurs over a long-enough distance. Analogously, a tapered RCF transition region is used to guide the generated OAM light into the OAM mode propagation fiber.

Usually, the RCF with large-index-difference was adopted as primary design to separate the near-degeneracy modes and increase the number of OAM modes supported by the fiber [4,13–15]. However, this design would significantly increase the intrinsic crosstalk among OAM modes due to strong spin–orbit coupling phenomenon [26]. It has been found that the graded-index fiber structure has higher purity than the RCF. A GI-MMF is designed for supporting 16 modes (10 OAM modes) propagation, all the purities of synthesized OAM lights are higher than 99.9%, and the intrinsic crosstalk has been greatly alleviated to be lower than $-30dB$, where the design details of GI-MMF are shown in Ref. [23]. The tapered RCF transition region is used only for providing low-loss interfaces between MCF and GI-MMF. These fibers are fused together to form an entire all-fiber orbital angular momentum mode generation and transmission system. The schematic diagram of the system is displayed in Fig. 3.

3. Results and discussion

The theoretical results discussed above are used to design the specific structure parameters shown in Fig. 3. The MCF is designed to be $N = 8$ cores, diameter d = 5 μm, core pitch Λ = 15 μm, fiber length L = 180 μm and n_{cl} = 1.444 at λ = 1550 nm. In the case of 15 μm core pitch, the power-conversion efficiency between adjacent fiber cores is less than