An optical beam having a helical wavefront phase of $2\pi l$ is associated with an optical orbital angular momentum of $\hbar l$ of a photon [1]. Recently, orbital angular momentum (OAM) modes have gained much interest for increasing transmission capacity and spectral efficiency in optical communication systems because of their ability to carry independent data streams on orthogonal modes [2], which could be used in mode-division multiplexing (MDM) in free-space and fiber communication systems [3]. The efficient generation and multiplexing of OAM modes has been a key challenge. Generation has typically been accomplished by using spatial-light modulators (SLMs) [4] or other free-space components [5], which are generally bulky and expensive. The multiplexing of multiple spatial modes is usually achieved by using beam splitters [2,3], which is inherently lossy. One of the promising approaches to efficiently generate and multiplex multiple OAM modes without significant loss is to use the interference of multiple coherent Gaussian modes in the far field [6,7]. However, the mode purity of the generated OAM mode will not be high enough due to the discontinuity of the input conditions, which may not be preferable to some applications such as optical communications that require low crosstalk among the spatial channels.

In this Letter, we propose and show, by using simulation, a new approach to generate OAM modes of high purity in a ring fiber from multiple coherent inputs of Gaussian mode. We further show that, in an OAM-based MDM system, there is a discrete Fourier transform (DFT) relationship between the data modulation of the input Gaussian mode channels and the output OAM channels. Compared to the existing methods of generating OAM modes in an optical fiber [8,9], this approach is able to generate and multiplex multiple different OAM modes simultaneously with fairly low loss.

Figure 1(a) illustrates the proposed approach to generate and multiplex OAM modes by using multiple coherent inputs (which could be from a multicore fiber [10] or a grating coupler [11]) followed by a fiber with a ring refractive index profile [12]. The linear-polarized modes in the ring fiber can be expressed as $OAM_{l,p} = R_p(r) \exp(i l \phi)$, where $l$ is the OAM charge number, representing an azimuthal phase change of $2\pi l$, and $p$ is the radial index, indicating there are $p$ intensity peaks in the radial direction. $OAM_{l,p}$ modes with different values of $p$ or $l$ are spatially orthogonal to one another. Figure 1(b) shows the refractive index of the ring fiber. The background refractive index is $n_1 = 1.46$ and the refractive index difference is $\Delta n = 0.12\% \times n_1$. The $N$ inputs to the ring fiber are fundamental Gaussian modes in multiple single-mode fibers of the diameter $d_i$ and of the same linearly polarized state. They are evenly distributed around a circle of diameter $D = (d_{in} + d_{out})$. The designed ring fiber should have two properties: (i) only $OAM_{l,p}$ modes with $p = 1$ can be supported by this fiber,

Efficient generation and multiplexing of optical orbital angular momentum modes in a ring fiber by using multiple coherent inputs

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We propose an approach to efficiently generate and multiplex optical orbital angular momentum (OAM) modes in a fiber with a ring refractive index profile by using multiple coherent inputs from a Gaussian mode. By controlling the phase relationship of the multiple inputs, one can selectively generate OAM modes of different states $l$. By controlling both the amplitude and phase of the multiple inputs, multiple OAM modes can be generated simultaneously without additional loss coming from multiplexing. We show, by simulation, the generation of OAM modes (OAM state $|l| < 3$) with mode purity greater than 99%. The power loss of generating and multiplexing seven modes is about 35%. A transmitter for an OAM-based mode-division multiplexing system is proposed based on the discrete Fourier transform between the data carried by the multiple inputs and the data carried by the OAM modes. The experimental implementation of the proposed approach could be achieved by integrating ring fiber, multicore fiber, and photonic integrated circuit technology. © 2012 Optical Society of America

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which means it is a “single-mode” fiber in the radial direction; and (ii) the number of the total azimuthal modes is not larger than $N$ (i.e., $-N/2 \leq l \leq N/2$). Under these two conditions, when the $N$ coherent inputs of the same power and polarization have the phase relationship of $\Delta \Phi = \Phi_0 - \Phi_{m-1} = 2\pi l/N$, a linearly polarized OAM$_l$ mode will be generated. Here, we show the generation of OAM modes with $l$ ranging from $-3$ to $+3$ when $N = 8$, $d_{\text{out}} = 44 \mu m$, $d_{\text{in}} = 32 \mu m$, and $d_s = 8 \mu m$. At 1550 nm, the ring fiber supports OAM$_{l;p}$ from $l = -3$ to $3$ and $p = 1$. The modes of $l > 3$ are cut off.

We use the beam propagation method (BPM) to simulate the generation of the OAM modes of a different $l$ in the ring fiber by controlling the input phase difference of $\Delta \Phi = 2\pi l/N$. The fiber length is 2 cm. Figure 2(a) shows the intensity of eight coherent inputs of a fundamental fiber mode at the input of the ring fiber (left), and the intensity and phase of the generated OAM$_1$ when $l = 0 \sim 3$, and the superposition of OAM$_{+1;1}$ and OAM$_{-1;1}$ having the expression $R(r) \cos(4 \times \varphi)$ when $l = 4$ at the output (right). Figure 2(b) shows the normalized total power in the ring fiber for generating OAM modes of different $l$. The power for generating OAM$_1$ modes of $l = 0 \sim 3$ decreases at first, and is then sustained at a constant level. In contrast, the power of the cutoff mode OAM$_{+1;1} + \text{OAM}_{-1;1}$ keeps falling along the propagation. We then calculate the mode purity of the generated beam, beam using the overlap integral.

$$C_{l;p} = \int F(x,y)\Psi_{l;p}(x,y)dxdy,$$  \hspace{1cm} (1)

where the $F(x,y)$ is the normalized electric field of the generated beam. $\Psi_{l;p}(x,y)$ is the normalized electric field of the linearly polarized mode supported by the ring fiber, which has the expression of $\Psi_{l;p} = R_p(r) \exp(i lp)$. $|C_{l;p}|^2$ is the power weight of each eigenmode in $F(x,y)$ and $\sum |C_{l;p}|^2 = 1$, which determine the mode purity [8].

As shown in Fig. 2(c), the mode purity of all the generated OAM$_{l;1}$ modes is above 99%. To see how the conditions (i) and (ii) of the fiber design are crucial for the generation of the high-purity OAM modes, we replaced the ring fiber with a regular step index multimode fiber. The diameter of the step index fiber is the same as the outer ring diameter $d_{\text{out}} = 44 \mu m$. The refractive index is $\Delta n = 0.36\mu m$. The step index fiber totally supports 38 spatial modes of $|l|$ up to 8 and $|p|$ up to 4. As shown in Fig. 2(c), the purity of the OAM$_{1;1}$ modes obtained by a step fiber is much lower (i.e., <60%) because the inputs also excite many other undesired modes supported by the step fiber. The lower mode purity leads to higher crosstalk among the spatial modes. The mode crosstalk is defined as $10 \times \log(1 - |C_{m,n}|^2)$. The ring fiber crosstalk is $<-30$ dB, while the step fiber crosstalk is $>-5$ dB.

The principle of generating high-purity OAM modes can be explained as follows: Due to the periodic input condition $\Phi_m - \Phi_{m-1} = 2\pi l/N (|l| < N/2)$, the input field is the superposition of the OAM modes with charge $l, l \pm N, l \pm 2N, ... l \pm mN, ...$. Since the ring fiber is designed to support OAM modes with $|l| < N/2$ only, those higher-order modes $l \pm N, ... l \pm mN, ...$ are cut off in the ring fiber and their power dissipates along the propagation, which can be seen in Fig. 2(b) where the optical power drops at the beginning. Actually, the ring fiber acts as a spatial mode filter to maintain the desired OAM modes and to filter out the higher-order undesired modes. Figure 3 shows an example of $l = -3$, which shows the power of the ring fiber’s OAM states at (a) $z = 0 \ cm$ and (b) $z = 2 \ cm$. The ring fiber helps increase the mode purity ~40%.

We further show the tolerance of the generated OAM$_{l;1}$ mode purity to the imperfect launching conditions. Figure 4(a) shows the generated OAM mode purity and crosstalk dependence on the offset (i.e., misalignment) between the ring fiber and the eight inputs. Figure 4(b) shows the dependence on the phase error of the inputs. As illustrated in the inset, we assume that the phase of the $N$ inputs has deviation $\alpha$ and $-\alpha$ alternatively from the exact phase of $\Phi_m = 2\pi ml/N$. One can see that the purity and crosstalk of higher-order OAM modes are more sensitive to the imperfect launching conditions.

By controlling both the amplitude and phase of the multiple inputs, this approach can generate multiple spatial modes.
OAM modes simultaneously without further power loss multiplexing. For example, to generate and multiplex seven modes of the same power, from Fig. 2(b) we can calculate that the total loss is only $\sim 35\%$ compared with the multiplexing power loss ($\sim 1 - (1/2)^N \times 100\%$) by using beam splitters [2,3]. Our scheme shows good scalability in terms of power loss, especially when the mode number $N$ increases.

Figure 5 shows a transmitter diagram in an OAM-based MDM system which uses multiple coherent inputs to generate and multiplex $N$ OAM modes. Each input carries an independent data channel $D_i(t)$. First, the light from a single source is split into $N$ paths. In order to generate mode $\text{OAM}_{l,1}$ carrying data $D_i(t)$, the $m$th input should be

$$d_m(t) = \sum_{l=-N/2+1}^{N/2-1} \exp(i2\pi lm/N)D_i(t),$$

where the vector $d_m(t) = [d_0, d_1, \ldots, d_{N/2}, d_{-1}, \ldots, d_{-(N/2-1)}]^T$ is actually a DFT of the vector $D_i(t) = [D_0, D_1, \ldots, D_{N/2}, D_{-1}, \ldots, D_{-(N/2-1)}]^T$. The DFT can be performed by the digital signal processing in the electrical domain and control modulators to generate $N$ input optical signals. These $N$ inputs carrying $d_m(t)$ are mixed into the ring fiber and then evolve to multiple orthogonal OAM$_{l,1}$ mode carried data $D_i(t)$. Mathematically, the ring fiber performs an inverse DFT operation, which transforms $d_m(t)$ on the spatial basis of $N$ separated Gaussian modes back to $D_i(t)$ on the spatial basis of OAM$_{l,1}$.

The experimental implementation of this approach relies on several techniques. First, an integrated splitter would split the light source into the $N$ path, and maintain the mutual coherence of the $N$ beams along propagation. An array of phase (and amplitude) modulators would control the phase (and amplitude) of the $N$ inputs. Finally, a special designed ring fiber would connect to either a grating coupler or a multicore fiber that has multiple output beams of Gaussian mode. By integrating those existing techniques, one could implement the proposed approach in the real-world.

In summary, we propose an approach to efficiently generate and multiplex OAM modes in a ring fiber by using multiple coherent inputs of Gaussian mode. There is a DFT relationship between the input Gaussian mode channels and the output OAM channels, which could be used to construct a transmitter of a OAM mode-division multiplexing system.

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