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All-optically mode conversion of beams carrying orbital angular momentumusing 2D multi-mode interferencecoupler

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Abstract-In this work, a two dimensional multimode interference (2D MMI) coupler for switching between orbital angular momentum (OAM) modes with opposite topological charge of $l = \pm 1$ has been designed. The proposed device consists of two MMI waveguides and four intermediate ports including two linear waveguides and two tapering phase shifters. Input OAM mode is decomposed into four field patterns at up, down, right and left sides of the end of the first MMI waveguide. Up and down field patterns are related to the real part of the input OAM mode and sided field patterns are related to its imaginary part. Based on the fact that OAM modes with opposite topological charges have π phase difference in imaginary parts and identical real parts, the phase shifters are controlled by the waveguide width at the end of the first MMI waveguide in such a way to apply π phase shift between the sided output field patterns. Following the intermediate ports, second MMI waveguide manipulates the field patterns in order to provide the output OAM mode with topological charge opposite to the input one.

Keywords: 2D Multi-Mode Interference, Orbital Angular Momentum,Phase Shifter.

1. Introduction

Raised by Allen in 1992 [1], light beams with the phase dependence of $e^{il\varphi}$ carries orbital angular momentum (OAM) independent of the polarization state, where φ is the azimuthal angle, and l indicates the topological charge that can take any integer value, positive or negative. Topological charge represents the number of light twists in one wavelength. OAM modes with different topological charge values of l, are theoretically unbounded and orthogonal to each other. This fact introduces a new degree of freedom and can therefore be effectively exploited to enhance the integrated optical devices such as optical beam splitters[4-6], mode convertors[7], couplers[8], wavelength-division (de)multiplexers [9] and capacity of the optical communication links through mode division multiplexing (MDM) technique which loads channel's data on different simultaneous carrying modes[2]. Hence, in order to implement their commercial communication systems, switching and conversion of OAM modes are essential operations. Multimode interference (MMI)[3]structures with many interesting features like their compact size, low sensitivity to fabrication parameters, and ease of fabrication, are efficient candidates for this purpose. MMI structures, based on the interference between the modes of a multimode waveguide, are now widely used in both 1D and 2D as a basic element in many

switches[10]. In 1-D MMI devices, the waveguide is single-mode in the transverse dimension and multimode in the other dimension, whereas in 2D ones MMI waveguides are multimode in both horizontal and vertical directions[11]. In order to carry the power by higher order modes with 2D field distributions, 2D MMI devices are required. From this point of view, a 2D MMI structure can be utilized for OAM mode transmission, too.

Accordingly, this paperproposes an integrated optical device using 2D MMI waveguidesto switch OAM beams with opposite topological charges of $l = \pm 1$, for the first time to the best of our knowledge. Based on the theory of OAM-MMI waveguides[12], the decomposition of any order of OAM modes ($l = \pm 1$) into odd- and even-mode field components [13] occurs at the specificlengthof the MMI waveguide. This issue and the fact that the OAM modes with opposite topological chargeshave even-mode with π phase difference, is utilizedto design a noveltwo stage MMI waveguide joint with tapering phase shifters in between, in order to switch the OAM beams with opposite topological charges.

2. Structure Design

Based on the multimode interference theory[11],self-imaging in a 2D multimode waveguide produces $N \times M$ images at the distances$L$that can be expressed as [11]:

$$L = \left(\frac{S_x}{N}\right) 3L_{\pi x} = \left(\frac{S_y}{M}\right) 3L_{\pi y} \qquad (1)$$

where $N$and M are positive integers without common divisors with the positive integers S_x and S_y, respectively, which are the positional numbers in the $X$and Ydirections, respectively. $L_{\pi x}$ and $L_{\pi y}$ also represent the coupling lengths between the two lowest order modes; the former in X direction and the latter in Y direction. They can be approximately related to the waveguide material refractive index, n_f, and working wavelength, λ_0, as $L_{\pi x} = \frac{4 n_f W_x^2}{3\lambda_0}$ and $L_{\pi y} = \frac{4 n_f W_y^2}{3\lambda_0}$.For simplicity, in the following discussion, $S_x = S_y = 1$ which is also a common practice for the shortest device length.

According to the imaging properties of OAM mode in 2D square cross sectionalMMI waveguide ($L_{\pi x} = L_{\pi y} = L_c = \frac{4 n_f W^2}{3\lambda_0}$),an incidentOAM mode with $l = +1$, exhibit field-splitting at $3L_c/4$ and OAM-maintaining image at $3L_c/2$,as displayed schematically in Fig. 1a[12].

It is worth mentioning that any order of OAM modes (± 1)can be decomposed into odd- and even-mode field components as[13]:

$$f_{OAM}(x, y) = f_{odd}(x, y) \pm i f_{even}(x, y) \qquad (2)$$

where ± sign is determined by the sign of the OAM order (± 1). This decomposition has been shown in Fig. 1b for OAM mode with $l = +1$. In accordance with Eq. (2), OAM modes with opposite topological charges have identical real parts and π phase difference in imaginary parts. We use this fact to design a 2D MMI switch between OAM modes with $l = \pm 1$by applying π phase shift between sided decomposed field components at $3L_c/4$ length of Fig. 1a.

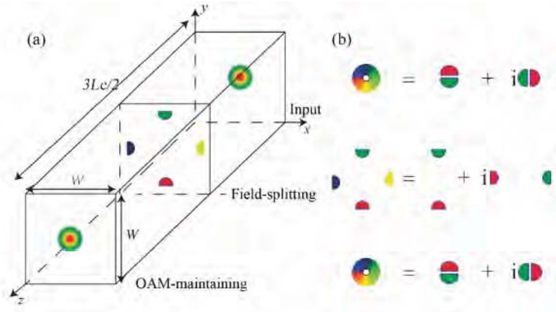

Fig. 1: a) Scheme of incident OAM mode in a square cross-sectional MMI waveguide; b) decomposition of $l = +1$ OAM mode into odd and even modes [12]

Thus, as shown in Fig. 2, the proposed structureconsists of three parts:

1. The first MMI waveguide for decomposition of input OAM mode.

2. Intermediate ports including two linear waveguides for guiding up and down field patterns with no change in phase, and two tapering phase shifters in right and left sides for applying π phase shift between the sided decomposed fields.
3. Second MMI waveguide for composing the manipulated fields in the last part and making OAM mode with opposite topological charge.

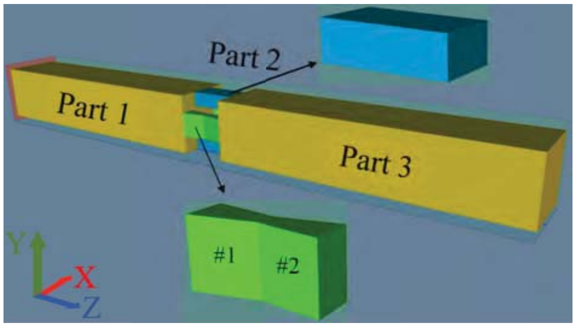

Fig 2:Schematics of the proposedstructure: Part 1 (first MMI waveguide), Part 2 (Intermediate ports) and Part 3 (second MMI waveguide)

The simulation of the structure performance has been done using the commercially available simulation software package OptiBPM13.1. All the simulations assume a vacuum wavelength of $\lambda_0 = 1550$ nm ,and a silicon waveguide $(n_f = 3.45)$ surrounded by silica $(n_c = 1.45)$. The proposed device parameters are presented in table I.

Fig. 3 shows the amplitude and phase of an $l = +1$ OAM mode with waist radius of $1.5\ \mu$m as the input field. Mode decomposition occurs at the end of the first MMI waveguide. As displayed in Fig. 4, the phase of the field pattern at the right and left sides are 0 and $-\pi$, respectively. The second part of the proposed device shifts the phase of the sided field patterns in π value and keeps the phase of the up and down field patterns unchanged (Fig. 5).

Table I. The proposed device parameters

components			$W_x(\mu m)$	$W_y(\mu m)$	$L\ (\mu m)$
Part 1	First MMI waveguide		25	25	1221
Part 2	Up and down linear waveguides		10	6	189
	Sided phase shifters	Section 1	6~3	10	94.5
		Section 2	3~6	10	94.5
Part 3	Second MMI waveguide		25	25	1219

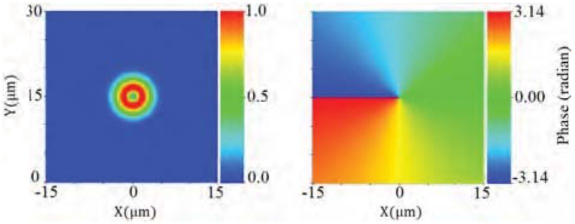

Fig. 3:The amplitude (left) and phase (right) distributions of the input OAM mode with $l = +1$

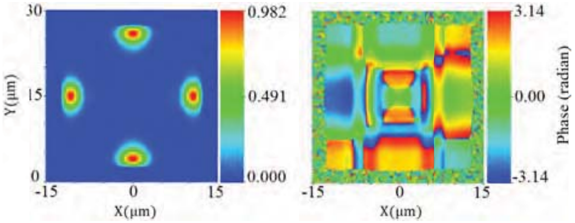

Fig. 4:The amplitude (left) and phase (right) distributions of the decomposed fields at the end of the first part of theproposed device.

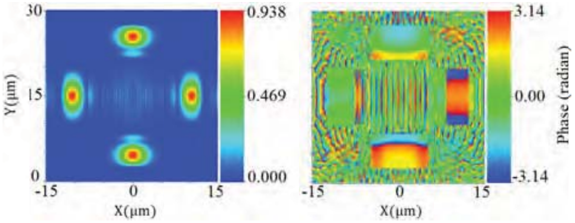

Fig. 5: The amplitude (left) and phase (right) distributions of the decomposed field at the end of the second part of theproposed device

As displayed in Fig. 6, the last part of the proposed devise, second MMI waveguide, compose field patterns and produce OAM mode with opposite topological charge of $l = -1$.

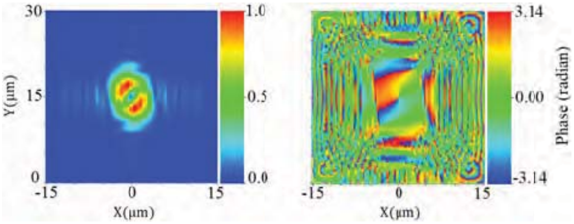

Fig. 6: The amplitude (left) and phase (right) distributions of the output OAM mode with $l = -1$.

The calculated efficiency of the output mode of the proposed device equals to 82%. Fig. 7 shows the output field of the proposed device for input OAM mode with $l = -1$.

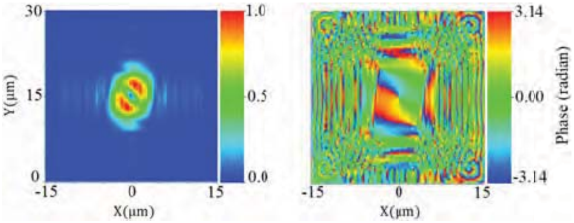

Fig. 7: The amplitude (left) and phase (right) distributions of the output OAM mode with $l = +1$

3. Conclusion

In this paper, a 2D MMI coupler for switching between OAM modes with opposite topological charge of $l = \pm 1$ has been proposed. This structure decomposes the OAM modes into odd- and even-mode field components and provides switching conditions between opposite topological charges by using phase shifters controlled by waveguide width between two 2D MMI waveguides.

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