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Generation of Optical Higher-Order OAM Mode by Using Higher-Order Elastic Vortex Wave in Graded-Index Optical Fiber

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***Abstract*—This report provides the efficiency of higher optical OAM mode conversion using higher order elastic vortex wave. Also, we analyze the contribution of components of dielectric change by elastic vortex wave to the optical OAM mode conversion.**

Keywords—elastic wave, optical fiber, orbital angular momentum, optical mode conversion

I. Introduction

In recent years, required information transmission capacity is increasing. For that reason, methods of increasing capacity is being considered, which include time division multiplexing (TDM), wavelength division multiplexing (WDM) and polarization division multiplexing (PDM). Among them, orbital angular momentum mode division multiplexing (OAM MDM) especially has a large impact for increasing information capacity. The OAM mode is the special optical mode having spiral phase front. This mode is characterized by the discrete twisting rate. From this characterization, the different OAM modes have orthogonality and are multiplexed [1]. Therefore, we need to generate the multiple optical OAM modes efficiently for increasing information transmission capacity.

The elastic vortex wave (EVW) is the elastic wave in the optical fiber. Optical OAM mode conversion by EVW in the optical fiber is efficient method for optical communication. In this report, we consider the optical OAM mode conversion by a higher-order EVW carrying OAM.

II. Plinciple

A. Higher Order Elastic Vortex Wave in fiber

Elastic vortex wave (EVW) is the elastic wave composed by two orthogonal flexural waves in the cylindrical coordinate (r, θ, z) [2]. The displacements of EVW are expressed by

$$\begin{aligned} u_r &= U(r)\exp(im\theta)\exp(-ikz) \\ u_\theta &= jV(r)\exp(im\theta)\exp(-ikz) \\ u_z &= W(r)\exp(im\theta)\exp(-ikz)\,, \end{aligned} \tag{1}$$

where *X(r)* are the radial variations, *m* is the rotation order of the EVW and *k* is the wavenumber of EVW. If the rotation order *m*=1, this mode is called fundamental mode. In addition, When the rotation order *m* is larger than 2, that mode is called higher order mode. We show the absolute value and phase profile of displacement u_z for *m*=2 in Fig. 1. If we use higher order EVW modes, optical OAM mode is converted to higher order optical OAM mode.

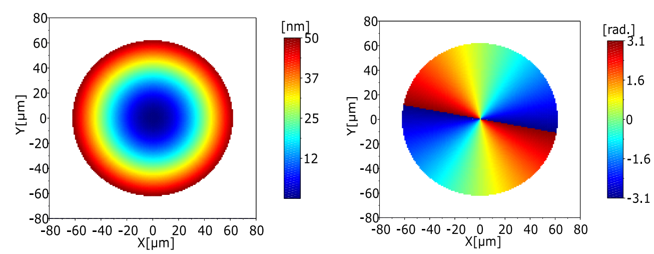

Fig. 1. Displacement absolute value (left figure) and phase profile (right figure) of EVW for *m*=2

B. Optical OAM Mode in GI fiber

Optical OAM mode is a special optical mode having helical phase front. Graded-index (GI) fiber supports optical OAM modes. The optical OAM modes in the GI fiber is called Laguerre-Gaussian (LG) modes [3]. This mode is characterized by rotation order ν and node order *n* and expressed by

$$\mathrm{LG}_{\nu n} = E_{\nu n}(r)\exp(j\nu\theta)\exp(j\beta z)\,, \tag{2}$$

where β is the propagation constant of the LG mode and *E*(*r*) is the radial component of electric field. We show the intensity and phase profile of LG_{20} in Fig. 2. From the left figure, we find that the LG mode has donut shape intensity profile. In addition, from the right figure, we find that the LG mode has a helical phase front and that twisting rate is corresponding to the rotation order ν.

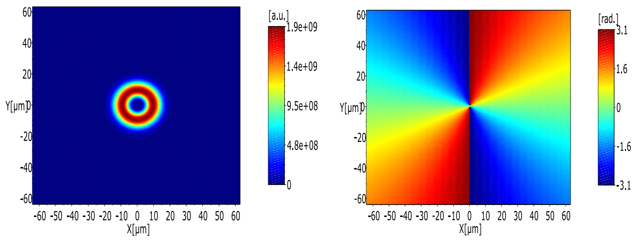

Fig. 2. Intensity (left figure) and phase profile (right figure) of LG mode at $\boldsymbol{\nu}$=2

C. Optical OAM Mode Conversion

We consider the simulation of optical OAM mode conversion using EVW with a setup shown in Fig. 3. The optical OAM mode conversion is calculated by coupled mode theory. From the coupled mode theory, we obtain the coupling mode equation and mode coupling coefficient ϑ_{pl} as shown in (3) (4) [4]-[6].

$$\frac{dA_p(z)}{dz} = \sum_{l=0}^{q} A_l(z)\vartheta_{pl} e^{j(\beta_p-\beta_l-k)z} \tag{3}$$

$$\vartheta_{pl} = \frac{\omega}{4(\beta_l-\beta_p)} \iint \frac{E_p(r,\theta)\cdot E_l^*(r,\theta)}{N_p N_l} \frac{d\varepsilon}{dz} r dr d\theta, \tag{4}$$

where A is the complex amplitude, ω is the angular frequency of optical mode, E and N is the electric field and the normalization coefficient of optical mode. Also, $\frac{d\varepsilon}{dz}$ means variation of dielectric constant along with propagation direction of fiber. Here, subscript p and l mean to converted and input optical mode. Also, we need to consider the phase-matching condition for perfect mode conversion. Here, the phase-matching condition is given by

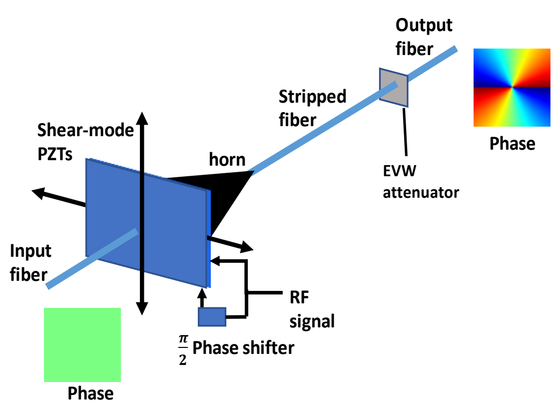

Fig. 3. Schematic diagram of the optical OAM mode conversion setup

$$\beta_l - \beta_p = k.$$

From this phase-matching condition and dispersion relation of EVW, we identify the frequency of EVW for achieving the perfect mode coupling.

III. Results

We consider the mode conversion between LG_{00} and LG_{20} using second order EVW. We show the phase-matching condition and perfect mode coupling length between LG_{00} and LG_{20} as shown in Fig. 4. From the cross point of dashed line and solid curve of left figure, we find that the frequency of EVW satisfied the phase-matching condition is 22.245 MHz. So, we obtain that the perfect mode coupling length is the 67mm from right figure. Here, we set to the $u_z = 0.5$nm. If we change displacements of EVW, perfect mode coupling length become variable.

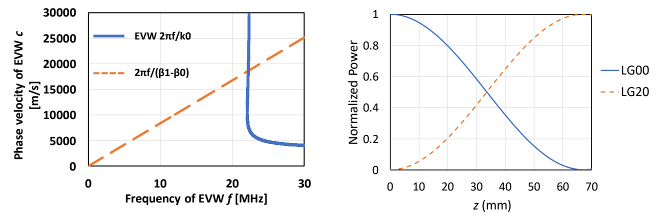

Fig. 4. Phase-matching condition (left figure) and coupling length between $\mathbf{LG_{00}}$ and $\mathbf{LG_{20}}$ (right figure)

IV. Conclusion

In this paper, we considered the optical OAM mode conversion by using higher order EVW. We calculated the frequency of EVW from phase-matching condition for perfect mode conversion between LG_{00} and LG_{20}. As a results, we found that the frequency of EVW is 22.245 MHz. Also, we calculated the mode coupling equation and found that the perfect mode coupling length is 67 mm. From these results, we show that the higher-order optical OAM mode conversion using higher-order EVW is available.

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