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Analysis of Elastic Vortex Wave for Optical Orbital Angular Momentum Mode Conversion in Ring Core Optical Fiber

リングコア光ファイバ中における光軌道角運動量モード変換のための弾性波渦の解析

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1. Introduction

In the future optical communications, increasing transmission capacity is required. Therefore, various multiplexing methods are examined. Recently, orbital angular momentum (OAM) mode multiplexing is attracting as a method of increasing transmission capacity [1]. OAM mode is the optical mode having a helical phase front. From that characteristic, OAM mode can theoretically be multiplexed with infinite modes. In this situation, efficient optical OAM mode generation techniques are required. Fiber-based optical mode generation methods would be low loss and compact rather than free space OAM mode generations. Among these methods, we focus on using acousto-optic (AO) interaction methods due to its controllability and tunability [2]. For the optical OAM mode generation by AO interaction, it is good to use the elastic vortex wave (EVW) which is generated by two orthogonal acoustical waves and possesses OAM on the elastic wave [3]. So, in my previous research, we analyzed the OAM mode conversion by EVW in graded-index optical fiber [4]. In this research, we choose the ring core optical fiber (RCF) as the optical fiber for OAM mode conversion because the RCF strongly supports the optical OAM modes due to its refractive index profile matching to optical OAM mode intensity profile [5]. From this characteristic, we consider that RCF is suitable for optical fiber to convert the optical mode more than the graded-index optical fiber. Therefore, in this paper, we analyze the EVW conditions for more efficient optical OAM mode conversion in RCF.

2. Optical Modes in Ring Core Optical Fiber

We show the RCF geometry in **Fig. 1**. It is characterized by the inner radius a and outer radius b, and by the refractive indices of cladding n_2 and ring core n_1. The optical modes in the RCF are found by solving Maxwell's equations in cylindrical coordinates (r,θ,z). So, we use the longitudinal electric fields defined by

$$E_z = \begin{cases} C_1 I_\nu \cos\nu\theta & r \le a \\ [A_1 J_\nu + A_2 N_\nu]\cos\nu\theta & a < r \le b \\ C_2 K_\nu \cos\nu\theta & r > b, \end{cases} \quad (1)$$

where J_ν and N_ν are Bessel functions of the first and second kind, and I_ν and K_ν are modified Bessel functions of the first and second kind [5].

Here, we choose the parameters as shown in **Table. 1**. From the calculation using that parameters in **Table I**, we obtain the optical mode dispersion as shown in **Fig. 2**. Here, normalized propagation constant $B' = \frac{\beta^2 - n_2^2 k_0^2}{n_1^2 k_0^2 - n_2^2 k_0^2}$, normalized frequency $V = k_0 b\sqrt{n_1^2 - n_2^2}$, so β is the propagation constant of optical mode and k_0 is the wavenumber in the vacuum. From **Fig. 2**, we find the conditions of generating the fundamental optical mode HE_{11} and secondary mode HE_{21} constituting OAM modes at ν=1 and ν=2. Generally, OAM modes can be consisted by $\mathrm{HE}_{\nu n}^{\mathrm{odd}}$ and $\mathrm{HE}_{\nu n}^{\mathrm{even}}$ with a π/2 phase difference as shown in **eq.(2)**.

$$\mathrm{OAM}_{\nu n} = \mathrm{HE}_{\nu n}^{\mathrm{odd}} \pm i\mathrm{HE}_{\nu n}^{\mathrm{even}} \quad (2)$$

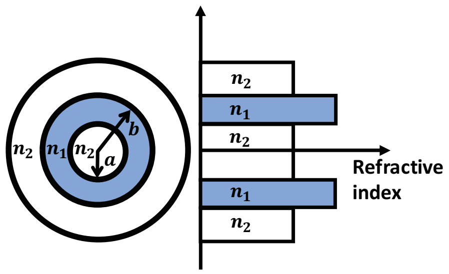

Fig. 1. RCF geometry (top view, and profile).

Table I. Parameter of the RCF.

Parameter	Value
a	0.97 μm
b	2.78 μm
n_1	1.474
n_2	1.444

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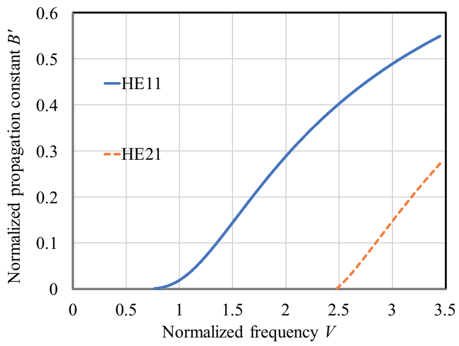

Fig. 2. Dispersion relation of RCF.

3. Elastic Vortex Waves in RCF

The EVW in the optical fiber is analyzed by general wave equations of motion [6]. From that wave equations, we obtain 3 components of displacements induced by the EVW as

$$u_r = U(r)\exp(im\theta)\exp(-ikz)$$
$$u_\theta = jV(r)\exp(im\theta)\exp(-ikz) \quad (3)$$
$$u_z = W(r)\exp(im\theta)\exp(-ikz),$$

where $X(r)$ are the radial variations, m is the rotation order of the EVW and k is the wavenumber of EVW [3] [6]. So, we obtain the strain tensor and stress tensor from these displacements. Finally, we obtain the dispersion equation by applying the boundary conditions.

4. Simulation Results

In this report, we will report the analyzation of the EVW for optical OAM mode conversion in the RCF. For mode conversion, we need to specify the frequency and phase velocity of the EVW satisfying the phase-matching condition between the optical mode and elastic wave. The phase-matching condition is expressed by the relation between optical modes and elastic wave as

$$\beta_l - \beta_p = k, \quad (4)$$

where, β_l and β_p are the propagation constants of input optical mode and output optical mode.

From the phase-matching condition and the dispersion relation of the EVW, we specify the frequency and phase velocity of the EVW for perfect mode conversion as shown in **Fig. 3**. The frequency and phase velocity are $17.016\,\mathrm{MHz}$ and $v = 2993.4\,\mathrm{m/s}$ respectively. Also, **Fig. 4** is the displacement of the EVW at the above condition. The u_r and u_θ are mostly constant and the u_z increases with *r* and has the largest value around the fiber edge.

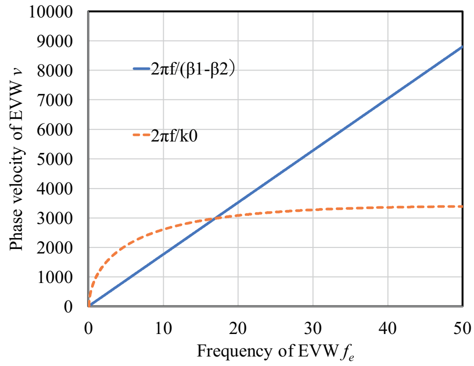

Fig. 3. Phase-matching condition between HE_{11} and HE_{21} constituting OAM modes at $\nu = 1$ and $\nu = 2$.

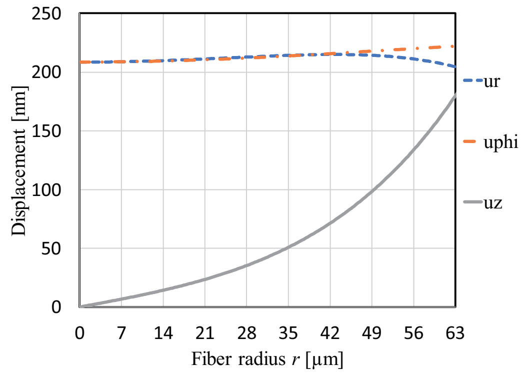

Fig. 4. Absolute value of displacements at $f = 17.016\,\mathrm{MHz}$ and $v = 2993.4\,\mathrm{m/s}$.

5. Conclusion

In this research, we have discussed the EVW conditions for optical OAM mode conversion in RCF. As a result, we found that need to use the EVW at $f = 17.016\,\mathrm{MHz}$ and phase velocity $v = 2993.4\,\mathrm{m/s}$ for perfect OAM mode conversion. As a future plan, we will analyze the optical OAM mode conversion by AO interaction in RCF using these results.

References

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