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Analysis of Elastic Vortex Waves in Optical Fiber for Optical Vortex Mode Conversion

光ファイバにおける光渦モード変換のための弾性波渦の解析

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1. Introduction

Optical vortex carrying Orbital Angular Momentum (OAM) has potential to increase capacity in the future optical network. For OAM multiplexing, it is necessary to generate and handle plural OAM modes. Elastic vortex waves along an optical fiber can be used for mode conversion between OAM modes through acousto-optic(AO) interaction. [1-4] In this study, we discuss elastic vortex waves and the frequency required for the AO mode conversion between OAM modes.

2. OAM mode conversion by elastic wave

According to previous study, the interaction between elastic waves and optical waves causes optical mode conversion in an optical fiber. This study, we consider vortex waves formed from orthogonal flexural waves as shown in Fig.1. We consider a graded index fiber as an optical fiber. The incident OAM mode is converted to the other OAM mode along the fiber.

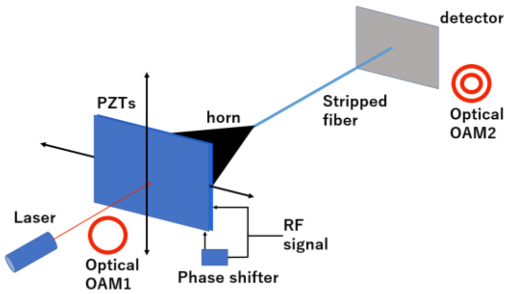

Fig. 1 OAM mode conversion by elastic vortex waves

3. Flexural wave dispersion relation

We analyze flexural wave in the cylindrical waveguide to obtain the dispersion relation. The displacement is expressed by equations (1) - (3) .

$$u_r = [Ak_d J_n^{'}(k_d r) + Bk_0 J_n^{'}(k_t r) + C\frac{n}{r} J_n(k_t r)]\begin{Bmatrix}\sin(n\phi)\\ \cos(n\phi)\end{Bmatrix} e^{i(\omega t - k_0 z)} \quad (1)$$

$$u_\phi = [A\frac{n}{r} J_n(k_d r) + B\frac{k_0 n}{k_t r} J_n(k_t r) + Ck_t J_n^{'}(k_t r)]\begin{Bmatrix}\cos(n\phi)\\ -\sin(n\phi)\end{Bmatrix} e^{i(\omega t - k_0 z)} \quad (2)$$

$$u_z = -i[Ak_0 J_n(k_d r) - Bk_t J_n(k_t r)]\begin{Bmatrix}\sin(n\phi)\\ \cos(n\phi)\end{Bmatrix} e^{i(\omega t - k_0 z)} \quad (3)$$

Here, ω is the angular frequency, r is the cylindrical waveguide radial direction length, k_0 is the propagation constant in the z direction, and J_n is the Bessel function of the first kind and of order n, $J_n^{'}$ denotes its derivative with respect to the argument , and k_d and k_t are given by

$$k_d^2 = \frac{\omega^2}{c_d^2} - k_0^2 \quad (4)$$

$$k_t^2 = \frac{\omega^2}{c_t^2} - k_0^2 \quad (5)$$

where the bulk dilatational and transverse wave velocities c_d and c_t are given by the density $\rho = 2.20 \times 10^3 kg/m^3$, Lame's constants $\lambda = 1.6 \times 10^{10}$, and $\mu = 3.12 \times 10^{10}$ through

$$c_d^2 = (\lambda + 2\mu)/\rho \quad (6)$$

$$c_t^2 = \mu/\rho \quad (7)$$

So, the following determinant (8) is given from the boundary conditions for the stress tensor.

$$\begin{vmatrix} n^2 - 1 - q_0^2(x-1) & n^2 - 1 - q_0^2(2x-1) & 2(n^2-1)[\gamma_n(q_t) - n] - q_0^2(2x-1) \\ \gamma_n(q_d) - n - 1 & \gamma_n(q_t) - n - 1 & 2n^2 - 2[\gamma_n(q_t) - n] - q_0^2(2x-1) \\ \gamma_n(q_d) - n & -(x-1)[\gamma_n(q_t) - n] & n^2 \end{vmatrix} = 0 \quad (8)$$

Here, $\gamma_n(q) = qJ_{n-1}(q)/J_n(q)$ and $x = c^2/2c_t^2$. The dispersion relation is obtained as shown in Fig.2.

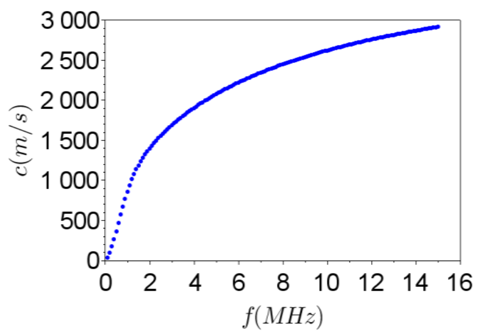

Fig. 2 Mode dispersion relation of flexural mode

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4. Phase matching condition

From the phase matching condition for the mode coupling between the optical waves and elastic waves, and dispersion relation of the elastic waves, the frequency that mode coupling occurs is obtained. The phase matching condition is given by

$$\beta(\omega_l)-\beta(\omega_p)=k. \qquad (9)$$

Here, β is the propagation constant of optical wave. k is the propagation constant of elastic wave. From this equation and Fig.2, we can identify elastic frequency that executes mode conversion of optical mode. We consider a graded index fiber. Then, the propagation constant is given by

$$\beta=\sqrt{\beta_0^2 n^2(0)-2\beta_0 n(0) g(2m+\nu+1)}. \qquad (10)$$

Here, β_0 is the optical propagation constant in vacuum. $n(0)$ is the refractive index of center of the fiber and g is the focusing constant. m is the vortex rotation order and ν is the number of nodes in radial direction. As an example, we consider m=0 → 1 and ν =1. The optical wavelength is 1550nm and we assume $n(0)$=1.46. The graph obtained from equation (9) is Fig.3. The intersection points of Fig.3 are about 1.2MHz and 0.80MHz.

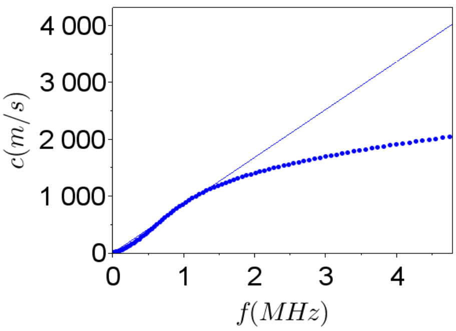

Fig. 3 Frequency for OAM mode conversion

5. Elastic vortex wave

Based on the equation of displacement, we confirmed whether the flexural wave is a vortex wave by making graphs of intensity and phase. It can be confirmed that the flexural wave is the vortex wave when synthesized by orthogonalizing x-axis component and y-axis component of displacement with phase difference of $\frac{\pi}{2}$.

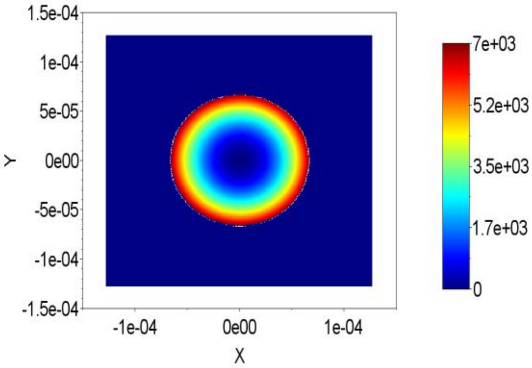

Fig. 4 Elastic vortex intensity of u_z component

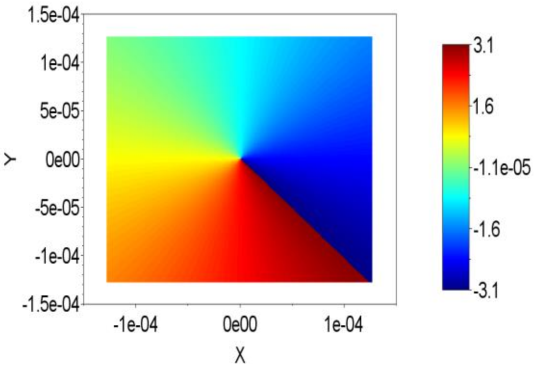

Fig. 5 Elastic vortex phase of u_z component

6. Conclusion

In this study, we found that the ultrasonic wave frequency for mode coupling are 1.2MHz or 0.80MHz. We showed a vortex elastic wave formed from flexural waves. As a future plan, we investigate AO coupling efficiency for OAM mode conversion.

References

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