Mode Coupling Analysis of Hollow Ring-Core Fibers for OAM Transmission

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Abstract

We examine **mode coupling in hollow ring-core OAM fibers** to develop better propagation models. We discuss the interactions among OAM modes, as well as their interactions with parasitic TE and TM modes.
Specifically, we study the effect of fiber **core ellipticity and stress birefringence**, and we discuss coupling among modes of different order due to each of these impairments.

Orbital Angular Momentum Modes Components

Composition of OAM Modes

$$\boldsymbol{E} = [f_l(r) + jg_l(r)]e^{j(l+1)\varphi}\hat{\boldsymbol{R}} + [f_l(r) + jg_l(r)]e^{j(l-1)\varphi}\hat{\boldsymbol{L}} + jh_l(r)e^{jl\varphi}\hat{\boldsymbol{z}}$$

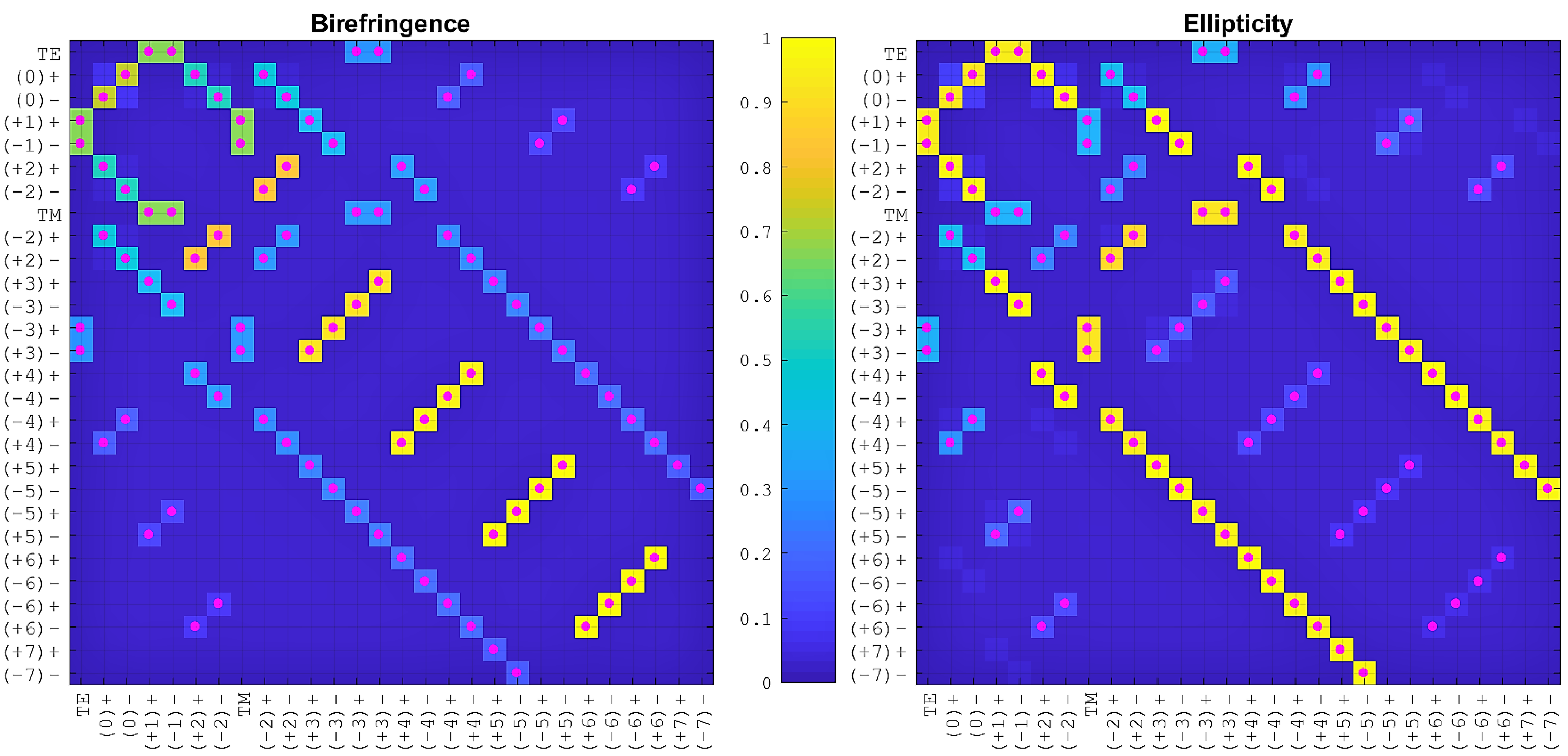
In a cylindrical ring-core fiber we can express hybrid-mode electric fields ($HE_{l,1}$ or $EH_{l,1}$) with respect to circular-polarization basis as a combination of two OAM "beams" of azimuthal orders $l+1$ and $l-1$, and a longitudinal component of order l.

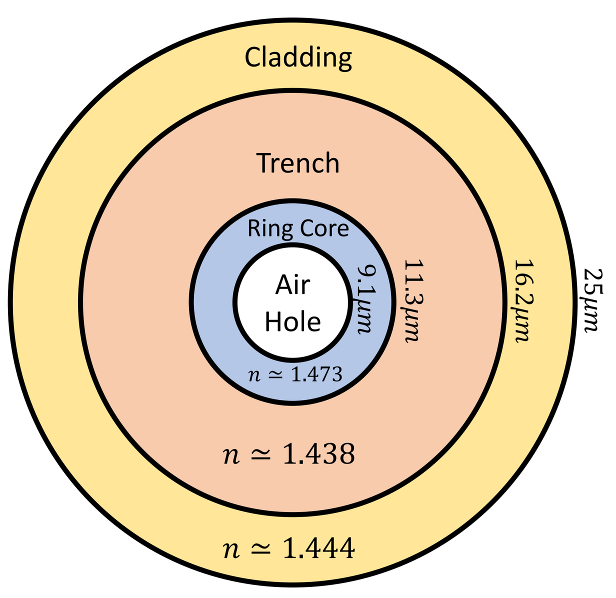
Dominant and Secondary Components

In weak-guiding fibers one of the two "beams" remains (the **dominant**), while the other becomes negligible (the **secondary**); however **both are significant in case of strong guiding fibers**.
OAM definitions and azimuthal orders are summarized in the table, where pink, white, and yellow identify respectively longitudinal, weak, and strong components.

	OAM^+_{+l}	OAM^+_{+l}	OAM^-_{+l}	OAM^+_{-l}
$\hat{\boldsymbol{R}}$	$l+2$	$-l$	l	$-l+2$
$\hat{\boldsymbol{L}}$	l	$-l-2$	$l-2$	$-l$
$\hat{\boldsymbol{z}}$	$l+1$	$-l-1$	$l-1$	$-l+1$

Analysis and Results





We **numerically evaluated the coupling coefficients for a hollow ring-core fiber** supporting 26 (@1550nm) modes and 2 parasitic TE/TM modes (see sketch on the left).
We report the coupling coefficients for stress birefringence and ellypticity (assuming $\gamma_k = \gamma$ for all interfaces) in the figures above, normalized to the largest one.
The magenta dots are the couplings predicted by theoretical analysis. All non-zero values are forecast by theory.
Quite surprisingly, birefringence and ellipticity give the same coupling although with different strengths.

Coupled Mode Analysis

According to coupled mode theory, the complex amplitudes of the N propagating modes vary along z as [1]:

$$\frac{d\boldsymbol{c}}{dz} = -j(\boldsymbol{\beta} + \boldsymbol{K})\boldsymbol{c}$$

where $\boldsymbol{\beta}$ is the diagonal matrix of propagation constants and $\boldsymbol{K}$ matrix represents the **linear coupling per unit length**.
For small perturbations, elements of $\boldsymbol{K}$ are [1]:

$$K_{\mu,\nu} = \int_0^\infty \int_0^{2\pi} r\boldsymbol{E_\mu}^* \tilde{\boldsymbol{\epsilon}} \boldsymbol{E}_\nu^* d\varphi dr = K^*_{\mu,\nu}$$

where $\tilde{\epsilon}$ is the 3×3 matrix of dielectric perturbation.
Although evaluation of these integrals can be quite involved, in almost every case of interest elements of $\tilde{\epsilon}$ can be expressed as the product of two functions each depending either on r or $e^{jh\varphi}$, where h is an integer, called perturbation azimuthal order. Hence, **integration over φ is nonzero only if specific "resonances" occur**: [2]

$$n_\mu - n_\nu = \pm h$$

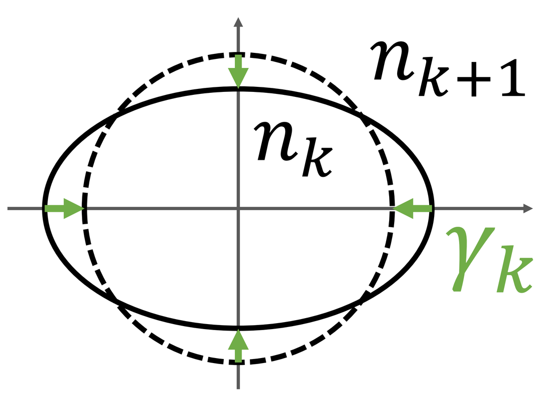
Stress Birefringence ($h = 0$)

Considering stress birefringence, with respect to the basis of circular polarizations, the corresponding dielectric perturbation is [3]

$$\tilde{\boldsymbol{\epsilon}} = \varepsilon_{co}\Delta n \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Core Ellipticity ($h = 2$)

In the case of slight ellipticity in a cylindrical fiber made of M concentric rings, the dielectric perturbation is given by [3]



$$\tilde{\boldsymbol{\epsilon}} = \varepsilon_0 \left[\sum_{k=1}^{M-1} \gamma_k (n_k^2 + n_{k+1}^2)\delta(r - r_k)\right] cos(2\varphi)$$

Conclusions

- We developed a preliminary, but promising, step towards a better description and deeper understanding of coupling mechanism in ring-core fibers for OAM transmissions.
- We evaluated coupling coefficients that provide rich quantitative information about coupling mechanisms in OAM fibers.
- This analysis is fundamental for the assessment of mode coupling effects, which depends also on mode propagation constants difference and the distance of propagation.

References

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