Kerr-induced Rotation of Mixed Orbital Angular Momentum States in Hollow Ring-Core Fibers

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Abstract

We demonstrate that when two spin-orbit coupled orbital angular momentum (OAM) modes of opposite topological charge co-propagate in the Kerr nonlinear regime in a hollow ring-core optical fiber, the mode superposition exhibits a power-dependent rotation effect. This effect is analogous to nonlinear polarization rotation (NPR) in single-mode fibers (SMFs). Unlike NPR in SMFs, the spatial dimension produces a visually observable rotation of the spatial pattern emerging from the fiber when imaged through a linear polarizer.

Orbital Angular Momentum (OAM) Fiber Modes

Fiber modes carrying orbital angular momentum (OAM) are characterized by a spiral azimuthal phase distribution of their electric fields: $e^{il\phi}$, where l is an integer called the topological charge. Each photon in such a mode has an OAM of $l\hbar$. While conventional optical fibers do not support such modes, ring core fibers (RCFs) that consist of ring-shaped refractive index (R.I.) profiles are capable of stable propagation of OAM modes over several kms of fiber length. [Ramachandran et al., Opt. Exp. 23, 3721-3730]

For a given value of $|l|$, there exist 4 modes corresponding to 4 possible combinations of OAM and spin angular momentum (SAM), i.e. polarization. For example, for $|l| = 10$, the 4 modes are :

- $l = +10$, right circularly polarized (referred to as "Spin-Orbit Aligned" (SO_a))
- $l = +10$, left circularly polarized (Spin-Orbit Anti-aligned (SO_{aa}))
- $l = -10$, right circularly polarized (SO_{aa})
- $l = -10$, left circularly polarized (SO_a)

Because of the sharp step in the R.I. profile, the linear propagation properties of an OAM mode of a given OAM, i.e. l, depends on its SAM. This is the so-called "spin-orbit coupling" effect. As a result, the two SO_{aa} modes are degenerate with each other, while they are not degenerate with the SO_a modes, and vice versa.

In this work, we consider the power-dependent evolution of an unequal superposition ($\alpha \neq 1$) of the $|l| = 10$ SO_{aa} modes.

Such a mode superposition has a spatially varying elliptical SOP (shown in Fig. 1 (b)). This arises from the fact that the two spatially overlapping modes have opposite-signed l values, i.e. opposite helicities of azimuthal phase.

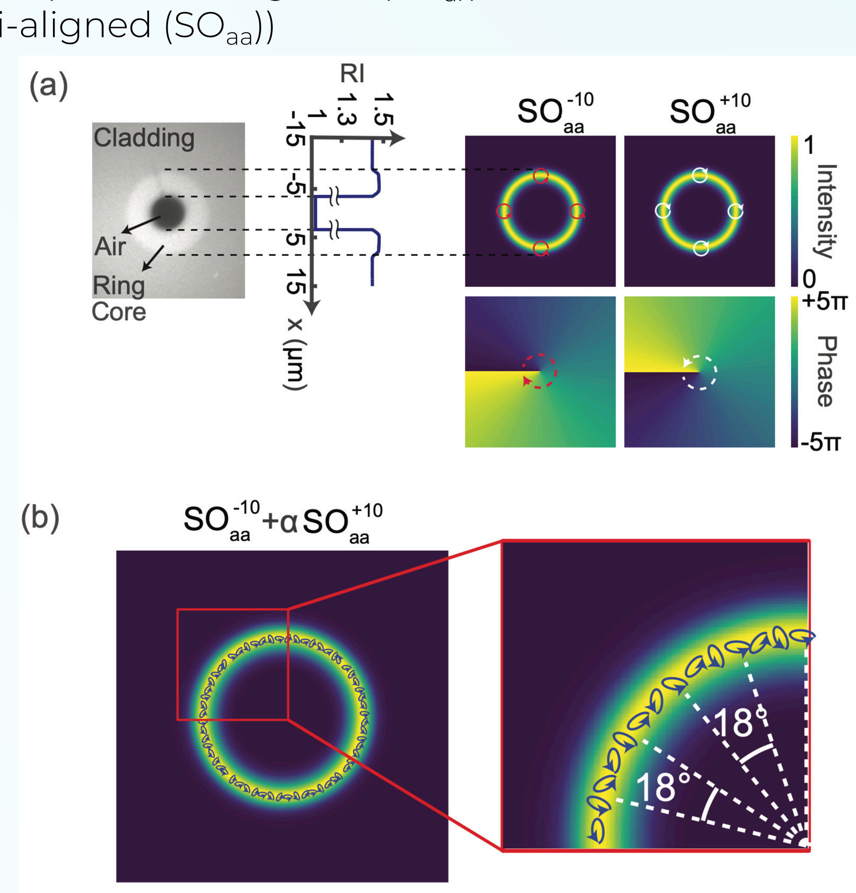
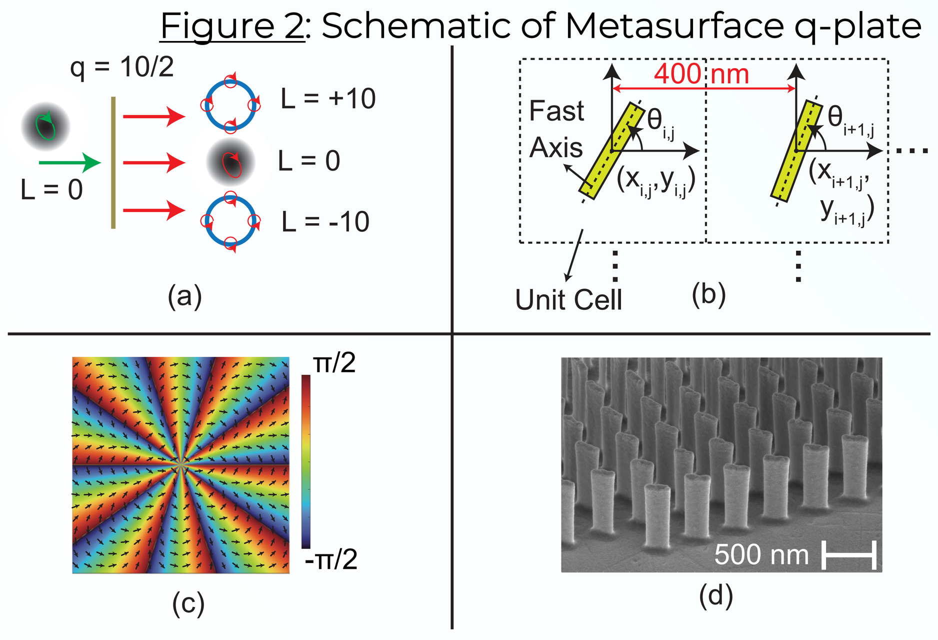


Figure 1: OAM Modes of a Hollow RCF

Experiment

The most common method to excite a tunable combination of SO_{aa} modes is the use of an SAM-to-OAM conversion device such as a q-plate. Conventional q-plates are based on liquid crystal (LC) technology. In this work, we designed and fabricated a q-plate based on a more recent technology, namely dielectric metasurfaces.

Figure 2: Schematic of Metasurface q-plate



Metasurface devices have the unique capability to structure light in both polarization and phase at a sub-wavelength scale (see Fig. 2(b)). Furthermore, LC devices are often prone to damage under high intensity illumination that is required to perform nonlinear optical measurements.

Fig. 2(c) illustrates the q-plate design, which consists of a 2D grid of half-wave plates (HWPs) with a spatially varying orientation of fast axis. Fig. 2(d) is a close-up Scanning Electron Microscopy (SEM) image of the fabricated q-plate.

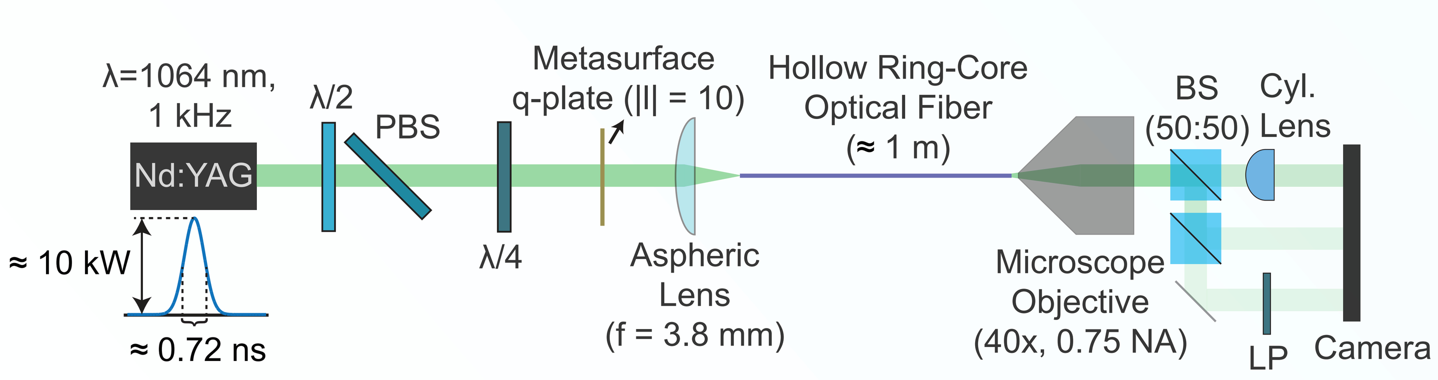
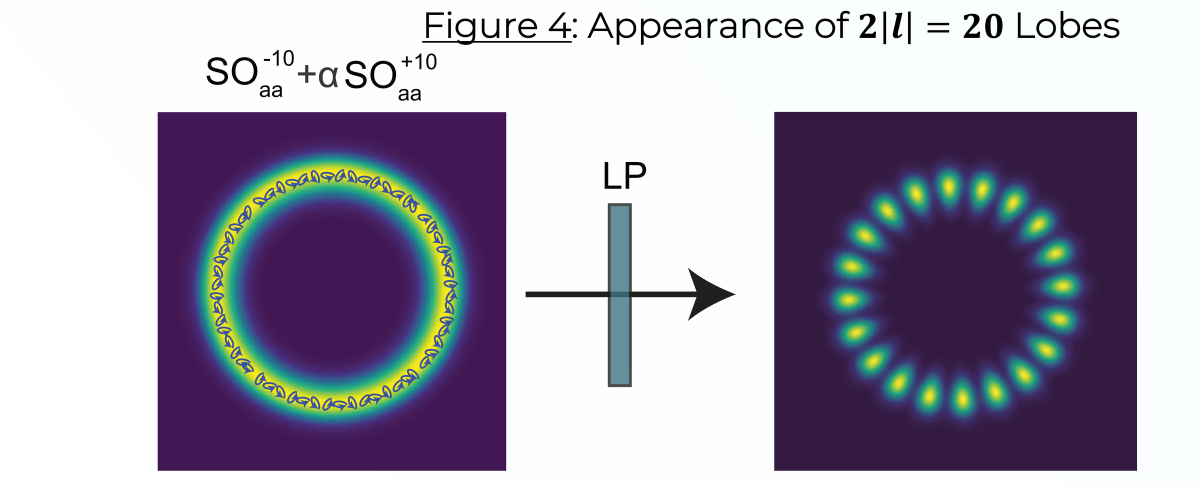


Figure 3: Experimental Setup

Fig. 3 shows a schematic of the experimental setup. The relative power levels in the two SO_{aa} modes (i.e. α) is tuned by adjusting the SOP of the gaussian laser beam incident on the q-plate. When the output beam is imaged on a camera through a linear polarizer, the spatially-varying elliptical SOP for $\alpha \neq 1$ leads to the formation of $2|l| = 20$ lobes, as shown in Fig. 4.

To study the nonlinear evolution of the mode superposition for $\alpha \neq 1$, we experimentally measure the variation of this lobe pattern as a function of input power.

Figure 4: Appearance of $2|l| = 20$ Lobes



Power-dependent Rotation of Lobe Patterns

The coupled NLSEs of the two modes are given by:

$$\frac{\partial V_+}{\partial z} = \frac{2i}{3}\gamma(|V_+|^2 + 2|V_-|^2)V_+ \quad \text{and} \quad \frac{\partial V_-}{\partial z} = \frac{2i}{3}\gamma(|V_-|^2 + 2|V_+|^2)V_-$$

where $V_\pm$ are slowly-varying pulse envelopes of the $l = \pm 10$ SO_{aa} modes, and γ is the nonlinear coupling coefficient. These NLSEs are identical to those for polarization modes in SMFs. In the SMF case, the NLSEs describe a power-dependent rotation of elliptical SOP, namely the well-known **nonlinear polarization rotation** effect. **In the case of OAM modes, we observe a spatially generalized version of this effect.**

The overall orientation of the polarization ellipse pattern shown in Fig. 1(b) is determined by the phase difference between the overlapping modes. At high input powers, self-phase modulation (SPM) and cross-phase modulation (XPM) lead to a power dependence of the phase difference between the overlapping modes. As a result, the overall orientation of the polarization ellipse pattern – and consequently the observed lobe pattern – depends upon the input power.

Because we use a non-square (Gaussian) pulse, the lobe pattern undergoes a time-dependent rotation within one pulse duration. When we perform time-averaged imaging using a conventional camera, the time-averaged patterns show an apparent "smearing out" (i.e. reduction in lobe contrast) in addition to the rotation of the lobes.

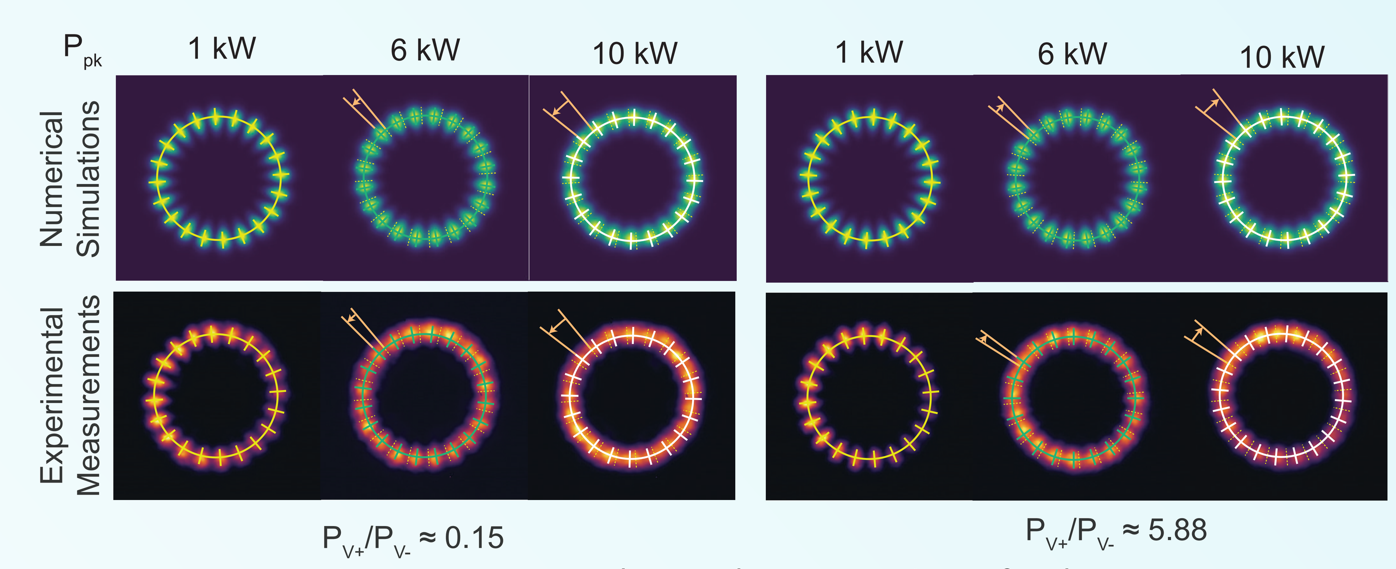


Figure 5: Power-dependent Rotation of Lobe Patterns

Fig. 5 demonstrates numerical simulations and experimental measurements of this nonlinear phenomenon for two values of α: one where the $l = +10$ mode is dominant, whereas another in which the $l = -10$ mode is dominant. Because the two modes have opposite helicities of azimuthal phase, the two cases exhibit opposite senses of rotation.

Further quantitative analysis of the measured lobe patterns indicate agreement with numerical simulations as shown in Fig. 6. For the control cases of equal power in the two modes, or all of the power in only one mode, the lobes exhibit no rotation. **This is consistent with the NPR in SMFs analogy in that NPR is only observed for an elliptical state of input polarization, i.e. with unequal power in right and left circularly polarized states.**

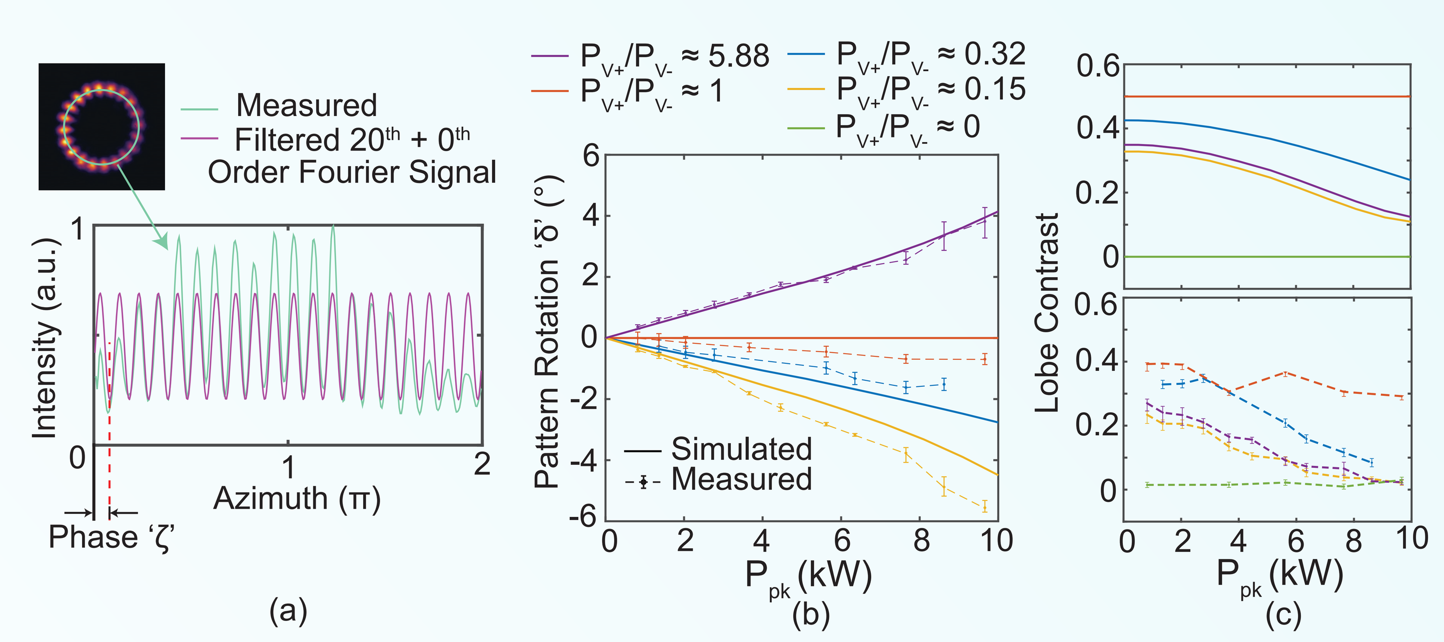


Figure 6: Lobe Rotation and Smearing Out of Lobe Pattern: Experiment vs Simulation

Conclusions

In this work, we have demonstrated a novel phenomenon wherein the spatial pattern exhibits a power-dependent rotation effect. This phenomenon constitutes a spatial generalization of the nonlinear polarization rotation phenomenon known to occur in SMFs. This work adds to a relatively new body of research on nonlinear interactions between OAM modes, which is of great interest for spatial division multiplexing, quantum optics and quantum communication applications.

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