Observation of Aharonov-Bohm Suppression of Optical Tunneling in Twisted Multicore Fibers

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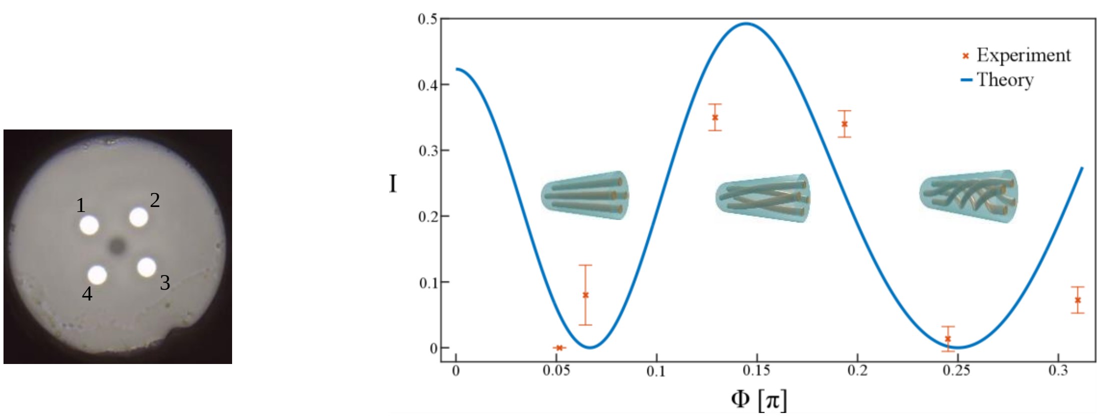
Abstract: We report the first observation of Aharonov-Bohm-like topological suppression of optical tunneling in twisted multicore fibers. Experimental results show that this effect is insensitive to imperfections, nonlinearities and mode-mixing processes, in agreement with theoretical predictions.

OCIS codes: (350.1370) Berry's phase; (260.3160) Interference; (190.4370) Nonlinear optics, fibers

A major conceptual advance in quantum mechanics occurred when Aharonov and Bohm first realized that, contrary to common belief, electromagnetic vector potentials play in fact a physical role when interacting with charge carriers [1]. Indeed, electron wavefunctions are directly influenced by the vectorial magnetic potential $\boldsymbol{A}$, even in regions where the magnetic field itself is zero. An intriguing phenomenon directly related to the Aharonov-Bohm (AB) effect is the possibility of totally decoupling two quantum channels having degenerate eigenvalues, for specific values of magnetic flux with respect to the unit flux h/e [2]. This effect can be explained if one considers the destructive interference of the eigenstates involved, that results from the differential phase accumulated by the tunneling electron wavefunctions. In solid state however, this suppression of tunneling can only be demonstrated in the presence of ultrastrong magnetic fields-a factor that has so far impeded any experimental observation of this process. A possible optical realization of this effect was previously suggested in a twisted multicore [3] or annular fiber configuration [4] where evanescent light coupling can be totally suppressed between opposite channels. In addition, theoretical predictions in [3] suggest that the effect should persist even in the presence of optical nonlinearities.

In this work, we report the first observation of the AB-like suppression of light tunneling in a four-core twisted optical fiber. Our experimental results are in good agreement with those expected from theory for different values of the twist rate. Moreover, we investigate the response of this structure for high optical input powers - where nonlinear effects start to antagonize the coupling mechanisms in this multicore system. We find that due to the topological nature of the AB-phase, the suppression of tunneling still persists even in the nonlinear regime. In the case each core is multimoded, this same effect occurs in a universal fashion, i.e. tunneling of all higher-order modes can be totally eliminated using this scheme.



(a) (b)

Figure 1: (a) Microscope image of the input facet of an in-house fabricated four-core fiber (the notch engraved on the cladding is used as a marker), (b) Normalized light intensity at the output of core 3 when core 1 is initially excited at $\lambda = 1550\ nm$, as a function of the coupling phase Φ (induced by different twist rates). At $\Phi = \pi/4$ the third core always remains dark because of AB suppression.

The fabricated fiber structure used in our experiments consists of four coupled cores, each with a diameter of $\sim 7.5\ \mu m$ and a numerical aperture of 0.12, while the distance between neighboring elements is $D = 23\ \mu m$. A fluorine-doped, low-index core of diameter $\sim 5\ \mu m$ is incorporated in the center (Fig. 1 (a)) to further inhibit any cross coupling between cores 1 and 3. As a result, light can only couple via nearest neighbors. The system is then uniformly twisted along its propagation axis with a spatial pitch Λ. In the rotating frame, the evolution of the local mode field amplitudes a_n are described by the following set of equations:

$$i\frac{da_n}{dz}+\beta_n a_n+\kappa(a_{n+1}e^{-i\Phi}+a_{n-1}e^{i\Phi})=0, \tag{1}$$

where n denotes the core number modulo 4, κ is the nearest neighbor coupling coefficient, $\Phi=(k_0\, n_0\, \epsilon D^2)/2$ is the coupling phase introduced by the twist, D is the core distance between neighboring sites, n_0 is the cladding refractive index, and $\epsilon=2\pi/\Lambda$ is the angular twist pitch. Figure 1 (b) shows the measured normalized light intensity in core 3 at the output of the fiber when core 1 was initially excited using CW light from an external cavity laser at $\lambda=1550\, nm$ with a power of $\sim 1\, mW$, for different values of Φ associated with various twist rates. The theoretically expected results are also depicted in the same figure for the sake of comparison. It is clear from these observations that the AB-like suppression of light tunneling from core 1 to 3 occurs provided that $\Phi=\pi/4$.

In order to explore how optical nonlinearities may affect the light AB dynamics in this same structure, we launched high intensity pulses of duration $\sim 400\, ps$ at $\lambda=1064\, nm$ from a Q-switched microchip laser into core 1. The recorded light intensity distribution at the output of the fiber is shown in Figs. 2 (a)-(c) for different twist rates at an input peak power of $\sim 1\, kW$. Note that in this case each of the individual cores support degenerate LP_{11} modes in addition to the fundamental LP_{01} mode. As evident from these results, for the optimum twist rate corresponding to $\Phi=\pi/4$, the AB-like tunneling suppression is maintained even in this nonlinear setting. Moreover, since in this case the nonlinear effects start competing with the coupling strengths, light coupling is further subdued between nearest-neighbor channels.

We finally examined the AB topological behavior of the twisted four-core fiber in the multimode regime, with a CW input excitation at $\lambda=665\, nm$ and a power of $\sim 2mW$. In this scenario, LP_{02} happens to be the highest order mode (associated with the highest coupling coefficient) supported by the individual cores of this system. Figures 2 (d)-(f) illustrate the output intensity profiles for three different twist rates. As clearly indicated by these measurements, AB suppression of tunneling persists even in this highly multimode regime in our platform.

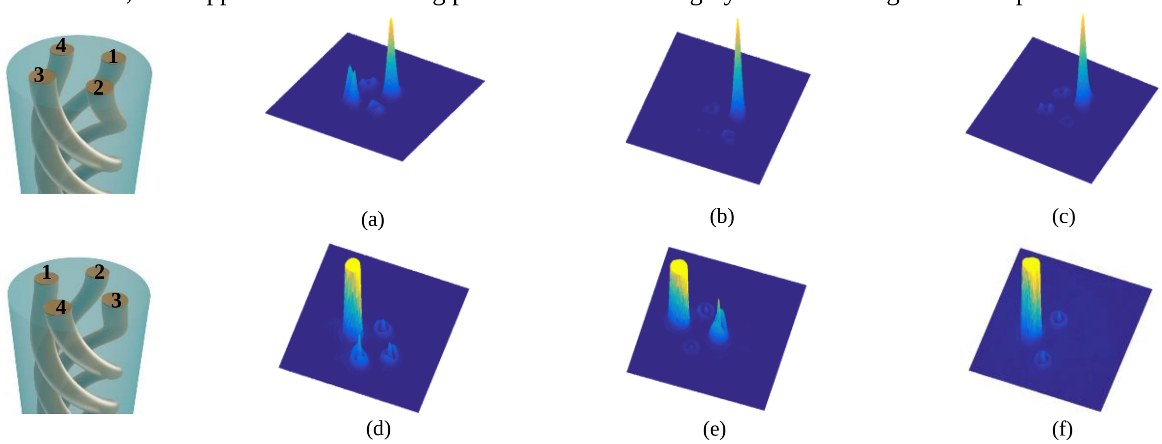


Figure 2: Light intensity distributions in a 24 cm long four-core twisted fiber when core 1 is initially excited by pulses of peak power $\sim 1kW$ at $\lambda=1064\, nm$, for (a) $\Phi=0$ (no twist), (b) $\Phi=\pi/4$, and (c) $\Phi\approx 0.27\pi$. Similar results for a low power excitation at $\lambda=665\, nm$ when (d) $\Phi=0$, (e) $\Phi\approx 0.11\pi$, and (f) $\Phi=\pi/4$. Notice how the AB-like suppression of tunneling persists even in the presence of nonlinearity and/or multimode behavior in these two scenarios for the LP_{11} and LP_{02} modes, respectively.

In conclusion, we observed for the first time the Aharonov-Bohm suppression of light tunneling in a twisted multicore fiber structure. Our experimental results are consistent with theoretical predictions for different twist rates, and confirm that the AB phase remains invariant with respect to optical nonlinearity and/or multimode behavior in this setting.

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