

Properties of Waveguides Based Upon the Pancharatnam-Berry Phase

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Abstract: A waveguide based upon the Pancharatnam-Berry phase (PBP) confines light even in the absence of a refractive index gradient. Here, we investigate theoretically the properties and the robustness of the PBP waveguide. © 2022 The Author(s)

1. Working mechanism of a PBP waveguide

The PBP waveguide [1, 2] exploits geometric phase (GP) instead of dynamic phase, to balance the natural diffraction of light. As a matter of fact, PBP is gained when polarization changes, geometrically represented as a path on the Poincaré sphere (PS) [3]. Owing to the geometric nature of the PBP, for closed loops, its value is determined by the solid angle subtended by the trajectory ranged by the polarization state on the PS. Thus, its value is strongly dependent on the input polarization. Natural candidates for the investigation of the PBP are anisotropic media, where light polarization in general varies along propagation due to the different values of the two refractive indices associated with the two eigenwaves. In an anisotropic material of length corresponding to a half-wave plate (HWP), for a circularly polarized (CP) input the PBP is two times the local rotation of the optical axis [4]. Furthermore, the sign of the imposed phase delay depends on the beam helicity. Thus, when the optic axis of the anisotropic medium is rotated along the beam cross-section, the PBP is responsible for a strong spin-orbit interaction, i.e., the intensity strongly depends on the input polarization [4, 5]. This fundamental property has been used to design flat optical devices, in the last two decades, to impart a given wavefront.

PBP in an anisotropic medium homogeneous along the propagation direction does not accumulate on propagation. Indeed, in the following HWP distance the phase undergoes a local variation opposite in sign, thus leading to a null transversal PBP gradient. The trick for the existence of PBP waveguides is the rotation of the optical axis at each HWP distance, similar to quasi-phase matching in nonlinear optics. This configuration allows the accumulation of the PBP as light propagates thereby making the waveguide feasible. This mechanism is demonstrated experimentally in Refs. [1] and [2] in a discrete linear case and in a continuous nonlinear case, respectively.

2. Structured modes supported by PBP waveguides

Following the numerical results presented in Ref. [1], we use here a combination of FDTD and FEM simulations to study the properties of the guided beam in this new type of waveguide. We limit ourselves to the (1+1)D case to make the numerical cost of a parametric investigation manageable. We choose an anisotropic material of birefringence 0.2. The wavelength of the input beam is $1\mu\text{m}$; the longitudinal modulation of the optical axis is assumed to be sinusoidal, with a period equal to $5\mu\text{m}$ Fig. 1(a). To enable light confinement we assume the rotation amplitude to be Gaussian-distributed along the transverse axis, with a maximum angle Γ_0 . The input is CP, with the transverse distribution being determined by the eigenmode of a scalar potential proportional to the local amplitude of the optic axis rotation, but with the sign dependent on the input helicity [1]. Results are shown in Fig. 1(b-i). The spin-dependent nature of the effective potential associated with the PBP is clear: light is confined or repelled according to its input helicity. Nonetheless, for $\Gamma_0 = 90^\circ$ a portion of the input energy undergoes confinement also for the polarization subject to repulsion at smaller angles. To explain this phenomenon theoretically, we use a combination of gauge transformations and more accurate modelling for the plane wave propagation in a longitudinally rotated anisotropic medium. We demonstrate for considerably larger rotation angles, the input eigenmodes are no longer CP. The theory shows that the beam polarization undergoes a strong modulation along its cross-section, explaining the increased oscillations observed in propagation with increasing Γ_0 . Due to the strong spin-orbit interactions in the PBP waveguide, its quasi-modes are fully structured beams with a point-dependent polarization. The optical fields injected into the waveguide do not possess this feature, yielding a low

overlap for large rotation angles. We demonstrate such properties by extracting the spatial distribution of the Stokes parameters from the numerical simulations. Finally, we model these effects like the analogue of a point-dependent magnetic field acting on the electrons, with the exotic properties stemming from the lack of invariance with respect to local rotational symmetry for twisted anisotropic media.

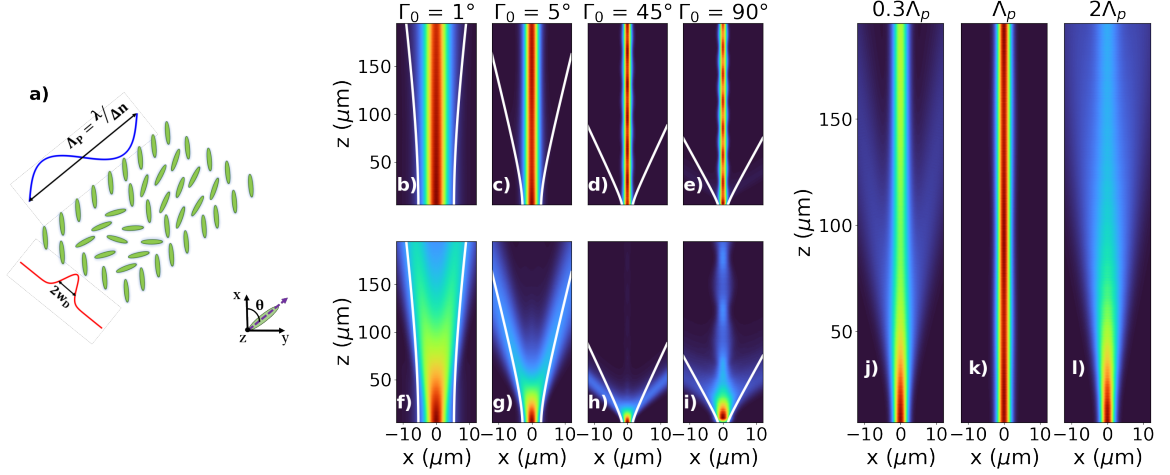


Fig. 1: (a) Illustration of a continuously modulated PBP waveguide (b-i) Intensity distribution of a quasi-mode (b-e) RCP, (f-i) LCP; propagating in a PBP waveguide with $w_D = 3 \mu m$ and increasing Γ_0 as stated above each column. The white lines indicate the extent of natural spreading of light in a homogeneous material. (j-l) Propagation of a quasi-mode in a PBP waveguide with $w_D = 5 \mu m$, $\Gamma_0 = 15^\circ$ and different longitudinal modulation period, as stated above each column.

In the next step we study the influence of the modulation period on the behavior of the PBP waveguide. The maximum amplitude of the longitudinal oscillation Γ_0 is fixed to 15° . The longitudinal modulation period of the optical axis is varied from $0.3\Lambda_p - 5\Lambda_p$, where Λ_p is the synchronous period discussed above. Numerical results are plotted in Figure 1(j-l). Surprisingly enough, the confinement is quite robust to variations of the longitudinal modulations, with a certain degree of localization (coupled power up to 60% with respect to the matched period) retained for periods comprised in the range between $0.3\Lambda_p$ and just below $2\Lambda_p$. Such a behavior is explained by considering the effective phase delay induced by a twisted anisotropic material on a plane wave, i.e., by turning off the diffraction, in full analogy with the splitting operator technique largely employed in numerical analysis.

3. Conclusion

We have demonstrated numerically and theoretically that the modes supported by PBP waveguides possess a highly structured polarization configuration, both on the longitudinal and the transversal direction. The trapping mechanism also shows a strong resilience with respect to changes in the longitudinal modulations. From a basic physics point of view, we framed our results in the context of a strong spin-orbit interaction taking place in twisted anisotropic materials.

References

1. S. Slussarenko, A. Alberucci, C.P. Jisha, B. Piccirillo, E. Santamato, G. Assanto, and L. Marrucci, “Guiding light via geometric phases,” *Nat. Photon.* **10**, 571 (2016).
2. C.P. Jisha, A. Alberucci, J. Beeckman, and S. Nolte, “Self-Trapping of Light Using the Pancharatnam-Berry Phase,” *Phys. Rev. X* **9**, 021501 (2019).
3. E. Cohen, H. Larocque, F. Bouchard, F. Nejdassattari, E. Karimi, “Geometric phase from Aharonov–Bohm to Pancharatnam–Berry and beyond,” *Nat. Rev. Phys.* **1**, 437–449 (2019).
4. Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, “Space-variant Pancharatnam–Berry phase optical elements with computer-generated subwavelength gratings,” *Opt. Lett.* **27**, 1141–1143 (2002).
5. L. Marrucci, C. Manzo, and D. Paparo, “Optical spin-to-orbital angular momentum conversion in inhomogeneous anisotropic media,” *Phys. Rev. Lett.* **96**, 163905 (2006).