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Numerical calculation of the operation wavelength range of a polarization controller based on rotatable wave plates

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ABSTRACT

We calculate the operation wavelength range of polarization controllers based on rotating wave plates such as paddle-type optical fiber devices. The coverages over arbitrary polarization conversion or arbitrary birefringence compensation are numerically estimated. The results present the acceptable phase retardation range of polarization controllers composed of two quarter-wave plates or a quarter-half-quarter-wave plate combination, and thereby determines the operation wavelength range of a given design. We further prove that a quarter-quarter-half-wave-plate combination is also an arbitrary birefringence compensator as well as a conventional quarter-half-quarter-wave-plate combination, and show that the two configurations have the identical range of acceptable phase retardance within the uncertainty of our numerical method.

1. Introduction

Polarization controllers (PCs) are widely used to compensate for unwanted polarization rotations in optical fiber cables. Such compensation can alleviate the degradation of optical communication fidelity due to polarization-dependent loss or polarization mode dispersion [1,2], and is essential for fiber lasers and polarimetric optical fiber sensors [3]. Polarization compensation is also critical for polarization-encoded data transmission through optical fibers in applications such as quantum information processing [4].

Analogous to a series of wave plates, a PC is composed of sections of optical fiber, each wound around a paddle-like disk [5]. Each section introduces a phase difference between two orthogonal polarization states: this phase is proportional to the fiber cladding diameter squared, the inverse of the disk diameter squared, and the number of windings of the fiber around the disk [5]. Analogous to a rotating wave plate, the plane of each disk can be rotated, determining which pair of orthogonal linear polarization states experience the relative phase. Standard PC designs consist of either two or three paddles. In the two-paddle design, both paddles are quarter-wave plates (QWPs), enabling conversion of any specific input polarization $\vec{p_i}$ to any desired output polarization $\vec{p_o} = U \cdot \vec{p_i}$, where $\vec{p_i}$ and $\vec{p_o}$ are Jones vectors and U is the Jones matrix [6,7]. A three-paddle PC with QWP-half-wave plate (HWP)-QWP combination can produce arbitrary birefringence, represented by any desired rotation of the Poincaré sphere with respect to an arbitrary vector $\vec{v}$ by an angle $\alpha \in [0, 2\pi)$ [8].

Interestingly, commercial PCs (e.g., Thorlabs FPC020 and FPC030) often do not come with precise working wavelength specifications, only with recommendations for the appropriate number of turns around each disk for a relatively broad range of operation wavelength. Since the phase retardance is inversely proportional to wavelength, this suggests that the PC's operation does not depend critically on the phase retardance applied by each paddle.

Our work supports by numerical estimation the effectiveness of a PC with phase retardances deviating significantly from the optimal values. Specifically, we determine the coverage of the set of required transformations enabled by a PC with non-optimal phase retardances. Although we discuss these calculations in the context of fiber PCs, our results are equally applicable to the free-space case of non-optimal rotating wave plates. Therefore, we present a practical guideline for choosing a PC with non-optimal optics.

2. Calculation procedures

Our model for the system is shown in Fig. 1. The PC is composed of paddles that apply a phase difference ϕ_i between the linear polarizations along the direction θ_i and $\theta_i + 90^\circ$ $(i = 1, 2, \ldots)$. The rotation angles are discretized to grids $\theta_i = 0^\circ, 180^\circ/N_\theta, 2\cdot 180^\circ/N_\theta, \ldots, (N_\theta - 1)\cdot 180^\circ/N_\theta$, where N_θ is the number of angle settings for each paddle. The space of polarizations states for $\vec{p}_{in}$

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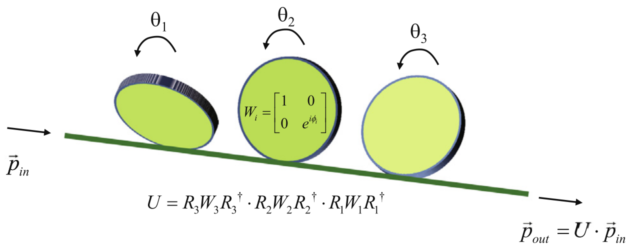

Fig. 1. Structure of the polarization controller. W_i's and R_i's are Jones matrices denoting relative phase shift by ϕ_i and rotation by θ_i, respectively. Other notations are defined in the text.

and $\vec{p}_{out}$ is also discretized according to Marsaglia's method [9,10] as follows. First, each polarization state is represented by a point (x, y, z) $(x^2 + y^2 + z^2 = 1)$ on the Poincaré sphere; this point is then mapped to a point inside a unit circle $(x_1, x_2) \in (-1, 1)$ $(x_1^2 + x_2^2 < 1)$ such that $x = 2x_1\sqrt{1 - x_1^2 - x_2^2}, y = 2x_2\sqrt{1 - x_1^2 - x_2^2}, z = 1 - 2({x_1}^2 + x_2^2)$; finally, we only retain the discrete set of points $x_1, x_2 \in \{-1 + 1/N_x, -1 + 3/N_x, \ldots, -1 + (2N_x - 1)/N_x\}$, where N_x is the number of values on the grid for x_1 and x_2. To analyze a PC's performance for a given input polarization $\vec{p}_{in}$, we calculate the output polarizations for all discrete settings of the θ_i's, and round the results to the nearest grid points (x_1, x_2). At each of these accessible output grid points we mark a flag parameter, and we define the ratio of marked flags to the total number of output grid points $\sim N_x^2 \cdot \pi/4$ as the *coverage* of the output for input $\vec{p}_{in}$. We average the coverage for all discretized input polarizations $\vec{p}_{in}$.

When characterizing a PC as a generator of arbitrary birefringence (arbitrary phase shift between arbitrary two orthogonal polarizations), birefringence U is also discretized. Note that sampling birefringence U with [polarization axis $\vec{v}$, rotation angle α] is intuitive but irrelevant because sample points become overcrowded near $\alpha = 0$. Instead, we use, without rigorous proof about the uniformity, the following sampling method shown in Fig. 2: arbitrary birefringence can be defined by the two target polarizations of $\vec{H}$ (horizontal) and $\vec{D} = (\vec{H} + \vec{V})/\sqrt{2}$ (diagonal). We define $x_1, x_2 \in (-1, 1)$ to denote the output polarization $U\vec{H}$ according to the method defined in the previous paragraph, and $\psi \in [0, 2\pi)$ to be the angular position of $U\vec{D}$ within the circle that is perpendicular to $U\vec{H}$ on the Poincaré sphere. We set the origin $\psi = 0$ as the destination of $\vec{D}$ by the rotation defined by $\vec{H} \times (U\vec{H})$. Polarizations and ψ are discretized by N_x and N_ψ points, respectively. The coverage of birefringence compensation is estimated by counting the marked flags on the set of points (x_1, x_2, ψ) after scanning all the wave plate directions θ_i's.

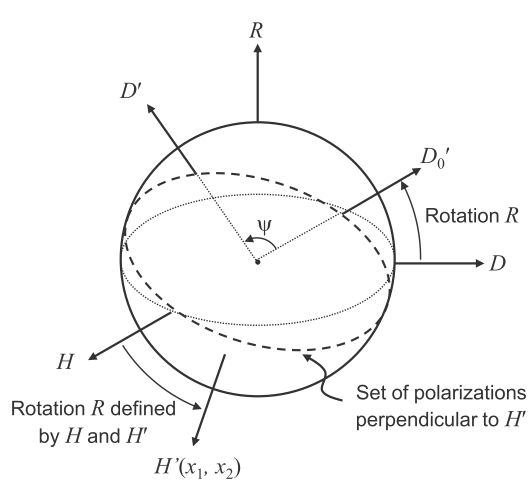

Fig. 2. Sample parameters (x_1, x_2, ψ) for an arbitrary birefringence U. U is uniquely defined by the two output polarizations H' and D' of horizontal polarization H and diagonal polarization D, respectively. D'_0 denotes the output polarization of D under the rotation R defined by H and H' (rotation by $(\arcsin(|\vec{H} \times \vec{H}'|) - \pi/2) \cdot \mathrm{sign}(\vec{H} \cdot \vec{H}') + \pi/2$with respect to $\vec{H} \times \vec{H}'$). Angle ψ is measured between D' and D'_0 on the set of polarizations perpendicular to H' with respect to the rotation axis $\vec{H}'$. x_1 and x_2 define H' as described in the text.

3. Results for conventional two- and three-component PCs

We first test the polarization conversion capability of a two-component PC, where the two paddles have identical birefringence ϕ. For the input, we only need to consider a quarter circle connecting the horizontal polarization and the right-circular polarization on the Poincaré sphere as shown in Fig. 3 because (*i*) overall rotations of the input state that maintain the polarization ellipticity do not change the coverage ratio, and (*ii*) the coverage ratio for orthogonal input polarizations is the same, since orthogonal inputs give orthogonal outputs. We average the coverage of the points on this quarter circle, weighting the contribution from each point by the density of inputs with the same coverage ratio (see the shaded area in Fig. 3): this weighted average is the average coverage of polarization conversion between arbitrary input and arbitrary output polarizations.

The calculation results are shown in Fig. 4(a). Average coverage greater than 95% is achievable for retardation ϕ between 90% and 130% of the optimal value $\pi/2$. In this calculation, the number of angle grids $N_\theta = 80$ and the number of polarization grids $N_x = 30$. These grids are sufficiently fine for our purpose, as discussed below. A three-component PC is also tested with $N_\theta = 50$ and $N_x = 30$ as shown in Fig. 4(b). The phase retardances of the three wave plates are respectively $\phi, 2\phi$, and ϕ. In this case, within our calculation accuracy, complete coverage over arbitrary polarization conversion is achievable for ϕ between 50% and 160% of the optimal value $\phi = \pi/2$.

Thus far, we have only considered the ability of two- and three-component PCs to convert arbitrary single input polarizations to

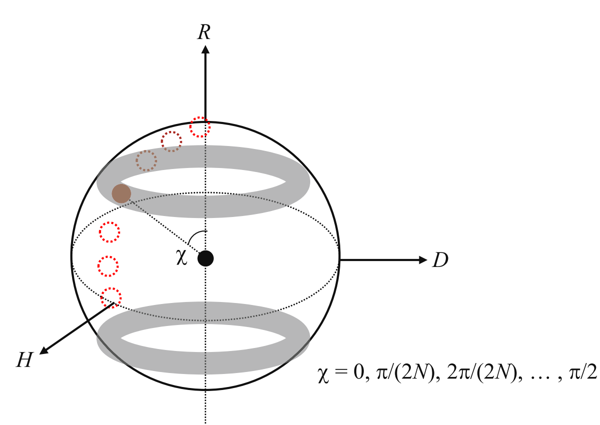

Fig. 3. Input polarizations (circles) on the Poincaré sphere for calculation of the polarization conversion capability. H, D, and R denote horizontal, diagonal, and right-circular polarizations, respectively. $(N + 1)$ is the number of input polarizations, and the average coverage is calculated as the weighted sum (with the weighting factor being the shaded area) of the results of the points. $N = 10$ in this work.