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Intuitive understanding of the connection between Pancharatnam-Berry optical beam deflectors and polarization volume holograms

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Abstract: An approximate beam propagation method is proposed as an intuitive simulation to explain the optics, similarity, and differences of Pancharatnam–Berry phase (PPD) and polarization volume hologram (PVH) devices. © 2022 The Author(s)

Polarization volume gratings (PVH) and Pancharatnam–Berry phase devices(PPD) have wide application in optical systems. These two types of devices, when considered separately have much different optical effects and intuitive explanations. In the remaining discussion, it is assumed that the thickness of each device is close to $\lambda/(2\Delta n)$.

Both of these effects can be quantitatively modeled using the rigorous coupled wave approach (RCWA) or by using the finite difference time domain (FDTD) method. But these computational approaches do not provide an intuitive analytical connection between the PPD and the PVH type devices, or a predictive analytical expression to explain their properties.

In this paper, the approach of Gaylord[1] is extended to birefringent materials using a beam propagation method to clearly show the analytical connection between the optical properties of PPD and PVH devices.

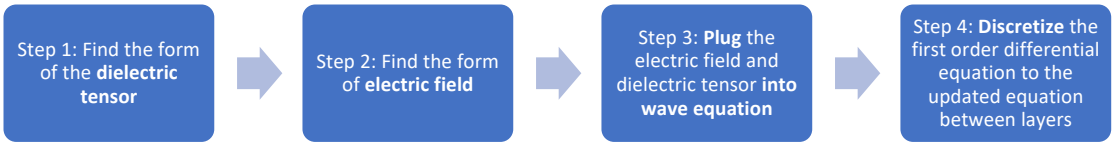

Fig. 1. Flow chart of the steps in this beam propagation method.

Following the steps shown in Fig.1, when the director tilt angle is small, and light is normally incident (electric field has small component along the z direction), the equation that relates the values of S_l in a layer to the next one (layer+1) in the light propagation direction for the -1,0,+1 diffraction orders is,

$$S^{layer+1}{}_{-1} = S^{layer}{}_{-1} - \frac{i\pi d}{2A_{-1}}\left\{\frac{-4}{\Lambda^2}S_{-1}{}^{layer} + \frac{\Delta N^2}{2\lambda^2}M_{-}S^{layer}{}_{0}\right\}$$

$$S^{layer+1}{}_{0} = S^{layer}{}_{0} - \frac{i\pi d}{2A_{0}}\left\{\frac{\Delta N^2}{2\lambda^2}M_{-}S^{layer}{}_{1} + \frac{\Delta N^2}{2\lambda^2}M_{+}S^{layer}{}_{-1}\right\}$$

$$S^{layer+1}{}_{+1} = S^{layer}{}_{+1} - \frac{i\pi d}{2A_{1}}\left\{\frac{\Delta N^2}{2\lambda^2}M_{+}S^{layer}{}_{0}\right\}$$

S_l is the complex wave amplitude for the lth diffraction order specified by the Floquet condition.

This equation is used to find the output amplitude and polarization state of light exiting a film of many layers. The result is verified with RCWA.
From this equation:

1. the ‘p’ parameter, used to distinguish PPD and PVH, for a birefringent media defined.

$$p = \frac{4 * \lambda^2}{\Lambda^2 * n_{ave}' * \Delta n}$$

2.The polarization state is calculated, and the phase information of different diffraction orders is obtained.

3. A explanation is given for the different polarization responds of PVH and PPD based on the result of point one and two:

First, the incident polarization state only has the possibility to excite either the +1 or -1 order depending on its polarization state being LHC or RHC. Second, the distinction between the optical effect of a PPD vs a PVH is related to the changing relative phase between the -1 order and the 0 order that results in no net energy to be transferred from the 0 order to the -1 order if the ‘p’ parameter is large.

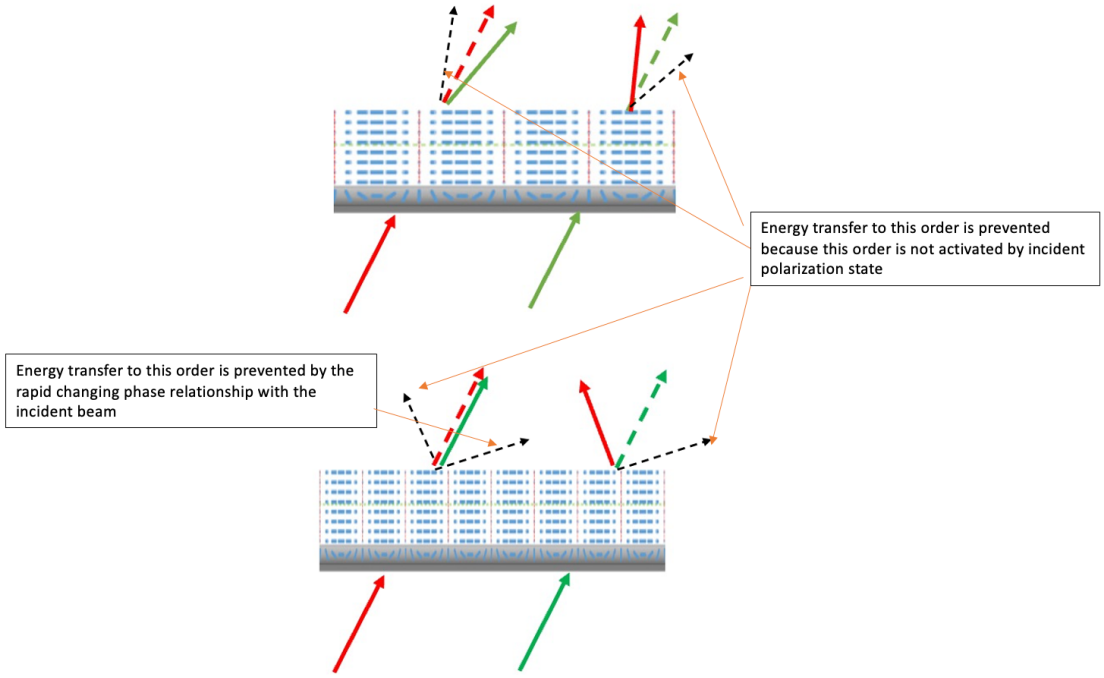

Fig. 2. Explanation of the different polarization responds of PPD and PVH. The polarization state of light represented by the green arrow is LHC, while the red arrow is RHC.

Reference

[1] Gaylord, T., and M. Moharam. “Planar dielectric grating diffraction theories.” Applied Physics B 28 (1982): 1-14.