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An Achromatic Quarter-Wave and Half Wave Phase Retarder Combination Operating in Near-Infrared (NIR) Region

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Abstract. Optical phase retarders are major components in design of different optical systems. Normally these retarders exhibit retardance which varies with wavelength. But achromatic phase retardation is necessary in optical system design. These achromatic phase retarders can be designed using different waveplates, sub-wavelength grating (SWG), liquid crystals, and polymers etc in different wavelength ranges. Present communication focus on designing of quarter-wave phase retarder in the near infrared range (NIR) with waveplates of different birefringent materials having different thicknesses. This system in NIR range shows comparable performance with those developed with SWGs and it also removes some drawbacks. The proposed system deals with an achromatic combination of four birefringent plates in 800–2000 nm range using Sapphire, CdSe, Calcite, and Rutile crystals having good transmittance in the NIR range. This system can also be used as a half wave phase retarder in NIR.

***Keywords:** Quarter-wave plates, NIR, Birefringence, Phase retarder*

I. INTRODUCTION

Quarter-wave and half-wave retarders are key optical components which are widely used with systems in different wavelength ranges for various applications. With the development of new optical instruments to be used in NIR region this wavelength region is exploring a new way for infrared physics. Earlier scientists had designed various achromatic combinations in different ways with birefringent plates, SWGs, liquid crystals etc. It was Pancharatnam who designed a combination of three plates fabricated from the same materials which shows a good achromatism over a range of visible wavelength [1]. Then Hariharan [2] also proposed an achromatic system with two plates of different materials for the visible region. Nicolas Passily *et al* for first time studied achromatic phase retardation based on sub-wavelength dielectric diffraction grating (SWGs) in both the visible and near-infrared regions [3]. Achromatic retarders can also be designed with a single piece of dielectric sub-wavelength grating (SWG) with period comparable to the illuminating wavelength [4].

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However, this kind of grating designed in the resonance region has non zero-order diffractions and is sensitive to the variance of incident angle. But, the birefringence of a single piece of grating changes monotonically with wavelength [5], therefore its birefringence dispersion curve can't keep the same proportionality factor over a broad waveband [6]. Designing such systems require high complexity, regarding the development of the period of the grating structure and the orientation angle. Recently Saha *et.al* proposed a combination of three plates in the near infrared region from 800-2000 nm [7]. Increasing the number of wave plates in a system is also an option to improve performance like one proposed by Masson and Gallot [8].
In this current communication, an achromatic quarter-wave retarder has been proposed in the 800-2000 nm wavelength spectrum which shows comparable performance with the system having SWGs. The materials chosen show good optical transmittance in the proposed wavelength region. The following section 2 deals with the designing of achromatic quarter-wave retarder. In section 3 simulation results and discussion are described followed by conclusion in section 4.

II. THEORETICAL BACKGROUND

During the passage of the light wave through the birefringent plates the path difference will be considered as an important parameter for the retardation calculation. Assuming the thickness of the plates as d_X, d_Y, d_Z and d_K for the performance of the system as quarter- wave plate (i.e. phase difference of $\pi/2$), then thicknesses can be calculated by solving the following equation[9],

$$\begin{vmatrix} \triangle n_{X1} \triangle n_{Y1} \triangle n_{Z1} \triangle n_{K1} \\ \triangle n_{X2} \triangle n_{Y2} \triangle n_{Z2} \triangle n_{K2} \\ \triangle n_{X3} \triangle n_{Y3} \triangle n_{Z3} \triangle n_{K3} \\ \triangle n_{X4} \triangle n_{Y4} \triangle n_{Z4} \triangle n_{K4} \end{vmatrix} \begin{vmatrix} d_X \\ d_Y \\ d_Z \\ d_K \end{vmatrix} = \pm\frac{1}{4} \begin{vmatrix} \lambda_X \\ \lambda_Y \\ \lambda_Z \\ \lambda_K \end{vmatrix}$$
(1)

Here λ_X, λ_Y, λ_Z and λ_K are the three selected design wavelengths which are taken to be 0.8μm, 1.2μm, 1.6μm, and 2.3μm respectively. Here the representation of birefringence of the materials at the design wavelengths are given as Δn_{X1}, Δn_{X2}, Δn_{X3}, Δn_{X4}; Δn_{Y1}, Δn_{Y2}, Δn_{Y3} ,Δn_{Y4}; Δn_{Z1}, Δn_{Z2}, Δn_{Z3}, Δn_{Z4} and Δn_{K1}, Δn_{K2}, Δn_{K3}, Δn_{K4} respectively. The overall phase difference between two orthogonal directions of light may be either $+\pi/2$ or $-\pi/2$, which means that if the input is a linearly polarized light at 45° then the output light will be either left or right circularly polarized [7].

In this case positive values are considered which can be satisfied with the combination of Sapphire (negative), CdSe (positive), Calcite (negative) and Rutile (positive).

A. Thicknesses of the plates

To compute the thickness of the individual plates when the system is designed for quarter-wave plate four designing wavelengths λ_X=0.8µm , λ_Y=1.2 µm, λ_Z=1.6 µm, and λ_K=2.0 µm are considered from the 0.8-2.0 µm spectrum with the birefringence values of the four crystals taken from table 8 in [10]. Using those values of birefringence in the Equation.(1), we get the thickness values as shown in Table 1.

Table1 Calculated thickness values of the four plates

Name of the plates	Thickness value (µm)
Sapphire (d_X)	142.9
CdSe (d_Y)	190.5
Calcite (d_Z)	14.3
Rutile(d_K)	4.0

III. SIMULATION RESULTS & DISCUSSIONS

Achromatic behavior of the proposed system has been studied after evaluating the overall phase retardation and then plotting with respect to wavelength. Figure.1 illustrates that the maximum deviation of retardation from the intended phase retardation of 90^o and that is within ±2.05° over the mentioned wavelength range 0.8µm to 2.0 µm which shows the achromatic nature of the proposed system. Also the percentage deviation of the intended quarter-wave retarder is shown in fig.2. It is seen that the maximum deviation from achromatism is within +3.5% and -1.0% throughout the spectrum. The overall retardation values for different wavelengths can be calculated from the following equation.

$$\varphi = (2\pi/\lambda) \times [(\triangle n_1 \times d_X) + (\triangle n_2 \times d_Y) + (\triangle n_3 \times d_Z) + (\triangle n_4 \times d_K)] \quad (2)$$

Here $\triangle n_1$,$\triangle n_2$,$\triangle n_3$,$\triangle n_4$ are the birefringence of the four materials for different wavelengths in the mentioned spectrum and d_X,d_Y,d_Z,d_K are the thickness of the four materials respectively, and λ is the wavelength.

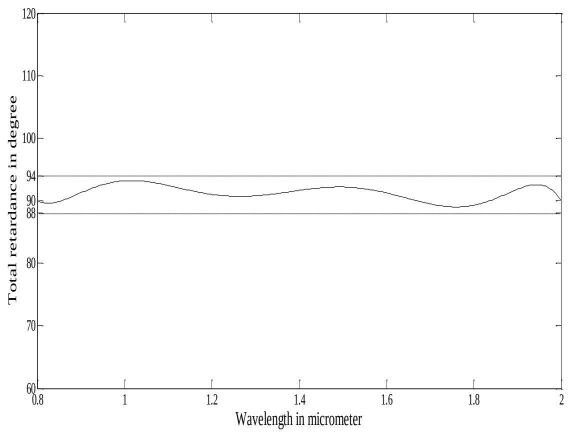

Figure 1. Retardation variation with wavelength for quarter wave retarder.

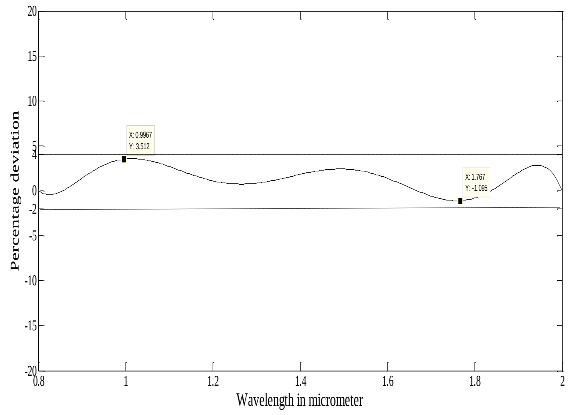

Figure 2. Percentage deviation of retardation with wavelength.

The overall retardation of the four plate system varies within 90°±2.05° as shown in fig. 1. The earlier reported study in this region shows a deviation of 90°±4.5° [7], furthermore an achromatic phase retarder based on the metal-multilayer grating was reported with deviation 90°±4° working over a wavelength range 900nm-1200nm [11]. While developing such achromatic systems with SWGs designing of the depth and orientation angle of each grating is very complex and moreover to increase the IR transmittance proper arrangement is supposed to be done. But our present system reported with very less deviation shows better performance over those systems and can be used in different optical systems in the NIR range where quarter wave phase retarder is a key component. Behavior of the system as half wave phase retarder is shown in fig. 3 & fig.4 respectively. The required thickness of the four plates for half wave phase retarder is shown in Table 2.

Table2 Calculated thickness values of the four plates

Name of the plates	Thickness value (µm)
Sapphire (d_X)	285.7
CdSe (d_Y)	381.0
Calcite (d_Z)	28.6 4
Rutile(d_K)	16.6

From the simulation result it is clear that the maximum retardation variation is within +4.5^0 and that of percentage variation is within +2.5%.

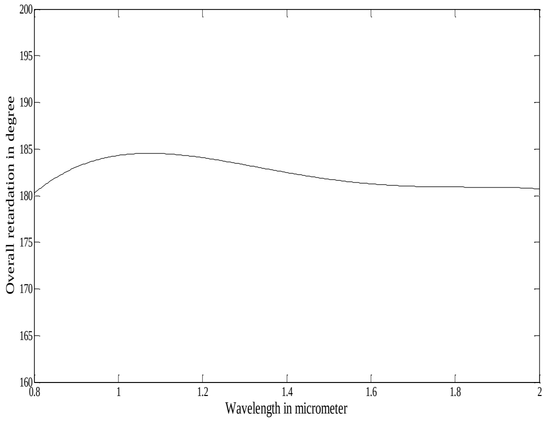

Figure 3. Retardation variation with wavelength for half wave retarder.

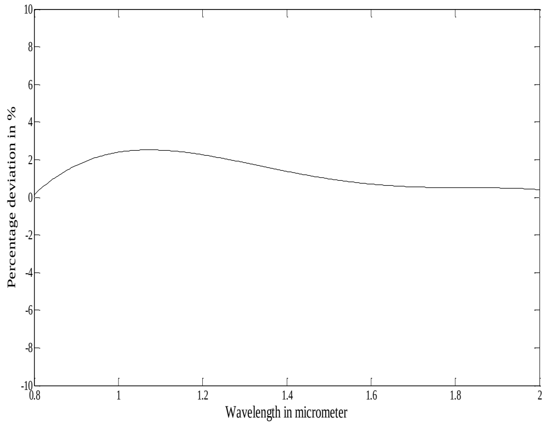

Figure 4. Percentage deviation of retardation with wavelength for half wave retarder.

All the techniques are simulated using Matlab 2009a in a laptop with 2 GB RAM, Dual Core processor and Windows7 operating system. The selected materials shows good transmittance over the mentioned wavelength band along with less hygroscopic property and cost effectiveness. Overall transmittance of the system is shown in Table 3. All these properties are well supported by Sapphire, CdSe, Calcite and Rutile.

Table 3.Overall transmittance of the system

Wavelength(µm)	Overall transmittance (%)
0.8	49.8
1.2	50.2
1.6	49.9
2.0	52.2

IV. CONCLUSION

In this present study, an achromatic quarter-wave combination having four birefringent wave plates of different materials has been designed, which shows fairly good achromatism over the intended wavelength region. The combination can be used as an achromatic half-wave plate also with proper choice of thicknesses of the individual plates. In the proposed study, the combination shows a deviation over the entire range of intended wavelength spectrum up to only ±2.05° which is comparable with systems designed with SWGs and other wave plates combinations reported earlier. Our present system will reduce the manufacturing cost compared to the system made with SWGs. All the four crystals show good transmission characteristics over the intended wavelength region.

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