Inorganic Reflective Waveplates

JDSU has demonstrated an all-inorganic retarder product fabricated as dielectric thin film mirrors on φ200 mm wafers.

Thin film coatings are out-of-plane (C-plate) retarders having an optic axis aligned parallel to the device normal. The retardance can only be accessed at oblique incidence. Therefore, these are termed geometric retarders. On the other hand, polymer foil and single-crystal retarders have traditionally been used to modify the polarization of light beams. These components exhibit linear retardance and linear retardation orientation and are classified as Cartesian retarders because an in-plane retardation axis can be configured. These definitions are similar to Cartesian and geometric polarizers, where the relevant examples are stretched foil and subwavelength-grid Cartesian polarizers, as well as MacNeille and plate geometric polarizers, respectively.

The primary advantages of using geometric retarders are high reliability, low cost, and flexible retardance targeting for design and fabrication via vacuum deposition. In addition, other thin film interference properties can be integrated into the same film stack. While transmissive thin film retarder applications are well known, reflective designs enable additional flexibilities. This technical note describes the operating principles, thin film design examples, and a retarder application example of these reflective waveplates.

Principle of Operation

Cartesian versus Geometric Retarders

The main difference of geometric from Cartesian retarders is in the invariance of retardation property (magnitude and axis orientation) versus rotation about the device normal. Whereas Cartesian retarders are nearly always single pass or double-pass transmissive components, the geometric retarder can be configured as a transmissive or reflective component.

The operating principle of the Cartesian retarder is based on an index difference between light rays propagating as extraordinary and ordinary modes through molecular structures exhibiting polarizability or via the polarization sensitivity of subwavelength structures. On the other hand, geometric retarders give rise to optical admittance difference of the S-polarization (S-pol.) and P-polarization (P-pol.) light rays (linear polarizations that lie orthogonal and parallel to the plane of incidence, respectively). The S-pol. corresponds to the ordinary wave, and the P-pol. corresponds to the extraordinary wave.

In both transmissive[1] and reflective[2] thin-film retarders, one cannot decouple the plane of incidence from either the fast or slow axis. At a given off-axis illumination, the retardation properties of a uniform film is independent of the rotation of the device versus its normal axis. At normal incidence, there is no retardance as the beam propagates along the optic axis. Hence, the retardance is only realized by the geometric configuration of the thin film vs. incidence direction.

Thin Film Device and Equivalent Retarder

An example of reflective thin-film C-plate is schematically shown in Figure 1(a). The film stack comprises multiple alternating high- and low-index isotropic layers. The high-reflection function is built into the film stack. The off-axis retardation effects of the multilayer thin film stack can be compared to the corresponding off-axis retardation effects of a single-layer birefringent medium, as illustrated in Figure 1(b). An ideal mirror is inserted to simulate a nonpolarization-dependent reflection. The stack of thin film can be analyzed as a C-plate retarder[3].

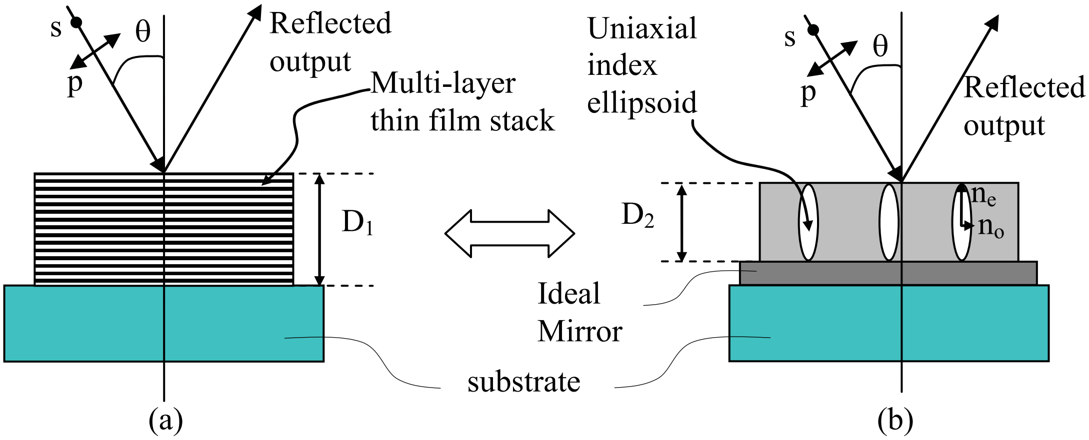


Figure 1: Schematic diagram of a geometric retarder showing (a) actual device, comprising isotropic layers on a substrate and (b) equivalent retarder model comprising a single uniaxial C-plate layer on an ideal mirror mounted on a substrate.

Reflective Quarterwaveplate and Halfwaveplate Designs

The S-pol. and P-pol. light reflected off a thin-film retarder mirror experience differential phase delay, or retardation. In contrast to transmissive designs, reflective thin film designs are not constrained by the cross-coupling of intensity and phase properties. As a result, the dispersion of the constituent thin film materials can be mitigated such that true achromatic reflected retardance can be obtained over a broadband wavelength range while maintaining a high reflection. Whereas transmissive C-plate is more commonly used to compensate for cone illumination of light, such that off-axis rays are made to accumulate a certain amount of retardance, reflective waveplates are best suited for abnormal, collimated illumination[4]. The transmissive component may be targeted at a very small fraction of wave retardance at a moderate angle (three degree retardance at a 12-degree angle of incidence, or AOI) while the reflective component can achieve very large retardances, (90- and 180-degree retardance at a 45-degree AOI).

Accessing the Retardance of Thin Film Retarders

A geometric retarder must be configured off-axis in order to yield any retardance. Moreover, the input polarization must not coincide with the fast and slow axis of the inclined retarder. The fast and slow axes of the inclined retarder are aligned parallel and orthogonal to the plane of incidence, respectively, or vice versa, due to geometry. An example of inclined reflective halfwaveplate (HWP) at

45-degree, off-axis incidence is shown in Figure 2. In common retarder applications of converting a linear polarization input to circular polarization output and to orthogonal linear polarization output, the reflective retarder must be designed as a quarterwaveplate (QWP) and HWP, respectively. Moreover, with a QWP/HWP reflective retarder, the input linear polarization must comprise an equal amount of S-pol. and P-pol. components at zero relative phase. This means the input linear polarization is aligned ±45 degrees versus the local plane of incidence. The incident light is resolved into e-wave and o-wave propagation, and the resulting phase delay difference causes the polarization modification.

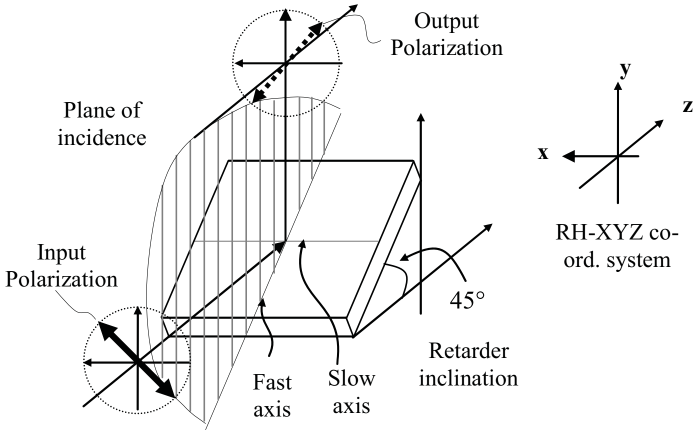


Figure 2: An example of an inclined reflective halfwave plate showing input and output polarization states for linearly polarized incident light.

Typical Performance Attributes

An example of broadband (BB) 430-680 nm reflective HWP has been designed and coated. The thin dielectric film of about five µm thick was coated on 200 mm wafers in a fast cycle-time Ucp-1 vacuum deposition chamber[5]. The retarder mirror has a high reflectance of >98 percent in-band. The measurements and simulation results of the reflected retardance at a 45-degree AOI are shown in Figure 3. There are some retardance ripples across the spectrum, but the achromaticity of retardance over the BB is clearly demonstrated.

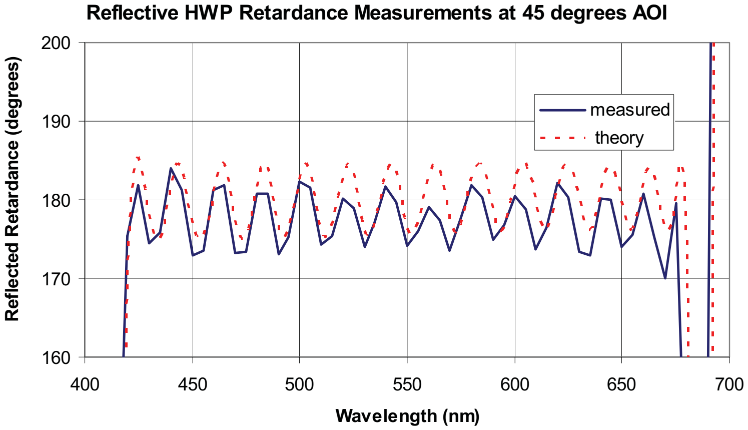
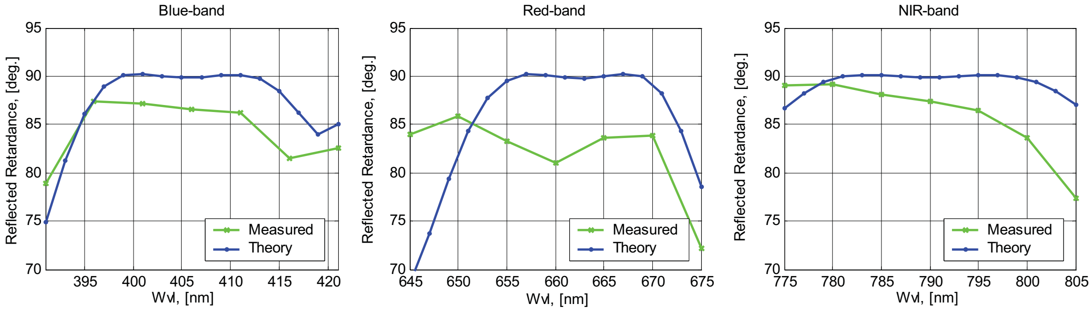


Figure 3: Measured and simulated reflected retardance of a BB polarization-sensitive mirror.

In some applications, the span of wavelength range is very wide, but the required wavelength windows of operation are not continuous. Example of this include the next-generation, high-definition, optic-disc access system, incorporating short wavelength blue-violet laser (~405 nm wavelength), legacy DVD red laser (650 and 660 nm), and CD NIR laser (780 nm) lines. The results of an example design for a reflective QWP targeting all three wavelength windows are shown in Figure 4 as plots for the blue, red and NIR channels.

In each wavelength channel, the modeled and measured reflected retardance at a 45-degree AOI are compared. The model yields a 90-degree retardance for each center wavelength with a bandwidth of approximately ±2 percent. While there is some error in the retardance targeting, these first iteration parts showed good achromatic retardance properties, even for approximately 2:1 wavelength ratio.



(a) *(b)* *(c)*

Figure 4: Modeled and measured retardance at a 45-degree AOI for a triple laser-line-reflective QWP.

In addition to the reflected retardance performance, these filter designs also produce high reflectance over the required bands. An optional transmitted tap output can also be implemented. These thin-film devices are also very stable in high-flux exposure and in adverse environmental conditions. These retarders are coated on rigid substrates, and the dense films are very durable. Moreover, the high-reliability, birefringent component is engineered from thin film designs, without the need for birefringent crystal growth.

Example of Reflective Waveplate Applications

One particularly suitable application of a reflective waveplate design based on a vacuum coated thin film stack is the optical pickup unit (OPU) for next-generation, high-definition, disc-media access systems. In this case, the ratio of long- to short- wavelength is large (approximately 2:1) and the high light flux stability requirement is extremely important for future high-speed read/write access, which makes conventional transmissive QWP based on multilayer birefringent crystals and organic foil retarders unsuitable. A conventional polarization conversion element within the OPU system is schematically shown in Figure 5.

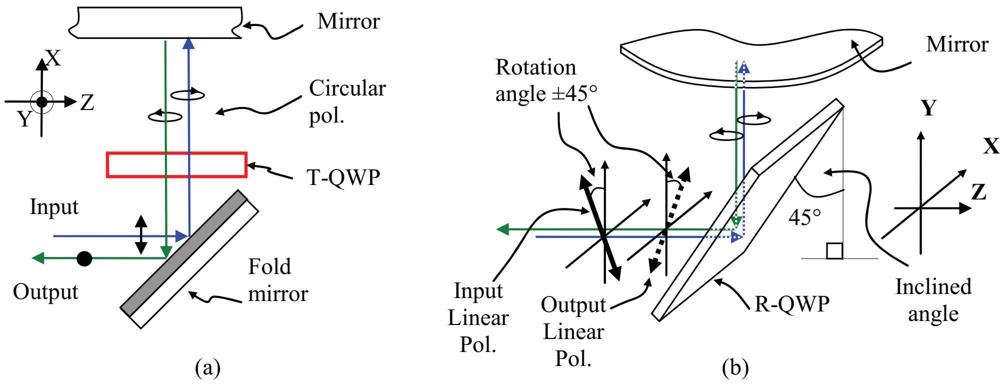


Figure 5: (a) Conventional OPU subsystem using a T-QWP component and a beam-folding mirror; and (b) new OPU subsystem using a reflective QWP component for retardation and beam folding.

Using a modified set-up as the conventional OPU layout, the functionality of QWP and fold mirror can be integrated into a single reflective QWP, as shown by the OPU subsystem layout in Figure 5. In order to set up two components of light rays at the reflective retarder, the PBS array (not shown) has to be rotated about its Z-axis by ±45 degrees. In this way, the LD output sets up half P-pol. and half S-pol. at the retarder mirror. The 90-degree relative phase delay of P-pol. and S-pol. upon reflection from this retarder mirror converts the linear polarization into a circular polarization. On its return from the disc media, another polarization conversion takes place, and the output light beam in the common path section is again orthogonally polarized versus the LD output.

Conclusion

The all-inorganic reflective waveplates developed by JDSU are flexible, durable, highly reliable for high light exposure, and potentially low cost for polarization control applications. In one application example, the three-channel, high-definition optical disc access system uses this reflective QWP component to future-proof the device stability against high light flux exposure, and achieves true achromatic 90-degree retardance over all three diode laser wavelength bands.

References

1 P. Yeh, et al., “Compensator for liquid crystal display, having two types of layers with different refractive indices alternating,” US Pat. No. 5,196,953, 1993.

2 W.H. Southwell, “High reflectivity coated mirror producing 90 degree phase shift,” US Pat. No. 4,312,570, 1982.

3 K.D Hendrix et al., “Birefringent films for contrast enhancement of LCoS projection systems,” J. Vac. Sci. Technol. A, 24(4), pp. 1546-1551, 2006.

4 K.L. Tan, et al., “Thin films provide wide-angle correction for waveplate components,” *Laser Focus World*, p. 59, March 2007.

5 M.K. Tilsch et al., “Production scale deposition of multilayer film structures for birefringent optical components,” *Thin Solid Films*, 516(2-4), pp. 107-113, 2007.

JDSU-pending or Issued Patents

The design and application of these all-inorganic reflective retarders are covered in two US patent applications, one of which is published: 20070285601, “*Thin-Film Design For Positive and/or Negative C-Plate*.” In addition, the form birefringent thin film designs are disclosed in US patent 7,170,574, “*Trim Retarders Incorporating Negative Birefringence*.”

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