L-3: *Late-News Paper:* Extremely Broadband Retardation Films

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Abstract

We disclose here the design and construction of retardation films with any desired dispersion properties by using conventional dispersive uniaxial retardation films. In particular we demonstrate the design of retardation films which have constant retardation over the entire visible spectrum. They also have very large viewing angles.

1. Introduction

Retardation films are used widely in optical systems. The retardation value Γ of a n uniaxial retardation film is defined as the phase difference between the two orthogonal polarizations and is given by

$$\Gamma = \frac{2\pi d\Delta n}{\lambda} \qquad (1)$$

where d is the thickness and Δn is the birefringence of the retardation film, and λ is the wavelength of the input light. Halfwave plate (HWP) and quarterwave plate (QWP) correspond to $\Gamma = \pi$ and $\Gamma = \pi/2$ respectively.

Retardation films such as HWP and QWP have many applications such as in polarization manipulation, phase compensation, viewing angle enhancement and dispersion compensation [1]. In projection systems, QWP and HWP are used in polarization conversion optics and in skew ray compensation [2,3]. In all applications, the HWP and QWP should have constant retardation in the whole visible spectrum (400~700nm). However, conventional HWP and QWP using uniaxial retardation films have large wavelength dependence. As well, their angular dependence is not totally desirable.

Various methods have been proposed to extend the wavelength range of retardation films [4-7]. In this paper, we disclose a new concept for broadband film design, making use only of simple conventional wavelength dispersive uniaxial films. Our method is based on stacking of ordinary dispersive retardation films to make the broadband retardation film. By using this method, general solutions for optimal designs can be obtained. Based on this new technique, specific examples of very broadband QWP and HWP can be obtained using commercial uniaxial retardation films.

2. Design of broadband retardation films

In our method, the design of the retardation film such as the HWP and QWP is treated as similar to the design of polarization interference filters (PIF) [8]. A PIF, together with an output polarizer, will transmit a particular band of wavelengths. PIF is different from conventional interference filter in that the two complementary spectra can be separated by a polarizing beam splitter [3,9]. Now a HWP rotates the polarization of incoming light by 90^o if the c-axis of the waveplate makes an angle of 45^o with the incoming polarization. Thus a broadband HWP can be regarded as equivalent to a PIF with a very broad spectrum covering the entire visible range. Similarly, a QWP can be regarded as a special PIF which upon reflection rotates the polarization of the entire visible spectrum by 90^o.

The basic structure of a PIF is shown in Fig. 1. It consists of a number of birefringent films placed between two polarizers. In the design of a PIF, the variables are the individual angles ϕ_i, as well as the retardation value Γ of the films. In most cases, we use only films with the same retardation in order to simplify the manufacturing process. It is not a severe constraint on PIF design.

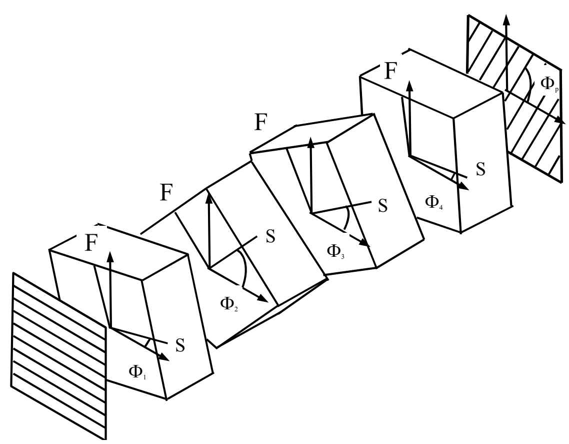

Fig. 1. The basic structure of PIF.

 ISSN/007-0966X/07/3802-1390-$1.00 © 2007 SID

The output spectrum of a PIF is given by

$$E_{out} = \begin{bmatrix} E_u \\ E_v \end{bmatrix} = \begin{bmatrix} \cos\phi_p & \sin\phi_p \\ -\sin\phi_p & \cos\phi_p \end{bmatrix} \prod_{i=1}^{N} W_i \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

where ϕ_i are the orientations of the N retardation films and ϕ_p is the angle of the output analyzer relative to the original x-axis. W_i are the Jones matrices of the individual films. E_u is the real output in frequency domain, and E_v is the complementary function of E_u.

The idea of designing PIF based on Jones matrix is the same as finding the values of θ_i such that

$$E_u(\Gamma) = C(\Gamma) \qquad (2)$$

where $C(\Gamma)$ is the target spectrum of the PIF. It can be narrow band or in this a broadband function. A numerical procedure can be used to obtain the values of ϕ_i and ϕ_p. The target output can be anything. In fact it can have a dispersion that matches that of a liquid crystal for instance.

3. Broadband HWP

The broadband HWP works in the transmissive mode, and rotates the input linearly polarized light by 90° for the whole visible spectrum. Thus a HWP PIF between two crossed polarizers should have 100% efficiency. The desired transmission is given by

$$T(\Gamma) = |C(\Gamma)|^2 = C(\Gamma) \bullet C^*(\Gamma) = 1(400 \sim 700\,nm)$$

Because the constraint condition is rather loose, there are multi-solutions to $C(\Gamma)$. This is different from PIF color filters where there are more constraints [8].

For easy fabrication, the broadband HWP or QWP should comprise of 3 or less number of ordinary dispersive films. For a specific design of the broadband HWP, a commercial uniaxial HWP retardation film from Nitto-Denko with a retardation value Γ of π at 540nm is used. The normalized dispersion property of this film is given by the Cauchy's equation

$$\Delta nd = 270\left(A_0 + \frac{B_0}{\lambda^2} + \frac{C_0}{\lambda^4} \right) \qquad (3)$$

where $A_0 = 0.8646$, $B_0 = 3.7018\text{x}10^4(\text{nm}^2)$, $C_0 = 1.2\text{x}10^9(\text{nm}^4)$.

A 2-layer and a 3-layer broadband HWP has been so fabricated. Fig. 2 shows the experimental transmission of a 3-layer broadband HWP between two crossed polarizers as compared to a single nitto HWP. It can be seen that it practically has no wavelength dispersion over the entire spectral range from 400nm to 700nm as designed.

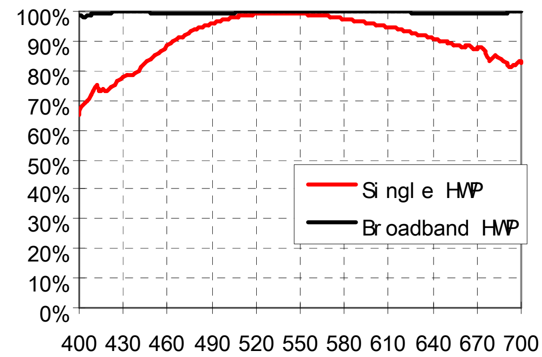

Fig. 2. Broadband halfwave plate.

It turns out that the angular dependence of the retardation of the new HWP is also very good. Fig. 3 shows the calculated polar plots of the transmission of the broadband HWP between parallel polarizers. It can be seen that the maximum transmission is only 1% for most of the viewing cone. For the 3-layer design, the viewing cone is less than 1% leakage for the entire viewing cone.

Experimentally, the new broadband HWP and the commercial HWP can be more dramatically illustrated by placing them between two crossed polarizers and comparing them side by side. Fig. 4 shows the picture. It can be seen that our HWP works very well at the whole visible spectrum even for larger viewing angles.

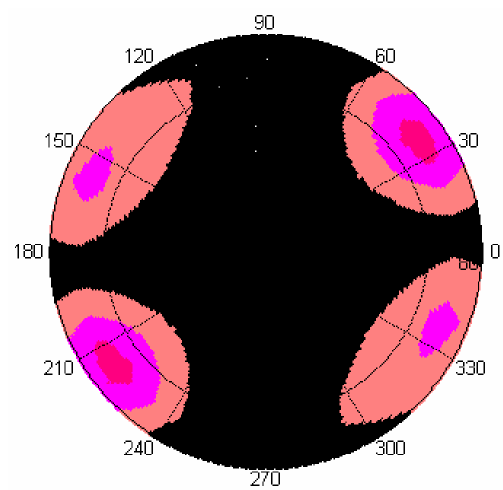

Fig. 3 Angular dependence of HWP. Black area indicates less than 1% light leakage between regular cross polarizers.

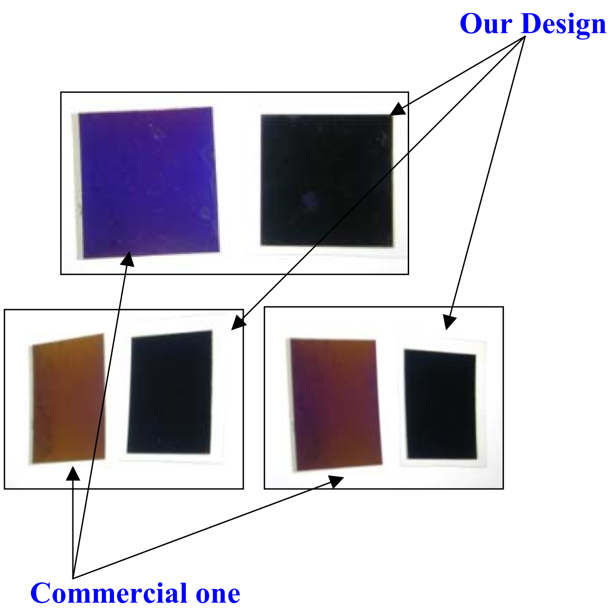

Fig. 4. Experimental films at large angles.

4. Broadband QWP

A broadband QWP changes the linearly polarized input light into circular polarization if the input polarization is at 45^o to its optical axis. In this case, we cannot simply repeat the formulation above. However, we can allow the QWP to work in the reflective mode. The QWP will rotate the linearly polarized light by 90^o upon reflection. This reflective PIF system can be equivalent to the transmissive PIF with two QWP in a symmetric configuration. Fig. 5 shows the theoretical transmission of a broadband QWP using this design. Again there is absolutely no dispersion and the QWP is extremely broadband. On the other hand, the single layer QWP has large dispersion.

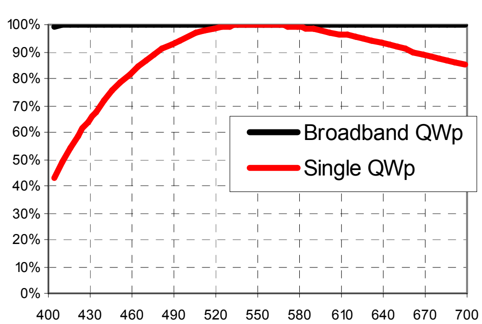

Fig. 5. Broadband QWP.

5. Summary

In summary, we have introduced a new concept in the design of extremely broadband retardation films, including HWP and QWP. The idea is to treat the retardation films as a polarization interference filter. Such HWP and QWP consist of a stack of 2 to 3 conventional dispersive retardation films. The optical properties of these stacks are extremely desirable for many optical applications since there is practically no dispersion and the acceptance angle is very large.

As mentioned, it is also possible to tailor the dispersion properties of any retardation for exact wavelength compensation. For example, one can design QWP or HWP with retardation values that match exactly the birefringence of a liquid crystal material for all wavelengths. This will allow exact compensation in many cases.

This research was supported by the Hong Kong Government Innovations and Technology Fund.

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