Optical properties of multilayer optical compensator

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Optically anisotropic thin films like polarizer and compensator are crucial elements in optical scheme of LCD. Improving brightness and contrast, color and gamut, off axis viewing and uniformity of LCD relates with improving the quality of compensator and polarizer. Market demands on every year cut cost impose the requirement for tight quality control during the manufacturing. The methods providing control have to meet few requirements: accuracy, high rate of measurement synchronized with the speed of role–to-role technology, high spatial resolution.

This paper comments optical properties of thin film compensator measured by the spectral method. It is shown that the spectral analysis of the light reflected at compensating side provides correct measurement. To meet the requirements of measurement a modification of the method is proposed. It is shown that the modified method gives information for the refractive index and thickens and extends sufficiently the application. Modified and unmodified methods are compared in requirements they impose about accuracy of measurement and algorithms for modeling of date.

1. Method of measurement

The spectral method is based on two-beam interferometry producing channel spectra [1]. The technique requires the use of a white light source with the plane of fringes localization focused on the slit of spectrometer. This can be easily provided by a fiber reflection probe and collimating lens. Measuring the anisotropic film can be done if principal dielectric axes are preliminary known [2].

Consider light incident in isotropic non-absorbing medium of thickness d in which one of the optic axis lies normal to the plane of the film – Fig. 1. The plain of incidence coincide with one of principal dielectric axis (azimuth angle Θ is 0^0 or 90^0) and the incident angle is α. The refractive index of optical film is specified by three indices n_x, n_y and n_z.

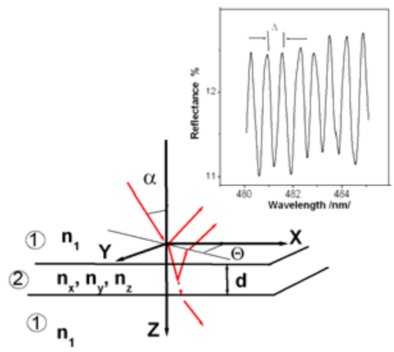

Fig. 1 The film under he measurement and typical denotes used; the spectral response of reflected light represents a channel spectrum with a period Λ(λ).

2. Chanel spectrum

Usually the quality inspection of retardation film has to be inspected after it is cover with an optically inhomogeneous protecting film. The measurement has to deal with a masking effect created by it.

2.1 Row data of measurement

Our measurement shows that this effect can be cancel measuring the reflected light from the retardation film. Fig. 2 a/b illustrate spectral dependences of polarized reflected light from compensating film and polarized reflected light from protective film respectively. Reflection from compensating film is well expressed in whole spectral range with clear modulation period – Fig.2a. The reflected light from protecting film (Fig.2b) “feels” the retardation film behind – the observed channel spectrum coincides with the channel spectrum at Fig.2a, but it is blurred and appears in limited spectral range.

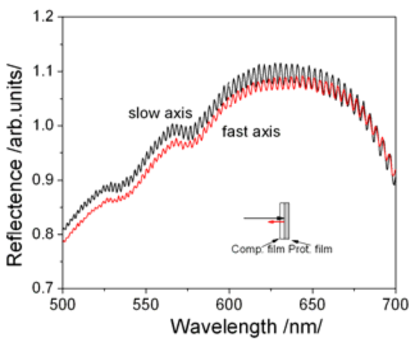

Fig 2a

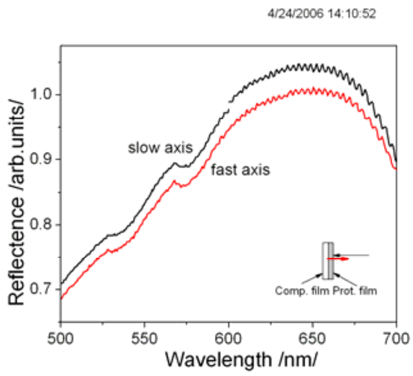

Fig. 2b

Fig. 2 Channel spectrum of light reflected from retardation film (Fig. 2a) and from protective film (Fig. 2b)

Evidently, the spectrum of reflected light from the retardation film provides more information. It is necessary to check to such a degree the spectrum is influenced by the optically inhomogeneous substrate (protecting film). Fig. 3 compares two spectra: of light reflected from compensating film only (no substrate) and of light with the same polarization reflected when the substrate is not removed.

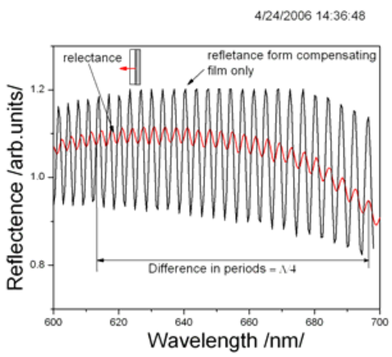

Fig 3a

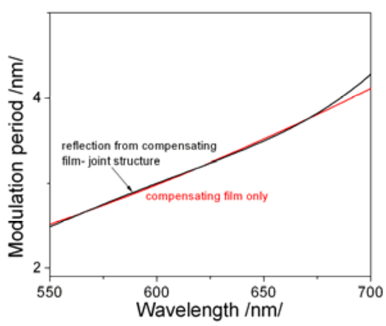

Fig 3b

Fig. 3 The influence of the protective film on the reflected spectra (Fig. 3a) and on its period (Fig. 3b)

There are no differences in two spectra with an exception of a phase shift due to the influence of the substrate. This effect depends on relative difference of refractive indices of protective and compensating films and in our case this effect is negligible. Although, this effect have to be consider because alters the extreme points' position what is crucial when a conventional modeling of date is applied.

2.2 Modeling channel spectrum data

The spectral positions of maximums of an interference fringe satisfy:

$$2n(\lambda_i)d = m\lambda_0 = (m+1)\lambda_1 = (m+2)\lambda_2 ... = (m+p)\lambda_{p-1} \qquad i = 0.....p-1 \qquad (1)$$

If observed fringes are P number, it will have 2P equations. If we are interested only in absolute phase shift, we have to find P+1 unknown (the order number is treated as an unknown) from 2P equations. If the thickness is known, it will be possible to find $n(\lambda_i)$ applying the same procedure. Another approach [3,4] is to assume a functional dependence of the refractivity what increases the number of unknown. For all cases the common problems are two:

- to estimate enough accurately the spectral coordinate of the interference fringes;
- to solve accurately a system of 2P equations.

While the first problem is related only with the spec of the experimental set-up, the second problem is closely related with a properly chosen mathematical method of solving. So far as not all measurements are independent, a system of 2P equations could be singular. A good choice for Eq.1 solving is a Singular Value Decomposition (SVD) method; still more, the number of unknown is smaller than the number of equations [5].

Fig. 4 illustrates the necessity of precisely measured peaks' position. Few measurements have been completed at different spectral resolution, showing that results depend strongly on the measurement error. The absolute phase shift of main axes of the retardation film has been determined by SVD method. The required accuracy of measurement is $\pm 0.01nm$ what can be met not so easily.

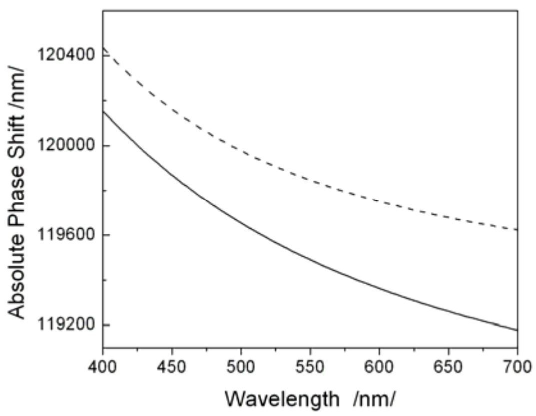

Fig. 4 Different results for the absolute phase shift determined from measured channel spectra; dashed curve – random deviation from "true" peak positions $\pm 0.2nm$ *; solid curve – deviation lower than* $0.05\ nm$

Shifting of peaks' position decreases the accuracy too, but this factor is not so critical. If the shift is in the framework of Λ/2, the system of equations is a linear combination of "no shifted" system and the solution is the same. The row data of measurement will be used for finding the retardance unless the normalization of intensity can't shift the peaks' positions.

Other problem comes from a deviation of measurement error from a normal distribution what could cause instability of the system of equations and an error of determined order. Allotting a wrong number to one of fringes discounts the method.

3. Modified channel spectrum

As was mentioned, the protective film causes a phase shift altering the peaks' positions keeping the period Λ(λ) the same. That suggests to look for a method of measurement exploring Λ(λ) and being insensitive to peaks' position.

Proposed modification of method of measurement meets these requirements and provides information for the refractive index and thickness simultaneously.

According to [2] the channel spectrum provides the relationship between refractive indices in the form:

$$n_{x,y}(\lambda) - \lambda \frac{dn_{x,y}(\lambda)}{d\lambda} = \frac{\lambda^2}{2\Lambda_{x,y}(\lambda)d} \qquad (2)$$

The solution of this equation gives the dispersion for in-plane main refractive indices of retardation film:

$$n_{x,y}(\lambda) = n_{x,y}(\lambda_0)\frac{\lambda}{\lambda_0} - \frac{\lambda}{2d}\int_{\lambda_0}^{\lambda} \frac{d\lambda}{\Lambda_{x,y}(\lambda, d)} \qquad (3)$$

if a reference measurements provide the film thickness d and the refractive indices $n_{x,y}(\lambda_0)$ at fixed wavelength λ_0. Obviously, independent measurements at fixed wavelength λ_0 are an additional impediment.

3.1 The principle of modification

The proposed modification provides an absolute measurement of the physical quantity represented by the phase shift at the interference of light from the film under the measurement. As a result, an additional measurement for determination of film's refractive index or film's thickness using a separate method is not necessary to be provided.

The principle of the method consists in spectral dependence of a change of phase of reflected light at one of film's surface. The proposed method requires placing one of film's surfaces in contact with a dielectric etalon.

There is a change of phase on reflection of light, π at the surface if the film is optically denser, and there isn't a change of phase if it is optically less dense than the surrounding medium. A wavelength dependence of the change of phase at the surface film - etalon can be provided only in the case of crossing dispersion curves of the film and the etalon (Fig 5).

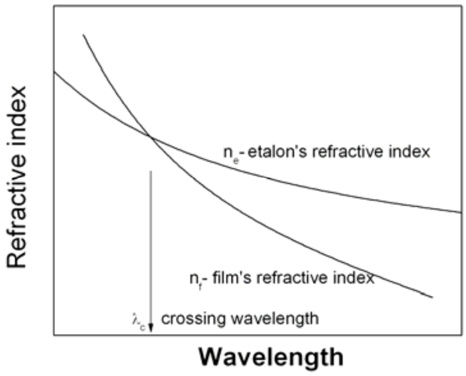

Fig. 5 Dispersion curves of the etalon and of the film; at the crossing wavelength $n_e = n_f$

At the crossing wavelength λ_0 the both film and etalon have equal refractive indices. Assuming a normal dispersion, for $\lambda < \lambda_0$ there is π phase jump, while for $\lambda > \lambda_0$ there isn't (Fig. 6).

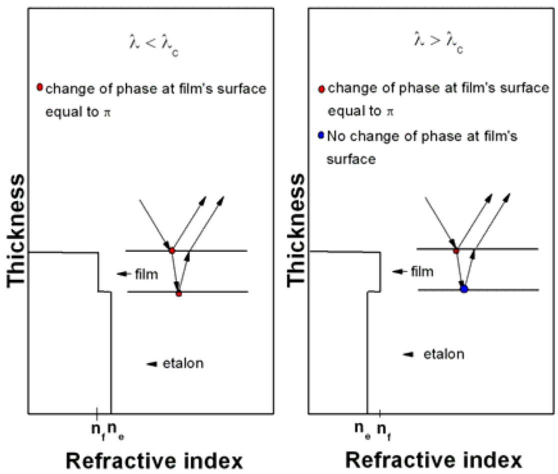

Fig. 6 A wavelength dependence of the change of phase on reflection of light at the surface film - etalon

Thus the phase difference between the first two reflected beams is:

$$\delta(\lambda) = \frac{2\pi}{\lambda}\left(2dn_f \cos(\theta)\right) \pm 2\pi \qquad for\ \lambda < \lambda_c$$

$$\delta(\lambda) = \frac{2\pi}{\lambda}\left(2dn_f \cos(\theta)\right) \pm \pi \qquad for\ \lambda > \lambda_c$$

where n_f is a film's refractive index, θ is an angle of incidence. At the crossing wavelength $\lambda = \lambda_c$ the phase difference $\delta(\lambda)$ changes abruptly what affects the observed quasi-periodical channeled spectrum (Fig. 7).

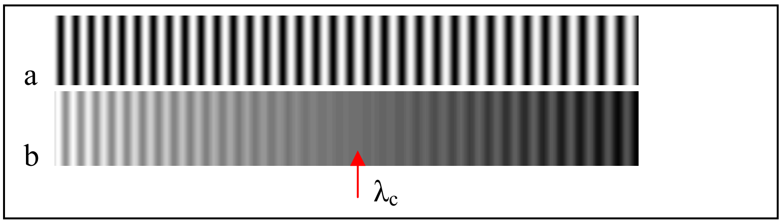

Fig. 7 Channel spectra: a/ for film not contacting with an etalon; b/ for film contacting with an etalon

Thus the crossing point can be experimentally detected. If the etalon's dispersion characteristic $n_e(\lambda)$ is preliminarily known the film's refractive index is determined - $n_f(\lambda_0) = n_e(\lambda_0)$. Experimentally, film's refractive index determination consists in measuring the crossing wavelength λ_c in the reflected channel spectrum. After the refractive index is determined at λ_c, its dispersion can be found from Eq. 3 while the film's thickness can be found assuming equality of group refractive indices:

$$n_f(\lambda) - \lambda \frac{dn_f(\lambda)}{d\lambda} = n_e(\lambda) - \lambda \frac{dn_e(\lambda)}{d\lambda} \equiv n_g(\lambda)$$

From Eq (2) we get the thickness:

$$d = \frac{\lambda_0{}^2}{2\Lambda_{x,y}(\lambda_0) n_g(\lambda_0)} \qquad (4)$$

3.2 Experimental results

Fig. 8 illustrates the experimental proof of the basic idea of the modified method of measurement – it shows the results of measuring the retardation film contacting with an etalon-substrate.

The etalon is made by Schott glass N-SSK5 which dispersion curve cross the dispersion curve of fast axis $n_x(\lambda)$ of the film. Measured is the channel spectrum of reflected light when fast and slow axes lies in the plane of incidence. The spectrum of reflected light in direction of slow axes is not influenced at all. The channel spectrum of light reflected in direction of fast axes is strongly influenced because of change of phase near to 456 nm, while the theory has provided $\lambda_c = 458$ nm.

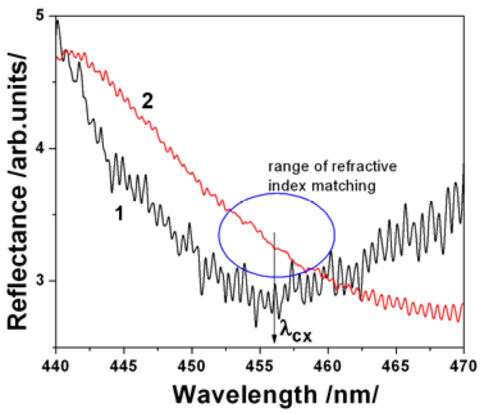

Fig. 8 An experimental confirmation of the based idea of the method of measurement; 1 -the spectrum of reflected light in direction of slow axes; 2- the spectrum of reflected light in direction of fast axes; the range of equal crossing of refractive indices is marked.

Fig. 9 illustrates normalized reflectance of a film contacting with the etalon and of a film surrounded by an air when the fast axis lies in the plane of incidence. Evidently, equal crossing of refractive indices has a strong influence in the range of 456 nm. Because of finite dispersions' slope the channel spectrum distortion is extended for about 6 nm. The middle point in this region, say λ_c = 456 nm, is determined to be the crossing point of dispersion curves. From N-SSK5 spec we have got $n_e(\lambda_c)$ = 1.6715, then $n_x(\lambda_c)$ = 1.6715.

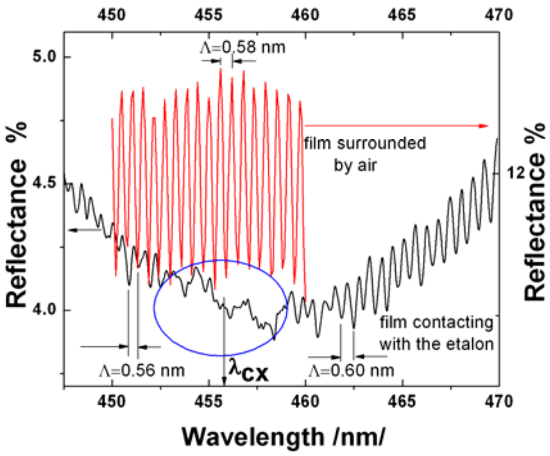

Fig 9 Reflectance in direction of fast axes from film contacting with the etalon and from film surrounded by air; the measured value of the quasi-period at different wavelength is shown

It is impossible to observe a channel spectrum near to λ_c = 456 nm because of the interference contrast is low. There is either-or solution- to interpolate a quasi-period at λ_0 measuring at symmetric point in regard to λ_0 or to provide a measurement without an etalon. The result is $\Lambda(\lambda_0)$ = 0.58 nm. Can be assumed with high accuracy that $dn_e/d\lambda|_{\lambda=\lambda_c} = dn_f/d\lambda|_{\lambda=\lambda_c}$ and from precisely known dispersion characteristic of N-SSK5 the group refractive index has been determined – $n_{ge}(\lambda_c)$ = 1.8235. Then Eq. 4 gives a film thickness d = 98.3 μm while a reference measurement has provided $d = 99 \pm 3\mu m$.

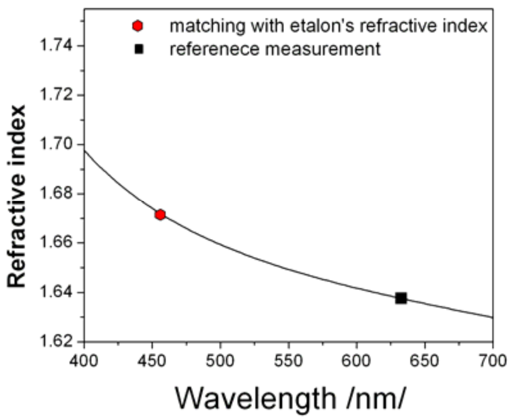

Fig. 10 The refractive index of fast axes determined according to Eq. 3; $n(\lambda_c)$ and d found from modified channel spectrum (Fig. 7b) and Eq.4

After the thickness d and the refractive index $n_f(\lambda_c)$ at fixed wavelength $\lambda_0 \equiv \lambda_c$ are determined, the film refractive index dispersion in visible range can be found from Eq. 3. Fig. 10 shows the refractive index of fast axes of the film under the measurement. To check the accuracy of modified method a reference measurement of film refractive index has been done at λ_0 = 632.8 nm. The measured value exactly coincides with the value obtained from Eq. 3. This perfect matching illustrates that, in spite of assumed approaches about equality of group refractive indices and approximate evaluation of λ_c and $\Lambda(\lambda_c)$, the modified spectral method provides high accuracy measurements.

4. Comparing unmodified and modified method

Fig. 11 compares the refractive indices determined by two methods. Measurements for modified method were provided at spectral resolution 0.1 nm, while for unmodified method it is 0.025 nm.

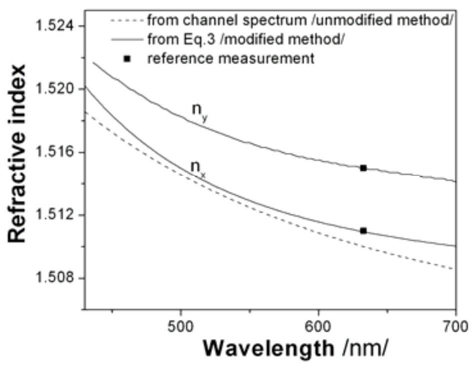

Fig. 11 A comparison between the results of unmodified and modified method; the modified method provides higher accuracy data

The results of two methods coincide in the framework of evaluated accuracy of finding the refractive index $\delta n/n = 0.0006$. Although modified method requires quite lower accuracy of measurement than unmodified, it provides more accurate data for the refractive indices. The mathematics inside is that modified method is based on the exact solution of a differential equation and measurement at equal crossing of refractive indices provides a boundary condition.

In contrast, the method of modeling the conventional channel spectrum is focused in finding an interferometry order, what correspond with finding a boundary condition. This approach chooses the right solution among the solutions of the differential equation Eq. 2. However, these solutions are very close in the space wavelength – interferometry order and require higher accuracy of measurement so to ensure finding the right one. An saditional impediments are an assumption about the functional dependence of refractivity and knowledge the film thickness.

Conclusions

A method of measurement based on two-beam interferometry provides accurate and reliable information about the refractive index and birefringence of compensating film. The channel spectrum of light reflected by compensating film cancels the blurring effect of optically inhomogeneous protective film.

Proposed modification of measurement is based on two-beam interferometry too but provides simultaneously information about the film's thickness and refractive index at fixed wavelength. The modified method guaranties higher accuracy of measurement than unmodified; doesn't require any assumption about functional dependence of reflectivity; the method is fast and accurate and can be applied for in-line inspection of quality of optical anisotropic films.

References:

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