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A New Stress Measurement Method by Integrating Photoelasticity and Spectrometry

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Abstract

In photoelasticity, based on the stress-optic law, the isochromatic fringe order is directly proportional to the in-plane principal stress difference. With the increase of the level of the stress difference, the extinction of component colors of an isochromatic fringe pattern follows the sequence of the increasing wavelength and repeats periodically. By integrating this periodic extinction phenomenon in photoelasticity with spectrometry, a new stress measurement method was proposed in this paper.

To implement the proposed method, a calibration specimen made of the same material as the test specimen was prepared for the uniaxial tensile testing. A spectrometer was used to record the transmissivity spectrum of a point at the center of the calibration specimen under different magnitudes of tensile loading. By analyzing the spectrometry, the wavelength of each extinct component color can be individually and accurately obtained. In addition, the empirical relationship between the increasing value of wavelength of the extinct component color of the isochromatic fringe pattern and increasing value of stress difference can be established by taking average. With the established relationship obtained from the calibration specimen, the stress difference of test specimen under load can be easily and fast calculated. In contrast to the traditional photoelastic technique, there is no need to determine the refractive index and stress optic coefficient of the test specimen. A popular commercially available photoelastic material, PSM-1 was used to verify the feasibility of the proposed method. The experimental results show that the stress measured is good agreement with the actual loading stress.

Key words: Photoelasticity, Isochromatic fringe pattern, Stress measurement, Wavelength, Spectrometer

1. Introduction

Photoelasticity is a real-time, whole-field and non-destructive stress measurement method. Based on the stress-optic law, the isochromatic fringe order is directly proportional to the in-plane principal stress difference. In the past, lower sensitivity image analysis system was sufficiently accurate to analyze the acquired isochromatic fringe pattern. With the increasing demand of determining low level stress in various industrial applications, e.g. the unavoidable residual stresses produced in the manufacturing process in the glass plate of the thin film transistor liquid crystal display (TFT-LCD), the traditional photoelastic technique and lower sensitivity image analysis system may no longer be

practical. Development of new methodology by integrating the classical photoelastic theory and modern optic instrumentation is urgently needed.

Since the light intensity difference of different wavelengths can provide useful information for calculating the stress, multi-wavelength photoelasticity is a good approach to overcome the predicament of low level stress measurement. The first technique applying the spectrometry is the spectral content analysis (SCA) proposed by Render [1]. Based on SCA, Ajovalasit et al [2] developed the RGB photoelasticity by analyzing the light intensity of red, green and blue light produced by the wide band color filters constructed in the CCD camera to measure the retardation. In the following research, Ajovalasit et al [3] also discussed the benefits of RGB light intensity spectra, in particular the white light source. The three fringe photoelasticity (TFP) proposed by Ramesh and Deshmukh [4] also evaluated the fringe order by analyzing the RGB light intensity. The noise in TFP can be removed by additionally considering the fringe orders around the pixel of interest in the evaluation equation [5]. Oka and Kato [6] applied two retarders with large retardation to extract the birefringence dispersion of the test specimen by filtering from light intensity spectrum in frequency domain. Otani and Wakayama [7, 8] proposed a method with improving the setup of Oka and Kato [6] for measuring the birefringence dispersion and azimuthal angle.

Spectrometer can be used to analyze the detailed light intensity spectrum. It is also more sensitive to the light intensity variation than the conventional CCD camera. Moreover, it can easily obtain the transmissivity spectrum if the transmissivity calibration is done before the measurement. With the advancement of image acquisition technique, the information acquired from the spectrometer has been developed from a point to one dimension and maybe to two dimensions in the very near future. Therefore, the spectrometer is suitable to use in the high-speed on-line inspection.

In photoelasticity, with the increase of the level of the stress difference, the extinction of component colors of an isochromatic fringe pattern follows the sequence of the increasing wavelength and repeats periodically. Based on this periodic extinction phenomenon, a new stress measurement method by analyzing the spectrometry is proposed. The key of the proposed measurement method is to establish the empirical relationship between the increasing value of wavelength of the extinct component color and increasing value of stress difference. This is also the main difference compared with the above mentioned multi-wavelength technique. The use of the empirical relationship can not only simplify the stress measurement but also reduce the measurement time. Furthermore, the refractive index and stress-optic coefficient are no longer needed to be determined. In this paper, a popular commercially available photoelastic material, PSM-1 was used to verify the feasibility of the proposed method.

2. Methodology of stress measurement

2.1 Principle of the method

In this proposed method, a calibration specimen made of the same material and same thickness as the test specimen must be prepared for tensile test. The loading applied to the calibration specimen is progressively increased to produce the known principal stress differences. The light extinction spectrum corresponding to these known stresses is also progressively recorded. The record is not for comparing the similarity of the light extinction spectrum between the test and calibration specimens, but for refining the more useful information to be used in stress quantifying formula.

By exploring the periodic extinction phenomenon mentioned above, a rule can be found from the experimental results. That is, if the period is identified by the number of the peaks similar to that in the Gaussian distribution, the increasing value of wavelength of the

extinct component color is proportional to the increasing value of stress difference in the same period. Therefore, by dividing the sum of the increasing value of wavelength of the extinct component color by the sum of the increasing value of stress difference, the light extinction spectrum record can be refined to obtain the proportional relationship in each period. The evaluation can determine the average increasing value of the extinct wavelength under the unit increasing value of stress difference, K_i , and the unit is m/Pa. where i represents the different period. Since K_i is known, the relationship can be represented as follows

$$\Delta\lambda = K_i \cdot \Delta\sigma \quad (1)$$

where $\Delta\lambda$ represents the variation of extinct wavelength from a selected point of the test specimen, and $\Delta\sigma$ represents the variation of stress difference corresponding to $\Delta\lambda$. The selected point can be selected from the light extinction spectrum record and provide the known basis of extinct wavelength λ_b and the corresponding stress difference σ_b . By substituting λ_b and σ_b into Eq. (1), the stress quantifying formula can be written as

$$\sigma_i = (\lambda_i - \lambda_b) / K_i + \sigma_b \quad (2)$$

where σ_i and λ_i are the test stress and the extinct wavelength corresponding to the test stress of the test specimen, respectively. By applying Eq. (2), the test stress can be measured simply and rapidly as long as the extinct wavelength of the test specimen is known. The extinct wavelength can be determined by analyzing the spectrum. One must note that the selected point must be assigned in the same period with the test stress. In other words, σ_b and σ_i should be in the same period.

2.2 Performance of measurement

To understand the periodic extinction phenomenon and to check the feasibility of the proposed method, a popular commercially available photoelastic material, PSM-1 (Measurements Group, Inc.) was used in this paper. The schematic of the experimental setup is depicted in Fig. 1. A xenon lamp (LPX150, Zolix) covering the UV-VIS-IR wavelength range was applied to the white light source, and it can provide parallel light with the diameter of 38mm. Dark field cross-circular polariscope was employed to produce the isochromatic fringe order. An optical fiber was employed to conduct the point light intensity information to the spectrometer. The spectrometer can provide the digitized light intensity spectrum and transmissivity spectrum to the computer for following analysis. For recording the spectrum corresponding to the different magnitudes of stress difference, the uniaxial tensile test was used. Figure 2 shows the complete experimental arrangement. A digital video camera was employed to acquire the isochromatic fringe pattern in real-time for easily observing the color variance by human eyes. A zoom in image of the front view of the loading frame is shown in Fig. 3. The tensile load was measured by the load cell and a strain indicator (P3500, Measurements Group, Inc.) was utilized to readout the load. The geometrical dimensions of the calibration specimen are depicted in Fig. 4. The calibration specimen was supported on the holders of the loading frame by two pins. This mechanism can ensure the tensile load is uniaxial. The spectrometer aimed at the calibration specimen's center to record the spectra under different tensile loads.

Before measuring the stress of test specimen, the uniaxial tensile test must be applied to the calibration specimen first. In the experiments performed, the load progressively increased from 0Kg to 90Kg with the interval of 1Kg, and the corresponding principal stress difference increased from 0MPa to 3.041MPa with the interval of 0.034MPa. The spectrometer recorded the light intensity spectra and transmissivity spectra corresponding to the 91 different stress differences, and the wavelength range of spectrum between 400nm and 800nm was analyzed. Note that the transmissivity spectra were analyzed for determining the appearing wavelength rather than analyzing the light intensity spectra to

determine the extinct wavelength. The main reason is the spectrum of the white light source used in the experiment is not horizontal but with fluctuant variations. It may affect the judgment of the appearing or extinct wavelength, especially under the low level stress. Either the appearing or extinct wavelength could be utilized in the methodology of the proposed method. However, the appearing wavelength is much better for judgment and observation than the extinct wavelength.

After the transmissivity spectra were completely recorded, the period can be identified by the number of peaks that is similar to the Gaussian distribution. The stresses corresponding to the spectra occurred to the same number of peaks are within the same period. In the transmissivity spectrum, the last occurred peak curve was fitted by the Gaussian function, hence the appearing wavelength is determined when the maximum transmissivity of fitting curve occurs. But under the lower level stress, as shown in Fig. 5, the peak may not occur in the transmissivity spectrum. In this situation, the appearing wavelength is determined when the 50% transmissivity occurs. By the above definition, the sum of the increasing value of the appearing wavelength and sum of the increasing value of stress difference in each period can be easily obtained. Therefore, K_i in each period can be evaluated.

For measuring the stress of test specimen, the period of the test stress should be known firstly. The period can be easily known by judging the number of peaks of transmissivity spectrum corresponding to the test stress. Therefore, K_i and selected point can be correctly assigned. As long as the test appearing wavelength is determined, the test stress can be easily measured by Eq. (2).

3. Results and discussions

Figures 5-7 show the spectra and isochromatic fringe patterns under the principal stress difference of 0.338MPa, 0.676MPa, and 1.352MPa, respectively. By observing the transmissivity spectrum shown in Figs. 5-7, the number of peaks is 0, 1, and 2, respectively. It represents the three stress differences are respective in the three different periods. Figure 8 shows the six transmissivity spectra under the stress difference between 1.115MPa and 1.284MPa with the interval of 0.034MPa. The periodic extinction phenomenon can be clearly observed. The appearing wavelength sequentially increases with the increase of the stress difference in the same period, and the increasing value of appearing wavelength is approximately equal under the stress difference increasing with the equivalent interval. The same phenomenon can also be shown in Fig. 9. Figure 9 shows the six transmissivity spectra under the stress difference between 2.839MPa and 3.008MPa with the interval of 0.034MPa. The multi-peak may occur in the transmissivity spectrum, but only the last occurred peak is analyzed for judging the appearing wavelength. That also is the peak occurring near the wavelength range between 400nm and 450nm. There is a notable phenomenon in Fig. 8, i. e. the second peak is oncoming under the stress difference of 1.115MPa. Therefore, the different period is separated by the stress of this kind of phenomenon.

The complete results are listed in Table 1. In the experiments performed, the stress range between 0MPa and 3.041MPa can be separated into four periods. The four different periods are corresponding to the four different values of K_i . To verify the feasibility and accuracy of the proposed method, four stress differences corresponding to the four different periods are chosen. These four stress differences are 0.169MPa, 0.854MPa, 1.791MPa, and 2.501MPa. The measurement results are listed in Table 2. The selected points are assigned arbitrarily in the same period with the test stresses. It is obvious from Table 2 that the maximum difference between actual and measured stresses is less than 5.5%. Therefore, for all practical purposes, the proposed method can measure the stress accurately

and fast.

4. Conclusions

A new stress measurement method was proposed in this paper. With the capability of performing spectral analysis and high sensitivity measurement in light intensity, a spectrometer was utilized to analyze the periodic extinction phenomenon commonly appears in photoelasticity. Then the stress quantifying formula can be established by refining the periodicity. The experimental results verified that the stress quantifying formula can determine the stress accurately and fast. By applying the hyperspectrometer, it is possible to acquire one dimensional information at a time. In addition, the determination of refractive index and stress-optic coefficient are unnecessary in this method. The proposed measurement method is very suitable for high-speed on-line inspection.

Acknowledgement

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References

- [1] A. S. Redner, "Photoelastic measurements by means of computer-assisted spectral contents analysis," *Experimental Mechanics*, Vol. 25, No. 2, pp. 148-153, 1985.
- [2] A. Ajovalasit, S. Barone, and G. Petrucci, "Towards RGB photoelasticity: full-field automated photoelasticity in white light," *Experimental Mechanics*, Vol. 35, No. 3, pp. 193-200, 1995.
- [3] A. Ajovalasit, S. Barone, and G. Petrucci, "Phase shifting photoelasticity in white light," *Optics and Lasers in Engineering*, Vol. 45, pp. 596-611, 2007
- [4] K. Ramesh and S.S. Deshmukh, "Three fringe photoelasticity-use of colour image processing hardware to automate ordering of isochromatics," *Strain*, Vol. 32, No. 3, pp. 79-86, 1996.
- [5] K.R. Madhu and K. Ramesh, "Noise removal in three-fringe photoelasticity by adaptive colour difference estimation," *Optics and Lasers in Engineering*, Vol. 45, pp. 175-182, 2007
- [6] K. Oka and T. Kato, "Spectroscopic polarimetry with a channeled spectrum," *Optics Letters*, Vol. 24, No. 21, pp. 1475-1477, 1999.
- [7] T. Wakayama, Y. Otani, and N. Umeda, "Real-time measurement for birefringence dispersion using double retarder," *Proceedings of SPIE*, Vol. 5888, pp. 588807_1-6, 2005.
- [8] T. Wakayama, Y. Otani, and N. Umeda, "One-shot birefringence dispersion measurement based on channeled spectrum technique," *Optics Communications*, Vol. 281, pp. 3668-3672, 2008.

Table 1 Stress ranges and K_i corresponding to different periods

Peak number	Stress range corresponding to different period (MPa)	Sum of the increasing value of stress difference (MPa)	Sum of the increasing value of appearing wavelength (nm)	K_i (nm/MPa)
0	0.000 ~ 0.372	0.372	338.12*	908.92
1	0.372 ~ 1.115	0.743	132.00**	177.66
2	1.115 ~ 1.892	0.777	72.00**	92.66
3	1.892 ~ 3.041	1.149	73.00**	66.14

*The appearing wavelength is determined when the 50% transmissivity occurs.

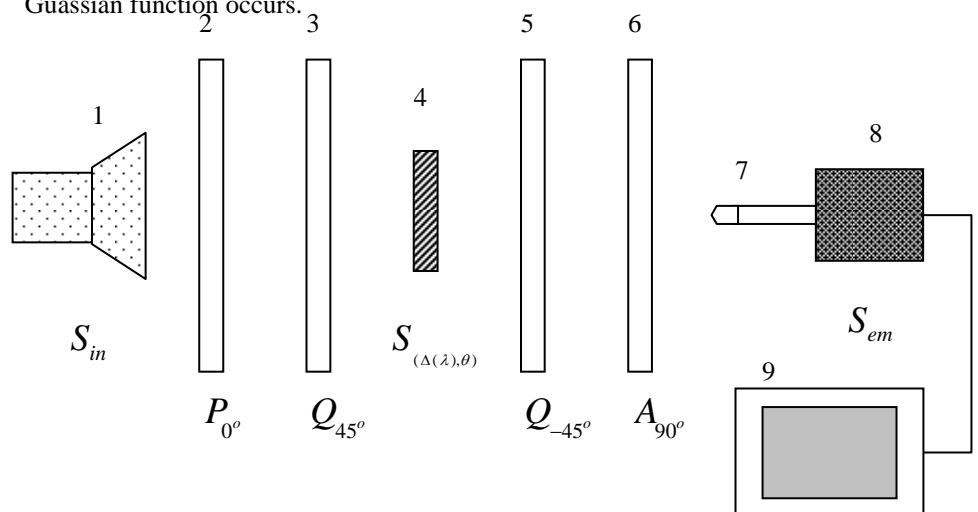
**The appearing wavelength is determined when the maximum transmissivity fitting by Gaussian function occurs.

Table 2 Comparisons between actual and measured stress

	Actual stress (MPa)	Peak number	Standard point σ_s (MPa)	$\lambda_r - \lambda_s$ (nm)	Measured stress σ_r (MPa)	Diff. (%)
Ex.1	0.169	0	0.068	83.8*	0.160	5.3
Ex.2	0.845	1	0.642	31.0**	0.816	3.4
Ex.3	1.791	2	1.318	47.0**	1.825	1.9
Ex.4	2.501	3	2.028	30.0**	2.482	0.8

*The appearing wavelength is determined when 50% transmissivity occurs.

**The appearing wavelength is determined when maximum transmissivity fitting by Gaussian function occurs.



- 1. Light Source
- 2. Polarizer
- 3. Quarter Wave Plate
- 4. Specimen
- 5. Quarter Wave Plate
- 6. Analyzer
- 7. Optical Fiber
- 8. Spectrometer
- 9. Personal Computer

Fig. 1 The schematic of the experimental setup

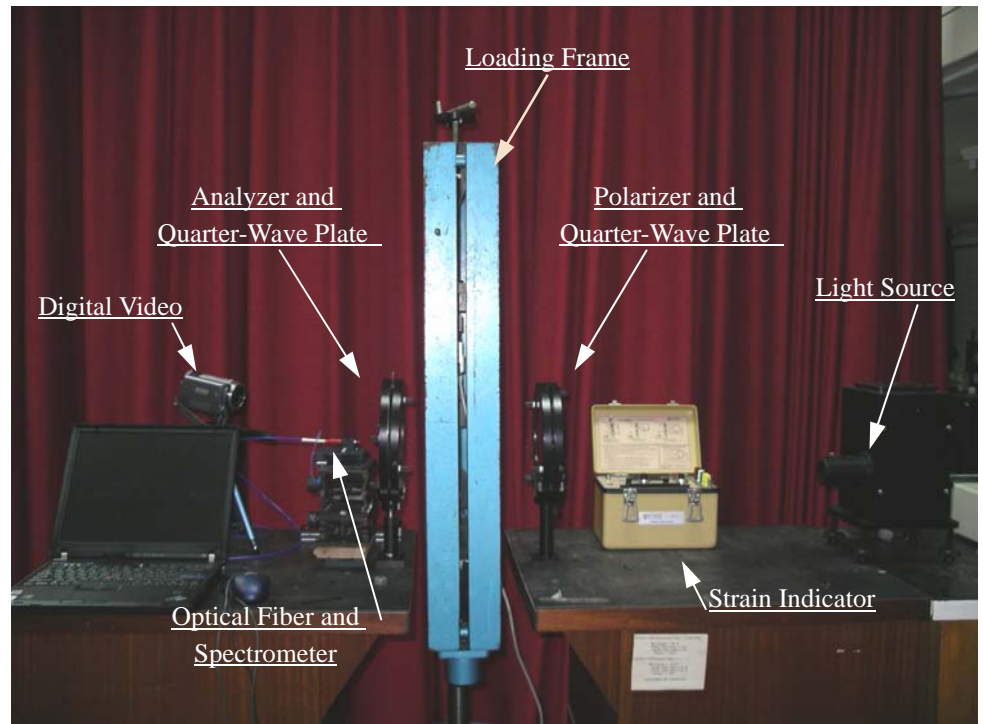


Fig. 2 Photograph of the experimental setup

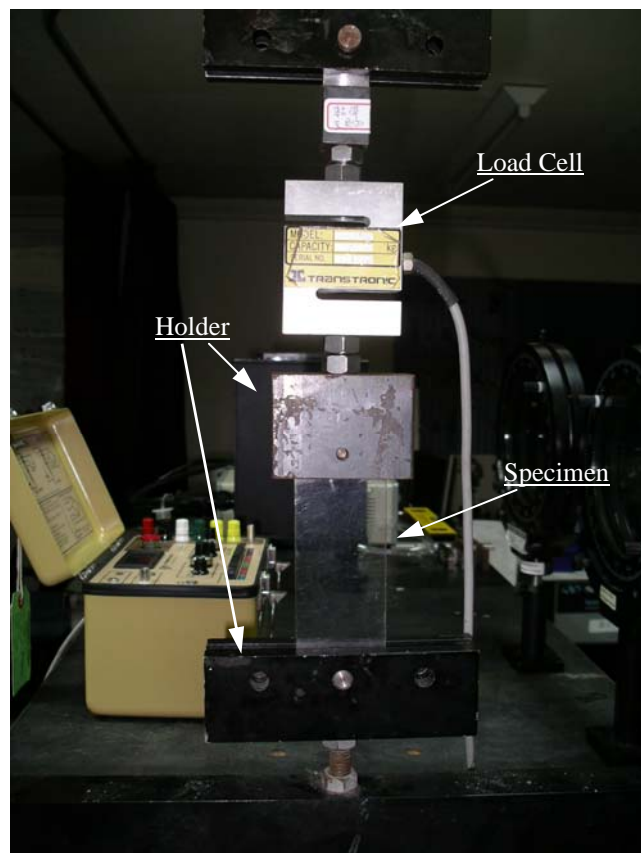


Fig. 3 The loading frame

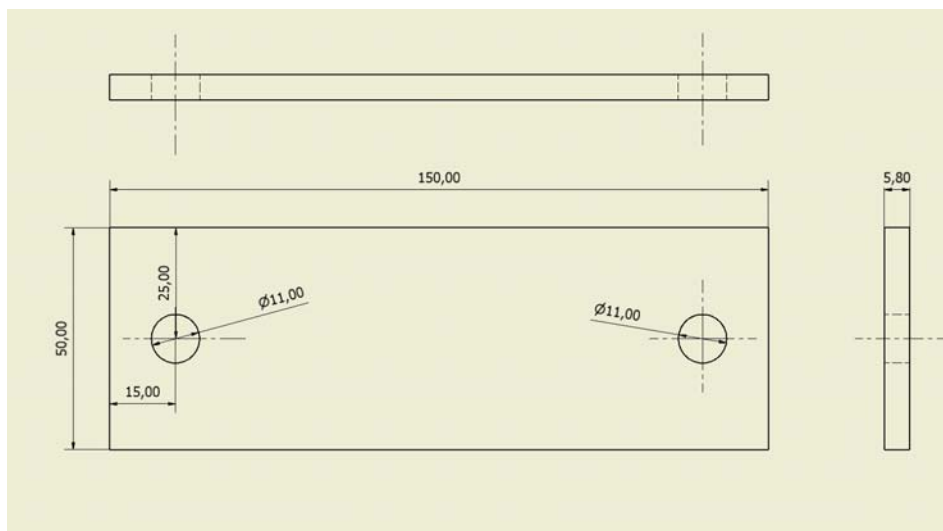
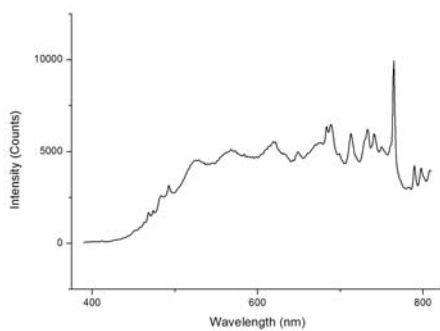
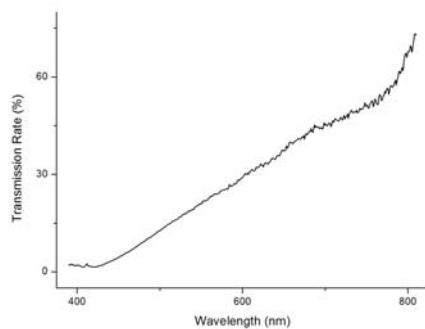


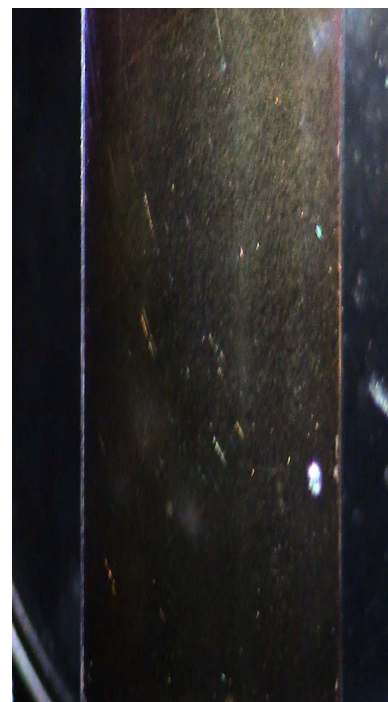
Fig. 4 The dimensions of PSM-1 calibration specimen (unit: mm)



(a) Light intensity spectrum

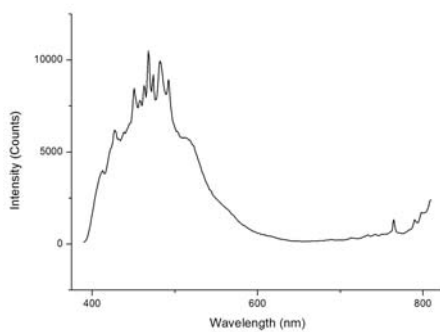


(b) Transmissivity spectrum

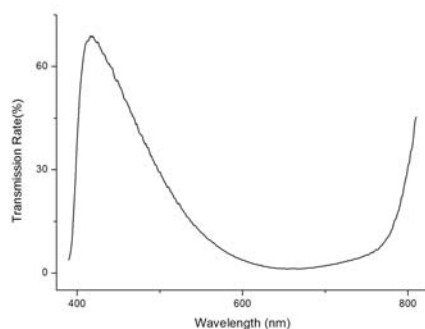


(c) Isochromatic fringe pattern

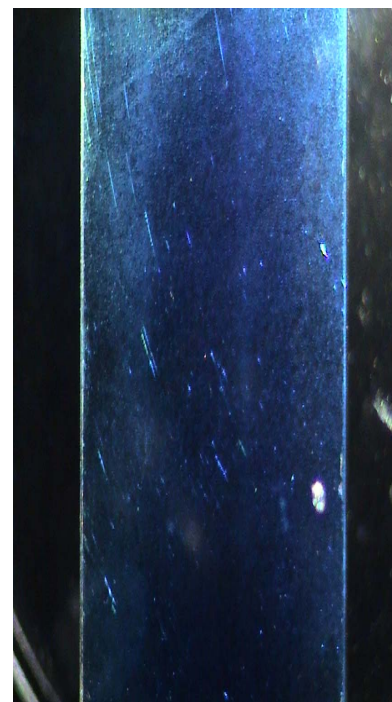
Fig. 5 The results under principal stress difference of 0.338MPa



(a) Light intensity spectrum

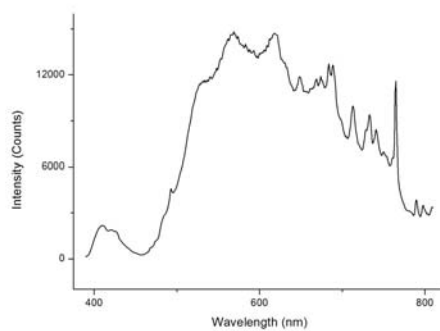


(b) Transmissivity spectrum

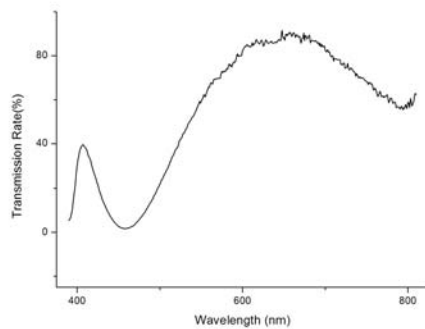


(c) Isochromatic fringe pattern

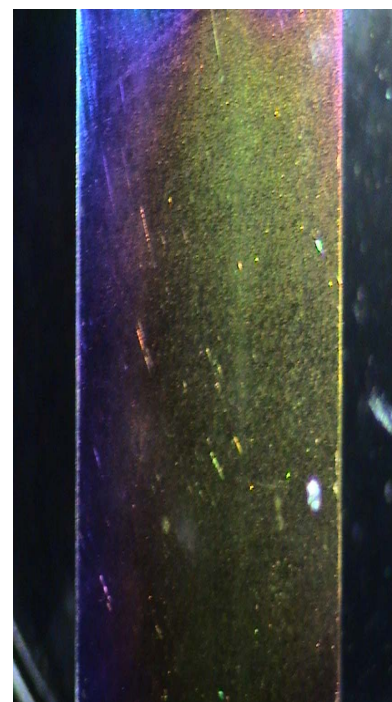
Fig. 6 The results under principal stress difference of 0.676 MPa



(a) Light intensity spectrum



(b) Transmissivity spectrum



(c) Isochromatic fringe pattern

Fig. 7 The results under principal stress difference of 1.352 MPa

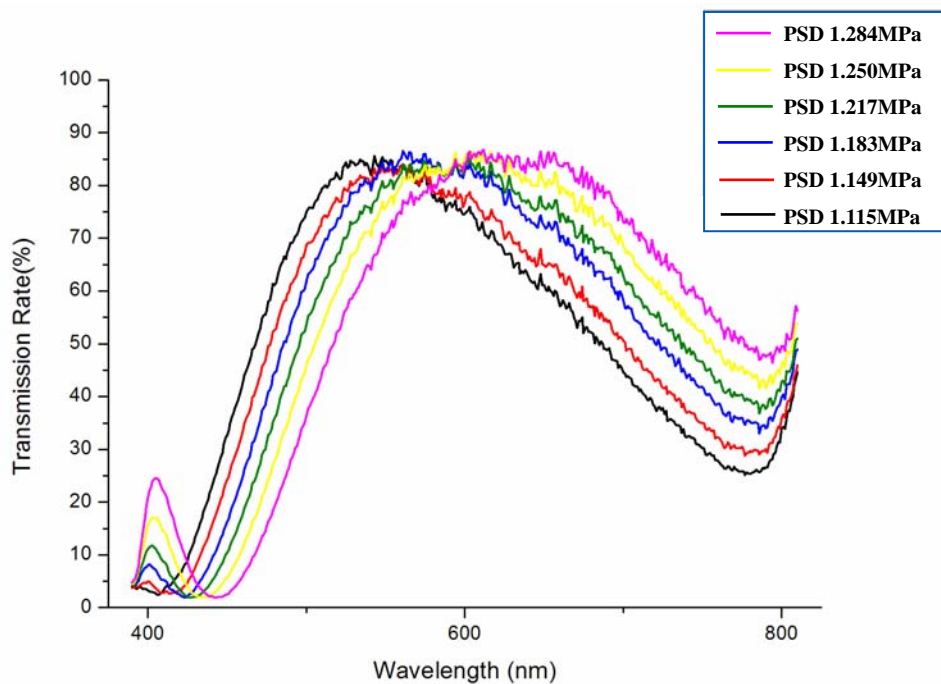


Fig. 8 The variation of transmissivity with stress magnitude of 1.115MPa and 1.284MPa

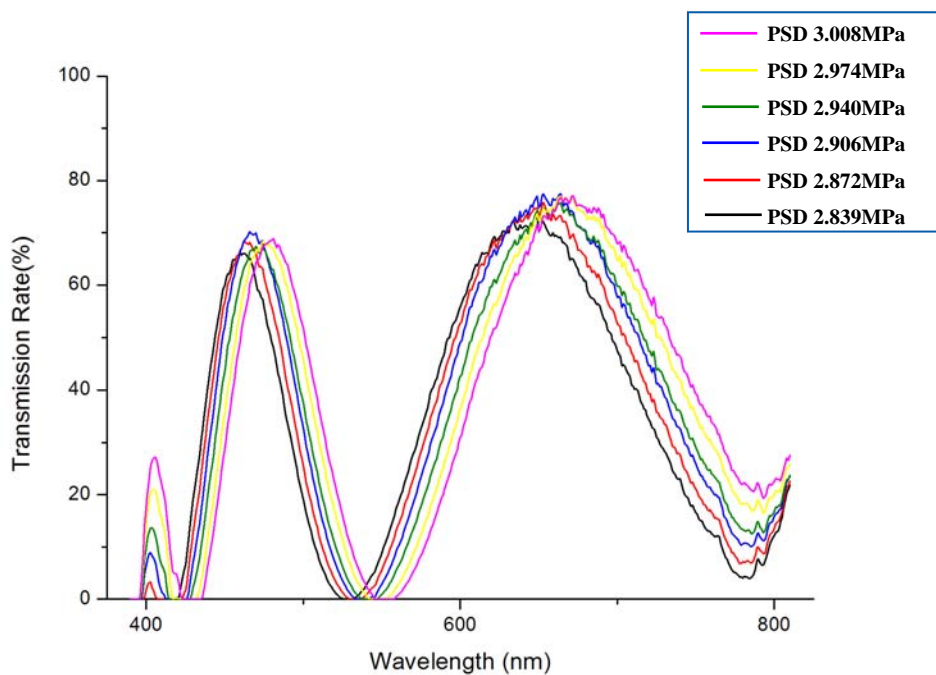


Fig. 9 The variation of transmissivity with stress magnitude of 2.839MPa and 3.008MPa