

Review Article

Research Progress of Stress Measurement Technologies for Optical Elements

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It is of great significance to measure the residual stress distribution accurately for optical elements and evaluate its influence on the performance of optical instruments in optical imaging, aviation remote sensing, semiconductor manufacturing, and other fields. The stress of optical elements can be closely related to birefringence based on photoelasticity. Thus, the method of quantifying birefringence to obtain the stress becomes the main method of stress measurement technologies for optical elements. This paper first introduces the basic principle of stress measurement based on photoelasticity. Then, the research progress of stress measurement technologies based on this principle is reviewed, which can be classified into two methods: polarization method and interference method. Meanwhile, the advantages and disadvantages of various stress measurement technologies are analyzed and compared. Finally, the developing trend of stress measurement technologies for optical elements is summarized and prospected.

1. Introduction

Residual stress is an important factor affecting the performance of optical precision measurement and imaging systems. It may occur in the process of forming, annealing, polishing, coating, and mechanical assembly of optical elements. The residual stress will bring some adverse effects to optical elements, such as surface deformation of optical substrate and film, refractive index change of glass lens [1], mechanical crack, and intensity damage [2, 3], thus affecting their optical property and imaging quality. Therefore, it is of great significance to accurately measure and control the stress distribution and reduce the adverse effects on the system in the progress of designing, manufacturing, and using optical elements. In addition, the accurate measurement and controlling of stress can also make contributions to polarization controlling [4], new optical elements designing and manufacturing, etc. [5].

It is difficult to determine the magnitude and direction of the stress theoretically because of its complicated causes and great randomness. In practice, experimental methods are

often used to measure the stress [6], such as the X-ray diffraction (XRD) method [7] and Stoney's curvature method [8]. Recently, with the development of optoelectronic technology, there are increasing requirements for optical element measurement and control. The optical glass, including liquid crystal display [9], automobile window [10], and super large telescope [11], has more and more demand for large-scale measurement. For high-power laser system [12], it is necessary to conduct high-precision stress measurement to prevent intensity damage on glass materials. For example, neodymium glass is the gain medium of high power laser, and it requires that the retardation is below 15 nm. Another example is the residual stress birefringence in high-quality fused silica and calcium fluoride, which is in order of magnitude of 0.1 to 1 nm/cm. Therefore, large scale, high efficiency, and high precision have become the main development trend of the current stress measurement technologies.

Residual stress is an important cause of accidental failure of metal elements, ceramic crowns, optical elements, and complex geometrical structures [13–16], but it is difficult to

measure and predict. There are usually two types of destructive testing and nondestructive testing methods to evaluate the residual stress and the operation safety. The destructive stress measurement method is obviously not suitable for the detection and estimation of residual stress. Instead, optical nondestructive testing (NDT) has attracted more and more attention in recent years, mainly due to its advantages of high-precision and high-sensitivity nondestructive imaging. At present, the main optical nondestructive testing technologies include fiber optics, electronic speckle, infrared thermography, and endoscopic and terahertz technology [17–21], which provide effective tools for nondestructive testing of the surface or interior of optical elements. In addition, the research idea of stress measurement of optical elements performed by measuring optical path difference or phase difference will open up a new direction of optical nondestructive testing, which has great application value in the field of optical nondestructive testing.

According to photoelasticity, the existence of stress leads to the change of the refractive index and then induces birefringence in the optical elements. Therefore, stress is closely related to birefringence. The way of quantifying birefringence to calculate stress has become the main method of stress measurement for optical elements. There are two kinds of stress measurement methods based on optical birefringence: polarization method and interference method. Those two methods are both based on the analysis of optical path differences between the two birefringence directions of the sample. Each method has both advantages and disadvantages, so a choice is made according to the accuracy demand in combination with application scenarios. According to the classification above, this paper is evolved in the following issues. First of all, the principle of stress measurement based on photoelasticity is given. Next, the latest research progress of stress measurement methods for optical elements is reviewed, in which the key technologies of each method are analyzed and the main factors affecting the measurement accuracy are discussed in detail. Finally, we do a comparison between these methods and make a summary and give prospects for the future, providing some reference for further study of measuring the stress for optical elements.

2. Principle of Stress Measurement Based on Photoelasticity

Photoelasticity is also called the stress birefringence effect. For isotropic optical materials, the stress will lead to structure deformation, resulting in local density difference along the axis and the change of refractive index. Consequently, the birefringence will occur when the light beam passes through those materials. According to the plane stress-optic law [22], in the plane perpendicular to the light propagation direction, the relationship between the stress and the refractive index can be described as follows:

$$n_e - n_o = K \cdot (\sigma_1 - \sigma_2), \quad (1)$$

where n_e and n_o are the refractive index along the refraction direction of extraordinary light and the ordinary light,

respectively, σ_1 and σ_2 represent the first and second principal stress, respectively, and K is the photoelastic coefficient of the material. When the linear polarized light is perpendicularly incident to the sample with thickness d , the light vector can be resolved into two in the plane perpendicular to its propagation direction, which vibrates along and perpendicular to the direction of principal stress. According to the birefringence effect, we obtain the optical path difference Δ of the two linear polarized lights after passing through the sample:

$$\Delta = d \cdot (n_e - n_o). \quad (2)$$

The relationship between stress and optical path difference can be derived from equations (1) and (2):

$$(\sigma_1 - \sigma_2) = \frac{\Delta}{K \cdot d}. \quad (3)$$

Stress can be also described as

$$(\sigma_1 - \sigma_2) = \frac{\delta}{K \cdot d \cdot 2\pi} \cdot \lambda, \quad (4)$$

where δ is the phase difference, and the birefringence retardation Δ/d (nm/cm) refers to the optical path delay (nm) after passing through a sample with a certain thickness (cm). It is shown from equations (3) and (4) that the birefringence retardation is proportional to the principal stress difference. Thus, the stress can be calculated according to the optical path difference or phase difference of the optical elements obtained by the experiment, combining with the sample thickness and photoelastic coefficient. Therefore, the stress measurement of the optical elements could be performed by measuring the optical path difference, phase difference, or birefringence retardation when the photoelastic coefficient is unknown. The direction of residual stress can be expressed by azimuthal angle.

3. Stress Measurement Method Based on Polarization Analysis

The polarization analysis method is to determine the birefringence of the elements by measuring the change of the beam polarization state after passing through the medium. The variation of the polarization state is expressed and calculated with the Jones matrix or Mueller matrix. The incident light and emergent light of the optical elements to be measured are modulated by the polarization optical devices, and the stress field is obtained by calculating the polarization of the light tested. In recent years, the digital photoelasticity (PD) method, photoelastic modulator method, laser Doppler vibrometer method, and other methods based on the principle of polarization analysis have been increasingly developed.

3.1. Digital Photoelasticity. The photoelasticity method is an effective experimental analysis method to study the stress distribution. Based on the birefringence effect of photoelastic material, this method is derived from the stress-optic law, and it obtains the full-field isochromatic line

representing the difference of principal stress and the isoclinic line representing the direction of principal stress through the polarized light field, so as to provide the full-field stress information in the structure. The digital photoelasticity method is an automatic stress measurement technology based on photoelasticity, rising with the development of computer video and image processing technology. Compared with the traditional photoelasticity method, the digital photoelasticity method can accurately measure the low-level stress and birefringence retardation.

In 2017, Hasegawa et al. carried out experiments on thin silicate glass based on the digital photoelasticity method [23]. They explained the stress field caused by engraving wheel indentation through the phase difference distribution below the high-speed polarization camera. The distribution of residual phase difference and the significant change of crack propagation were observed at the load of 30 kPa to determine whether the sample morphology changed. The experiments showed that the surface morphology transition zone is in good agreement with the phase difference transition zone. Laser processing of optical materials has been widely used in the waveguide, integrated element, diffracted optical element, and other manufacturing fields, but a large amount of residual stress will be released when laser radiation materials cool down. In the same year, Doualle et al. measured the optical path difference between two wavefronts with different polarization axes by using a wavefront sensor, which is placed in the image plane of a polarization microscope [24]. The experimental configuration is as shown in Figure 1. They also simulated the birefringence distribution of fused silica due to residual stress after CO₂ laser treatment by a thermodynamic model. The experimental and simulation results of residual stress measurement of fused silica treated with laser are shown in Figure 2. In the experiment, the calculated birefringence distribution after laser irradiation is shown in Figure 2(a). The measurement accuracy of optical path delay measurement and birefringence retardation reaches 1 nm and 2 nm/cm, respectively. The measurement accuracy is limited by the sensitivity of the wavefront sensor in the experimental configuration. Based on the thermodynamic model, the birefringence was integrated along the sample thickness to simulate the stress-induced birefringence distribution of the fused silica sample after cooling to the ambient temperature, as shown in Figure 2(b). The experimental results are consistent with the simulated quantitative results, which confirm that the method can quantify the stress-induced birefringence with high spatial resolution, and it has certain significance for optimizing the laser processing process.

In 2020, Iwatsuki et al. detected internal stress by the digital photoelasticity method [25]. They obtained the internal stress distribution of soda-lime glass (S9224) during laser cutting by observing the birefringence retardation at the crack tip with a high-speed polarization camera. Additionally, the thermal stress is calculated according to the plane stress model [26]. The effectiveness of this method is confirmed due to the matching of measured results and numerical results. The schematic diagram of the digital photoelasticity measurement principle is as shown in

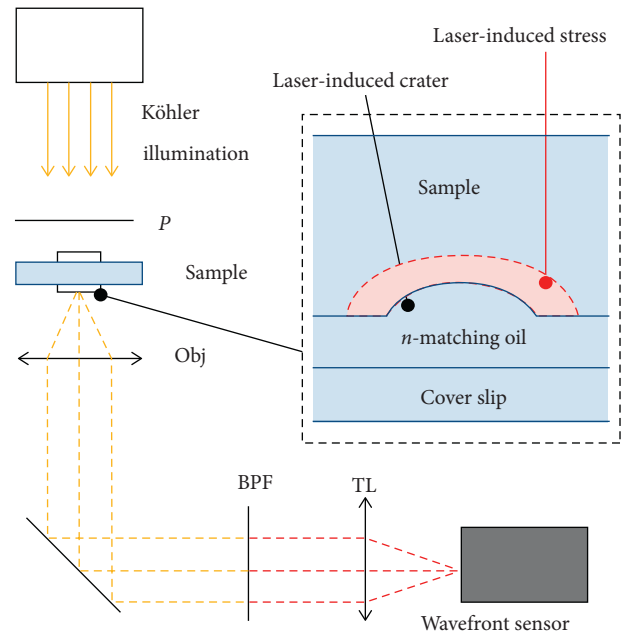


FIGURE 1: Experimental configuration. P: polarizer; Obj.: microscope objective; BPF: bandpass filter; TL: tube lens [24].

Figure 3. In this experiment, a light-emitting diode light source with a wavelength of 520 nm is used. The glass is fixed on the stage and placed parallel to the X-Y plane. The high-speed polarization camera is placed along the normal direction of the glass sample. The circularly polarized light is obtained through a polarizer and a quarter-wave plate and focused on the glass. The laser beam is scanned along the X-axis; meanwhile, the sample moves along the X-axis through the electric stage. Four polarizers with different polarization axes are set on the camera to obtain the images on each polarization axis. In fact, the birefringence retardation and azimuth angle are observed according to the images, which are obtained by the polarizing camera, and the results of measurement and calculation are shown in Figure 4. The residual birefringence is close to axisymmetric, and there is a slight difference between the experimental results and the numerical results of birefringence retardation, which is due to the deformation of the laser spot in the experimental process. The azimuthal angle is measured through a polarization camera experiment based on photoelastic theoretical analysis to indicate the stress direction. The azimuthal angle, which maintains the radial direction of the laser spot, indicates one of the two principal stress directions. And the experimental results in the elliptical region in Figure 4(c) rotated by 90° are in accordance with the calculated results in Figure 4(d).

Pallicity et al. measured the residual birefringence distribution of the plane convex lens made of P-SK57™ glass by digital photoelasticity method [27]. Also, the change of the axial stress of glass is simulated by the finite element method. The residual birefringence distribution and difference of the two methods are shown in Figure 5. The difference in residual stress is due to the uneven cooling rate of the lens sample. The measurement accuracy of optical path delay and

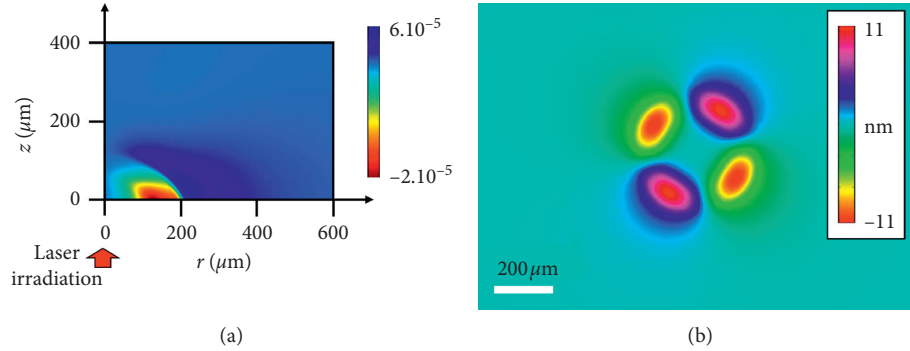


FIGURE 2: Experimental and simulation results of residual stress measurement of fused silica treated with laser. (a) Calculated birefringence distribution after irradiation. (b) Simulated retardation cartography [24].

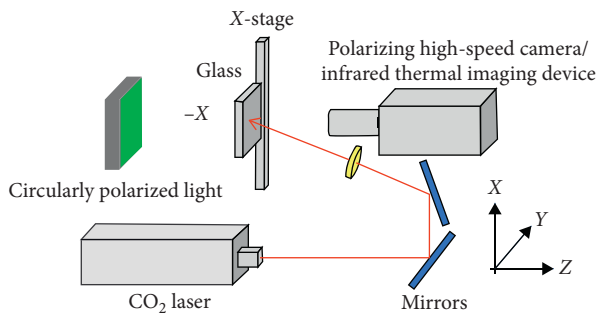


FIGURE 3: Schematic diagram of digital photoelasticity measurement principle [25].

birefringence retardation is 2 nm and 4 nm/cm, respectively, and the stress measurement accuracy of 184 kPa is calculated based on the photoelastic coefficient of P-SK57™ glass of $2.17 \times 10 \text{ TPa}^{-1}$. The residual stress direction is based on the theoretical solution model, and the full-field residual birefringence distribution of the P-SK57 lens is measured with the six-step phase shift technique.

3.2. Photoelastic Modulator Method. A photoelastic modulator (PEM) is a kind of phase modulation device based on photoelastic modulation. As a matter of fact, when the piezoelectric material is driven by voltage, the periodic mechanical force will be applied to the isotropic optical materials. As a result, periodic birefringence occurs on the optical materials, modulating the optical retardation [28]. In general, the peak retardation of the photoelastic modulator is adjusted to $\pi/2$ or π , which is used as a variable quarter-wave plate or half-wave plate. The photoelastic modulator is a polarization modulation technique based on photoelastic modulation. Because of its excellent performance of high sensitivity and high speed in measuring low-level birefringence in optical materials, this technology is suitable for biochemical analysis and other fields.

The typical PEM birefringence measurement system was developed by Hinds Instruments. In 1999, a single PEM system was developed [29]. The sensitivity of optical path difference amplitude is better than 0.005 nm, while the sensitivity of fast axis angle is less than 1° . Then, for the

specific application of measuring low-level residual birefringence in high-quality optical components, a double PEM system was designed [30]. Optical path difference sensitivity of 0.005 nm and phase retardation sensitivity of 5×10^{-5} rad (0.003°) are obtained by using the He-Ne laser with a wavelength of 632.8 nm in this system. The accuracy of residual stress in the fused silica sample can reach 0.223 kPa, according to the thickness of the sample and its photoelastic coefficient. The principle of stress birefringence measurement of single PEM is shown in Figure 6(a). The measurement accuracy is improved by combining the lock-in amplifier with a photoelastic modulator. First, the light beam emitted from the laser source first becomes polarized light through the polarizer. Next, the light is modulated by the photoelastic modulator, and incident on the sample. Then, the light passes through the polarizer, photodetector, etc. successively. Finally, through continuous measurement and data analysis of the two signal channels by computer, the retardation amplitude and fast axis angle are obtained. The anti-interference ability of the system is enhanced because the optical signal is modulated and extracted by a photoelastic modulator in the PEM system. For the double PEM system, whose principle of stress birefringence measurement is shown in Figure 6(b), there are two modulators with different frequencies. The small retardation has high accuracy in the double PEMs system. The residual retardation level of some high-quality optical elements is usually at 0.1–1 nm/cm. Therefore, the double PEM system can meet the needs of high-precision retardation measurement for high-quality optical components such as lens blank and photomask substrate, which will determine the mechanical quality of the super telescope.

Although the PEM system has the advantage of measuring low-level retardation, it encounters the upper measurement limit due to the calculation method when measuring larger retardation. So, how to expand the measurement range of the PEM system is a problem that needs focusing on. In order to expand the measurement range, there are two feasible ways: one is improving the function to calculate the retardation, by which the retardation range is extended to half wavelength; the other is using a light source with multiple wavelengths. In 2015, Achyut et al. performed a stress measurement experiment based on the principle of

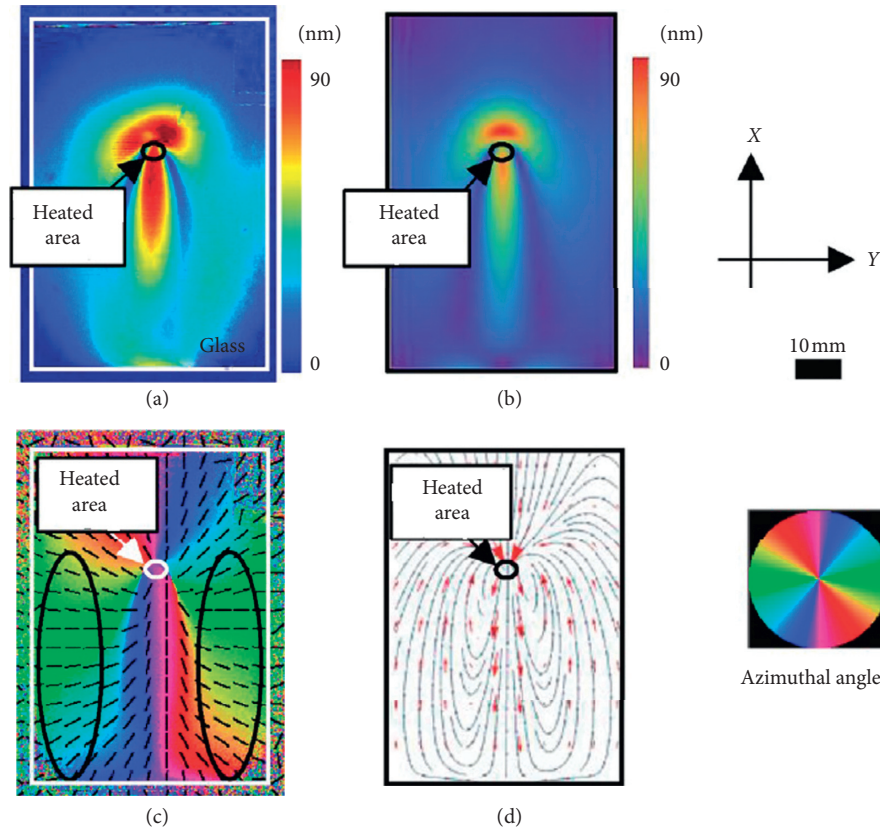


FIGURE 4: Measured and calculated results of birefringence retardation and azimuthal angle near the center of the glass [25]. (a) The measured result of birefringence retardation, (b) calculated result of birefringence retardation, (c) measured result of azimuthal angle, and (d) calculated result of azimuthal angle.

photoelastic modulation [31]. The stress birefringence in the transparent optical samples with the size of $150\text{ mm} \times 150\text{ mm} \times 250\text{ mm}$ is measured. The optical path retardation range is 0–316 nm. The uniformity of 20 kinds of microplates is evaluated by comparing the birefringence retardation value and standard deviation. The system has great properties of high sensitivity and high speed in measuring low birefringence samples, and the error of stress measurement is within 0.3%.

3.3. Laser Doppler Vibrometer Method. The Laser Doppler vibrometer (LDV) method is based on the laser Doppler effect. When dynamic birefringence exists, the dynamic stress caused by the elastic wave will lead to the change of local refractive index, which will cause the length change of optical path, thus causing Doppler frequency shift [32]. Therefore, by the detection of Doppler frequency shift, we can detect the dynamic elastic wave and measure the dynamic stress.

In 2014, Malkin et al. proposed a highly sensitive, noncontact, quantitative measurement method for elastic wave and dynamic strain based on laser Doppler vibrometer [33]. A mechanical excitation test was carried out in an acrylic rod at the frequency of 10–25 kHz. The effectiveness of this method is verified by finite element analysis, where

internal strain is as low as 1×10^{-11} , and the stress measurement accuracy is up to 0.036 Pa. The dynamic propagation of the longitudinal wave is visualized and quantified. For the excitation frequency of 20 kHz, the time evolution of the longitudinal wave in the whole scanning area is shown in Figure 7.

LDV method is only sensitive to dynamic stress; it has no response to static stress. Hence, this method is independent of the residual stress of the sample. In addition, LDV has the advantages of high sensitivity and intuition and has been used as a tool to observe the ultrasonic longitudinal wave stress field in transparent solid. However, only a longitudinal wave is observed, because the laser beam emitted by LDV is unpolarized, and the shear wave is not detected directly by this method. Aiming at the limitation of this technology, Zuo et al. in 2020 improved this situation by adding a rotatable linear polarizer to convert the laser beam emitted by LDV into different linear polarization states, realizing the measurement of shear wave [34]. And they obtained the photoelastic coefficient of the K9 glass of 2.7 TPa^{-1} in the process of measuring longitudinal wave and thus calculated the two-dimensional dynamic stress field in the K9 glass. The experimental results are consistent with those of finite element analysis. The schematic diagram of the measurement setup is shown in Figure 8.

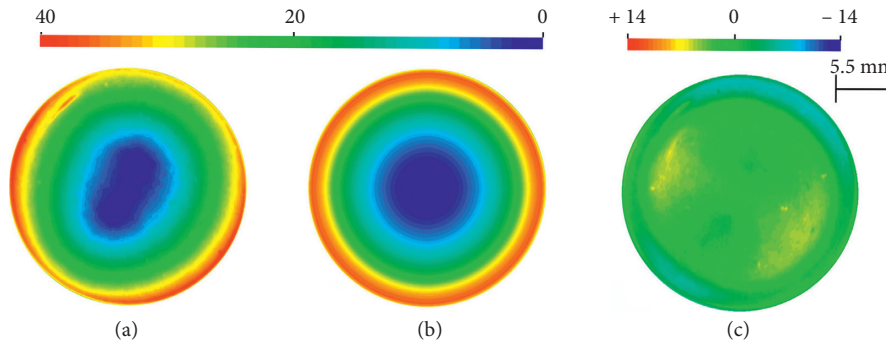


FIGURE 5: Residual birefringence distribution. (a) Digital photoelasticity experiment. (b) Finite element simulation. (c) Difference between experiment and simulation [27].

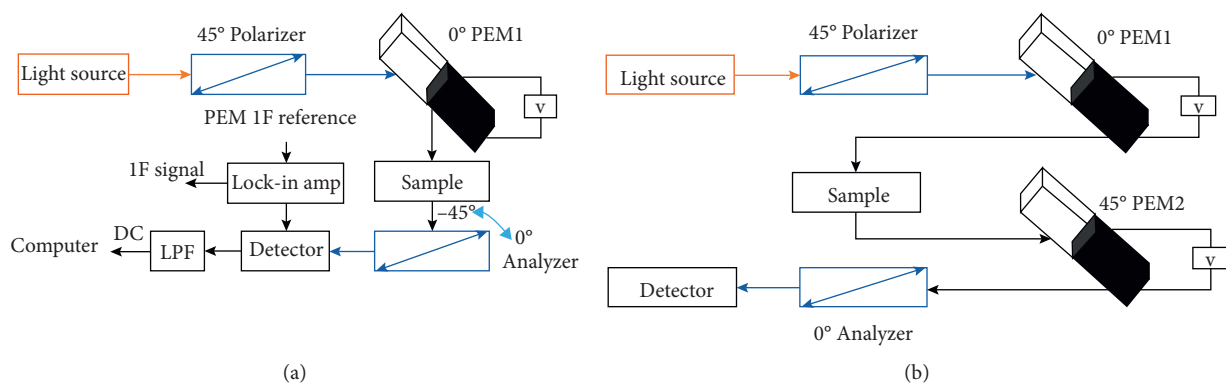


FIGURE 6: PEM birefringence measurement system. (a) Single PEM. (b) Double PEMs.

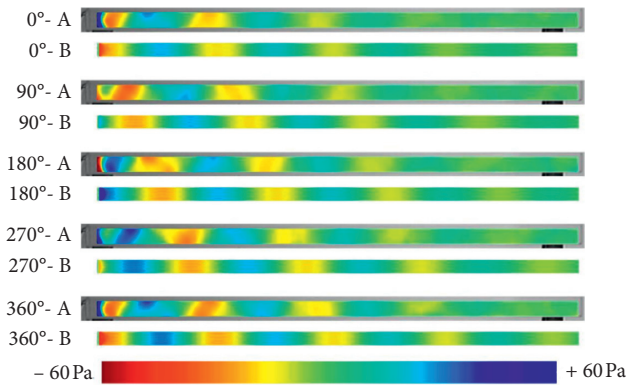


FIGURE 7: Quantified time evolution of longitudinal stress wave at 20 kHz [33]. (a) Experimental value. (b) FEA value.

4. Stress Measurement Method Based on Interference

Laser interferometry was invented in 1967, with the advantages of noncontact, large range, and high precision; it has been widely applied to biochemical test, production control, aerospace, and many other fields. The measurement principle of laser interferometer is described as follows. First, reference light and probe light are generated by a laser source. Then, an interference signal is generated based on the

principle of light interference. Next, the information from the interference signal to be measured is demodulated by a detector. Therefore, the velocity, displacement, stress, surface morphology, and other information of the object in need are determined according to the frequency difference, phase retardation, or optical path difference of the interference signals. With about 50 years of development, heterodyne interferometry, phase-shifting interferometry, laser self-mixing interferometry, laser feedback interferometry, cavity ring-down method, and other technologies have emerged, which have been applied to many fields owing to their advantages.

4.1. Laser Self-Mixing Interferometry. Laser self-mixing interferometry (LSI) remained the impression that it is harmful to the system at its early discovery period. Since the 1980s, it has gradually become a noninvasive measurement technology. The birefringence measuring process of laser self-mixing interferometry refers to increasing the frequency difference of the laser cavity, meanwhile, maintaining the single longitudinal mode, thus measuring the birefringence of the sample placed in the external cavity. And the birefringence of the external cavity is directly obtained by the phase difference of the output tuning curve of the self-mixing interference system. This method has the characteristics of a simple system, low cost, and wide measurement range.

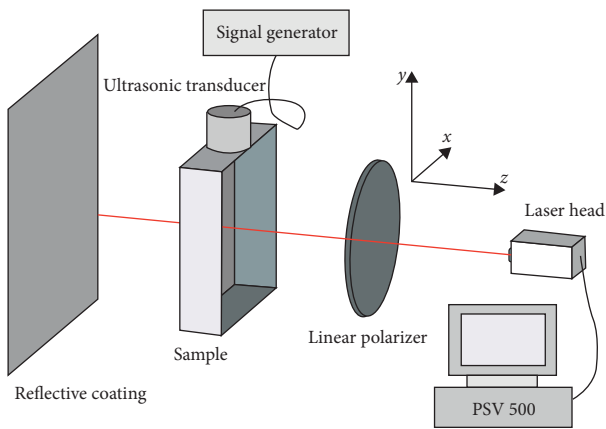


FIGURE 8: Two-dimensional dynamic stress experiment setup based on LDV [34].

In 2018, Niu et al. conducted experiments on a piece of neodymium glass with a size of $18 \times 20 \times 14.5 \text{ mm}^3$ by using a large frequency difference laser self-mixing interference (LFDSI) system and a birefringence instrument [35]. The schematic diagram of the experimental setup of the LFDSI system is shown in Figure 9. The measurement accuracy of the optical path difference is 0.01 nm, and the measurement range of optical path difference is 0–72 nm in BI. The optical path difference error is 0.22–0.53 nm, and the birefringence measurement accuracy is 0.152 nm/cm in LFDSMI. Without increasing the system cost and algorithm complexity, the working range of birefringence measurement is greatly improved, reaching 1.76 nm–315.04 nm (1° – 179°). And this system has high measurement sensitivity, so that the practical application demand of neodymium glass is perfectly satisfied.

In addition, in order to improve the accuracy of self-mixing interferometry, researchers have begun to pay attention to the importance of phase demodulation and proposed time-domain coherent demodulation [36], orthogonal demodulation [37], Fourier analysis [38], and other algorithms to demodulate the displacement and vibration information.

4.2. Laser Feedback Interferometry. Laser feedback interferometry (LFI) refers to the phenomenon that when the laser output enters the laser cavity repeatedly, the intensity will be modulated. The laser intensity modulation caused by the movable external mirror is similar to that generated by the traditional optical interferometer [39]. When the feedback mirror moves at the distance of half of the laser wavelength, the fringes will be produced. Compared with the traditional laser interferometer, the laser feedback interferometer does not need additional optical elements. The laser feedback interferometer and self-mixing interferometer both use the laser reflected from the outer surface. The difference between them is where the interference occurs; it is outside the cavity for laser feedback interferometer, while it is opposite for laser self-mixing interferometer. In 1995, the first laser feedback interferometer was invented by Donati et al. [40], who measured the displacement of the object through a single

interference measurement channel, according to the reflection of the laser diode on the measured surface. The experimental result is in good agreement with the basic theory, and it has aroused extensive attention about laser feedback interferometer. After that, the number of research studies on laser feedback interferometer has grown rapidly, and the application of this technology has covered many aspects, such as velocity measurement, displacement sensing, vibration measurement, and many aspects until now [41].

In 2017, Niu et al. developed a stress birefringence measurement system based on the reflective laser feedback (RLF) effect [42], where the stress is obtained by monitoring the polarization state and optical power modulated by birefringence. A silica glass under extrusion stress is tested by the RLF system and a birefringence measurement instrument from Hinds Instruments. The experimental results of the two methods are consistent, and the measurement accuracy of optical path difference and birefringence is 1.9 nm and 19 nm/cm, respectively. In addition, large area samples will be measured at any position by adjusting the position of the aluminum film used as the feedback mirror. Therefore, this system has the advantages of simple structure and low cost, which is expected to be applied to the measurement of large area transparent samples on the spot. The schematic diagram of birefringence measurement of the RLF system is shown in Figure 10.

4.3. Cavity Ring-Down Method. A cavity ring-down method is a form of birefringence interferometry, where the super reflectivity birefringence is determined by measuring the beat frequency. Also, the stress birefringence measurement technology based on the cavity ring-down method has high sensitivity and a large dynamic range. The cavity ring-down method is very useful for substrate annealing process optimization and coating stress estimation due to its high sensitivity and mapping ability for residual stress measurement.

For example, in 2016, Fleisher et al. performed a stress measurement experiment with the cavity ring-down method [43]. In this experiment, the birefringence of the mirror was directly measured in a double mirror Fabry-Perot cavity with a reflection coefficient of 99.99%, by observing the beat frequency of TEM_{00} mode in the process of cavity ring-down. The experimental result of sensitivity of 10^{-8} and the dynamic range of more than 10^3 is obtained, which confirms that the cavity ring-down method has high accuracy and a large dynamic range of more than three orders of magnitude.

In 2018, Xiao et al. measured the residual stress birefringence of fused silica substrate using the polarization cavity ring-down technique and obtained a repetition accuracy of phase retardation of 2.38×10^{-6} rad [44]. The repetition accuracy of optical path difference is 2.4×10^{-4} nm corresponding to the wavelength of 633 nm, and the spatial resolution is 0.01 mm. The stress accuracy to be calculated is 34 Pa, according to the stress-optic law and the photoelastic coefficient of fused silica in the literature, which is 3.5 TPa^{-1} [45]. The stress result is basically consistent with that measured by commercial stress birefringence measurement instrument. The schematic

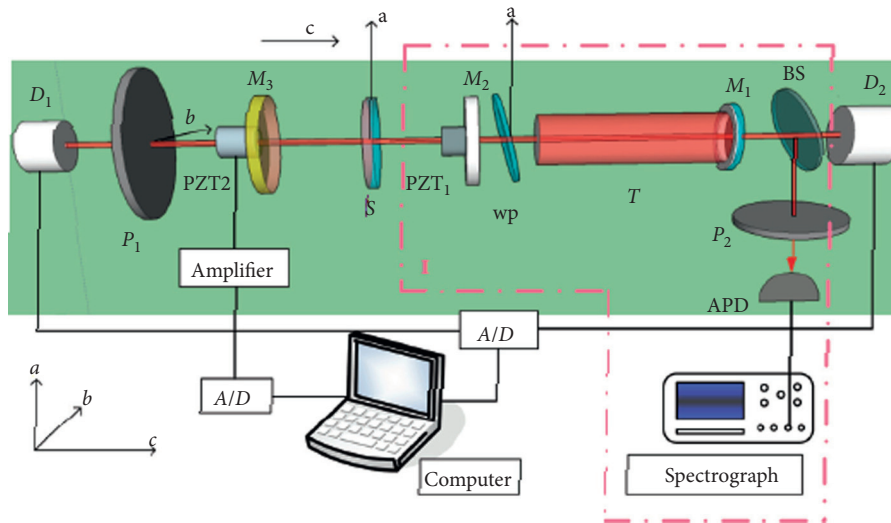


FIGURE 9: The schematic diagram of the experimental setup of LFDSI system [35].

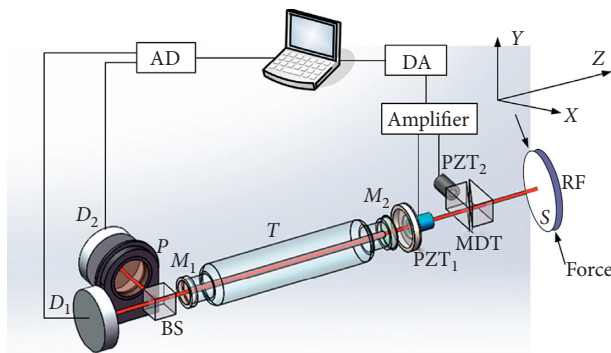


FIGURE 10: Schematic diagram of birefringence measurement of RLF system [42].

diagram of the birefringence measurement device with cavity ring-down technology is shown in Figure 11.

Xiao et al. also used the PEM method to measure the optical path difference (OPD) of fused silica substrate samples, and the result is shown in Figure 12. It is found that the sensitivity of the PEM method is 8×10^{-3} nm, while that of the cavity ring-down method is 2.4×10^{-4} nm. The maximum stress birefringence of the sample is 0.09 nm. The measurement sensitivities of the two methods are basically consistent; the slight difference between them is mainly caused by the position misalignment and the size difference of detection beams of the two methods.

5. Discussion

According to the measurement principle, the stress measurement for optical elements mainly methods consists of two categories: one is based on polarization analysis, including digital photoelasticity, photoelastic modulator method, and laser Doppler vibrometer method; the other is based on interference, including laser self-mixing interference method, laser feedback interferometry, and cavity ring-down method. This paper is based on the plane stress model for theoretical analysis, mainly about the two-dimensional plane stress.

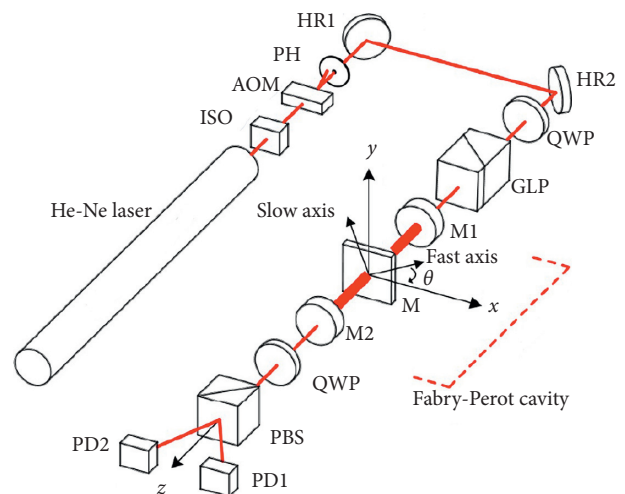


FIGURE 11: Schematic diagram of birefringence measurement of CRV system [44].

Based on the birefringence measurement principle of photoelasticity, the residual stress is expressed by the difference of main stress. The main stress difference can be calculated according to birefringence retardation on the premise of obtaining the photoelastic coefficient. In the case of an unknown photoelastic coefficient, the residual stress is expressed by the birefringence retardation Δ/d (nm/cm). We compared the measurement accuracy of birefringence retardation or stress measurement precision of the above methods. The comparison between them is listed in Table 1.

The digital photoelasticity, photoelastic modulator, and cavity ring-down methods are difficult to measure dynamic stress, so they are often used to measure residual stress. In contrast, the laser Doppler vibrometer method only responds to dynamic stress. The common disadvantage of laser self-mixing interferometry and laser feedback interferometry is that the stress measurement accuracy is low. The former is limited by the phase demodulation accuracy, while the latter is limited by the laser frequency drift. Compared with the laser

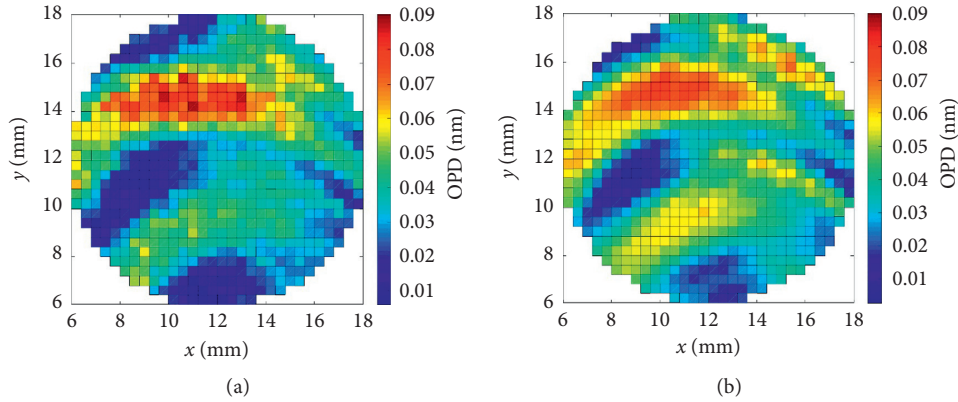


FIGURE 12: Stress birefringence comparison of fused silica substrates. (a) CRV. (b) PEM [44].

TABLE 1: Comparison between different methods.

Method	Key equipment	Advantage	Disadvantage	Stress precision
DP	Polarization camera, image sensor	Automatic, high resolution	Complexity, Inflexibility	184 kPa (4 nm/cm)
PEM	Photoelastic modulator	High sensitivity, high speed, good stability	Limited measurement range	0.2 kPa (0.008 nm/cm)
LDV	Laser Doppler vibrometer	High sensitivity, good visualization, good stability	Inability to detect the shear wave directly	0.036 Pa
LSI	Laser self-mixing interferometer	Simple, low cost, wide range	Limited measurement accuracy	0.152 nm/cm
LFI	Laser feedback interferometer	Simple, low cost	Limited measurement accuracy	19 nm/cm
CRD	Light source, optical resonator	High sensitivity, wide range	Low engineering applicability	0.03 kPa (12×10^{-4} nm/cm)

self-mixing interferometry, the cavity ring-down method also has a wide dynamic measurement range, but it has low engineering applicability owing to its high cost, the strict requirement of the light source, and high reflectivity mirror. The laser self-mixing interferometry and laser feedback interferometry are both nonintrusive, without moving the sample in the measuring process.

6. Conclusions

The traditional polarization analysis and interferometry method are both based on the principle of photoelasticity in line with stress-induced birefringence, where a certain correlation exists. In general, the measurement system often has the problems of high complexity, high cost, and low measurement accuracy and efficiency, which is difficult to meet the increasing requirements of various industries, especially large size, high efficiency, high precision, low cost, real time, etc. Therefore, some new stress birefringence techniques emerge, and every performance index is improved compared with the traditional methods, which overcomes some limitations of these two kinds of measurement methods. Due to the complexity of stress direction, the research on residual stress direction is scarce and needs to be further studied. How to measure the azimuthal angle of the principal stress

accurately with the help of the existing measurement technology needs to attract much attention, and the measurement of the stress direction has a great development prospect. In the future, the stress measurement technology for optical elements will be developed in the direction of high precision, large dynamic range, large size, and real-time measurement, which will contribute to the process controlling and quality examination of ultraprecision optical elements manufacturing. At the same time, the related technologies are expected to extend practical applications in the fields of velocity measurement, vibration measurement, displacement sensing, microimaging, morphology detection, etc.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

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