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HIGH STABILITY DUAL BEAM INTERFEROMETER SENSOR FOR NON-CONTACT PHOTOACOUSTIC IMAGING

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Abstract

As a non-contact photoacoustic sensor, the reflector of one arm of dual beam interferometer sensor is usually composed of the upper surface of the ultrasonic coupling liquid coated on the surface of the sample. The vibration of the outside and the scanning motor cause the liquid level to shake, causing the reflected probe light path to deviate from the incident light path, which then reduces the detection stability of the sensor. In view of the above problems, a novel high stability dual beam interferometer sensor is introduced in this paper, in which the reflected probe light is derived from the original optical path by using the combination of PBS and quarter wave plate, and the reflected probe light is coupled into 50/50 beam splitting fibre by using aspheric mirror group. The influence of the radius and focal length of each aspheric mirror and the numerical aperture of the optical fibre on the detection stability of the sensor is theoretically analyzed. The results show that the structural design greatly reduces the effect of the vibration of the outside and the scanning motor on the detection stability of the sensor, and provides a theoretical basis for the development and performance optimization of the sensor.

Key words: dual beam interferometer sensor, high stability, aspheric mirror, 50/50 beam splitting fibre

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1. Introduction. Photoacoustic imaging system based on dual beam interferometer sensor can image biological samples with high resolution and high contrast under non-contact condition, and has the advantages of high sensitivity, low vulnerability to be affected by external electromagnetic interference, large bandwidth, safety and non-invasive procedures, which meets the requirements of modern biomedical imaging, and has become a research hotspot in the current imaging field [1–3]. At present, the commonly used dual beam interferometer sensors are Michelson Interferometer and Mahzender Interferometer. In 2011, WANG et al. [4] used Michelson Interferometer to carry out photoacoustic imaging. By smearing mineral oil on the surface of organisms, the detection sensitivity was improved, the influence of speckle was eliminated, and the interlayer interference of biological tissues was successfully avoided. In 2013, HOCHREINER et al. [5] built a photoacoustic mesoscopic imaging system by using the Mahzender Interferometer combined with optical amplification technology, which improved the signal-to-noise ratio of the detected photoacoustic signal by optical amplification of the reflected light on the rough surface of the sample. In 2014, LIU et al. [6] used the Michelson Interferometer as the photoacoustic sensor, and achieved the maximum detection sensitivity by using the reference arm phase active modulation method to collect the photoacoustic signal at the zero-crossing point of the interference signal. In 2017, LU et al. [7] used optical fibre Michelson Interferometer to perform homodyne detection of photoacoustic signals, and used an achromatic lens to focus probe light and excitation light to eliminate the influence of dispersion on the quality of reconstructed images. In 2019, PARK et al. [8] built a set of multi beam Michelson interferometer using 3×3 optical fibre coupler with inherent 120° phase delayed, the photoacoustic signals obtained by detecting two interference signals with two photodetectors had the same interference sensitivity at any position within the detected optical coherence length, which solved the phase sensitivity problem of the orthogonal working point. Although the above research results have more or less solved the problems of low light power, high phase noise, low detection signal-to-noise ratio and phase sensitivity of the reflection probe in the experiment, the vibration of the outside and the scanning motor can cause the liquid surface of the ultrasonic coupling liquid coated on the sample surface to shake during the imaging process, resulting in the deviation of the reflected probe light path. It can be seen from the reversibility of the light path, this can cause the mode matching between the reflected probe light and the background light to deteriorate, and then reduce the detection stability of photoacoustic signals. As for this problem, no solution has been raised yet.

In this paper, a novel high stability dual beam interferometer sensor is subtly designed by focusing on the advantage of aspheric mirror that it makes the focal positions of paraxial and paraxial rays coincide and the advantage of 50/50 beam splitting fibre having a large numerical aperture. Through theoretical analysis of the influence of aspheric mirror's effective radius and focal length and optical

fibre's numerical aperture on the detection stability of the sensor, the newly-designed sensor can greatly improve its detection stability compared with the traditional dual beam interferometer sensor.

2. Structure of high stability dual beam interferometer sensor. Figure 1 is the structural diagram of high stability dual beam interferometer sensor. A single frequency laser with a central wavelength of 1064 nm is used as the detection light source, and the output laser becomes linearly polarized light after passing through the polarizer. Then it passes through the collimation device, the half wave plate and the PBS 1 accordingly, and later it is divided into two lasers. The reflected S-polarized light is used as the background light, which is coupled into the 50/50 beam splitting fibre through the focusing lens; The transmitted P-polarized light is used as the probe light, and after passing through the PBS 2, quarter wave plate, light guide mirror and aspheric lens 1, respectively, it is vertically focused to the glycerin liquid surface coated on the surface of the sample to be imaged. The probe light reflected by the liquid surface passes through the aspheric lens 1 and quarter wave plate again, and its polarization direction changes from P polarization to S polarization, the probe light reflected by the PBS 2 is coupled into the 50/50 beam splitting fibre through the aspheric lens 2. The photoacoustic signal can be detected by connecting the 50/50 beam splitting fibre with the balance detector. The dotted lines in Fig. 1 indicate the probe light path reflected by the glycerin liquid level when it shakes.

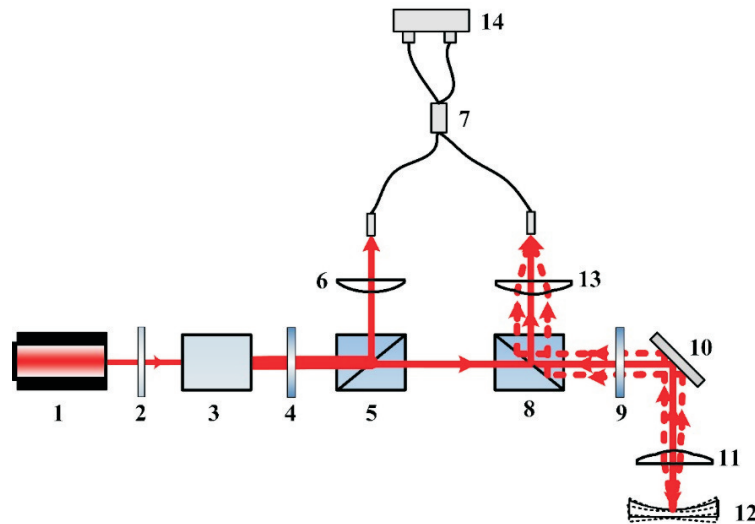


Fig. 1. Structural diagram of high stability dual beam interferometer sensor: 1 – single frequency lasers; 2 – polarizer; 3 – collimator apparatus; 4 – half-wave plate; 5 – PBS 1; 6 – focusing lens; 7 – 50/50 beam splitting fibre; 8 – PBS 2; 9 – quarter-wave plate; 10 – light guide mirror; 11 – aspheric lens 1; 12 – glycerol level on sample surface; 13 – aspheric lens 2; 14 – balance detector

The key technologies of the designed high stability dual beam interferometer sensor are as follows:

1. Using the aspheric lens 1 to focus the probe light on the glycerin liquid surface. When the liquid surface shakes, based on the fact that the aspheric mirror has the characteristic of making the focus position formed by the paraxial light and the paraxial light coincide, the reflected probe light passes through the aspheric lens 1 again, and its optical path is parallel to the original incident optical path.

2. The reflected probe light is led out of the original optical path by using quarter wave plate and PBS 1.

3. Using the probe light derived by aspheric lens 2, based on the characteristics of large numerical aperture of the optical fibre, when the maximum focus angle of the probe light is within the maximum allowable incidence angle of the optical fibre, the probe light is coupled into the optical fibre, and the 50/50 beam splitting fibre is connected with the balance detector, which can improve the detection stability of the sensor.

3. Theoretical model of high stability dual beam interferometer sensor. The designed high stability dual beam interferometer sensor can effectively solve the problem of optical path offset. In the theoretical model, the detection stability of the sensor can be measured by the included angle between the probe optical axis reflected by the glycerol liquid level and the incident probe optical axis. The larger the included angle, the higher the detection stability of the sensor. According to the theoretical analysis, the main factors affecting the detection stability of the sensor are the effective radius r_1 of the incident probe light, the radius r_2 and focal length f_1 of the aspheric lens 1, the side length L of the PBS 2, the radius r_3 and focal length f_2 of the aspheric lens 2, and the numerical aperture NA of the 50/50 beam splitting fibre.

Setting the probe light as a parallel beam, the optical path calculation formula after passing through the aspheric lens is as follows:

$$(3.1) \quad \tan \alpha = h/f.$$

Here α represents the included angle between the probe light axis reflected by the liquid surface and the incident probe light axis, and also represents the incident angle of the probe light reflected by the PBS 2 focused and coupled into the optical fibre through the aspheric lens 2, and h represents the offset of the probe light.

The calculation formula of numerical aperture NA of optical fibre is as follows:

$$(3.2) \quad NA = \sin \beta.$$

Here β represents the maximum incident angle that allows the laser to be coupled into the optical fibre through air.

Without considering the size of the aspheric lens group and the PBS 2, the relationship between NA , f_1 , f_2 , r_1 and the maximum included angle γ between the centre line of the probe light reflected by the liquid surface and the optical axis can be obtained by using the above two formulas. The calculation formula is as follows:

$$(3.3) \quad \tan \gamma = \left(\frac{NAf_2}{\sqrt{1-NA^2}} - r_1 \right) / f_1.$$

4. Theoretical optimization of high stability dual beam interferometer sensor. There are many factors affecting the detection stability of the dual beam interferometer sensor. The comprehensive analysis shows that the theoretical optimization of the sensor can be carried out by considering or without considering the influence of the size of the aspheric lens group and the PBS 2.

4.1. Unconsidering the influence of the size of the aspheric lens group and PBS 2. From formula (3.3), it can be concluded that when the parameters of each hardware of the dual beam interferometer sensor are determined, the maximum angle between the optical axis of the probe light reflected by the glycerol liquid surface and the optical axis of the incident probe light is inversely proportional to the effective radius of the probe light. It can be seen that the larger the effective radius of the probe light, the worse the detection stability of the sensor.

Figure 2 shows the relationship between γ and NA under different f_2 when r_1 and f_1 are equal to 1 mm and 30 mm, respectively. It can be seen from Fig. 2 that under the same f_2 , γ also increases with the increase of NA , and the higher the detection stability of the sensor; Under the same NA , with the increase of f_2 , γ also increases, and the detection stability of the sensor is higher. Under the

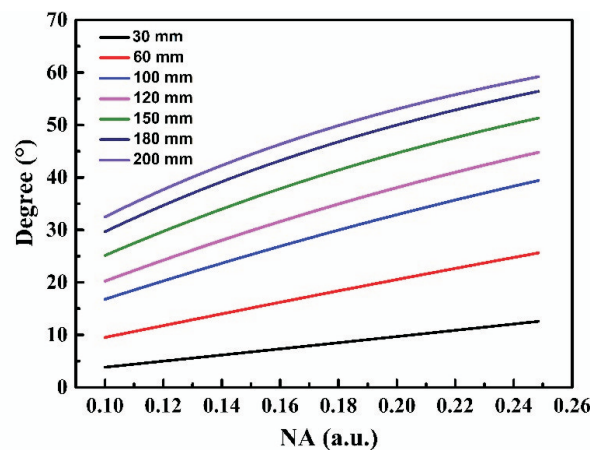


Fig. 2. Variation relationship between NA and γ under different f_2

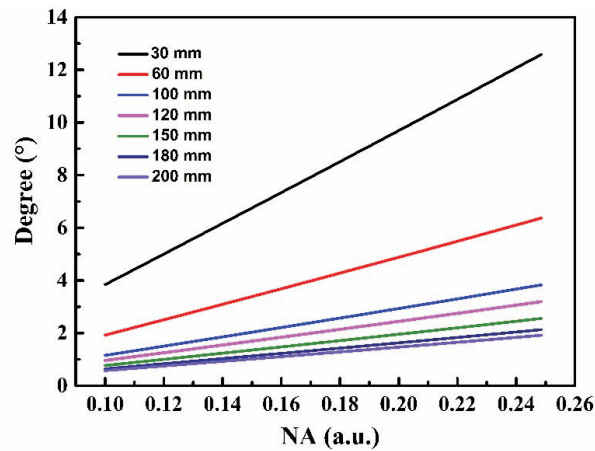


Fig. 3. Variation relationship between NA and γ under different f_1

same NA , by comparing the maximum included angle difference when f_2 is equal to 30 mm and 200 mm, respectively, with the maximum included angle difference when NA is equal to 0.1 and 0.26, respectively, it can be concluded that f_2 has a greater impact on the detection stability of the sensor than NA .

Figure 3 shows the relationship between γ and NA under different f_1 when r_1 and f_2 are equal to 1 mm and 30 mm, respectively. It can be seen from Fig. 3 that under the same f_1 , γ also increases with the increase of NA , the detection stability of the sensor is higher. Under the same NA , with the increase of f_1 , γ decreases, and the detection stability of the sensor becomes relatively poor. By

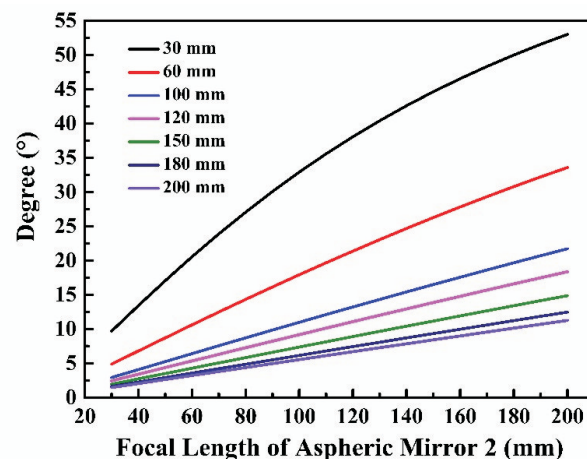


Fig. 4. Variation relationship between γ and f_2 under different f_1

comparing the maximum included angle difference formed when f_1 is equal to 30 mm and 200 mm, respectively, under the same NA with the maximum included angle difference formed when the NA is equal to 0.1 and 0.26, respectively, under the same f_1 , it can be concluded that with the increase of f_1 , the influence of NA on the stability of the sensor becomes smaller.

Figure 4 shows the relationship between γ and f_2 under different f_1 when r_1 and the NA are equal to 1 mm and 0.2, respectively. It can be seen from Fig. 4 that under the same f_1 , γ also increases with the increase of f_2 , and the higher the detection stability of the sensor. Under the same f_2 , with the increase of f_1 , γ decreases, and the detection stability of the sensor becomes relatively poor. By comparing the maximum included angle difference when the f_2 is equal to 30 mm and 200 mm, respectively, under the same f_1 with the maximum included angle difference when the f_1 is equal to 30 mm and 200 mm, respectively, under the same f_2 , it can be concluded that compared with f_1 , f_2 has a greater impact on the detection stability of the sensor.

4.2. Considering the influence of the size of aspheric lens group and PBS2. Under the condition that r_1 , NA , f_1 and f_2 are all determined, the maximum allowable offset $h_{\max}$ of the reflected probe light in the detection process can be calculated according to formulas 3.1 and 3.3. This value can be equivalent to the minimum radius $r_{2\min}$ and $r_{3\min}$ of the aspheric lens group and the minimum side length $L_{\min}/2$ of the PBS 2. The analysis shows that the side length of PBS 2 is the first factor affecting the detection stability of the sensor relative to the mirror radius of the aspheric lens group.

4.2.1. The side length L of the PBS 2 used in the experiment is longer than $L_{\min}$. When one or both of r_2 and r_3 used in the experiment is less than the corresponding $r_{2\min}$ and $r_{3\min}$, the reflected probe light offset h is equal to $\min(r_2, r_3)$, and the detection stability of the sensor is determined by $\min(r_2, r_3)$. When r_2 and r_3 used in the experiment are greater than the corresponding $r_{2\min}$ and $r_{3\min}$, h is equal to $h_{\max}$, and the detection stability of the sensor can reach the best state.

4.2.2. The side length L of the PBS 2 used in the experiment is shorter than $L_{\min}$. When one or both of r_2 and r_3 used in the experiment is less than the corresponding $r_{2\min}$ and $r_{3\min}$, the reflected probe light offset h is equal to $\min(r_2, r_3, L)$, and the detection stability of the sensor is determined by $\min(r_2, r_3, L)$. When the r_2, r_3 of the aspheric lens group used in the experiment are greater than the corresponding $r_{2\min}$ and $r_{3\min}$, h is equal to the side length L of the PBS 2, and the detection stability of the sensor is determined by the side length L of the PBS 2.

4.3. Test method of reflected probe light offset. Before building a set of high stability dual beam interferometer sensor, we must first determine the h . The test method is as follows:

1. In this experiment, the aspheric lens with smaller focal length and larger

radius can be selected as aspheric lens 1, and the offset of probe light reflected from the larger size PBS 2 during photoacoustic scanning can be measured and recorded by CCD;

2. The circle radius obtained by the circle fitting method is the maximum offset of probe light;

3. Use formula (3.1) to calculate the maximum included angle between the probe optical axis reflected by the liquid surface and the incident probe optical axis.

In order to meet the requirements of the non-contact photoacoustic imaging system for the dual beam interferometer sensor, the structure with the best detection stability can be designed according to the maximum included angle obtained from the experiment, the theoretical model and the actual parameters of each device that can be used.

5. Conclusion. In this paper, a novel high stability dual beam interferometer sensor for non-contact photoacoustic imaging is designed, in which the probe light reflected from the glycerol liquid surface is derived from the original optical path by using the combination of PBS, quarter wave plate and aspheric lens 1, and the derived probe light is coupled into 50/50 beam splitting fibre by using aspheric lens 2. This structural design solves the influence of the offset of reflected probe light path on the detection stability of the sensor, so as to improve the fidelity of the measured photoacoustic signal. Using the established theoretical model, the influence of the key device parameters in the sensor on the detection stability is analyzed, which provides a theoretical basis for the development and performance optimization of the high stability dual beam interferometer sensor.

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