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Laser interferometer with isolator function

WANG Lin-dou , WANG Jia-xin , XING Wen-lie , LI Yu-feng

(School of Electronic Information Engineering , Tianjin University , Tianjin 300072 , *China)*

Abstract : A laser interferometer with isolator function is proposed. It can be used to carry out interference measurement , and at the same time can be prevent reflected light from returning into the laser source to stabilize the source as an isolator does , thus the measurement accuracy can be guaranteed. So , the structure of the device is formed by organic combing two structures of the conventional interferometer and two-stage isolator , in which some elements can be combined two into one with double function. And the optical paths of the interference measurement and isolating are overlapped. Theoretic analysis and experiment results show that the device is effective , the isolation is agrees with that of a two-stage isolator , about 48 dB up to now. The results also show that the accuracy of the interference measurement depends on the wavelength of the laser like that of the general interferometer. But with compact structure , it simplifies the measurement system and is convenient for practical uses.

Key words : laser interferometer ; isolating function ; interference measurement

具有隔离器功能的激光干涉仪的研究

王林斗 ,王加新 ,邢文烈 ,李玉峰
(天津大学 电子信息工程学院 ,天津 300072)

摘要:提出了一种具有隔离器功能的激光干涉仪。既可以进行干涉测量 ,又具有隔离器功能 ,可以防止反射光回到光源 ,使光源保持稳定 ,确保了测量精度。该干涉仪由常规干涉仪和双级隔离器的结构有机的结合起来 ,其中某些元件合二为一 ,使一个元件起到双重功能的作用 ,同时使干涉光路和隔离光路也相互重合起来。理论分析和实验研究表明:该方案是可行的。隔离度与双级隔离器的隔离度相同 ,达到了 48 dB。该装置的干涉测量精度与一般干涉仪一样取决于激光波长 ,但该装置结构紧凑 ,简化了测量系统 ,实际使用更为方便。

关　键　词:激光干涉仪 ;隔离功能 ;干涉测量
中图分类号: TN206　　**文献标识码**:A

1　Introduction

A laser interferometer is one of the high-accuracy-measuring instruments , and it has the characteristics of non-contact measurement. It has been used in many measurement fields[1-2]. But in many situations of measuring with laser interferometers , e. g. the measurement of surface roughness and of

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intra-ocular pressure, etc., some reflective light from the surface of object returns inevitably into the laser source and influences the stability of the laser source, so that the measurement accuracy is bound to decline. Usually, the method to prevent reflective light from returning into the laser sources is to use optical isolators[3-4], but this method increases complexity and cost of the equipment.

A novel laser interferometer is proposed in this paper. This laser interferometer not only can be used to make interference measurement, but also can prevent reflected light from returning into the laser source. Its structure is compact, and its stability is higher. In addition, the cost of the equipment decreases because the optical isolator is saved.

2 Structure

The structure of the laser interferometer proposed in this paper is shown in Fig. 1, together with the Cartesian reference coordinate system of the three axes, x, y, and z. In Fig. 1, P is a polarizer. There are two ports on P, one is L_I, which is the input port of incident light, and the other is L_O, which is the output port of emerging light. The BC_1, BC_2, and BC_3 are all birefringent crystals. If the length of BC_1 (along z) is shown by a, the length of BC_2 and BC_3 are all $a/\sqrt{2}$. FR_1 and FR_2 are Faraday rotators. M_1 is a mirror that is connected with the measured object, or represents surface of the measured object. M_2 is also a mirror that reflects reference light. The figures (1-6) indicate the positions of 6 boundaries, respectively.

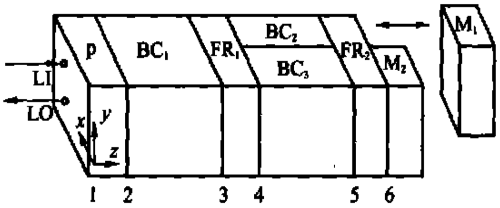
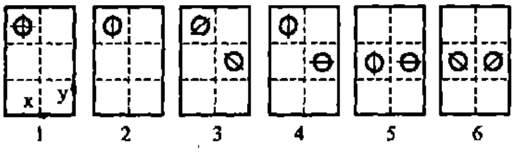


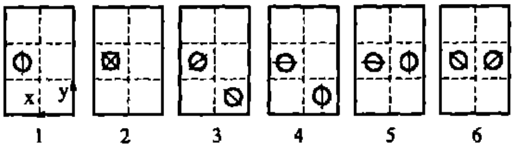
Fig. 1 Structure of the laser interferometer with isolator function

3 Interference principle

The interference principle of the laser interferometer is shown in Fig. 2. The circles and bisecting lines in Fig. 2 show respectively the spatial positions and the polarization directions of the beams, which are on the cross sections of six given boundary positions in Fig. 1. Suppose that an unpolarized light beam gets to the input port (position 1 in Fig. 2 (a)). After passing through P, the beam has changed into a linearly polarized beam in y direction (position 2 in Fig. 2 (a)). Then, the beam passes through BC_1 and is divided into two linearly polarized beams (position 3 in Fig. 2 (a)), in which one is an ordinary (o) ray and the other is an extraordinary (e) ray that walks off by distance d along $-135°$ direction from the x-axis. And then the two beams pass through FR_1, and the polarization directions are rotated by 45 °(position 4 in Fig. 2 (a)). Afterward, the two beams pass respectively through BC_2 and BC_3, in BC_2 the beam is e ray which walks off by distance $d/\sqrt{2}$ along $-y$ direction (position 5 in Fig. 2 (a)). Then, the beams pass through FR_2, and their polarization directions are rotated by 45 °(position 6 in Fig. 2 (a)). After that, the two beams are reflected by M_1 and M_2 respectively, and they return along $-z$ direction (position 6 in Fig. 2 (b)). Then, the two beams pass through FR_2 and their polarization di-



(a)Transmission in the direction fo positive z



(b) Transmission in the direction fo negative z

Fig. 2 Interference principle of the interferometer rections are rotated by 45 °(position 5 in Fig. 2 (b)). Next, the two beams pass through BC_2 and BC_3 respectively; in BC_3 the beam is e ray, which walks off by distance $d/\sqrt{2}$ along $-y$ direction (position 4 in Fig. 2 (b)). Afterward, the two beams pass through FR_1 and their polarization directions are rotated by 45 °(position 3 in Fig. 2 (b)). After that, the two beams pass through BC_1 and e ray walks off by distance d along 45 ° directions from x-axis, so that the two beams with different polarization directions combine into a single beam (position 2 in Fig. 2 (b)). Finally, the beam passes through P and two polarization components of y direction produce interference. The interferomic light beam emerges from output port (position 1 in Fig. 2 (b)). Suppose the electric field intensity of the linearly polarized beam (position 2 in Fig. 2 (a)) is

$$\vec{E}_i = A e^{j\omega t}\vec{a}_y , \tag{1}$$

where A is the amplitude and $\vec{a}_y$ is the unit vector in y direction. The beam passes through BC_1 and is divided into two beams (position 3 in Fig. 2 (a)). One beam is the measurement beam and the other is the reference beam. When they reach the output port passing through different paths, the electric field intensity ($\vec{E}_m$) of measurement beam and electric field intensity ($\vec{E}_r$) of reference beam are

$$\vec{E}_m = \frac{1}{2} A e^{jwt_1}\vec{a}_y , \tag{2}$$

$$\vec{E}_r = \frac{1}{2} A e^{j(wt_1+\alpha)}\vec{a}_y , \tag{3}$$

where α is the phase difference between two beams. And according to the beam paths it is

$$\alpha = \frac{2\pi}{\lambda}\left(4 n_f l + \frac{\sqrt{2}}{2} n_0 d + \frac{\sqrt{2}}{2\cos 6^{\circ}} n_e d + \frac{2}{\cos 6^{\circ}} n_e d + n_p w + 2v - 4 n_f l - 2 n_0 d - \frac{\sqrt{2}}{2} n_0 d - \frac{\sqrt{2}}{2\cos 6^{\circ}} n_e d - n_p w - 2u \right) = \frac{4\pi}{\lambda}\left(\frac{1}{\cos 6^{\circ}} n_e d - n_0 d + v - u \right) , \tag{4}$$

where n_f and n_p are the refraction index of FR and P respectively; n_0 and n_e are the refraction index of o-ray and e-ray in BC's, respectively; l, d and W ware the length of FR, BC_1 and P in z direction, respectively; the degree 6 is the size of the splitting angle in BC_1; λ is the wavelength in vacuum; u and v are the distance from M_1 and M_2 to FR_2, respectively.

The intensity of emerging light from output port is

$$I = (\vec{E}_m + \vec{E}_r) \times (\vec{E}_m + \vec{E}_r)^* , \tag{5}$$

where * indicates complex conjugation.

Substituting Eq (2), (3) and (4) into Eq. (5) yields

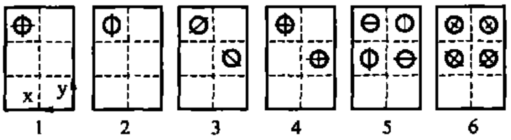
$$I = A^2\cos^2 \left[\frac{2\pi}{\lambda}\left(\frac{n_e d}{\cos 6^{\circ}} - n_0 d + v - u\right)\right] \approx A^2\cos^2 \frac{2\pi}{\lambda}(v - u) , \tag{6}$$

Only u is a variable in Eq. (6), it means that the amount of I is periodic variation with the variation of the distance from M_1 to FR_2. So the interference fringes can measure the displacement of M_1.

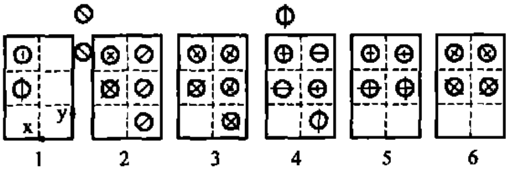
4 Isolating principle

The isolating principle of the laser interferometer is similar to that of some optical circulators and isolators[5-7]. The influence factors of isolation are as follows: (1) Rotation error of rotators; (2) Extinction radio of rotators; (3) Reflection from component facets.

Factor (3) can be easily eliminated by applying an antireflection coating and using slantwise fabrication of each component to the direction of a beam propagation[5]. Fig. 3 shows the influence of factor (1) and (2). The positions of the cross sections from 1 to 6 in Fig. 1 are shown in Fig. 3. The circles show the positions of beams in cross sections. The long lines bisecting circles indicate the polarization directions of main components of beams. The shorter and shortest lines indicate the polarization directions of the weak and very weak components, respectively which are caused by the rotation error and extinction ratio of rotators.



(a) Propagating along + *z* direction



(b) Propagating along – *z* direction

Fig. 3 Influence of the rotation error and extinction ratio of FR on isolation

Fig. 3 shows that only very weak components return into the input port along - *z* direction, so the isolation is very high.

The mathematical expression of isolation can be obtained in terms of the components of beams. In order to simplifying calculation the reference beam can be used to calculate the isolation. Suppose the power of the reference beam behind BC_1 (the lower beam in position 3 in Fig. 3 (a)) is unity, its Jones Vector is

$$[E_{ri}] = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 \\ 1 \end{bmatrix} , \tag{7}$$

Suppose that FR has no insertion loss, its extinction ratio is e_F, its rotation error angle is $\Delta\theta$, the Jones matrix of the FR is[8]

$$[F] = \frac{1}{\sqrt{1+e_F{}^2}}\begin{bmatrix} \cos(45° - \Delta\theta) & \sin(45° - \Delta\theta) \\ -\sin(45° - \Delta\theta) & \cos(45° - \Delta\theta) \end{bmatrix} \times \begin{bmatrix} j & -e_F \\ e_F & j \end{bmatrix} , \tag{8}$$

j in Eq. 8. is the imaginary unit. According to the changes of the beam in propagation, the power of the reference beam returning into input port (L_I) can be derived from $[E_{ri}]$ and $[F]$ step-by-step. It is

$$P_{ro} = \frac{8}{(1+e_F^2)^4}(e_F^2\cos^4\Delta\theta + \cos^2\Delta\theta\sin^2\Delta\theta)^2 , \tag{9}$$

So the isolation *g* is

$$g = -10\lg\left[\frac{8}{(1+e_F^2)^4}(e_F^2\cos^4\Delta\theta + \cos^2\Delta\theta\sin^2\Delta\theta)^2\right] , \tag{10}$$

Fig. 4 shows the results calculated with Eq. (10) for three extinction ratios (E_F = 35, 40, 45 dB).

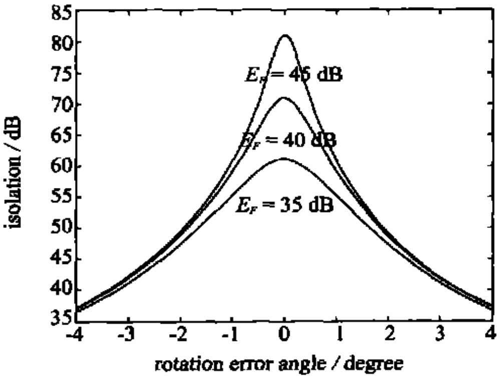


Fig. 4 Isolation vs rotation error

5 Experiment

The performance of the interferometer was tested. The birefringent crystals (BC's) in the structure of the tested interferometer were fabricated with calcite crystals. A Glan-Taylar prism was used as the polarizer (*P*). The bismuth-substituted yttrium iron garnet crystals surrounded by cylindrical SmCo permanent magnets were used as Faraday rotators. The surfaces of these elements were coated with antireflection film and slightly tilted to the propagation direction of the beams.

In order to measure the isolation of the interferometer, a laser beam was injected into the port L_O, and the emerging power from the port L_I was received. So the isolation could be calculated. A number of experiments have been carried about this, and the results are shown in Fig. 5. The isolation of this device is about 48dB. From the experiment results, some analysis can be made. First, the experiment results reflects synthetically the three factors influencing isolation mentioned above. After all, it is impossible to separate the three factors completely in practical measurement. Second, the measurement value of the isolation is not very high compared with the theoretic value because the precision of the art of facture is not very high. Third, in theory, the value of isolation will keep the same as the power of input and output beam changes. But as we can see in Fig. 5, the value of the isolation in each experiment has changed slightly, that is because some measurement errors exist unavoidably.

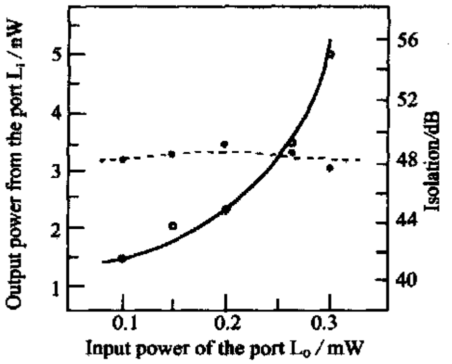


Fig. 5　Experiment results of isolation
Output power-input power (solid line)
Isolaton-input power (dashed line)

In order to observe the interference fringes, a laser beam was injected into the port L_I, and the emerging beam from the output port (L_O) was detected by a PIN diode, and the detected signals was displayed by a oscilloscope. Let the measurement mirror M_1 oscillate, the waveforms of the interference fringes can be observed from the oscilloscope. The measurement accuracy of this device, like the measurement accuracy of general interferometer, such as Michelson interferometer, depends on the wavelength of the laser, i.e. the measurement accuracy is the half of the wavelength of the laser. Adopt the method of photoelectricity receiving and the pulse counting to measure, and whenever M_1 moves half wavelength, count once. According to the number of the pulse, the distance that M_1 has moved can be figured out. The factors influencing the accuracy of measurement, similar to that of the general interferometer, are mainly the environments interferences[1-2,9]. So the shockproof mea-sure ment and the measures ment for preventing the electromagnetism interference and the background light interference need to be taken[1-2]. But because this device is a compact structure, it has certain ability of anti-interference itself, which is beneficial to reducing the influence of the environment.

In order to get the insertion loss of this device, the measurement should be going on in the condition of noninterference. Move the mirror M_1 away at first, then input the linearly polarized beam in *y* direction into the port L_I, and then measure the emerging beam from the port L_O. According to the power of the input and output beams, the insertion loss can be calculated. The average result is 7.78 dB through a lot of measurements. Considering that the mirror M_1 has been moved away, the light power reflected by M_2 is only the half power of the whole. So the insertion loss is 4.78 dB actually. In theory, the insertion loss of this device should be 3 dB at least, the same as general interferometers. It is caused by the factors on the craft that the actual insertion loss of this device is greater. The greater insertion loss doesn't influence the accuracy of measurement, just requiring the input power to be a little larger. Generally, the request for the index of insertion loss is not strict.

Anyway, the experiment demonstrates that the structure proposed in this paper not only has the function of interference measurement, but also the isolating function.

6　Conclusion

The laser interferometer proposed in this paper is a novel interferometer. In this interferometer, potentialities of some optical elements are fully used; one element plays a double role in the structure. So the laser interferometer has two functions of interference measurement and isolating reflected light. In any situations of interference measurement using this laser interferometer, the isolator is not needed and no reflected light can return into

the laser source. Compared with conventional interference measurement system, the structure of this laser interferometer is compact and its cost is lower. It also has the advantage of convenient uses.

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Biograph: WANG Lin-dou (1946 -), male, Prof., his current research interests are fiber-optic communication, optical passive devices and sensors. E-mail: xinerwang@21cn.com