Design of Polarization Dependent Optical Isolator Measurement System in Circularly Polarized Light Environment

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Abstract: In the detection process of optical isolator, the traditional linear polarization measurement method is not only limited in measurement accuracy, but also difficult to improve efficiency. In order to solve these problems, an automatic measurement system in circularly polarized light environment is designed. Firstly, based on the principle of free space optical isolator, the measurement method of linear polarization is analyzed; Then a circular polarization measurement method is designed. The measurement effects of the two methods are compared through Jones matrix calculation, and the effectiveness of the circular polarization measurement method is demonstrated; Finally, the bidirectional measurement optical path is designed, the whole system is completed combined with the control circuit, and the comparative test is carried out. Experiments show that the measurement error can be reduced from 0.1dB to 0.03db, and the measurement time can be reduced from 5.99s to 2S.

Keywords: Polarization dependent optical isolator; Circular polarization; Jones matrix

1. Introduction

In the optical communication system, due to various reasons, there will be reflected light opposite to the forward transmission direction of light. These reflected light will lead to self coupling effect and self excitation effect between optical path systems, destroy the stability of transmission and bring damage to devices[1,2]. Therefore, the use of optical isolators to suppress the propagation of back light is an essential link in the construction of optical path.

Optical isolator is a non reciprocal device, which only has a great inhibitory effect on the reverse transmission light in the system, but only has a small insertion loss on the forward transmission light in the system[3]. Its main performance indexes include insertion loss, isolation, polarization dependent loss, mode dispersion and return loss[4]. Under the background of large-scale production and application of optical isolator in various optical communication systems, in order to ensure the accuracy and efficiency of the detection of optical isolator insertion loss and isolator, a large number of literatures have studied the performance detection methods of optical isolator.

In reference[5], the self focusing lens is used to collimate the LED light source into the free space, and then the polarizing prism is used to polarize to obtain the linear polarizing environment and measure the optical isolator. Its structure is simple, but the linear polarizing environment obtained by polarizing only once with the polarizing prism can not obtain a good degree of polarization, which affects the accuracy of measurement. In reference[6], the tunable laser and polarization controller are used to obtain the linearly polarized light environment. Under the dark room condition of the light blocking diaphragm, the test light source passes through the optical isolator to be tested, and finally the measurement is completed by the optical power meter. This measurement method uses a higher degree of polarization of the linearly polarized light environment, but it is very vulnerable to the interference of the ambient light. Therefore, it is highly dependent on the dark room environment created by the light blocking diaphragm, Affect the detection efficiency. A detection method based on beam splitter, optical circulator, total mirror and optical power meter is proposed in document[7]. On the premise of measuring the beam splitter power ratio and optical circulator insertion loss in advance, the ability of optical isolator to isolate reflected light in practical application is measured, and the interference of ambient light is eliminated. However, this method can not detect the isolation and insertion loss at the same time. In reference[8], a bidirectional measurement system composed of multiple passive optical devices is designed. The system can complete the measurement of insertion loss and isolation at the same time, which improves the measurement efficiency. However, in the specific measurement process, the position of the optical isolator needs to be manually adjusted, which is not conducive to the mass measurement of the optical isolator, and a large number of polarization controllers are used in the whole measurement system, This also increases the production and measurement cost of optical isolator.

To sum up, the optical isolator measurement system currently used is running in the online polarized light environment, and this detection method has high accuracy[9], However, in a large number of optical isolator measurement scenarios, the efficiency of manual measurement is slightly low. Therefore, this paper demonstrates the feasibility of measuring the performance of optical isolator in circularly polarized light environment. Based on this principle, a free space polarization dependent optical isolator measurement system in circularly polarized light environment is designed and experimentally studied.

2. Principle and Measurement Principle of optical Isolator

2.1 Principle of Optical Isolator

The classical structure of free space polarization dependent optical isolator is shown in Fig. 1, which is composed of polarizer P1, polarizer P2 and Faraday rotator FR[10], The polarizer P1 and the polarizer P2 are at an angle to each other, and the Faraday rotator FR is placed between P1 and P2.

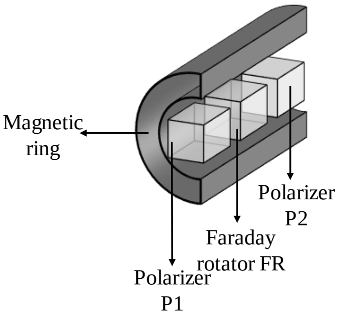

Figure 1. Typical structure of free space optical isolator

When the light is incident in the normal direction, the incident light turns into linearly polarized light. Under the action of FR, its polarization direction rotates parallel to the optical axis of P2 and passes through P2 smoothly. The reduction of optical power caused by this process is called insertion loss; When the light is incident in the reverse direction, the incident light becomes linearly polarized light after passing through P2. Under the action of FR, its polarization direction rotates orthogonal to the optical axis of P1 and cannot pass through P1. The attenuation value of optical power caused by this process is called isolation, and the insertion loss and isolation are defined as:

$$IL = -10 \cdot log^{\left(\frac{P_{out(+)}}{P_{in(+)}}\right)} \quad (1)$$

$$ISO = -10 \cdot log^{\left(\frac{P_{out(-)}}{P_{in(-)}}\right)} \quad (2)$$

Where $P_{out(+)}$ and $P_{out(-)}$ is the output optical power, $P_{in(+)}$ and $P_{in(-)}$ is the input optical power[11-13].

2.2 Principle of Linear Polarized Light Environment Measurement

The measuring optical path under the traditional linear polarization environment is shown in Fig. 2, and the direction of polarizer P1 is set parallel to the x axis, The rotation angle of Faraday rotator FR is $\theta_F = 45°$, The relative azimuth of polarizer P2 and polarizer P1 is $\varphi = 45°$, The angle between the polarization direction and the x axis of the forward linear polarizer is θ, The polarization direction of the reverse linear polarizer is parallel to P2.

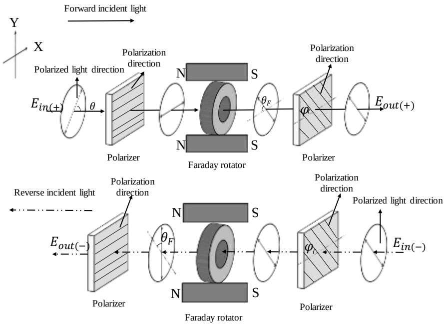

Figure 2. Measuring optical path under linear polarization environment

When the linearly polarized light is incident on the optical isolator in a normal direction, the Jones matrix of the emitted light is recorded as $E_{in(+)} = \begin{bmatrix} cos\,\theta \\ sin\,\theta \end{bmatrix}$, The Jones matrix of P1 is G_1, the Jones matrix of FR is G_F, and the Jones matrix of P2 is G_2 ,where $G_2 = \begin{bmatrix} cos\,\varphi & -sin\,\varphi \\ sin\,\varphi & cos\,\varphi \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \varepsilon_2 \end{bmatrix} \begin{bmatrix} cos\,\varphi & sin\,\varphi \\ -sin\,\varphi & cos\,\varphi \end{bmatrix}$, $G_F = \begin{bmatrix} cos\,\theta_F & -sin\,\theta_F \\ sin\,\theta_F & cos\,\theta_F \end{bmatrix}$, $G_1 = \begin{bmatrix} 1 & 0 \\ 0 & \varepsilon_1 \end{bmatrix}$, ε_1 and ε_2 is the amplitude extinction ratio of polarizer, about 3.2×10^{-3}, then the Jones matrix of the emitted light is

$$E_{out(+)} = G_2 G_F G_1 E_{in(+)} = \frac{1}{\sqrt{2}} \begin{bmatrix} cos\,\theta - \varepsilon_1 \varepsilon_2\, sin\,\theta \\ cos\,\theta + \varepsilon_1 \varepsilon_2\, sin\,\theta \end{bmatrix} \quad (3)$$

therefore

$$I_{out(+)} = \frac{\left(cos\,\theta + \varepsilon_1 \varepsilon_2\, sin\,\theta\right)^2 + \left(cos\,\theta - \varepsilon_1 \varepsilon_2\, sin\,\theta\right)^2}{2},$$

According to equation (1), there is insertion loss $IL = -10 \cdot \log^{\left(\frac{I_{out(+)}}{I_{in(+)}}\right)}$, $I_{in(+)}$ is the input light intensity, $I_{out(+)}$ is the output light intensity, and the loss curve of the output light intensity is shown in Figure 3.

It can be seen from the figure that the output light intensity loss increases gradually with the increase of polarization direction deviation. According to the investigation of the actual production process, when the operator measures in the online polarizing environment, the size of the optical isolator is very small, so the way of manually adjusting the direction is unstable, and the direction deviation is in the range of -, at this time, the reduction rate of light intensity is close to 3%. If 0.22db is taken as the insertion loss reference standard, the error curve of is shown in Figure 4.

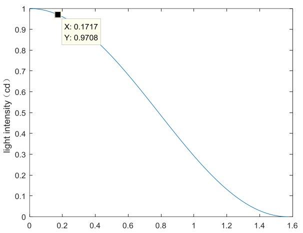

Figure 3. Output light intensity curve

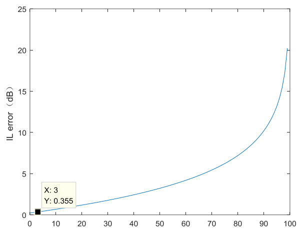

Figure 4. Error curve of IL

It can be seen from the figure that when the light intensity error is 3%, the measurement error has reached 0.13db. It can be seen that the manual measurement method is very easy to cause an error of about 0.1dB.

When the linearly polarized light reversely enters the optical isolator, keep the original optical path unchanged. If the polarization direction of the linearly polarized light source is parallel to P2, the Jones matrix of the incident light will be $E_{in(-)} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$. Therefore, the Jones matrix of the outgoing light will be

$$E_{out(-)} = G_1 G_F G_2 E_{in(-)} = \begin{bmatrix} 0 \\ \varepsilon_1 \end{bmatrix} \quad (4)$$

Then $I_{out(-)} = \varepsilon_1^2$, according to formula (2), there is isolation $ISO = -10 \cdot \log^{\left(\frac{I_{out(-)}}{I_{in(-)}}\right)}$, which $I_{in(-)}$ is the output light intensity and $I_{out(-)}$ is the output light intensity.

2.3 Measuring Principle of Circularly Polarized Light Environment

The measuring optical path in the linearly polarized environment shown in Fig. 2 can be equivalent to the optical path shown in Fig. 5. The general elliptically polarized light is used as the light source, and the polarization splitting prism (PBS) and 1 / 4 wave plate are cascaded in the optical path. When the elliptically polarized light passes through the PBS, the beam is divided into s light and P light, and the polarization directions of the two beams are perpendicular to each other, And the s light and P light are emitted from the side at an angle of 45 degrees, the P light propagates along the original optical path, and the slow axis of the quarter wave plate forms an included angle with the P light direction. Therefore, after passing through the quarter wave plate, the P light emits in the form of circularly polarized light and propagates in the optical path, and then passes through the linear polarizer with an included angle of 0 degrees with P1 to become linearly polarized light entering the optical isolator in the forward direction, or passes through the linear polarizer with an included angle of 0 degrees with P2 to become linearly polarized light entering the optical isolator in the reverse direction.

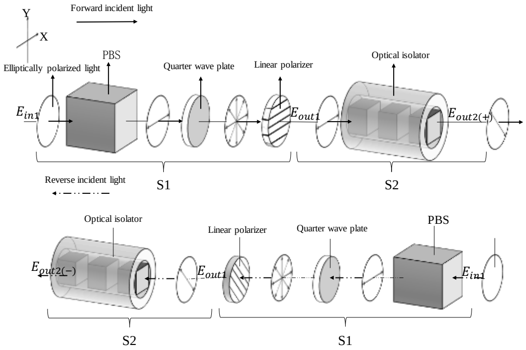

Figure 5. Equivalent measurement optical path in linear polarization environment

Note that the Jones matrix of the incident elliptically polarized light is $E_{in1} = \frac{1}{\sqrt{1+\gamma^2}}\begin{bmatrix}1\\ -\gamma \cdot e^{i\delta}\end{bmatrix}$, $\gamma = \frac{E_y}{E_x}$ is the amplitude ratio, $\delta = \varphi_y - \varphi_x$ is the Phase difference[14], the Jones matrix of PBS is G_P ,The Jones matrix of the quarter wave plate is G_W , The Jones matrix of the linear polarizer is G_L . Set the rotation angle of Faraday rotator FR $\theta_F = 45^{\circ}$, The relative azimuth of polarizer P2 and polarizer P1 is $\varphi = 45^{\circ}$, $G_P = \begin{bmatrix}1 & 0\\ 0 & \varepsilon_P\end{bmatrix}$, $G_W = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & \pm i\\ \pm i & 1\end{bmatrix}$, $G_L = \begin{bmatrix}1 & 0\\ 0 & \varepsilon_L\end{bmatrix}$, where ε_L and ε_P is about 3.2×10^{-3}.

For the optical path of the part $S1$, the Jones matrix of the outgoing light is

$$E_{out1} = G_L G_W G_P E_{in1} = \frac{1}{\sqrt{2\left(1+\gamma^2\right)}}\begin{bmatrix}1-\varepsilon_P\gamma e^{i\sigma} i\\ \varepsilon_L - \varepsilon_L\varepsilon_P\gamma e^{i\sigma}\end{bmatrix}$$

$$\approx \frac{1}{\sqrt{2\left(1+\gamma^2\right)}}\begin{bmatrix}1\\0\end{bmatrix} \quad (5)$$

Then its light intensity is $I_{out1} = \frac{1}{2\left(1+\gamma^2\right)}$.

When the light is incident in the normal direction, the Jones matrix of the outgoing light of t part $S2$ is

$$E_{out2(+)} = G_2 G_F G_1 E_{out1}$$

$$= \frac{1}{2\sqrt{\left(1+\gamma^2\right)}}\begin{bmatrix}1-\varepsilon_P\gamma e^{i\sigma} i - \varepsilon_1\varepsilon_2\varepsilon_L i + \varepsilon_1\varepsilon_2\varepsilon_L\gamma e^{i\sigma}\\ 1-\varepsilon_P\gamma e^{i\sigma} i + \varepsilon_1\varepsilon_2\varepsilon_L i - \varepsilon_1\varepsilon_2\varepsilon_L\gamma e^{i\sigma}\end{bmatrix} \quad (6)$$

Then its light intensity $I_{out2(+)} = I_{out1}$. According to formula (1)

$$IL = -10 \cdot \log^{\left(\frac{I_{out2(+)}}{I_{out1}}\right)} \quad (7)$$

When the light is incident reversely, the polarization direction of the polarizer is parallel to P2, so the outgoing light Jones matrix $E_{out1} = \frac{1}{2\sqrt{2\left(1+\gamma^2\right)}}\begin{bmatrix}\varepsilon_L+1-\left(\varepsilon_L-1\right)i\\ -\varepsilon_L+1+\left(\varepsilon_L+1\right)i\end{bmatrix}$ $\approx \frac{1}{2\sqrt{2\left(1+\gamma^2\right)}}\begin{bmatrix}1\\1\end{bmatrix}$,

Its light intensity $I_{out1}=\frac{1}{2\left(1+\gamma^2\right)}$

The outgoing light Jones matrix of the part $S2$ of the optical path is $E_{out2(-)}=G_1G_FG_2E_{out1}$ $= \frac{1}{2\sqrt{1+\gamma^2}}\begin{bmatrix}-\varepsilon_2\varepsilon_L\left(-\varepsilon_P\gamma e^{i\sigma}\left(1-i\right)-1+i\right)\\ \varepsilon_1\left(-\varepsilon_P\gamma e^{i\sigma}\left(1+i\right)+1+i\right)\end{bmatrix}$ $\approx \frac{1}{2\sqrt{1+\gamma^2}}\begin{bmatrix}0\\0\end{bmatrix}$, Its light intensity $I_{out2(-)}=0$. According to equation (2)

$$ISO=-10\cdot\log\left(\frac{I_{out2(-)}}{I_{out1}}\right) \qquad (8)$$

On the basis of the optical path shown in Fig. 5, moving the linear polarizer out of the optical path actually forms a measurement optical path for the free space polarization dependent optical isolator in a circularly polarized environment, as shown in Fig. 6.

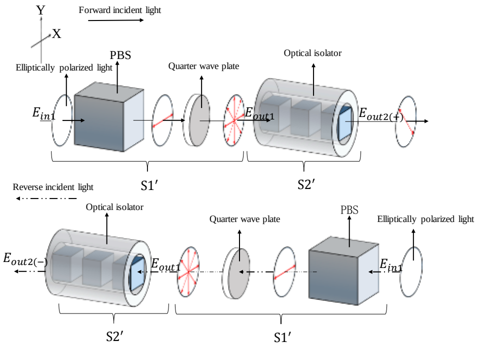

Figure 6. Measuring optical path in circularly polarized light environment

When light is incident in the normal direction, similarly, for the optical path of the part $S1'$, the Jones matrix of the emitted light is $E'_{out1}=G_WG_PE'_{in1}\approx\frac{1}{\sqrt{2\left(1+\gamma^2\right)}}\begin{bmatrix}1\\ \pm i\end{bmatrix}$, then its light intensity $I'_{out1}=2I_{out1}$, For the optical path of the part $S2'$, the Jones matrix of the outgoing light is $E'_{out2(+)}=G_2G_FG_1E'_{out1}\approx\frac{1}{2\sqrt{1+\gamma^2}}\begin{bmatrix}1\\1\end{bmatrix}$, then its light intensity $I'_{out2(+)}=I_{out2(+)}$, according to equation (7), for the same optical isolator, its insertion loss $IL=-10\cdot\log\left(\frac{I'_{out2(+)}}{I'_{out1}/2}\right)$, The insertion loss can be obtained by substituting $I'_{out(+)}$ and I'_{out1} measured in the circularly polarized environment into the formula. It is proved that the insertion loss can be measured in the circularly polarized environment.

When the light is incident reversely, similarly, $E'_{out1}\approx\frac{1}{\sqrt{2\left(1+\gamma^2\right)}}\begin{bmatrix}1\\ \pm i\end{bmatrix}$ can be obtained, its light intensity $I'_{out1}=2I_{out1}$. For the optical path of the part $S2'$, the Jones matrix of the outgoing light is $E'_{out2(-)}=G_1G_FG_2E'_{out1}\approx\frac{1}{2\sqrt{1+\gamma^2}}\begin{bmatrix}0\\0\end{bmatrix}$. Its light intensity $I'_{out2(-)}=0=I_{out2(-)}$, according to formula (8), the isolation degree $ISO=-10\cdot\log\left(\frac{I'_{out2(-)}}{I'_{out1}/2}\right)$, The isolation degree can be obtained by substituting $I'_{out2(-)}$ and I'_{out1} measured in the circularly polarized environment into the formula, which proves that the isolation degree can be measured in the circularly polarized environment.

3. System Design

3.1 Overall Structure Design of Measurement System

As shown in Figure 7, the whole measurement system is mainly composed of a DFB semiconductor laser (laser), an optical fiber coupler (coupler), two optical fiber circulators (circulator1, circulator2), two optical fiber collimating lenses (FC1, FC2), two photoelectric triodes (Pin1, Pin2), two stepping slides (plate1, plate2), two polarization splitting prisms (pbs1, pbs2) It is composed of two quarter wave plates (waveplate1, waveplate2), material tray, stepping motor, light isolator to be measured and control circuit.

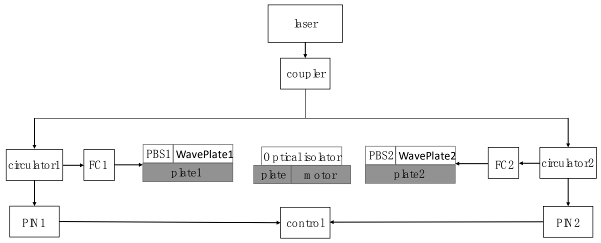

Figure 7 Overall structure of measurement system

The circularly polarized light is emitted from the laser outlet and output through the optical fiber coupler, and then transmitted to the P1 port of circulator1 and circulator2 respectively through the single-mode optical fiber. The P2 ports of circulator1 and circulator2 are respectively connected with FC1 and FC2. The output ends of FC1 and FC2 are cascaded with pbs1 and waveplate1, pbs2 and waveplate2 erected on the stepping slide table. In the free space between waveplate1 and waveplate2, a light isolator to be measured erected on the material tray is placed, and the material tray is rotated under the control of stepping motor to complete sorting. The P3 ports of circulator1 and circulator2 are connected with Pin1 and Pin2 respectively, and the output ends of Pin1 and Pin2 are connected with the control circuit.

The input light source is coupled into signal light that can be transmitted along two output fibers through coupler. When measuring the insertion loss, the input light source transmits along the left forward optical path. After the signal light enters the P1 port of circulator1, it is transmitted to FC1 through the P2 port of circulator1. Then FC1 changes it into spatial parallel light and transmits it in free space. At this time, the polarization state of the signal light is elliptical polarized light, and palte1 moves into the measurement optical path with pbs1 and waveplate1, plate2 carries pbs2 and waveplate2 out of the measurement optical path. After the signal light passes through pbs1 and waveplate1, it becomes circularly polarized light, which is received and coupled by FC2 into the optical fiber, input to port P2 of circulator2 and output to Pin2 by port P3. It is processed by the control circuit. This signal is used as the reference signal for measuring insertion loss and isolation. Then place the optical isolator to be measured on the material tray. After the signal light enters the optical isolator to be measured in the positive direction, it is output to Pin2 through port P2 and port P3 of circulator2 and processed by the circuit as the forward transmission signal of the optical isolator to be measured. The insertion loss is calculated by the program to complete the measurement. When measuring the isolation degree, similarly, the input light source transmits along the reverse optical path on the right. After entering the P1 port of circulator2, the signal light is transmitted to FC2 through the P2 port of circulator2, and then FC2 changes it into spatial parallel light for transmission in free space. At this time, the polarization state of the signal light is elliptically polarized light, and plate2 moves into the measuring optical path with pbs2 and waveplate2, plate1 carries pbs1 and waveplate1 out of the measuring optical path. After the signal light passes through pbs2 and waveplate2, it becomes circularly polarized light and enters the optical isolator to be measured in reverse. It is output to Pin1 through P2 port and P3 port of circulator1 in turn and processed by the circuit. It is used as the reverse transmission signal of the optical isolator to be measured, and the measurement of isolation is completed by program calculation. The completed optical path is shown in Figure 8.

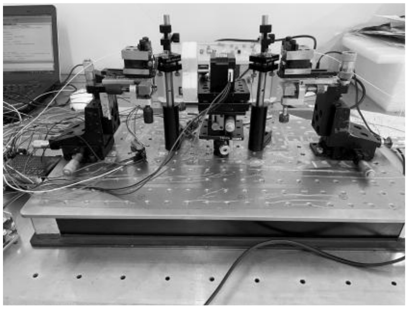

Figure 8. Measurement system of free space optical isolator

3.2 System Software and Hardware Design

On the basis of the above optical path, the control circuit needs to be used to complete the control and signal processing of stepping motor, sliding table and optical fiber coupler. As shown in Figure 9, the control circuit uses stm32f103zet6 as the main control chip, and uses mp2359 and lm1117-3.3 to design the power circuit to provide power for the control circuit, After the optical signal collected by the photoelectric triode is transformed into an electrical signal through the IV amplification circuit, it is collected by the ADC and transmitted to the main control chip for processing. After calculating the data, it makes logical judgment, and controls the optical fiber coupler, stepping motor and stepping slide to cooperate with the detection of the optical isolator to be measured and the display of the results.

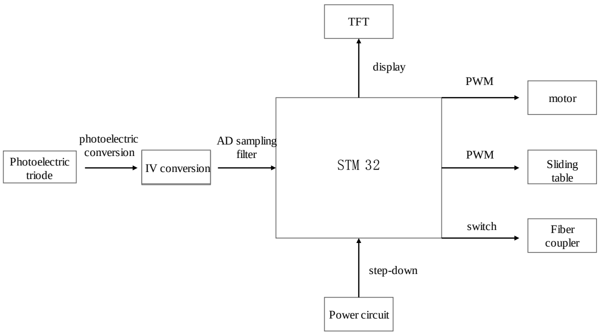

Figure 9. Main control circuit design of the system

When the whole system starts to operate, first control the optical fiber coupler and stepping slide to switch to the forward optical path, collect the optical signal, and then control the optical fiber coupler and stepping slide to switch to the reverse optical path, collect and calculate the optical signal, and complete the measurement of isolation, Finally, according to the measurement results, the stepper motor is controlled to sort the optical isolator.

4. Analysis of System Measurement Results

In the experiment, a batch of finished products obtained from the production line are free space polarization dependent optical isolators working in 1550nm band, and the values of insertion loss and isolation meet the standards.

Firstly, the optical path of traditional linear polarization measurement is built and tested; Then the measurement system designed in this paper is used to measure this batch of optical isolators, and the data measured in the two environments are compared with the factory data. The comparison results are shown in Figure 10. It can be seen that the insertion loss and isolation data measured in the circular polarization environment are similar to those measured in the linear polarization environment, and the errors are controlled within the range of 0.03db and 0.07dB respectively.

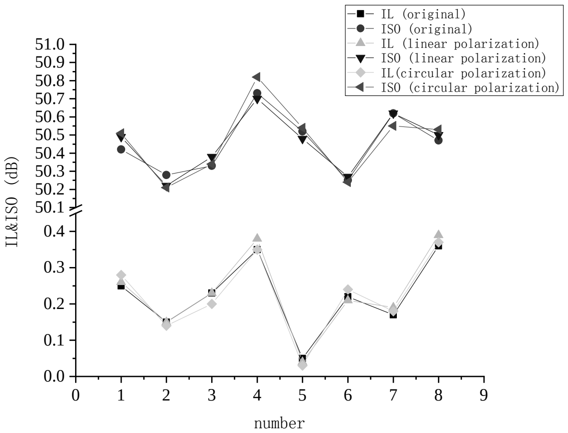

Figure 10. Comparison of insertion loss and isolation

The measurement time of linear polarization measurement system and circular polarization measurement system is shown in Table 1. The average manual detection speed of each index under linear polarization environment is 5.99 seconds, and the average detection speed of each index under circular polarization environment is 2 seconds, which improves the detection efficiency by three times, and fully meets the production demand for mass measurement of optical isolators.

Table 1. Comparison of measurement time

Number	TIME-L(s)	TIME-C (s)
1	6.34	2
2	5.37	2
3	6.20	2
4	6.02	2
5	6.36	2
6	5.66	2
7	6.16	2
8	5.86	2

5. Conclusion

Through data comparison, it can be found that the parameter error of the optical isolator detected by the system is within the ideal range, and the system is improved based on the traditional manual detection method of linear polarization. The detection speed can reach 30 / min, which is much faster than the average speed of 10 / min of the traditional detection method. Based on the above experimental data, the designed measurement system of free space polarization dependent optical isolator in circularly polarized light environment can accurately detect the two parameters of optical isolator isolation and insertion loss, and greatly improve the detection speed. It has good practical value and wide application prospects.

Acknowledgment

This work was supported by Science and technology research project in high-tech field of Henan Province (182102210309); Special project of basic scientific research business fee of Henan University of Technology (self discipline) (NSFRF180404); Innovation and entrepreneurship training program for college students of Henan University of Technology(202010460068)

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