Influence of Polarization Crosstalk of Y Branch Loop on Scale Factor in Fiber Optic Current Sensor

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Abstract. The influence of polarization crosstalk of Y branch loop on scale factor is analyzed in detail. In the Y branch loop, the scale factor is affected by only the output alignment angle of the PBS. The experiment result shows the range of output alignment angle of the PBS should not exceed from 0.2° to 2.5° over a range from -40°C to 70°C which corresponds to angle 1.8° at room temperature to make sure the measurement accuracy within ±0.2% from 0 to 100kA.

1. Introduction
Compared to the electro-magnetic current transformer (CT), the fiber-optic current sensor (FOCS) utilizes Faraday magneto-optic effect and digital closed-loop detection technology and can offer a number of more attractive benefits such as high accuracy, wide dynamic range, dielectric nature, immunity to electro-magnetic interference, digital output, small size and light weight1-5. The circuit with in-line polarizer and Ti-indiffused LiNbO3 phase modulator is widely used because of the excellent immunity to environmental disturbance. The influence of polarization crosstalk of phase modulator and polarization-maintaining (PM) fiber connectors is investigated6-8. To eliminate the effect of the PM fiber connectors the circuit with Y branch integrated-optics phase modulator and polarization beam splitter (PBS) is proposed. Typically, the sensors must have accuracy to within ±0.2%, the variation of polarization crosstalk of Y branch loop with temperature will cause the scale factor error and affect the measurement accuracy.

In the following, the configuration of FOCS Y branch integrated-optics phase modulator and PBS is reviewed firstly, the scale factor associated with the polarization crosstalk of Y branch loop is analyzed in detail and confirmed experimentally.

2. Focs Configuration
FOCS circuit with Y branch integrated-optics phase modulator and PBS is illustrated in Fig1. The optical wave from a light source is directed through a PM circular to the Y-branch phase modulator, and the two optical waves with parallel linear polarization are combined to orthogonal waves by the PBS. The orthogonal polarization waves are converted into left and right circular polarization waves by a quarter-wave retarder at the entrance of sensing fiber coil. The two optical waves with orthogonal circular polarization pass through the sensing fiber with different velocities, and the difference is proportional to the current traversing the sensing loop. They are reflected by the mirror and retrace...
their way through the sensing fiber. The phase difference is doubled during their return trip through the sensing fiber. The quarter-wave retarder converts the returning orthogonal circular polarization waves back to orthogonal linear polarization waves. Compared with the forward traveling linear polarization waves, the polarization directions of the backward traveling linear polarization waves are interchanged, i.e. the forward traveling X linear polarization waves become the backward traveling Y polarization wave and vice versa. The returning orthogonal waves are split into the upper and lower branches of the optical circuit according to polarization state by the PBS, and if the wave passes through the upper branches in the forward travel, it will return along the lower branches in the backward travel and vice versa. Finally, the two optical waves are interfered at the phase modulator and coupled to the photo detector. Both of the optical waves travel along the upper and lower branch of optical circuit and the X and Y axis of the PM fiber respectively only in reverse order, so the optical circuit is absolutely reciprocal, and the only phase difference is derived tom the non-reciprocal Faraday effect in the sensing fiber coil. To eliminate the Sagnac effect of Y branch loop we make the fiber length of upper branch 2m longer than the lower branch.

Fig 1 FOCS Configuration Based on Y Branch Loop

3. Scale Factor Error Analysis of Y Branch Loop

3.1. Y branch integrated-optics phase modulator model

We apply Jones matrix analysis to the total system, the model of Y branch phase modulator is given in (1)

\[
L_{1,2m} = \sin \beta \begin{bmatrix} 0 & \cos \theta_{12} & \exp[-j(\beta_{TE} L_{12})] & 0 \\ \cos \theta_{12} & 0 & \exp[-j(\beta_{TM} L_{12})] & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

\[
L_{1,3m} = \cos \beta \begin{bmatrix} \cos \theta_{13} & \sin \theta_{13} & \exp[-j(\beta_{TE} L_{13})] & 0 \\ -\sin \theta_{13} & \cos \theta_{13} & 0 & 0 \end{bmatrix}
\]

\[
L_{2,3m} = \cos \beta \begin{bmatrix} \cos \theta_{23} & \sin \theta_{23} & \exp[-j(\beta_{TE} L_{23})] & 0 \\ -\sin \theta_{23} & \cos \theta_{23} & 0 & 0 \end{bmatrix}
\]

Here, \(\varepsilon_v = 10^{-E_v/20}\) is the amplitude extinction ratio of waveguide chip. \(\beta_{TE}, \beta_{TM}\) is propagation constant of TE and TM mode in waveguide chip. \(\beta_{Yx}, \beta_{Yy}\) is propagation constant of fast and slow axis in fiber. \(\theta_{11}, \theta_{12}, \theta_{13}\) are the alignment angles between the birefringence axes of the input and output.
fiber pigtails and the TE-like and TM-like polarization direction of the waveguide. $\Phi_{TE, u}(t)$, $\Phi_{TM, u}(t)$, $\Phi_{TE, d}(t)$, $\Phi_{TM, d}(t)$ are the phase difference modulation of TE and TM mode in upper and lower branch, separately.

Therefore the output interference intensity is written as below in (2).

$$I = \left[ P(1 + d) \sin^2 \beta \cos^2 \beta \cos^2 \theta_{u,2} \cos^2 \theta_{u,1} \cos^2 \theta_{u,1} + P(1 - d) \sin^2 \beta \cos^2 \beta \cos^2 \theta_{d,2} \cos^2 \theta_{d,1} \sin^2 \theta_{d,1} \sin^2 \theta_{d,1} \right] \cos(\Phi_{u} - 4F)$$

(2)

According to Eq. (2)

$$\Phi_{u} = 4F$$

(3)

It can be seen from (2) and (3) that the scale factor is not affected by the alignment angles of the input and output coupling point of Y branch phase modulation. The alignment angle of the input coupling point merely affects the fringe visibility of interference signals because the closed-loop detective technology is adopted.

3.2. PBS model
The model of PBS is given in (4)

$$L_{P, 13 in} = \begin{bmatrix} \exp[-j(\beta_{x}L_{p3})] & 0 & \cos \theta_{p3} & \sin \theta_{p3} \\ 0 & \exp[-j(\beta_{y}L_{p3})] & -\sin \theta_{p3} & \cos \theta_{p3} \\ \exp[-j2\pi n_{e}L_{nt} / \lambda] & 0 & \cos \theta_{p1} & \sin \theta_{p1} \\ 0 & \exp[-j2\pi n_{e}L_{nt} / \lambda] & -\sin \theta_{p1} & \cos \theta_{p1} \end{bmatrix}$$

$$L_{P, 23 in} = \begin{bmatrix} \exp[-j(\beta_{x}L_{p3})] & 0 & \cos \theta_{p3} & \sin \theta_{p3} \\ 0 & \exp[-j(\beta_{y}L_{p3})] & -\sin \theta_{p3} & \cos \theta_{p3} \\ \exp[-j2\pi n_{e}L_{nt} / \lambda] & 0 & \cos \theta_{p1} & \sin \theta_{p1} \\ 0 & \exp[-j2\pi n_{e}L_{nt} / \lambda] & -\sin \theta_{p1} & \cos \theta_{p1} \end{bmatrix}$$

(4)

Here $n_{o}, n_{e}$ is the birefringence of Wollaston prism. $\beta_{x}, \beta_{y}$ is propagation constant of fast and slow axis in fiber. $\theta_{p1}$, $\theta_{p2}$, $\theta_{p3}$ are the alignment angles between the birefringence axes of the input and output fiber pigtails and the axis of Wollaston prism, separately.

The output interference intensity induced by polarization crosstalk of PBS is summarized in (5).

$$I = P \frac{1 + d}{2} \sqrt{(A_{x} + A_{y}) \cos F + A_{y}^2 + (A_{x} - A_{y})^2 \sin^2 4F} \cos \left( \Phi_{u} - \arctan \frac{(A_{x} - A_{y}) \sin 4F}{(A_{x} + A_{y}) \cos F + A_{y}} \right)$$

(5)

Where

$$\begin{aligned}
A_{x} &= \cos^2 \theta_{p1} \sin^2 \theta_{p2} \sin^2 \theta_{p3} \\
A_{y} &= -2 \cos^2 \theta_{p1} \sin^2 \theta_{p2} \sin^2 \theta_{p3} \cos \theta_{p3} \\
A_{z} &= \cos^2 \theta_{p1} \sin^2 \theta_{p2} \cos^2 \theta_{p3}
\end{aligned}$$

(6)

$$\Phi_{s} = \arctan \frac{(A_{x} - A_{y}) \sin 4F}{(A_{x} + A_{y}) \cos 4F + A_{y}}$$

(7)
According to (5) and (7), the scale factor is associated with the alignment angle of output fiber pigtails and the axis of Wollaston prism. Figure 2 shows the normalized scale factor as a function of the Faraday phase shift induced by measured current for various output alignment angle $\theta_{P3}$ of the PBS. To ensure the measurement accuracy within 0.2% from 0 to 100kA, the output alignment angle $\theta_{P3}$ should not exceed $3^\circ$ while the input alignment angle $\theta_{P1}$ and $\theta_{P2}$ is $2^\circ$. The normalized scale factor as a function of the output alignment angle $\theta_{P3}$ of the PBS is shown in Fig. 3. The scale factor increases with the increase of $\theta_{P3}$, as described in Eq. (7). Since the sensors must be accurate to within $\pm0.2\%$ the variation of angle should not exceed from $0.2^\circ$ to $2.5^\circ$ over wide temperature ranges which corresponds to angle $\theta_{P3}$ of $1.8^\circ$ at room temperature.

**Fig 2** The normalized scale factor as a function of Faraday phase shift for various output alignment angles $\theta_{P3}$

**Fig 3** The normalized scale factor as a function of the output alignment angle $\theta_{P3}$ of PBS
4. Experimental Result

Fig. 4 shows experimental results for the normalized sensor scale factor as function of output alignment angle \( \theta_{P3} \) of the PBS. The experimental data were obtained by representing alignment angle by PM fiber splices (Panda fiber) with various offset angles between the principal fiber axes ranging from zero to about 10°. The variation of the scale factor is up to 7.82% over the angle range from 0° to 10°. The influence of the output alignment angle of the PBS on the scale factor is verified experimentally.

![Fig 4 The scale factor error versus output alignment angle \( \theta_{P3} \) of PBS](image)

5. Conclusion

The relationship between the scale factor error of the FOCS and polarization-dependent crosstalk introduced Y branch loop in the system has been theoretically and experimentally investigated. The scale factor is only relevant to the output alignment angle of the PBS in Y branch loop. To ensure the measurement accuracy within ±0.2% from 0 to 100kA, the range of variation of output alignment angle should not exceed from 0.2° to 2.5° over a range from -40°C to 70°C which corresponds to angle 1.8° at room temperature.

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