A Novel Wavelength Demodulation Method Using Twisted High Birefringence Fiber

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Abstract. The mathematical model of twisted high birefringence fiber was established through theoretical analysis. A novel FBG wavelength demodulation method was put forward, by using the twisted high birefringence fiber. The numerical simulation and the experiments were carried out to the system. The standard cosine relationship was observed between the output intensity of polarization analyzer and the twist angle for the signal light with different wavelengths. When the twist angle of the high birefringence fiber is 0 and \( \pi/2 \), the output intensity ratio of the system presents the linear relationship with the wavelength approximately. The experiment shows that system is in agreement very well with theoretical analysis to demodulate quasi-linearly FBG wavelength shift in range of about 10 nm.

1. Introduction
In recent years, the optical fiber grating sensors have achieved great applications in the field of optical sensing [1,2]. It has many advantages, such as its strong interference immunity, simple structure, easy to multipoint multiplex, easy to realize distributed sensing network and so on. Sensing information of fiber Bragg grating is coded by the wavelength. Therefore, the studies in wavelength demodulation technology becomes the key to realize optical fiber grating sensing, which has high sensitivity, low cost, simple operation and suitable for the project application. To date, the domestic and foreign scholars have proposed many demodulation methods, such as matching FBG, tunable filter method, tunable Fabry Perot filter and non-equilibrium Mach-Zehnder interferometer demodulation method [3, 4]. These methods have different strengths and weaknesses. In this paper, a novel FBG reflected wavelength demodulation method was put forward by using twisted high birefringence fiber. The optical properties of twisted high birefringence fiber were investigated through theoretical analysis. The experiments show that the system has a wide demodulation scope for good linear, easily realized.

2. Theoretical analysis
The wavelength demodulation system is composed of the polarization controller, the rotational structure of high birefringence fiber and the polarization analyzer. The reflected light of FBG passing through the polarization controller becomes the linear polarized light. It is launched into a small section of high birefringence fiber. One end of the fiber is fixed; the other end controls the twist angle to rotate the optical fiber by using the stepping motor. The rotation of high birefringence fiber causes that the polarization states of the transmission signal light vary with the different of wavelengths and twist angle. Finally, the polarization states of signal light are detected by the polarization analyzer, and then we can obtain the FBG’s reflected wavelength value.
Assuming the output of the polarization controller is linearly polarized light, the indulged angle between its x-y coordinate system and the fast-slow axis direction of Bi-Hi fiber is angle $\phi$. The signal light transmitting in the High birefringence fiber can be decomposed into two components along the fast and slow axis, and these two components are propagated along the corresponding principal axes. As a result, the signal light before entering into high birefringence fiber is needed to make a coordinate transformation, for making the x-y coordinate axis and the fast-slow axis parallel. The Jones matrix for the coordinate rotation with angle $\phi$ is

$$ R(\phi) = \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \quad (1) $$

When the twist angle of a high birefringence fiber is $\alpha$, $L$ is the length of the twisted region. Its fast-slow axis coordinates will rotate (the twist angle of the fast-slow axis coordinates per unit of length is $\omega=\alpha/L$). Assuming polarized component of the signal light in A is $\begin{bmatrix} E_F \\ E_S \end{bmatrix}$. When the signal transmits $dz$ to B, the twist angle of the fast-slow axis coordinates is $\omega \cdot dz$. Therefore, polarized component in B becomes $\begin{bmatrix} E'_F \\ E'_S \end{bmatrix}$, as shown in figure 1.

![Twisted high birefringence fiber](image)

**Figure 1.** Twisted high birefringence fiber.

The component of polarized light in B can be deduced by

$$ \frac{d}{dz} \begin{bmatrix} E_F \\ E_S \end{bmatrix} = \begin{bmatrix} i\beta & \omega \\ -\omega & -i\beta \end{bmatrix} \begin{bmatrix} E_F \\ E_S \end{bmatrix} \quad (2) $$

Assuming that

$$ A = \begin{bmatrix} i\beta & \omega \\ -\omega & -i\beta \end{bmatrix} = P \Lambda P^{-1} = P \begin{bmatrix} i\gamma(z) & 0 \\ 0 & -i\gamma(z) \end{bmatrix} \cdot P^{-1} $$

$$ P = \begin{pmatrix} \omega & -\omega \\ i(\gamma - \beta) & i(\gamma + \beta) \end{pmatrix} \quad (3) $$

After solving the coupled mode equation, equation (2) can be deduced by imposing the boundary condition $\begin{bmatrix} E_{F0} \\ E_{S0} \end{bmatrix}$ as

$$ \begin{bmatrix} E'_F \\ E'_S \end{bmatrix} = P \cdot e^{\begin{bmatrix} i\gamma(z) & 0 \\ 0 & -i\gamma(z) \end{bmatrix} z} \cdot P^{-1} \begin{bmatrix} E_{F0} \\ E_{S0} \end{bmatrix} $$

$$ = \begin{bmatrix} \cos \gamma(z) - i \frac{\beta \cdot z}{\gamma(z)} \sin \gamma(z) & \omega \cdot \frac{z}{\gamma(z)} \sin \gamma(z) \\ -\omega \cdot \frac{z}{\gamma(z)} \sin \gamma(z) & \cos \gamma(z) + i \frac{\beta \cdot z}{\gamma(z)} \sin \gamma(z) \end{bmatrix} \begin{bmatrix} E_{F0} \\ E_{S0} \end{bmatrix} \quad (4) $$

here, $\gamma(z)=(\omega^2+\beta^2)^{1/2} \cdot z$, $\omega=\alpha/L$. 
This shows that the Jones transformation matrix of the signal light transmitting in the high birefringence fiber can be expressed as

\[
M(\alpha, L) = \begin{bmatrix}
\cos \gamma(L) - i \frac{\beta \cdot L}{\gamma(L)} \sin \gamma(L) & \alpha \frac{\sin \gamma(L)}{\gamma(L)} \\
-\alpha \frac{\sin \gamma(L)}{\gamma(L)} & \cos \gamma(L) + i \frac{\beta \cdot L}{\gamma(L)} \sin \gamma(L)
\end{bmatrix}
\]

(5)

From the above analysis, assuming that the output light of the polarization controller is \( \begin{bmatrix} E_x \\ E_y \end{bmatrix} \) and the output light of the polarization analyzer is \( \begin{bmatrix} E'_x \\ E'_y \end{bmatrix} \) for the system shown in figure 1, we can found that the relationship between them can be expressed as

\[
\begin{bmatrix} E'_x \\ E'_y \end{bmatrix} = P(\theta) \cdot R(-\phi) \cdot R(-\alpha) \cdot M(\alpha, L) \cdot R(\phi) \cdot \begin{bmatrix} E_x \\ E_y \end{bmatrix}
\]

(6)

where \( \phi \) is the included angle of signal light between the x-y coordinate and the fast-slow axis coordinate of high birefringence fiber, \( \alpha \) is the twist angle of high birefringence fiber, \( L \) is the length of the twisted region, \( P(\theta) \) is the Jones matrix of the polarization analyzer and can be described as

\[
P(\theta) = \begin{bmatrix}
\cos^2(\theta) & \cos(\theta)\sin(\theta) \\
\cos(\theta)\sin(\theta) & \sin^2(\theta)
\end{bmatrix}
\]

(7)

where \( \theta \) is the polarizer angle.

When the system parameters value are: \( \phi=0 \), \( L=100\text{mm}, \theta=\pi/4 \). Assuming the input polarized light is \( \begin{bmatrix} 1 \\ 1 \end{bmatrix} \), and the wavelength range is from 1540nm to 1560nm. The relationship between the output intensity of polarization analyzer and the twist angle can be obtained, as shown in figure 2.

![Figure 2. Relationship between the output intensity of polarization Analyzer and twist angle.](image)

Seen from figure 2, we can observe the standard cosine relationship between the output intensity of polarization analyzer and the twist angle for the signal light with different wavelengths. In the case of \( \alpha=0 \), the output intensities decrease with the increase in wavelength. Contrarily in the case of \( \alpha=\pi/2 \), these are illustrated in figure 3. When \( \alpha=0 \) and \( \pi/2 \) the ratio of the two output light intensities is defined as \( \eta=10\log(I_0/I_{90}) \). The wavelength and \( \eta \) present the linear relationship
approximately, as shown in figure 4. Therefore we can obtain the wavelengths of the signal lights through measuring output intensity ratio of the system when \( \alpha = 0 \) and \( \pi / 2 \).

**Figure 3.** Relationship between output intensities and wavelength when \( \alpha = 0 \) and \( \pi / 2 \).

**Figure 4.** Relationship between parameter \( \eta \) and wavelength.

### 3. Experimental results and analysis

Figure 5 shows the wavelength demodulation experiment system based on twisted high birefringence fiber. The light from a broadband source is launched into the FBG sensor through the circulator. The reflected light passing through the high birefringence fiber wavelength demodulation system transmits to the coupler. The signal light is divided into two bunches by the coupler. One is received by the spectrum analyzer; the other passes through the photo detector and then transmits to the computer. Realize the wavelength demodulation by calculating the Bragg wavelength shift.

**Figure 5.** Wavelength demodulation experiment system based on twisted high birefringence fiber.

The beat length of high birefringence fiber applied in this experiment is 3.4mm with 1550nm. The optical spectrum analyzer is EXFOIQS-5250B-Optical Spectrum Analyzer. The power meter is EXFOIQS-1100 with resolution of 0.001 dBm. In the wavelength demodulation system the high birefringence fiber length is 10cm. Its left band is fixed by the fiber holder, and the right band inserts into the spinning disk and is connected with the Grin lens. In order to maintain the twisted high birefringence fiber straight, we put a magnetic basement under the fiber holder and the Grin lens. The high birefringence fiber is pulled straight, and adsorbed on the optical table.

At first, adjust the polarization controller to obtain the maximum value of the output intensities in the experiment. Chang the FBG’s centre wavelength when the spinning disk don’t rotate (that is to say \( \alpha = 0 \)), the outputs of optical spectrum analyzer are shown in figure 6-a. Rotate the spinning disk with \( \pi / 2 \), the output of optical spectrum analyzer is shown in figure 6-b. In the case of different twist angles, output intensities vary with the changes in the Bragg wavelength shifts, as shown in figure 6.
The Bragg wavelength will change when the FBG is subjected to axial strain. We have recorded the experimental data of the parameter $\eta$ from the initial Bragg wavelength $\lambda_B=1543.512\text{nm}$ and every 0.3nm took a record to 1558.212nm, as shown in figure 7. It shows that the linear relevance is 0.9512 when the linear range of experimental curve is approximately 15nm, and the linear relevance is 0.9512 with the linear range from 1544nm to 1554nm. It shows very good linear relations between the parameter $\eta$ and the reflected wavelength of the FBG.

4. Conclusion
This paper has carried out the exhaustive theoretical analysis to the characteristic of the twisted high birefringence fiber. The experimental study was carried on to the FBG wavelength demodulation system using the high birefringence fiber. The experiments show that the system has a wide demodulation scope (the quasi-linear demodulation scope is about 10nm) and steadily performance, easily realized.

References
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