Design and nonlinearity compensation of Fabry-Perot type tunable optical filters for dynamic strain sensing systems*

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The collected spectrum of the fiber Bragg grating (FBG) and the loss of the detected optical power are discussed with respect to the 3-dB bandwidth of a Fabry-Perot (F-P) type tunable optical filter (TOF), respectively. And the optimized parameters of the TOF are obtained consequently. It is demonstrated that the relationship between the transmission wavelength of the TOF and its drive voltage is nonlinear. A new method to compensate the nonlinearity of the TOF is proposed. The linear sweeping of the transmission wavelength of the TOF is achieved through modifying the drive voltage using interpolation algorithm. It is observed that the average error and the maximum error of the transmission wavelength are reduced sharply under linear fit. The dynamic strain sensing is realized by use of a reference FBG and moving averaging algorithm in this system.

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Fiber Bragg gratings (FBGs) have successfully been developed for using in optical fiber communication and sensing fields since 1989[1]. One of the key issues in establishing an optical fiber sensing system based on FBGs is the selection of a suitable wavelength shift detection scheme[2]. Several interrogation systems have been proposed [3-10]. The methods are widely used for interrogating the wavelength shift of FBGs in fiber sensing systems[2][6][11][12]. However, the parameters of the TOF are different in different references, and the nonlinearity of TOF is usually ignored. Little research on the proper design and nonlinearity compensation of the TOF for dynamic strain sensing systems has been performed.

In this paper, the dynamic strain sensing system based on F-P type TOF is described first. Then the optimized 3-dB bandwidth of the TOF is obtained based on the collected spectrum of the FBG and the power loss with respect to the 3-dB bandwidth of the TOF respectively. It is demonstrated that the relationship between the transmission wavelength of the TOF and its drive voltage is nonlinear, which can be compensated by use of interpolation algorithm. Finally dynamic strain sensing is realized using this system.

The schematic diagram of the dynamic strain sensing system based on F-P type TOF is shown in Fig.1. Wavelength-division multiplexing (WDM), time-division multiplexing (TDM) and space-division multiplexing (SDM) technologies are combined within this system simultaneously[13][14].

The two most important parameters of the F-P type TOF are free spectral range (FSR) and 3-dB bandwidth. They are also the key issues in design of the TOF for dynamic strain systems. If the FSR of the TOF is larger than the spectral bandwidth of the broadband source, the quantity of the FBGs is only restricted by the spectral envelop of the broadband source. The FSR of the TOF can be set to 90 nm, which is much larger than the bandwidth of broadband sources in most applications.

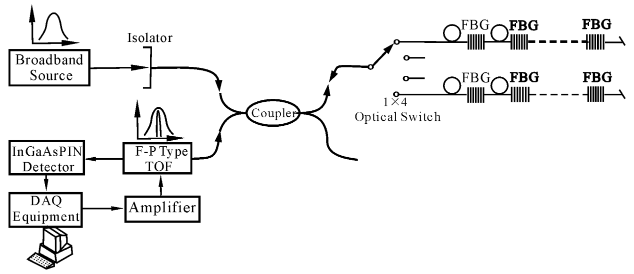

Fig.1 The schematic diagram of the dynamic strain sensing system based on F-P type TOF

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The optimized 3-dB bandwidth of the TOF can be calculated using optical spectrum analysis method. The FBG and the TOF are treated as spectral transfer functions. In Fig.1, the power spectra of the broadband source is $S(\lambda)$, where λ is the wavelength. For the sake of simplicity, the reflective spectra of the FBG and the transmitted spectra of the TOF can be both assumed to take a Gaussian form[11]:

$$G_{jR}(\lambda)=R_{jG}\exp\left(-\frac{4\ln 2(\lambda-\lambda_{jG})^2}{\sigma_{jG}^2}\right), \tag{1}$$

$$F_j(\lambda)=T_{jF}\exp\left(-\frac{4\ln 2(\lambda-\lambda_{jF})^2}{\sigma_{jF}^2}\right), \tag{2}$$

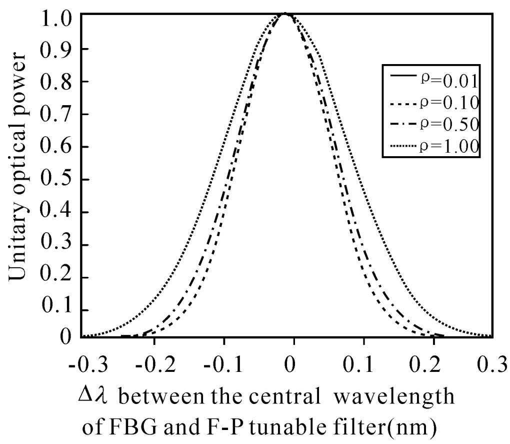
where $G_{jR}(\lambda)$ and $F_j(\lambda)$ are the spectral transfer functions of the FBG and the TOF respectively, R_{jG} and T_{jF} are the peak reflectivity of the FBG and the peak transmitivity of the TOF respectively, λ_{jG} and λ_{jF} are the Bragg wavelength of the FBG and the transmission wavelength of the TOF respectively, σ_{jG} and σ_{jF} are the spectral width of the FBG reflective spectrum and the TOF transmitted spectra respectively. Let ρ denote the ratio of σ_{jF} and σ_{jG},

$$\sigma_{jF}=\rho\sigma_{jG}=\rho\sigma, \tag{3}$$

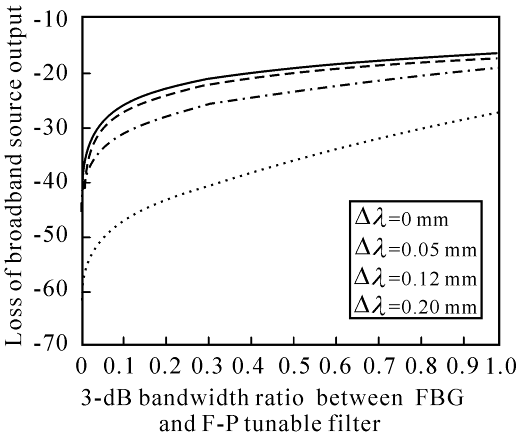
where σ is also treated as the spectral width of the FBG reflective spectrum for simplicity. $S(\lambda)$ is assumed as a constant in the reflective spectra of FBG and the transmitted spectrum of the TOF, because its bandwidth is much larger than that of the others. S is assumed as unit power of the broadband source. Then the optical power detected by the photodetector can be calculated as

$$\begin{aligned}
I &= \int_{-\infty}^{\infty}\frac{1}{4}S(\lambda)G_{jR}(\lambda)F_j(\lambda)\mathrm{d}\lambda = \\
&\int_{\lambda_{jF}-\rho\sigma/2}^{\lambda_{jF}+\rho\sigma/2}\frac{1}{4}SG_{jR}(\lambda)F_j(\lambda)\mathrm{d}\lambda = \\
&\frac{1}{8}SR_{iG}T_{iF}\left(\frac{\sqrt{\pi}\rho\sigma}{\sqrt{4\ln 2}\sqrt{1+\rho^2}}\right)\exp\left(-\frac{4\ln 2(\lambda_{jG}-\lambda_{jF})^2}{(1+\rho^2)\sigma^2}\right)\mathrm{erf}\left(\frac{\sqrt{4\ln 2}\left[(\lambda-\lambda_{jF})+\rho^2(\lambda-\lambda_{jG})\right]}{\rho\sqrt{1+\rho^2}\sigma}\right)\Bigg|_{\lambda_{jF}-\rho\sigma/2}^{\lambda_{jF}+\rho\sigma/2} = \\
&\frac{1}{8}SR_{iG}T_{iF}\left(\frac{\sqrt{\pi}\rho\sigma}{\sqrt{4\ln 2}\sqrt{1+\rho^2}}\right)\exp\left(-\frac{4\ln 2(\lambda_{jF}-\lambda_{jG})^2}{(1+\rho^2)\sigma^2}\right)\times \\
&\left[\mathrm{erf}\left(\frac{\sqrt{4\ln 2}\left[\rho\sigma/2+\rho^2(\lambda_{jF}-\lambda_{jG}+\rho\sigma/2)\right]}{\rho\sqrt{1+\rho^2}\sigma}\right)-\mathrm{erf}\left(\frac{\sqrt{4\ln 2}\left[-\rho\sigma/2+\rho^2(\lambda_{jF}-\lambda_{jG}-\rho\sigma/2)\right]}{\rho\sqrt{1+\rho^2}\sigma}\right)\right].
\end{aligned} \tag{4}$$

From eq. (4), it is obvious that the detected optical power I is the function of the wavelength difference $\Delta\lambda$ between λ_{jG} and λ_{jF} ($\Delta\lambda=|\lambda_{iG}-\lambda_{iF}|$) and ρ. When ρ is a constant, the normalized detected optical power is only the function of $\Delta\lambda$. The collected spectrum of FBG is shown in Fig.2 (a). The original bandwidth of the FBG is expanded by $\sqrt{1+\rho^2}$ in the collected spectra. The loss between the detected optical power and the broadband source output is shown in Fig.2(b). When ρ is large enough, I will approach a constant and increase very slowly. When ρ is reduced less than a value, I will decrease sharply. When the ratio ρ is set to 0.1, the peak detected optical power will be 26 dB less than the output of the broadband source. If the ratio ρ is decreased continuously, I will be too small, and then the signal noise ratio (SNR) of the detected optical power will be too low. From the analysis above, the optimized ratio ρ should be set to 0.1. Thus the collected spectra of FBG are close to the practical one, and the detected optical power is large enough to have good SNR. Additionally, the typical 3-dB bandwidth of FBG is 150 pm[1]. So the optimized 3-dB bandwidth of the TOF for the dynamic strain sensing systems is 15 pm.



(a) Relationship between I and $\Delta\lambda$



(b) Relationship between I and ρ

Fig.2 The detected optical power as the function of $\Delta\lambda$ (a) and ρ (b)

The relationship between the transmission wavelength of the F-P type TOF and its drive voltage is nonlinear due to the intrinsic nonlinearity between the displacement and voltage of the piezoelectric actuator in the TOF. Usually it is assumed that there is a linear relationship, or only part of the FSR is chosen to meet the linear response assumption if obvious nonlinearity does exit[2].

The nonlinear relationship can be measured using tunable laser with 1 pm resolution. When the drive voltage is varied linearly from 0 V to 18 V, the relationship between them is shown in Fig.3. Under two-order polynomial fit, it is defined as

$$\lambda_T = -0.048U^2 - 4.800U + 1627.332 , \tag{5}$$

where λ_T is the transmission wavelength of the TOF, U is the drive voltage. If it is assumed as linearity, there will be large error beyond several nanometers.

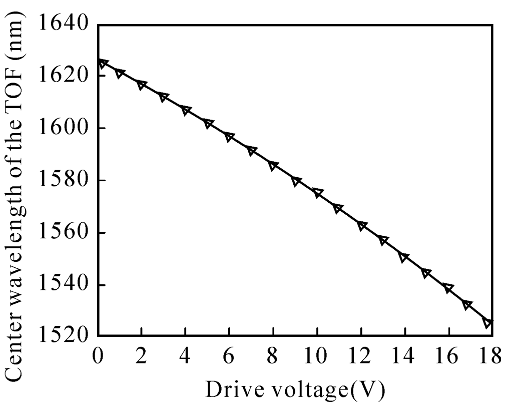


Fig.3 Relationship between the transmission wavelength of the TOF and its drive voltage

By use of interpolating algorithm, the compensated drive voltage of the TOF can be obtained. Under linear fit, the experiment data are used to calculate the relationship between the transmission wavelength of the TOF and the drive voltage as

$$\lambda_i = \lambda(v_i) , \tag{6}$$

where $\lambda_i \in \{\lambda_0, \lambda_1, \cdots \lambda_{k-1}\}$(k is the size of the experiment data) is the transmission wavelength of the TOF, $v_i \in \{v_0, v_1, \cdots v_{k-1}\}$is the corresponding drive voltage, and $\lambda(\bullet)$ is a linear function which is the aim to be obtained. On the fitting curve described by eq.(5), a set of wavelength $\lambda_i' \in \{\lambda_0', \lambda_1', \cdots \lambda_{k-1}'\}$is selected to be the nearest to λ_i, and the corresponding drive voltage $v_i' \in \{v_0', v_1', \cdots v_{k-1}'\}$is calculated according to eq.(5). The compensated drive voltage list of the TOF $u_j \in \{u_0, u_1, \cdots u_{n-1}\}$ (n is the size of the compensated drive voltage list) can be obtained using spline interpolation algorithm and $\{v_i'\}$. When the index j falls within the closed interval $[in/k , (i+1)n/k]$, u_j can be calculated as

$$u_j = A \times v_i' + B \times v_{i+1}' + C \times (v_i')'' + D \times (v_{i+1}')'' , \tag{7}$$

where

$$\begin{cases} A = i + 1 - \dfrac{j}{n}k \\ B = 1 - A \\ C = \dfrac{1}{6k^2}\left(A^3 - A\right) \\ D = \dfrac{1}{6k^2}\left(B^3 - B\right) , \end{cases} \tag{8}$$

and $(v_i')''$ is the second derivative of the cubic spline function obtained by $\{v_i'\}$.

By using interpolation algorithm, the compensated drive voltage list of the TOF is calculated between 7.2 V and 18.0 V. The transmission wavelengths of the TOF before and after compensation are measured using tunable laser. Before compensation, the curve of the TOF transmission wavelength is shown in Fig.4(a). Under linear fit, the average error and the maximum error are 0.250 and 1.201 respectively. After compensation, the curve of the TOF transmission wavelength is shown in Fig.4(b). Under linear fit, the average error and the maximum error are 0.009 and 0.229 respectively. By use of interpolation algorithm, the average error and the maximum error of the transmission wavelength are reduced by 96.4% and 80.9% respectively under linear fit. The average error is below 10 pm. This is very significant for spectroscopy and wavelength interrogation.

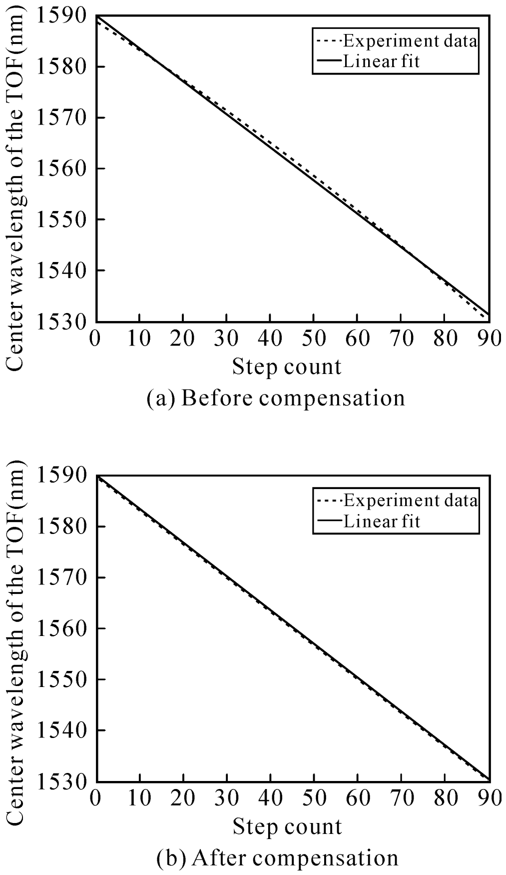


Fig. 4 Transmission wavelength of the TOF

The dynamic strain sensing system based on F-P type TOF described in Fig.1 can be used to realize dynamic strain sensing. Four FBGs are placed along a single-mode fiber, of which the Bragg wavelengths are within 1540 nm and 1560 nm without overlapping. When the compensated drive voltage is applied on the TOF, the spectrum of the FBGs collected by the system is shown in Fig.5. One of them is assumed to be the reference FBG, which is used to eliminate noise and error in the system. And to eliminate haphazard error, moving averaging algorithm is used to analyze the experiment data. Eight data points are used to calculate one strain value in this algorithm.

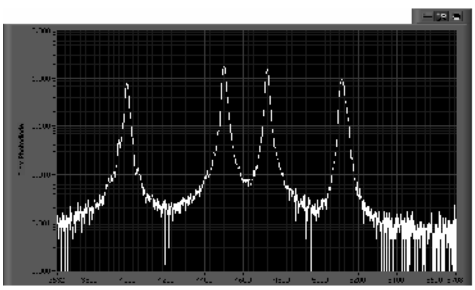


Fig.5 Spectrum of gratings collected by dynamic strain sensing system

Using a reference FBG and moving averaging algorithm, the demodulation strain values of the other three FBGs are calculated. When all of them are in free state, the deviations of the strain values for 800 time measurements are shown in Tab.1. They are all below 3 με. So the dynamic strain sensing sensitivity of this system is blow 3 με .

Tab.1 Demodulation strain of FBGs without stress (με)

	FBG1	FBG2	FBG3
Deviation	2.3	2.0	2.7

When the FBG is modulated by the stress along the direction of the fiber, the relationship between the stress and demodulation strain is shown in Fig.6(a). When the stress is decreased, the relationship between the stress and demodulation strain is shown in Fig.6(b). Under linear fit, the slopes of the curves in Fig.6(a) and Fig.6(b) are -0.0161 με/g and

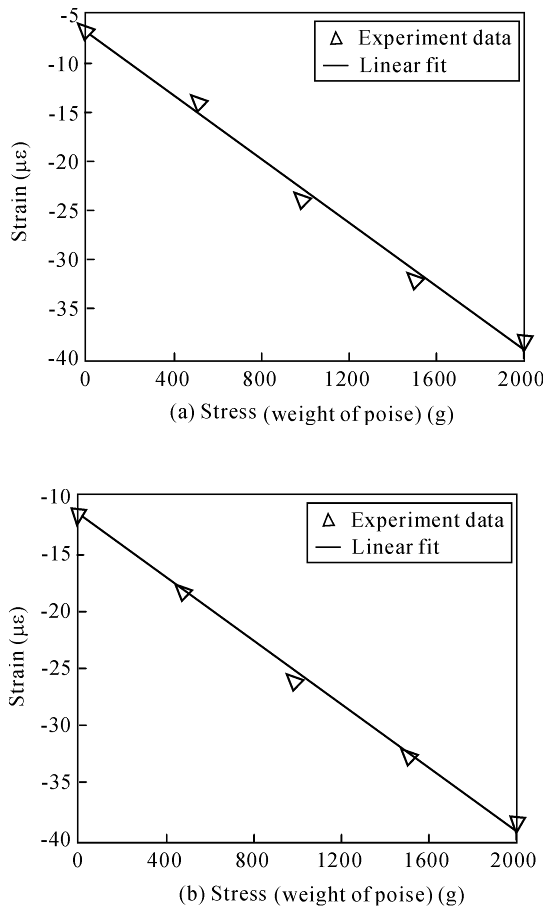


Fig.6 Relationship between demodulated strain and stress

-0.0135 με/g respectively. The latter is less than the former because of the strain remaining in the FBG when the stress is decreased.

On the other hand, according to elasticity mechanics theory, strain can be calculated as

$$E_p \times \Delta\varepsilon = \frac{F}{S} \ , \tag{9}$$

where $\Delta\varepsilon$ is the strain value, F is the positive stress along the axis direction, S is the effective area of stress, E_p is Young' s modulus. In this experiment, the maximum of stress is $F = 2 \times 9.8\ N$, the effective area of stress is $S = 2.4 \times 10^{-6}\ m^2$, and Young' s modulus is $E_p = 2.06 \times 10^{11}\ P_a$. So the maximum of the theoretical strain value is 39.6 $\mu\varepsilon$. And the maximum of the practical strain value demodulated by the system is 37.9 $\mu\varepsilon$. The error between them is below 5%.

In summary the optimized parameters of the TOF are FSR of 90 nm and 3-dB bandwidth of 15 pm. The nonlinearity between the transmission wavelength of TOF and its drive voltage is compensated using interpolation algorithm. Under linear fit, the average error and the maximum error of the transmission wavelength are reduced by 96.4% and 80.9% respectively after compensation. And the average error is below 10 pm after compensation, and there is only less than 0.4% variation over 60 nm. After compensation, the strain sensitivity of the system is below 3 $\mu\varepsilon$ by use of a reference FBG and moving averaging algorithm. The error between the practical strain value demodulated by the system and the theoretical value is below 5%.

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