

Chapter 23

Experimental Research on Fiber Bragg Gratings High-Speed Wavelength Demodulation Method

Lijun Meng and Fang Zhu

Abstract In order to detect weak signals of high frequency with fiber Bragg gratings (FBG), the FBG demodulation system based on matched filter is established. First, the output expression and maximum wavelength sensitivity as well as the main way to improve its demodulation property were analyzed in detail. On these bases, the FBG-matched filter demodulation device was set up to measure the vibration signals of an ultrasonic cleaning tank. A SLED broadband light source was used to provide light energy; an amplified InGaAs photo detector was used to measure the optical power; a digital oscilloscope was employed to display and record the output signals. The experiment results showed that ultrasonic signal with main frequency of 43.945 kHz and strain range of about $55\mu\epsilon$ has been achieved.

Keywords FBG · Matched filtering demodulation · Resolution · Ultrasonic wave

23.1 Introduction

Fiber Bragg gratings (FBG) is a new kind of optical passive component which is developing most rapidly in recent years. It has been used in many fields such as civil engineering, aerospace, shipping, electric power industry, etc [1]. FBG is used to measure the external parameters such as stress, temperature, displacement, vibration, and acceleration according to its reflection wavelength change. In practical application, it is one of the key technologies to obtain the reflection wavelength change quickly and accurately.

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The main FBG wavelength demodulation methods are interference method, filtering method, and chirped grating detection method [2–7]. However, the universal shortcomings for existing wavelength demodulation methods are relatively low demodulation frequency and not high demodulation resolution. In some FBG detection fields that require higher demodulation speed and resolution such as the structural damage detection with ultrasonic wave, high-frequency blade flutter measurement, submarine hydroacoustic detection, petroleum and natural gas exploring, and seismic geophone testing, ordinary FBG demodulation system cannot meet the requirements.

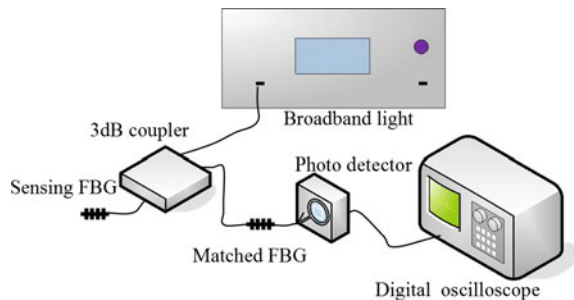
As the traditional FBG demodulation technology is relatively mature, it can increase the demodulation frequency and resolution by improving the appropriate equipment parameters. In this paper, the principle and the output characteristics of the transmission-matched filter demodulation technology were analyzed first. Based on this, the demodulation performance of this system was improved by increasing the light source intensity and the detector response. Finally, a matched filter wavelength demodulation system was established and applied to detect the vibration signal of ultrasonic cleaning tank. In the experiment, it measured the ultrasonic signal with the main frequency of 43.945 kHz successfully.

23.2 Demodulation Principle of Matched Filter Method

FBG-matched filter demodulation systems based on broadband light source are divided into two types: reflection type and transmission type. Owing to the relatively large S/N (Signal-to-noise ration) of the reflection one and the high luminous energy utility rate of the transmission type, we mainly analyzed the transmission type-matched filter demodulation method in this paper.

Figure 23.1 shows the structure of matched filter demodulation system for transmission type. The sensing FBGs were joined to a 3 dB coupler, and then the 3 dB coupler was connected to two parts: one to a broadband light source; another one first to a matched FBG, and then was linked to a photodetector which converted the optical power signal into electrical signals; finally, the electrical signals were

Fig. 23.1 Structure of matched transmission system based on broadband light source



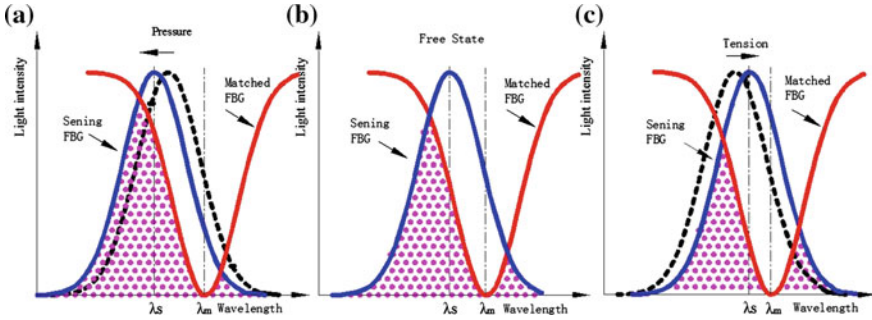


Fig. 23.2 Demodulation principle of matched transmission system based on broadband light source

displayed on the digital oscilloscope or collected by a data acquisition card for computer processing.

The demodulation principle is shown in Fig. 23.2 if that the initial wavelength of sensing FBG is slightly shorter than the wavelength of matched FBG. When the sensing FBG sustains tension, its center wavelength will increase compared to the initial state, so as to reduce the sectional area (shaded area) formed by the spectral lines of sensing FBG and matched FBG, as well as horizontal ordinate; in other words, the light power reaching photo detector is reduced. On the other hand, if the sensing FBG bears pressure, its wavelength will decrease contrasted with the initial state, so the corresponding sectional area (shaded area) expands, which means the luminous power arriving at photo detector is increased. The center wavelength change of the FBG can be achieved by detecting the output signal change of the photo detector. The demodulation principle is similar to this, if the initial wavelength of sensing FBG is slightly longer than the wavelength of matched fiber grating.

23.3 Demodulation Performance Analysis

According to the reference documentation [8] which gave the analysis about the output power spectrum curve of the transmission type-matched filter demodulation system, the output voltage of this system is obtained:

$$U_T = KIA_1A_2R_sR_m \frac{\sqrt{\pi}}{2\sqrt{\ln 2}} \Delta\lambda_s \cdot \left\{ 1 - \frac{\Delta\lambda_m}{(\Delta\lambda_s^2 + \Delta\lambda_m^2)^{\frac{1}{2}}} \times \exp[-4 \ln 2 \cdot \frac{(\lambda_s - \lambda_m)^2}{\Delta\lambda_s^2 + \Delta\lambda_m^2}] \right\} \tag{23.1}$$

where K is the luminous energy utility rate of the coupler. A 3 dB optical coupler was used in the system, so $K = 1/4$, if there was no light loss in the transmission

process; I is the incident light intensity of the broadband light source at its center wavelength; A_1 is the transimpedance gain for the photo detector; A_2 is the voltage current conversion factor for the photo detector; R_s , λ_s , $\Delta\lambda_s$ are the sensing FBG reflectivity at its center wavelength, center wavelength, and full width at half maximum (FWHM), respectively; R_m , λ_m , $\Delta\lambda_m$ are the matched FBG reflectivity at its center wavelength, center wavelength, and FWHM separately.

Wavelength measurement resolution can be considered as the wavelength change per unit voltage output, so according to Formula (23.1) and the reference [9], the maximum wavelength measurement resolution of this system is

$$\begin{aligned}\delta\lambda &= \frac{\delta U_T}{(dU_T/d\lambda_s)T} \\ &= \sqrt{\frac{e}{2\pi TKIA_1A_2R_sR_m}} \frac{\delta U_1}{|\Delta\lambda_s|\Delta\lambda_m} \frac{|\Delta\lambda_s^2 + |\Delta\lambda_m^2}{|\Delta\lambda_s|\Delta\lambda_m}\end{aligned}\quad (23.2)$$

where T is the normalized amplitude of the signal.

From the demodulation system structure shown in Fig. 23.1, the frequency response characteristic of the photoelectric detector needs to be improved for a higher demodulation speed. The main materials for the photo detector are InSb, HgCdTe, PtSi, and InGaAs/InP presently. InGaAs/InP has the advantages of direct band gap, room temperature operation, and high purity, and the photodiodes made of this material have a very low dark current and noise. As a result, it is commonly used in the photoelectric detection device [10].

The electrical signal directly converted from the optical signal reaching photoelectric is very weak, and it is easy to be submerged in the noise, so it is necessary to design the corresponding preamplifier circuit. The photoelectric detector preamplifier circuit improves the photoelectric conversion sensitivity while decreases the frequency response of the photoelectric conversion.

In addition, from Formula (23.2), the wavelength measurement resolution of the demodulation system is influenced by the output voltage resolution, the light utilization rate of the system, transimpedance gain A_1 , voltage current conversion factor A_2 , the optical intensity, and the FBG peak reflectivity. So the main methods to improve the system resolution are as follows: choose a broadband light source of high power, select FBGs with high reflectivity, and improve the transimpedance gain and voltage current conversion factor of the optical detector. Improving the output power of the light source and the voltage current conversion coefficient of the photo detector are the effective measures in practice.

According to the above analysis, in order to improve the demodulation speed and resolution of the matched filter demodulation system, the broadband light with high power was chosen to increase light energy, and the high bandwidth InGaAs photodiode was selected as a photo detector in this paper.

23.4 Experimental Studies

A matched filter demodulation system was constructed and used to measure the vibration signal of ultrasonic cleaning tank in this paper, and the experimental configuration is shown in Fig. 23.3. A piezoelectric ceramic plate was pasted on the bottom center of the tank's downward surface, and the piezoelectric ceramic was subjected to a sinusoidal alternating current with amplitude of 220 V and frequency of 43 kHz. A sensing FBG was glued at the bottom upper surface of the ultrasonic cleaning tank, 4 cm away from its bottom center to measure the vibration signal of the ultrasonic cleaning tank. The parameters of the sensing FBG were as follows: initial wavelength $\lambda_s = 1308.791$ nm, FWHM $\Delta\lambda_s = 0.485$ nm, reflectivity $R_s = 0.9$, and FBG length was 3 mm. Matched FBG was fixed on a flat paper board, and its main parameters were $\lambda_m = 1308.890$ nm, FWHM $\Delta\lambda_m = 0.485$ nm, reflectivity $R_m = 0.9$, and FBG length was 3 mm. In the test process, the paper board was kept in static state and was not affected by external force.

The broadband light source used in the experiment was an output power-adjusted SLED light made by OPEAK, with a center wavelength of 1322.8 nm and FWHM of 48.5 nm. During the test, the output power of SLED light source was set to 9 mW, and its output light intensity was $I = 0.1743$ mW/nm based on the literature [8]. The InGaAs photodiode with an adjustable gain was selected as a photo detector (Thorlabs-PDA10CS). In the experiment, the photo detector gain was set to 30 dB, with the bandwidth of 775 kHz, noise equivalent power of $1.25e-12$ W/ $\sqrt{\text{Hz}}$, which met the frequency requirements of ultrasonic measurement. Transimpedance gain A_1 and voltage current conversion factor A_2 for the photo detector were $A_1 = 0.913$ A/W and $A_2 = 2.38e4$ V/A, respectively. The digital oscilloscope (DS1102E RIGOL) was used to display the signal, its bandwidth was 100 MHz, the real-time sampling rate was 1GSa/s, and the output voltage resolution δU_1 was 1 mV.

It can be known from the demodulation system structure that the demodulation speed of the system can reach 775 kHz. The optimal wavelength resolution of the system was 2.4 pm in theory according to Formula (23.2). The theoretical output

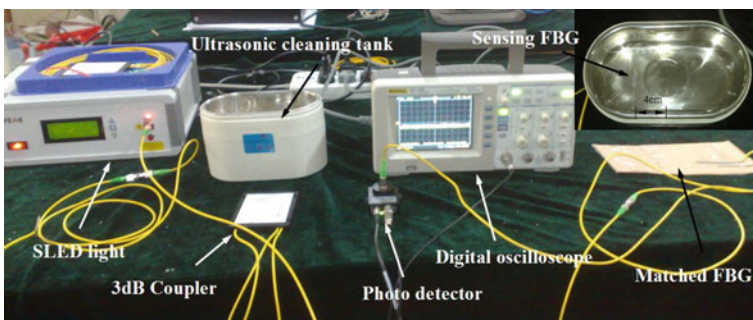


Fig. 23.3 Experimental setup of matched filter demodulation system

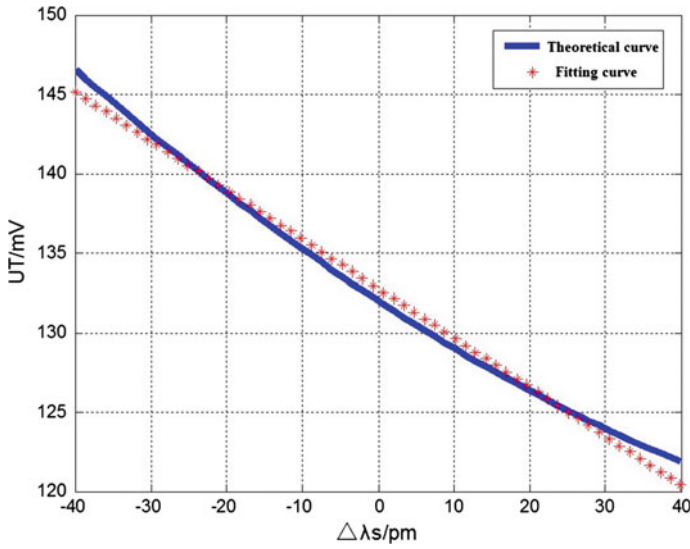


Fig. 23.4 Output characteristic of matched filter demodulation system

characteristic curve is shown in Fig. 23.4. It can be seen that the output voltage signal had good linear relationship with the center wavelength when sensing FBG wavelength change was relatively small. The sensitivity of the system was 0.309 mV/pm, and the system linearity was 0.94 when the measurement range was 40 pm.

The vibration signal of the ultrasonic cleaning tank measured by the demodulation system is shown in Fig. 23.5, where the figure (a) was the time-domain signals of the digital oscilloscope, and the figure (b) was the frequency signal obtained by FFT transform. It can be seen from Fig. 23.5 that the ultrasonic signal was approximately sinusoidal signal, with the main frequency of 43.945 kHz and the peak value of 17 mV. According to preceding analysis about the system sensitivity, the center wavelength change range of the sensing FBG was

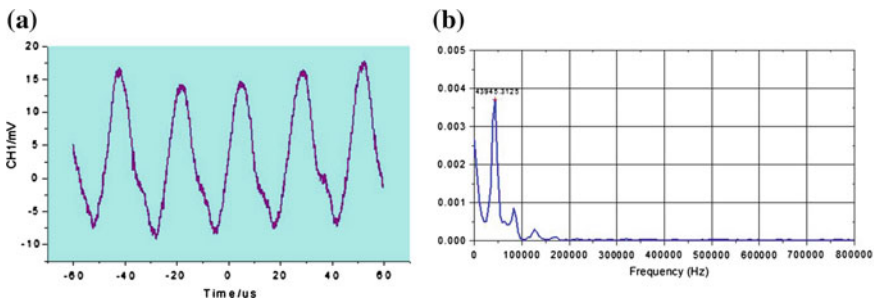


Fig. 23.5 Ultrasonic wave-cleaning tank signals detected by the demodulation system. a Time domain signal. b FFT signal

17/0.309 = 55.0162 pm. Due to the high ultrasonic vibration frequency, the temperature influence on the FBG wavelength change measurement can be ignored, so the strain measurement sensitivity of the FBG was about 1 pm/ $\mu\epsilon$. It can be inferred that strain range during ultrasonic cleaning tank vibration was about 55 $\mu\epsilon$.

23.5 Summary

In this paper, the working principle, output characteristic, and measurement resolution of FBG-matched filter demodulation system were analyzed, and the main approaches to improve the demodulation speed and sensitivity were discussed. The testing equipments of the matched filter demodulation system were built, and they were used to measure the vibration signal of 43.945 kHz about an ultrasonic cleaning tank. The results showed that the system had high demodulation speed and good wavelength resolution, which can meet the need of high-frequency weak signal measurement.

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References

1. Lin J, Wang W, Wang X (2004) Study of application and evolution of fiber grating sensor technique. *J Dalian Univ Technol* 44(6):931–936 (in Chinese)
2. Kersey AD, Berkoff TA, Morey WW (1992) High resolution fiber-grating based strain sensor with interferometric wavelength-shift detection. *Electron Lett* 28(03):236–238
3. Liu B, Sun G et al (2005) Application for high birefringence fiber sagnac loop mirror filter of fiber bragg grating sensing system biomolecular interactions. *Acta Scientiarum Naturalium (Universitatis Nankaiensis)* 38(05):9–12 (in Chinese)
4. Ferreira LA (1997) Pseudoheterodyne demodulation technique for fiber Bragg grating sensors using two matched gratings. *IEEE Photonics Technol Lett* 9(4):487–489
5. Davis MA (1995) Matched-filter interrogation technique for fiber Bragg gratings array. *Electron Lett* 31(10):822–823
6. Seim J, Schulz W, Udd E et al (1998) Low cost, high speed fiber optic grating demodulation system for monitoring composite structures. *Proc SPIE* 3326:390–395
7. Wang H, Zhang J, Qiao X, et al (2007) Prospect of research for signal demodulation in fiber Bragg grating sensing system. *Semicond Technol* 32(03):188–192 (in Chinese)
8. Lobo AB, Ferreira LA, Santos JL et al (1997) Analysis of the reflective-matched fiber Bragg grating sensing interrogation scheme. *Appl Opt* 36(7):934–939
9. Liu Y, Liu Z, Guo Z, Dong X (2001) Theoretical and experimental researches on tunable filtering detection technique of fiber grating senso. *Acta Optica Sinica* 21(1):88–92 (in Chinese)
10. Li T, Wang Y, Li YF et al (2010) Investigation on dark current and low frequency noise of mesa type InGaAs infrared detector. *J Optoelectron Laser* 21(4):500–503 (in Chinese)