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基于光纤布拉格光栅和压电转换器的电功率传感器

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摘要:针对传统功率计测量电功率存在线圈电感、电容与金属部分的涡流感应等限制,本文基于布拉格光纤光栅与压电转换器设计了电功率传感器来测量实功率与虚功率。将布拉格光纤光栅粘贴于压电转换器上,构建了动态应变模拟装置。负载电压与负载电流的乘积形成的等效电压施加在压电转换器上使布拉格光纤光栅动态变化,由此测量光栅动态变化所造成的波长改变量即可得到等效负载功率。相位检测电路用于测量负载电压与负载电流的相位差,由该相位差即可求得功率因数。所研究的传感器可以取代传统功率计用于实功率和虚功率的测量。

关键词:电功率传感器;实功率;虚功率;光纤布拉格光栅;压电转换器

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Electrical power sensor based on fiber Bragg grating and piezo-electric transducer

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Abstract: The measurement of power by conventional meters has some limitations due to the inductance and capacitance of coils and the eddy current induction in the metal parts of the meters. Optical fiber gratings are currently being used as sensors for a number of physical quantities such as temperature, strain and pressure; other quantities, such as current and electrical power measurements can be detected by fiber gratings using appropriate transducers. This paper demonstrates an optical fiber sensor using a Fiber Bragg Grating (FBG) and a piezo-electrical transducer (PZT) to measure real and reactive powers. Mounting an FBG on a PZT bar, a dynamic strain simulator is constructed. The voltage equivalent to the product of load voltage and load current applied on PZT is converted to the dynamic variation of the FBG Bragg wavelength. The load power will be achieved by measuring the changing value of the wavelength. A phase detector circuit is used to measure the phase angle between voltage and current signals. The power factor can be obtained from the phase angle. Thus, the sensor

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can be used to measure real and reactive powers without the use of a traditional power meter.

Key words: electrical power sensor; real power; reactive power; Fiber Bragg Grating (FBG); piezoelectric transducer

1 Introduction

Power measurement using traditional power meters is the most efficient and most accurate when rms and real power, as well as their dependent quantities such as reactive power and power factor, are concerned^[1]. Electrical power is the key to industrial progress, and efficient power management ensures it. To achieve this, the accurate measurement of power is very important. The measurement of power by conventional meters has some limitations due to the inductance and capacitance of coils and the eddy current induction in the metal parts of the meters^[2].

Optical fiber gratings are currently being used as sensors for a number of physical quantities such as temperature, strain and pressure^[3-4]; other quantities, such as current and electric power measurements can be detected by fiber gratings using appropriate transducers^[5-6]. In particular, a fiber Bragg grating (FBG) has been used to simultaneously measure stress and temperature^[7-11]. The FBG is proposed in this paper to measure the apparent power of AC power.

In this paper, we demonstrate a new approach to power measurement. The relationship between the electrostrictive characteristic of PZT and the driving voltage is linear. When applying voltage to the PZT, the material will distort, and the Bragg wavelength of the FBG attached to the surface of the PZT will also change. The voltage measurement produced by load power is deduced by measuring the changing value of the wavelength.

The advent of low-cost microcontrollers enables the development of a cost-effective phase detector circuit. This paper presents a totally e-

lectronic phase detector circuit to measure the phase angle between the current waveform and the voltage waveform based on Microchip Technology Inc. PIC family of microcontrollers^[12]. A four digit display is used to show the phase angle between voltage and current or the system frequency. The real power and reactive power can be computed by the apparent power and the phase angle. Thus, the proposed sensor can be used to measure real and reactive powers and overcome some of the disadvantages of traditional power meters.

2 Principles

A FBG is composed of periodic longitudinal changes of the refractive index that are formed by the exposure to an intense UV interference pattern in the core of an optical fiber. If a broadband light is put into the FBG sensor, it reflects only a particular wavelength component, called the Bragg wavelength. The Bragg condition is expressed as

$$\lambda_B = 2n_e\Lambda, \quad (1)$$

where λ_B is the Bragg wavelength of the FBG, n_e is the effective refractive index of the fiber core and Λ is the grating period. The Bragg wavelength, which is determined by the Bragg condition, is reflected at the Bragg grating all other wavelengths pass through it. If we introduce different Bragg wavelengths along a single strand of optical fiber, strain data can be measured at several positions.

The Bragg wavelength is a function of the refractive index of the fiber core and the grating period. If the grating is exposed to an external perturbation, such as strain and temperature, the Bragg wavelength change. By measuring the wavelength change accurately, the physical

properties can be measured. The shift of a Bragg wavelength due to strain and temperature can be expressed as

$$\Delta\lambda_B = \lambda_B [(\alpha_f + \xi_f)\Delta T + (1 - p_e)\epsilon] , \quad (2)$$

$$p_e = \left(\frac{n_e^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})] . \quad (3)$$

where α_f is the coefficient of thermal expansion, ξ_f is the thermo-optic coefficient, and p_e is the strain-optic coefficient of an optical fiber. In Eq. (3), ν is the Poisson's ratio, and p_{11} and p_{12} are components of the strain-optic tensor^[13].

The PZT is a material with a positive piezoelectric effect, in which its charge and strain are proportional. There also exists a negative piezoelectric effect, where exerting an E (electric field) on the PZT material, strain will be produced, which is proportional to E , and can be written as

$$S = dE , \quad (4)$$

where d is piezoelectric strain constant, the sign of S depends on the polarization direction of the sample material.

When exerting E on the PZT, the strain in the polarized direction that can be expressed as

$$\epsilon_e = d_{33}U/M , \quad (5)$$

where d_{33} is the strain coefficient, M is the distance between the electrodes and U is the drive voltage^[14-15].

Apparent power in an electric circuit is the product of voltage and current for AC power measurement, so any meter designed to measure apparent power must account for both of these variables. A special meter movement designed especially for apparent power measurement is called the dynamometer movement, as shown in Fig. 1. The horizontal coil of wire measures load current and the vertical coil measures load voltage.

All circuit connections are similar to a traditional power meter (Fig. 1), and the equivalent voltage produced by both load current i and load voltage v are applied to the PZT. The peak value of the load current and load voltage are measured

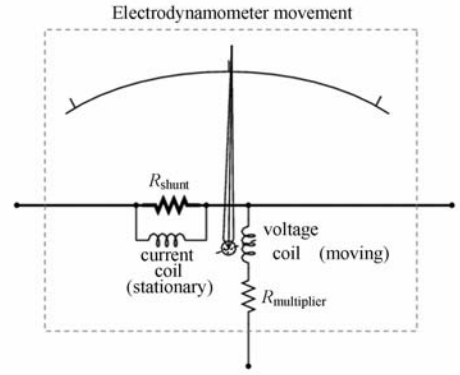


Fig. 1 Structure of traditional power meter

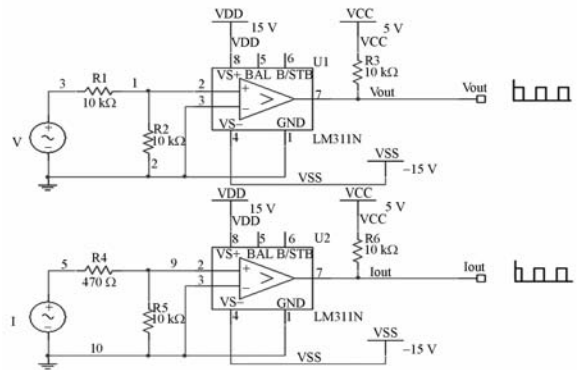


Fig. 2 Zero-crossing detector circuits

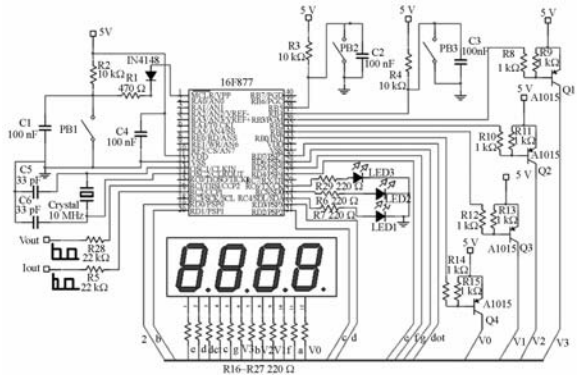


Fig. 3 PIC 16F877 microcontroller

through the peak detector circuits. Each circuit consists of a diode and a capacitor. The peak value of apparent power can be measured through this device.

The phase detector circuit is used to measure power factor. The voltage and current waveforms have been converted to a train of rectangular pulses using zero-crossing detector circuits, as shown in Fig. 2. The phase angle between

voltage and current signals can be determined by the PIC 16F877 microcontroller through the train of rectangular pulses, as shown in Fig. 3. The real power can be computed from Eq. (6) and reactive power can be computed from Eq. (7).

$$P = VI \cos(\theta_v - \theta_i), \quad (6)$$

$$Q = VI \sin(\theta_v - \theta_i), \quad (7)$$

where θ_v is the phase angle of the voltage and θ_i is the phase angle of the current.

3 Experiments

3.1 Measurement of apparent power

The PZT of PSt 150/5x5/20 produced by the PI-EZOMECHANIK company was used in this experiment. The FBG was written into a hydrogen-loaded single-mode fiber by using a phase mask writing technique using a KrF excimer laser (248 nm). The FBG is 15 mm in length with a Bragg wavelength of 1 546.384 nm. The FBG is attached on the surface of PZT in the polarization direction as shown in Fig. 4.

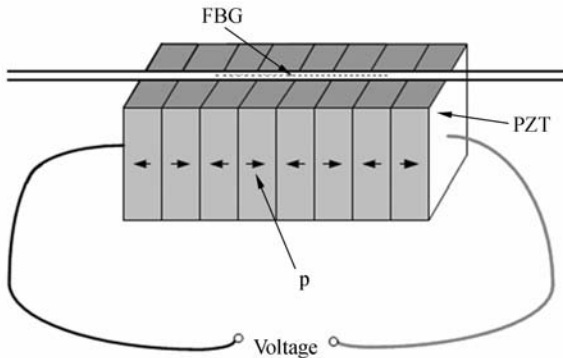


Fig. 4 Diagram of sensor

The principle of FBG voltage measurement can only be obtained if the PZT is attached to the FBG effectively. With the electrostrictive effect of PZT, the FBG can be modulated. Since the output of the voltage converter is proportional to the applied apparent power of AC circuit, the magnitude of the apparent power can also be determined. The experimental setup is as shown in Fig. 5. Measurements of apparent power for dif-

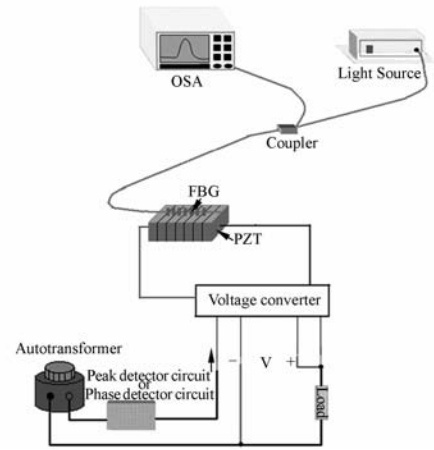
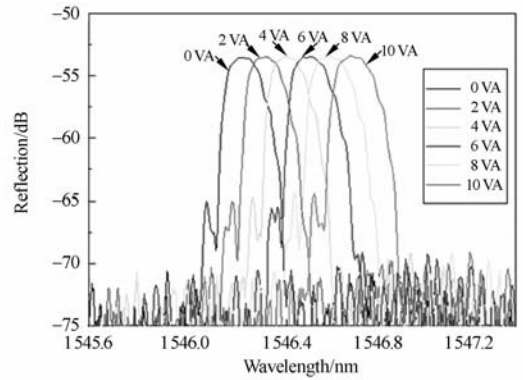
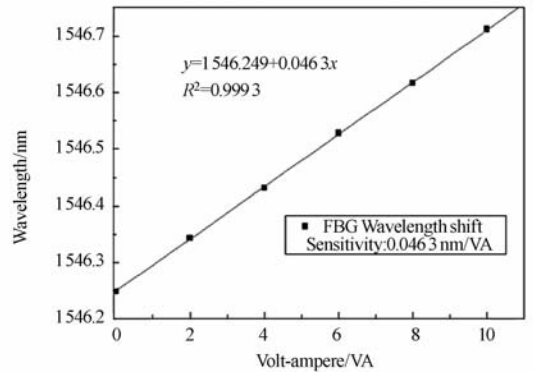


Fig. 5 Experimental setup



(a)

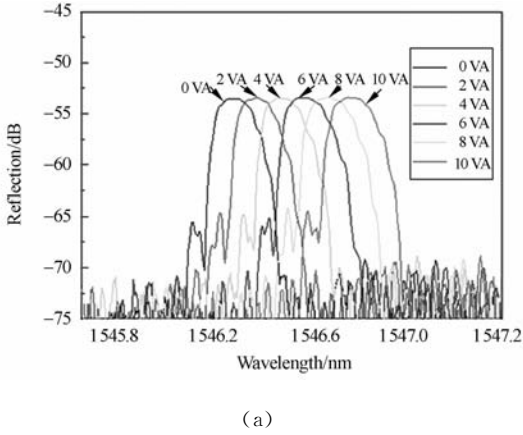


(b)

Fig. 6 (a) Reflection spectra of the FBG sensor for center-wavelength variations as a function of apparent powers for load of resistor. (b) Measured Bragg wavelength shift as a function of apparent powers for load of resistor.

ferent loads are carried out in this equipment. Fig. 6 (a) shows the reflection spectra of the FBG sensor for center-wavelength variations as a

function of apparent powers for a load of resistor ($R = 100 \Omega$). The sensitivity is approximately 0.0463 nm/VA . A plot of the measured Bragg wavelengths as a function of apparent power for the load of resistor, as shown in Fig. 6 (b), showing the linearity between the Bragg wavelength and the applied apparent power. Fig. 7(a) shows the reflection spectra of the FBG sensor for center-wavelength variations as a function of



(a)

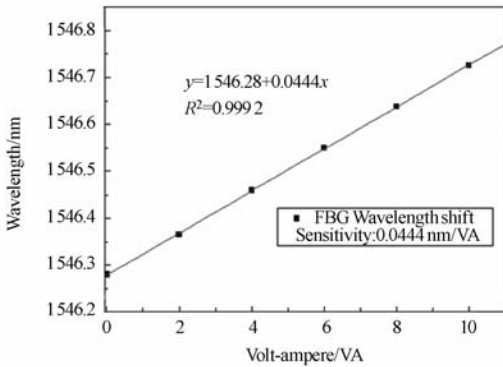
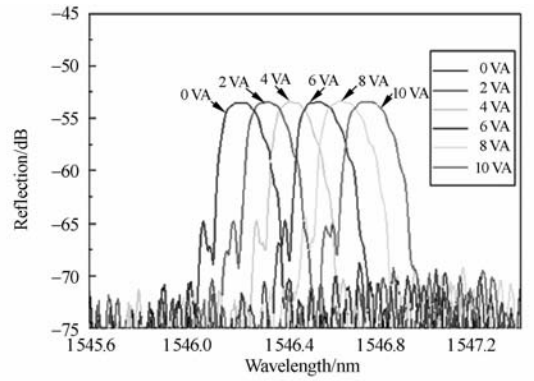
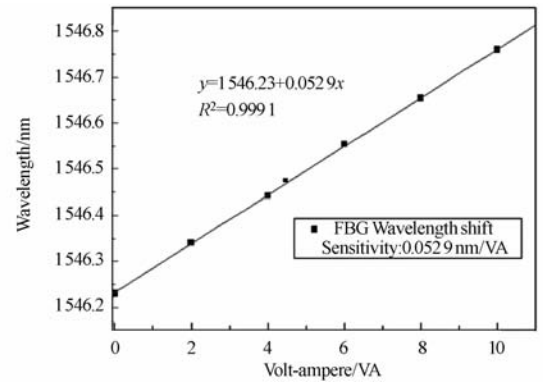


Fig. 7 (a) Reflection spectra of the FBG sensor for center-wavelength variations as a function of apparent powers for load of capacitor. (b) Measured Bragg wavelength shifts as a function of apparent powers for load of capacitor

apparent power for load of capacitor ($C = 47 \mu\text{F}$). The sensitivity is approximately 0.0444 nm/VA . A plot of the measured Bragg wavelength is a function of apparent power for capacitor load, as shown in Fig. 7(b), which also displays linearity between the Bragg wavelengths and the applied apparent power. Fig. 8(a) shows the reflection spectra of the FBG sensor for cen-



(a)



(b)

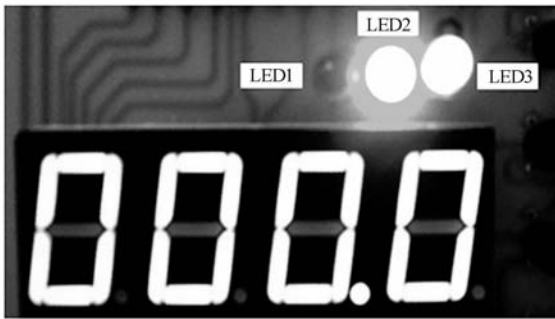
Fig. 8 (a) Reflection spectra of the FBG sensor for center-wavelength variations as a function of apparent power for load of inductor. (b) Measured Bragg wavelength shift as a function of apparent power for load of inductor

ter-wavelength variation as a function of apparent power for load of inductor ($L = 81 \text{ mH}$). The sensitivity is approximately 0.0529 nm/VA . A plot of the measured Bragg wavelength is a function of apparent power for load of inductor, as shown in Fig. 8(b), which also displays linearity between the Bragg wavelength and the applied apparent power.

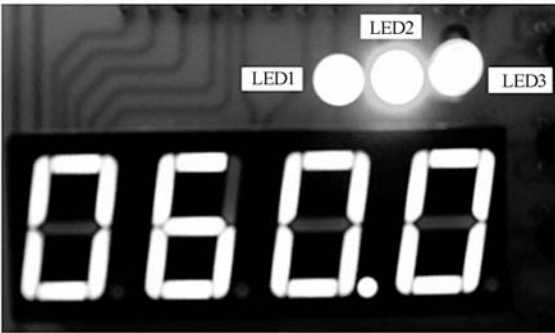
3.2 Measurement of power factor (PF)

In the microprocessor-based measurement of the phase angle between voltage and current signals, the corresponding AC waveforms have been converted to a train of rectangular pulses using zero-crossing detector circuits. The phase angle between voltage and current signals can be determined by the PIC 16F877 microcontroller

through the train of rectangular pulses. Measurement of phase angle between voltage waveform and current waveform for different loads is carried out in this equipment. There are three possible scenarios: (1) Both LED2 and LED3 are on. (2) LED2 is off and LED3 is on, and (3) LED2 is on and LED3 is off. Fig. 9 shows the results of measurement for load of resistor. Of the three scenarios, when both LED2 and LED3 are on, they are used to indicate if the voltage and current are in phase. The phase angle between current and voltage signals is zero. When



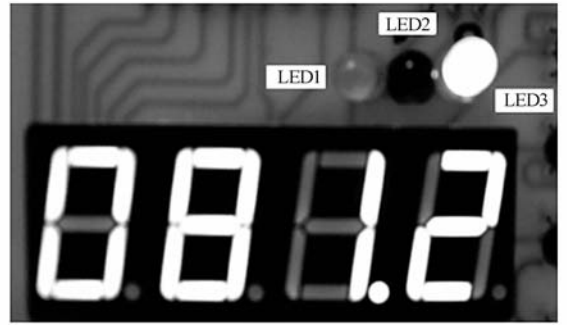
(a) Measured phase angle



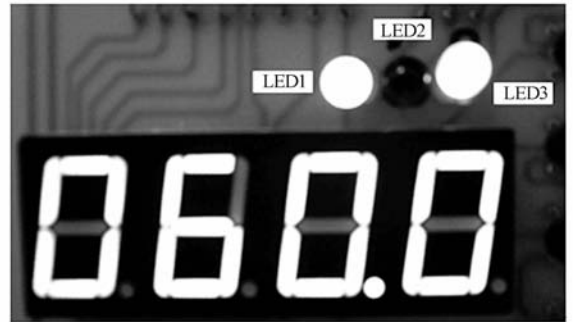
(b) Frequency of the system

Fig. 9 Measurements of phase detector circuit for load of resistor

LED1 is on, the device is used to measure the frequency of the system, and when LED1 is off, the device is used to measurement phase angle. Similarly, Fig. 10 shows the results of measurement for load of capacitor. Of the three scenarios, when LED2 is off and LED3 is on, they are used to indicate current leads voltage. The phase angle between current and voltage signals is 81.2° and it is not exactly 90° due to the resistor

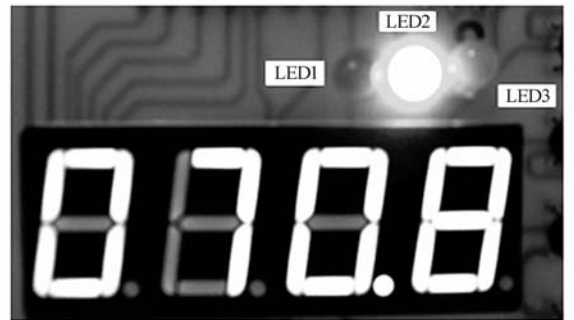


(a) Measured phase angle

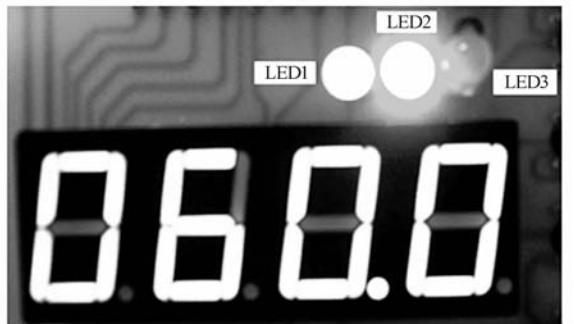


(b) Frequency of the system

Fig. 10 Measurements of phase detector circuit for load of capacitor



(a) Measured phase angle



(b) Frequency of the system

Fig. 11 Measurements of phase detector circuit for load of inductor

of the capacitor. Fig. 11 shows the results of measurement for the load of inductor. Of the three scenarios, when LED2 is on and LED3 is off, they are used to indicate of current lags voltage. The phase angle between current and voltage signals is 70.8° and it is not exactly 90° due to the resistor of the inductor.

4 Conclusions

It is feasible that the FBG and the PZT sensor can be used to measure power over a wide range. The sensing head is based on an FBG attached on the surface of PZT in the polarization direc-

tion; it has good linear properties and can be applied to monitor the wavelength shift caused by apparent power consumed by electrical equipment. The phase angle between voltage and current can be measured by phase detector circuit and PIC 16F877 microcontroller. Thus, the real power and reactive power can be obtained by the apparent power and the phase angle. The proposed scheme for measuring AC power is a simple and compact configuration and can provide a portable sensor for real power and reactive power measurements without the use of traditional power meters.

References:

- [1] YOON W K, DEVANEY M J. Reactive power measurement using the wavelet transform [J]. *IEEE Transactions on Instrumentation and Measurement*, 2000, 49:246-252.
- [2] SARKAR A, SENGUPTA S. A low-cost fault-tolerant real, reactive, and apparent power measurement technique using microprocessor [J]. *IEEE Transactions on Instrumentation and Measurement*, 2007, 56:2672-2680.
- [3] HILL K O, MELTZ G. Fiber Bragg grating technology fundamentals and overview [J]. *J. Lightwave Technol.*, 1997, 15:1263-1276.
- [4] KERSEY A D, DAVIS M A, PATRICK H J, *et al.*. Fiber grating sensors [J]. *J. Lightwave Technol.*, 1997, 15:1442-1463.
- [5] CHENG C H, CHEN M H, LIU W F. Measurement of AC current using a superstructure fiber grating [J]. *Microwave and Optical Technology Letters*, 2008, 50:1168-1171.
- [6] CHENG C H, LIN L M, LIU W F. Measurement of electric power using an optical fiber grating [J]. *Microwave and Optical Technology Letters*, 2009, 51(10):2438-2441.
- [7] JUNG J, NAM H, LEE J H, *et al.*. Simultaneous measurement of strain and temperature by use of a single-fiber Bragg grating and an erbium-doped fiber amplifier [J]. *Appl. Opt.*, 1999, 38(13): 2749-2751.
- [8] JAMES S W, DOCKNEY M L, TATAM R P. Simultaneous independent temperature and strain measurement using in-fiber Bragg grating sensors [J]. *Electron. Lett.*, 1996, 32:1133-1134.
- [9] PATRICK H J, WILLIAMS G M, KERSEY A D, *et al.*. Hybrid fiber Bragg grating/long period fiber grating sensor for strain/temperature discrimination [J]. *IEEE Photon. Technol. Lett.*, 1996, 8(9): 1223-1225.
- [10] DU W C, TAO X M, TAM H Y. Fiber Bragg grating cavity sensor for simultaneous measurement of strain and temperature [J]. *IEEE Photon. Technol. Lett.*, 1999, 11(1): 105-107.
- [11] GUAN B O, TAM H Y, TAO X M, *et al.*. Simultaneous strain and temperature measurement using a superstructure fiber Bragg grating [J]. *IEEE Photo. Technol. Lett.*, 2000, 12(6): 675-677.
- [12] LOSS P V A, LAMEGO M M, SOUSA G C D, *et al.*. A single phase microcontroller based energy meter[C]. *IEEE Instrumentation and Measurement Technology Conference*, 1998:797-800.
- [13] KANG L H, KIM D K, HAN J H. Estimation of dynamic structural displacements using fiber Bragg grating strain sensors [J]. *Journal of Sound and Vibration*, 2007, 305:534-542.
- [14] YAO Y, YI B. FBG based voltage measurement using PZT modulation[C]. *International Conference on wireless communications, Networking, and Mobile Computing, WiCOM 2006*.

- [15] CHENG C H, LAI L H, LIU W F. Noise sensor based on a Fiber Bragg Grating and a Piezo-electric

Transducer [J]. *Microwave and Optical Technology Letters*, 2011, 53(4):958-961.

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