# A relocatable resonant FBG-acoustic emission sensor with strain-insensitive structure*

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A novel resonant fiber Bragg grating (FBG) based acoustic emission (AE) sensor with relocatable, strain-insensitive and enhanced sensitivity structure is demonstrated for structure health monitoring (SHM) in this paper. With one end of the sensing FBG bonded to a polyimide (PI) plate acoustically coupled with the investigated structure via couplant and the other end free, the sensor can be easily redeployed around the monitored structure surface and get rid of the interference from the strain applied on the monitored structure. Experiment has been conducted to verify the characteristics of this FBG-AE sensor, whose results show that the sensor is insensitive to mechanical strain applied on the monitored structure. It is also shown experimentally that the sensitivity is enhanced by about 1.2 times than the conventional design, while the novel sensor possesses good resonant frequency response to the standard AE waves.

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Fiber Bragg grating (FBG)[1-4] is sensitive to the acoustic emission (AE) wave and has been used to develop AE sensor. The FBG-AE sensors described in Ref.[5] are surface-glued or embedded in the monitoring structures. FBG mounted on those kinds of sensors can detect acoustic vibrations sensitively, but the reflection spectrum shifts due to the strain applied on the structure. Acoustic vibration cannot be detected by FBG when its reflection spectrum deviates from the lasing wavelength. Therefore surface-glued or embedded FBG cannot detect AE continuously because AE usually occurs under varying strain conditions.

Lee et al[6,7] have reported that acoustic vibration could be transmitted along the optical fiber with low attenuation. In their subsequent work, a resonant FBG-AE sensor configuration[8] was proposed, but the structure cannot be relocatable.

To solve the problem above, a resonant FBG-AE sensor which is relocatable and insensitive to the strain is demonstrated in this paper. With one end of the sensing FBG bonded to a polyimide (PI) plate acoustically coupled with the investigated structure via couplant and the other end free, the sensor can be easily redeployed around the monitored structure surface and get rid of the interference from the strain applied on the investigated structure. An interrogation system with a narrowband tunable semiconductor laser is designed using rational parameters configuration to test the sensing characteristics of this sensor. Through tensile and standard signals test, the designed features of the sensor are experimentally verified. It is also shown experimentally that the sensitivity is enhanced obviously.

FBG is a periodic structure inscribed in a section of the optical fiber core. The peak wavelength of the FBG spectrum known as the Bragg wavelength is sensitive to both temperature and strain. When temperature is assumed to be constant, this strain induced Bragg wavelength shift can be expressed as

$$\Delta\lambda_{B}=\lambda_{B}(1-p_{e})(\varepsilon+\varepsilon_{AE}), \quad (1)$$

where $\varepsilon$ is the structural strain, $\varepsilon_{AE}$ is the high frequency strain induced by acoustic emission waves, and $p_e$ is the effective strain optic coefficient defined as

$$p_{e}=\frac{n_{eff}^{2}}{2}[p_{12}-v(p_{11}+p_{12})], \quad (2)$$

where $p_{11}$ and $p_{12}$ are two components of the strain optic tensor, $v$ is the Poisson's ratio, and $n_{eff}$ is the Bragg effective refractive index modulation under AE waves.

To study the interaction between FBG and AE waves, the time-dependent AE strain is modeled according to

$$\varepsilon_{AE}(t)=A_{AE}\cos(\frac{2\pi}{\lambda_{AE}}z-\omega_{AE}t), \quad (3)$$

where $A_{AE}$ denotes the AE wave amplitude normalized to the wavenumber $\frac{2\pi}{\lambda_{AE}}$, $\lambda_{AE}$ is its wavelength, and $\omega_{AE}$ is its angular frequency. Here, $z$ is the point along the fiber axis.

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An AE wave can also cause a refractive index change via the strain-optic effect and induce geometric deformation along the FBG. Taking the mentioned two effects into account, the Bragg effective refractive index modulation under AE waves can be expressed as[9]

$$n'_{\text{eff}}(z',t) = n_{\text{eff}0} - \Delta n \sin^2(\frac{\pi}{\Lambda_0}z) - \frac{n_{\text{eff}0}^3}{2}\cdot[p_{12} - \nu(p_{11}+p_{12})]\cdot A_{\text{AE}}\cos(\frac{2\pi}{\lambda_{\text{AE}}}z' - \omega_{\text{AE}}t), \quad (4)$$

where $n_{\text{eff}0}$ is the original effective refractive index, $\Delta n$ is the maximum index change, $\Lambda_0$ is the grating period, and $z'$ is the new point along the fiber axis due to the geometric deformation, which can be obtained as

$$z' = z + \int_0^z \varepsilon(\xi)\mathrm{d}\xi = z + A_{\text{AE}}\frac{\lambda_{\text{AE}}}{2\pi}\sin(\frac{2\pi}{\lambda_{\text{AE}}}z - \omega_{\text{AE}}t) + A_{\text{AE}}\frac{\lambda_{\text{AE}}}{2\pi}\sin(\omega_{\text{AE}}t). \quad (5)$$

A schematic diagram of the newly designed FBG-AE sensor is shown in Fig.1. Firstly, the pigtailed end of the FBG is immobilized on a polyimide (PI) plate via adhesive while the other end is left free. Then the PI plate is acoustically coupled with the monitored aluminum alloy plate by using vaseline as a couplant. The one end free configuration and the ambulatory deployment method make our FBG-AE sensor with the advantages of being relocatable and strain insensitive.

The resonance frequency of this FBG-AE sensor can be calculated using the following equation[10]

$$f = \frac{2n-1}{4L}c_{\text{f}}, \quad (6)$$

where $n$ is the order of an acoustic emission wave mode, $c_{\text{f}}$ = 4860 m/s is the group velocity of the acoustic emission wave propagating in the bare fiber, and $L$ is defined as the sensing fiber length. In this paper, the sensing fiber length of the novel FBG-AE sensor is 8 mm and as a result, the first resonance frequency of the sensor is 150 kHz according to Eq.(6).

The propagation situation of AE waves in the sensor is illustrated in Fig.2. The AE waves cannot be directly detected by the FBG that is not fully glued. They firstly propagate through the sensing fiber and detected by the FBG. Then, they are reflected from the fiber end and detected again by the FBG. The superposition of the direct and reflected AE waves with the same frequency propagating in opposite directions gives rise to the resonance phenomenon in the sensor.

To investigate the impact of applied strain on the FBG-AE sensor, a tensile test on an aluminum alloy plate with a width of 100 mm and a thickness of 3 mm has been performed using a tensile machine. For a comparative study, the newly designed FBG-AE sensor and a fully bonded FBG-AE sensor are deployed at the center of the respective faces of the aluminum alloy plate. The center wavelengths of both FBGs used in the two sensors are 1563 nm and 1563.9 nm, respectively. The loading speed is 0.05 kN/s and the loading procedure stops at 15 kN. As shown in Fig.3, unlike the fully bonded FBG-AE sensor with a nearly linear response to the applied tensile time, the newly designed FBG-AE sensor is insensitive to the applied strain.

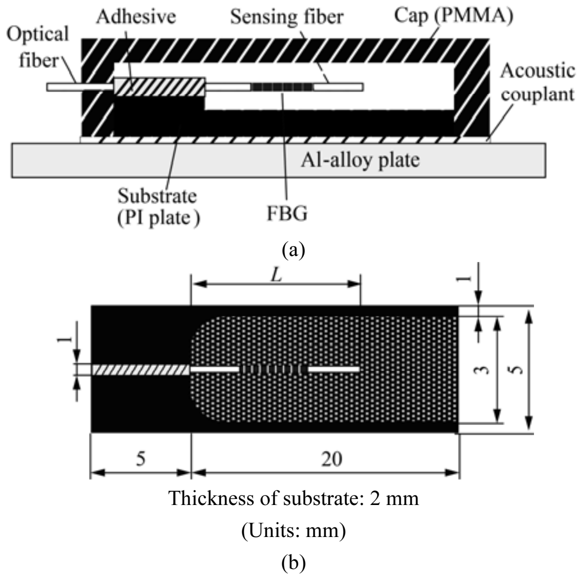


**Fig.1 (a) Schematic view of the relocatable FBG-AE sensor; (b) Key dimensions of the substrate of the sensor**

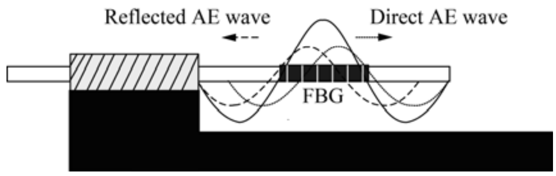


**Fig.2 Principle of resonance phenomenon in the relocatable FBG-AE sensor**

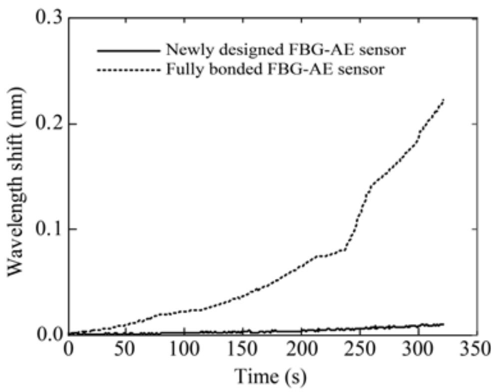


**Fig.3 Wavelength changes of the fully bonded FBG-AE sensor and the novel FBG-AE sensor with respect to tensile time**

The experimental setup for FBG-AE sensing is shown in Fig.4. A standard AE wave or a continuous sine wave is produced by a waveform generator. The generated wave propagates on an aluminum alloy plate and then modulates the FBG-AE sensor deployed on the surface of the plate. A 5-mW narrowband tunable semiconductor laser (TSL) with a linewidth of 100 kHz is used to illuminate the FBG-AE sensor. The lasing wavelength is tuned to match the left or right mid-reflection point of the FBG spectrum. The reflected light from the sensor is fed into a photodetector which is embedded with a band pass filter (100-300 kHz). The photodetector converts the variation of light intensity reflected from the FBG to an alternating voltage signal. By using this narrowband laser interrogation method, small spectral shifts caused by high frequency AE waves can be converted to large light intensity variations. Thus high AE sensitivity is expected for this sensing system.

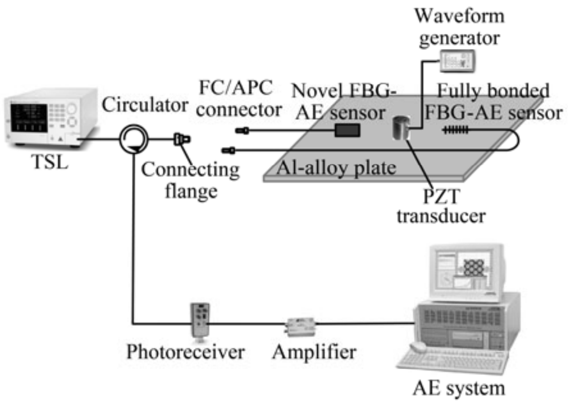


**Fig.4 Experimental setup of the FBG-AE sensing system**

To investigate the standard signal response of the resonant FBG-AE sensor, standard sinusoidal signals with the frequency tuned at 150 kHz and three amplitude options (90 dB, 80 dB and 70 dB) supplied by a waveform generator are used to drive a PZT transducer disposed at the excitation point on the aluminum alloy plate (Fig.4).

Fig.5 demonstrates the time domain responses of the novel resonant FBG-AE sensor and the fully bonded FBG-AE sensor for sinusoidal waves with three different amplitudes respectively. From Fig.5 we can see that the waveforms agree well with the standard sinusoidal waves. Under the excitation frequency of 150 kHz, the waveforms with different amplitudes from 70 dB to 90 dB are observed, which demonstrates a remarkable sensitivity enhancement. The sensitivity of the newly designed sensor is enhanced by about 1.2 times than that of the conventional design according to the experimental results.

The frequency spectra indicate the main frequency regions of the waves detected by the FBG-AE sensor. The amplitude-frequency characteristics of the two type sensors are investigated through excitation with a frequency band from 100 Hz to 400 kHz, whereas the resonant frequency is 150 kHz. High signal-to-noise ratios (SNRs) can be achieved with the 90 dB signal as shown in Fig.6. The amplitude at resonant frequency of the novel FBG-AE sensor is about 10 dB higher than that of the fully bonded FBG-AE sensor. The main frequency peaks of the two type sensors are both located at 150 kHz in despite of the varying signal amplitudes and consistent very well with the preset frequency of the waveform generator.

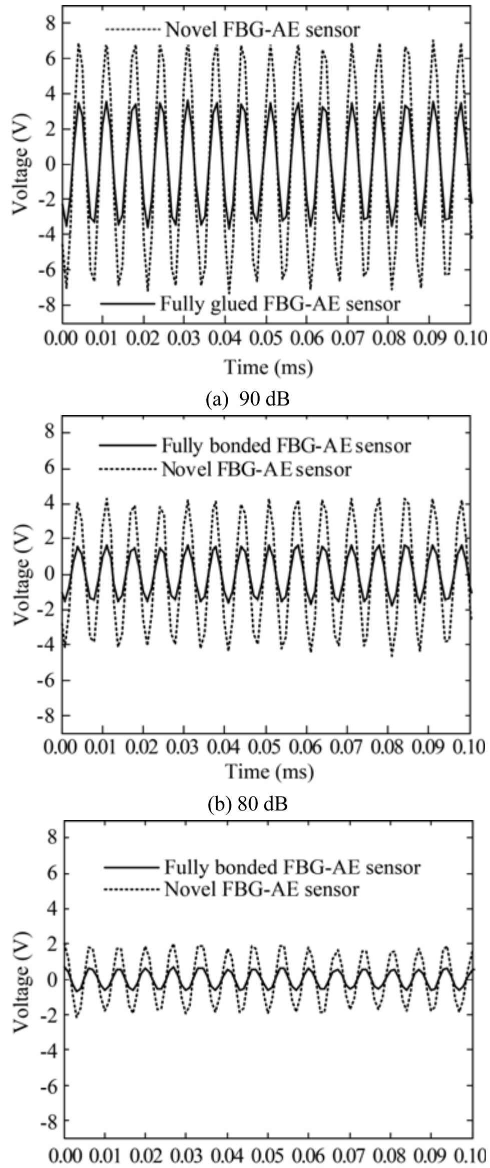


**Fig.5 Time responses of the novel FBG-AE sensor and fully bonded FBG-AE sensor for sinusoidal waves with different amplitudes**

In order to investigate the first resonance frequency response of the resonant FBG-AE sensor with 8-mm-long sensing fiber length, a standard AE signal with a resonant frequency of 150 kHz, rise time of 100 μs and fall time of 100 μs is generated by the waveform generator. Fig.7 shows the time domain response and frequency spectrum of the resonant FBG-AE sensor driven by the standard AE waves. According to Eq.(6), the theoretical first resonance frequency of the designed sensor with 8-mm-long sensing fiber length is 150 kHz. As shown in Fig.7, the experimental first resonance frequency of the FBG-AE sensor agrees very well with the theoretical one.

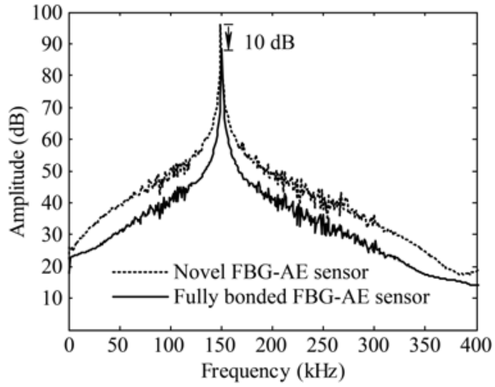


**Fig.6 Amplitude-frequency curves of two sensors**

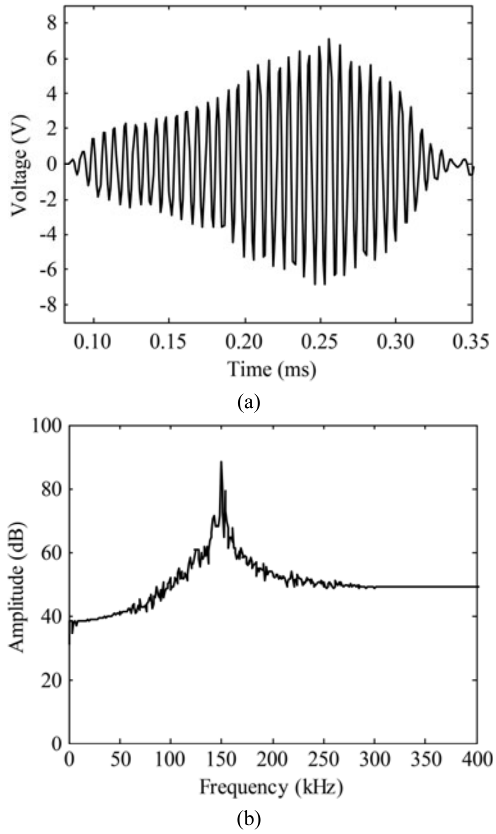


**Fig.7 (a) Temporal waveform and (b) corresponding frequency response observed during the standard AE wave test**

A novel FBG-AE sensor is demonstrated for AE monitoring in this work. By using the one end free configuration and the relocatable acoustic coupling method, the sensor is insensitive to the mechanical strain applied on the monitored structure and can be easily redeployed. Tensile test has verified the strain-insensitive characteristic of this FBG-AE sensor. Experimental results of comparison tests between the novel FBG-AE sensor and the fully bonded FBG-AE sensor demonstrate that the sensitivity is enhanced by about 1.2 times than that of the traditional design. The newly designed sensor possesses good resonant frequency response to the standard AE signals as well. It is believed that the good characteristics of this FBG-AE sensor will enable its applications in the development of SHM systems.

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