Optics and Lasers in Engineering 49 (2011) 110–120

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

A lasing wavelength stabilized simultaneous multipoint acoustic sensing system using pressure-coupled fiber Bragg gratings

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ARTICLE INFO

Article history:
Received 5 June 2010
Received in revised form
17 July 2010
Accepted 15 August 2010

Keywords:
Fiber Bragg grating
Tunable laser
Lasing wavelength stabilization
Integrated structural health management
Acoustic emission

ABSTRACT

A fiber Bragg grating (FBG) sensor head, using a pressure coupling mechanism, was designed for broadband frequency response and structural strain-free characteristic. The pressure-coupled sensor heads were connected to a simultaneous multipoint acoustic sensing system based on a tunable laser. An intelligent lasing wavelength stabilization algorithm capable of identifying the direction of spectrum movement, the wavelength shifting speed, and a fiber bending event was developed so that the simultaneous multipoint acoustic sensing system could be used in environments with rapid temperature variations. The lasing wavelength feedback control algorithm updated the lasing wavelength into the steep slope of the FBG spectrum even under conditions of rapid temperature change. The averaging lasing wavelength updating time was only 21 s because the system can decide a minimal size in scan window by finding the FBG spectrum shifting speed and direction in real time. The system was able to update the lasing wavelength which missed the steep slope of the FBG spectrum under maximum temperature variation rates 0.3014 and -0.3246 °C/s. The proposed system detected simultaneous impact waves at multiple points under conditions of rapid temperature change and change in dynamic strain.

1. Introduction

Acoustic emission (AE) is defined as transient elastic waves in the audible and ultrasonic regions. These waves are generated by the rapid release of energy within a material undergoing fracture or deformation due to material degradation, reversible processes, fabrication processes, or leak and flow [1]. AE detection and ultrasonic transmission and reception technologies are widely used for in-field nondestructive testing (NDT) and integrated structural health management (ISHM). Acoustic waves selected in the frequency range of up to 100 MHz [2] are generated and detected by piezoelectric transducers in NDT and ISHM. However, from the viewpoint of ISHM, conventional piezoelectric transducers are susceptible to electromagnetic interference (EMI) and temperature change. In addition, piezoelectric sensor networks are usually too large and heavy, especially for aerospace applications, and are often inappropriate for long-distance, long-time, and large structure monitoring. In the last decade, fiber optic acoustic sensor networks have been proposed to overcome the limitations of conventional piezoelectric sensor networks. Fiber optic acoustic sensor networks have potential advantages for ISHM due to their multi-functional sensing ability, small size, flexibility, durability, EMI immunity, corrosion resistance, and exceptional embedding and communication capabilities. Prior studies of fiber optic acoustic sensing were categorized into three categories: single fiber intensiometric, fiber optic interferometric, and fiber Bragg grating (FBG) techniques [1].

In the category of single fiber intensiometric techniques, Chen et al. [3] developed an ultrasonic fiber optic sensor based on a 2×2 fused-tapered optical fiber coupler that incorporated mechanical strain amplification and increased the frequency response range from several tens of kHz to several hundred kHz. Later work [4] incorporated in-line multiplexing of two sensors and demonstrated linear localization of a pencil lead break AE source on an aluminum plate. However, AE sensing capability in a state accompanying structural strain and environmental temperature change has not been reported, which is very important so that the sensor can be used as a built-in AE sensor for ISHM. Kim et al. [5] developed a filtering wavelength stabilized gold-deposited extrinsic Fabry–Perot interferometric (EFPI) sensor system composed of a broadband light source, the fiber Fabry–Perot tunable filter, and a control-circuit board. They demonstrated the detection of fracture-induced AE by compensating for the low frequency phase drift resulted from quasi-static strains and temperature variations. However, the filtering wavelength stabilization algorithm was unable to operate under

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doi:10.1016/j.optlaseng.2010.08.009

conditions of dynamic strain and rapid temperature change, and caused degradation in the signal-to-noise ratio. In addition, the EFPI AE sensors were very difficult to multiplex or multichannel due to high insertion losses introduced by the Fabry–Perot cavity formed inside the fiber [6].

The most attractive fiber optic acoustic sensors are based on fiber Bragg grating (FBG) with benefits such as self-calibration, multiplexing or multipoint sensing, and multi-parameter sensing capabilities. In regards to high speed simultaneous multipoint FBG interrogators, a four simultaneous channel system with 100 kHz acquisition speed [7] and an eight simultaneous multiplex system with 40 kHz sampling speed [8] are available in the market. However, since these interrogators allow frequency domain analysis up to 20–50 kHz and full waveform acquisition up to 8–20 kHz, it is still inappropriate for use as a full acoustic sensing system.

Regarding advances in FBG acoustic sensing technology, narrowband demodulation schemes converting FBG spectral shift into optical intensity variation have been proposed to perform high sensitivity interrogation of acoustic waves (45 picostrain/$\sqrt{\text{Hz}}$) [9]. Takahashi et al. [10] reported that a FBG showed the ability to operate over a wide range of acoustic frequencies from 1 kHz to 3 MHz. The use of a narrowband tunable laser (NTL) solved the problems associated with the low sensitivity of the combination of a broadband light source with either a fiber Fabry–Perot tunable filter [11] or arrayed waveguide gratings [12]. Lee et al. [13] developed resonant fiber acoustic wave grating (FAWG) sensors. Two FAWG sensors, each with a one-end-free configuration and an identical FBG spectrum to the other, were able to simultaneously detect impact signals and localize the AE source on carbon fiber-reinforced plastics (CFRP). In addition, the number of channels in the system was extended to 24. However, due to the narrow bandwidth in the resonant feature, the FAWG sensor was less sensitive in detecting unknown or variable AE signals over a wide frequency band range. The aforementioned systems [9–13] could not demonstrate AE detection under rapid temperature change.

In this study, we first designed a novel pressure-coupled FBG acoustic sensor for broadband spectral response and strain-free acoustic sensing. This implied that either a narrowband [13] or a broadband strain-free FBG acoustic sensor could be chosen for the simultaneous multipoint FBG acoustic sensing system requiring strain-free FBG sensor heads to apply for ISHM. Since a pressure-coupled sensor is almost insensitive to the strain of the structure where the sensor is installed, only temperature-induced spectral shift tracking was needed. Thus, a lasing wavelength stabilization system with a power meter to monitor the light intensity shared from a sensing channel was developed to construct a closed loop for the lasing wavelength control. Thus, we satisfied the FBG narrowband demodulation condition even under the rapid temperature changes of in-field structures. The performance of the system under the condition of maximum rate of temperature variation was experimentally evaluated. The stabilized acoustic sensing system was able to accomplish simultaneous multipoint AE wave detection using two pressure-coupled FBG acoustic sensors, each with a spectrum identical to the other.

2. Basic principle of fiber Bragg grating acoustic sensing

A FBG is a periodic modulation of the refractive index inscribed in a section of optical fiber core. The peak wavelength of the FBG spectrum is known as the Bragg wavelength, which is sensitive to temperature and strain. This relationship can be expressed as follows:

$$\Delta\lambda_B = \lambda_B\left[\alpha\Delta T + (1-p_e)(\varepsilon+\varepsilon_{AU})\right] \quad (1)$$

where ε is the structural strain, ε_{AU} is the acoustic wave-induced high frequency strain, p_e is the effective strain-optic coefficient, ΔT is the change in temperature, and α is the effective thermal coefficient.

Acoustic waves modulate the grating period and, as a result, the FBG spectrum shifts as rapidly as the wave frequency. To demodulate the rapid and minute spectral movement with a high sensitivity (as shown in Fig. 1) the lasing wavelength of a narrowband tunable laser (NTL) is tuned to the 50%-reflection wavelength within the dynamic range of the left or right slope in the main lobe of the FBG spectrum, and the reflected light intensity is measured using a photodetector. In this narrowband demodulation method, small spectral oscillations resulting from an acoustic wave with high frequency and small magnitude can be directly converted into a large light intensity variation.

3. Fabrication and characterization of the pressure-coupled FBG acoustic sensor

Fig. 2a shows assembly components of a pressure-coupled FBG acoustic sensor. The sensor includes a stainless steel (SUS304) sensor head, a thin silicone adhesive layer, and a stainless steel sensor cover. The sensor components (total mass 0.39 g) were assembled as illustrated in Fig. 2b. A 5 mm long FBG with a Bragg wavelength of 1591.3 nm and a reflectivity of 95% was inscribed in the stripped optical fiber and recoated with acrylate. The recoated fiber was embedded into the 0.5 mm groove on the sensor head with epoxy resin. The groove was completely filled with epoxy and then the cured epoxy, including the recoated FBG, was polished to obtain a smooth and flat surface. The silicone

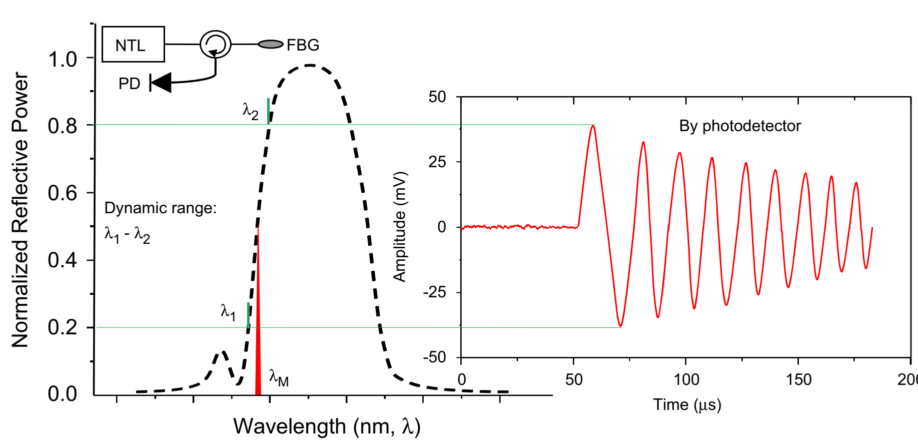

Fig. 1. The acoustic sensing principle based on a conventional FBG demodulation system using a narrowband tunable laser (NTL). PD (photodetector), λ_1 (lower), and λ_2 (upper) wavelength limits of dynamic range. λ_M represents 50% reflection wavelength.