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Employing optical code division multiple access technology in the all fiber loop vibration sensor system

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ABSTRACT

This study proposes a spectral amplitude coding-optical code division multiple access (SAC-OCDMA) framework to access the vibration frequency of a test object on the all fiber loop vibration sensor (AFLVS). Each user possesses an individual SAC, and fiber Bragg grating (FBG) encoders/decoders using multiple FBG arrays were adopted, providing excellent orthogonal properties in the frequency domain. The system also mitigates multiple access interference (MAI) among users. When an optical fiber is bent to a point exceeding the critical radius, the fiber loop sensor becomes sensitive to external physical parameters (e.g., temperature, strain, and vibration). The AFLVS involves placing a fiber loop with a specific radius on a designed vibration platform.

A $1 \times K$ coupler was adopted for the sensor system to divide a broadband light source into K light sources, which were then transmitted to various FBG encoders. The AFLVS was placed between the optical circulators of the various FBG encoders and multiple FBG arrays, and the stepping motor was directly placed on the fiber loops of the various AFLVSs. A signal generator was then used to input different frequencies into the stepping motors of the various sensors. After the light intensity for the reflectance spectrum, which was outputted by the FBG encoder, was modulated by the AFLVS, the modulated reflected signals were outputted to the $K \times K$ star coupler through the optical circulator and transmitted to the FBG decoders for the users. A balanced photodetector (BPD) was employed in this study to convert the light output of the FBG decoder into an electrical signal, and a digitizing oscilloscope was employed to conduct a Fourier transform on the BPD electrical signal output, thereby acquiring the vibration frequency of the test object. The results of the experiment are compared to a piezoelectric accelerometer. The comparison results indicate that the piezoelectric accelerometer is less sensitive when the frequency is lower than 90 Hz, whereas the AFLVS exhibits excellent measurement results at a low frequency ranging between 50 and 200 Hz.

1. Introduction

Optical fiber sensors (OFSs) are widely applied in measuring physical parameters, including rotation, acceleration, electromagnetic fields, temperature, pressure, sound, vibration, and humidity. OFSs are also commonly used in civil engineering, environmental and biochemical testing, and clinical biomedical fields. In addition, OFSs are advantageous because of their small size, light weight, low power, high sensitivity, high bandwidth, and ability to resist electromagnetic interference (EMI). Furthermore, OFSs possess the characteristic of light signal transmission, which enables multiplex measurements from multiple points by combining various multiplex network frameworks [e.g., wavelength division multiplexing (WDM), time division multiplexing (TDM), frequency division multiplexing (FDM), and optical code division multiple access (OCDMA)].

Traditional electric sensors (e.g., piezoelectric accelerometers), when used for vibration sensing, possess a broad range of working temperatures and can sense or detect higher frequencies. However, a relatively low signal-to-noise-ratio (SNR) is detected when traditional electric sensors are applied for low-frequency access. Moreover, these sensors are easily subjected to EMI; thus, they can only be applied to single-point simplex measurements. The sensitivity of the fiber loop sensor for external physical parameters is increased when the optical fiber is bent to a point exceeding the critical radius, and the sensor can be used to measure temperature, the refractive index, and vibration [1,2]. Theoretical and experimental results indicate that attributes regarding the significant influence of optical fiber diameter on bending loss can be used to develop vibration [3] and shift [4] sensors.

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OFSs can be integrated with multiplex techniques to achieve distributed sensing and decrease the cost and complexity of the multiple-point measurement system. OFSs are commonly applied to optical remote sensing (e.g., strain, temperature, and pressure sensing). Among various multiplex techniques, WDM is most commonly employed, and is a simple technique used to identify multiple OFSs. The number of OFSs applicable for this multiplexing system is limited by the light source bandwidth and fiber Bragg grating (FBG) reflected wavelength intervals [5]. TDM is another common technique, which uses a pulsed laser light source to emit pulses to FBG sensors at various distances. The reflected wavelengths of various FBG sensors differ, and the minimum distance for different FBG sensors is determined based on the time slot width of the light source. The pulse bandwidth must be equivalent to or less than the round-trip time for two random FBG sensors. The reflected wavelengths of various FBG sensors are separated according to the delay time of the optical fiber, and a rapid time-domain signal analysis is then employed to identify various sensor signals. However, significant power is required so that short pulses from light sources can increase SNR values for photodetector output signals [6].

To improve deficiencies in the TDM, the OCDMA framework can be used to implement additional FBG sensors by transmitting or emitting a modulated broadband light source to the FBG sensor arrays through an optical circulator. Based on the FBG encoding pattern, this light pulse possesses a unique sequence comprising zeros and ones. The reflected pulse sequence propagates through the detection system comprising the edge filter, balanced photodetectors (BPDs), and electrical signal processing units. The optical fiber delay line performs spatial modulations of the pulse sequence according to different sensor locations. Codes with various delay times can be used to calculate the autocorrelation function of the reflected signal while the wavelength messages of all sensors are demodulated. The edge filter is used as a passive wavelength demodulation device by converting wavelength variations into amplitude variations. Two photodetectors are employed to calculate the correlation function ratio of the wavelength shift in the FBG sensor. The analog-to-digital converter is then applied for sampling received signals [7].

In 2011, the research team for the present study proposed a fiber vibration sensor system combining an OCDMA framework and two optical collimators. This sensor system was capable of accurately measuring the vibration frequency of an object, and was successfully applied to complete a code division access experiment [8]. However, the framework employed in [8] was primarily applied to short-distance transmissions.

Consequently, this study also adopted a balanced incomplete block design (BIBD) [9] in which each user group had a specific spectral amplitude coding (SAC). FBGs were used as a primary component for the encoder/decoder for each user, thereby decreasing the number of FBGs in these devices. In this way the encoder/decoder was simplified and relevant costs reduced. SAC encoding can be used by a great number of active users because of its characteristic of eliminating interference and preventing phase-induced intensity noise during the photodetection process. The excellent characteristics of this system framework can be adopted for multiple-point multiplex measurements by using a distributed vibration sensing system combined with a sensor and encoding/decoding device. For the vibration sensor, this study proposed using an all fiber loop vibration sensor (AFLVS) to replace the fiber vibration sensor consisting of two optical collimators. This improvement transforms the entire sensor framework into an economical, simple, and flexible all fiber optical sensor design, facilitating the applicability of the optical sensor system for various situations in which vibration measurements are required.

2. Theories and principles

Optical fiber bending introduces considerable problems in fiber-optic communication, such as optical power loss and signal interference. The bending loss theory for the fundamental mode of fibers has been extensively researched for decades. The effects of microbending and macrobending are applied to OFSs, including effects for shift, pressure, and temperature sensors. Recent research has focused on relevant theories regarding macrobending loss characteristics for mono-mode fibers with a bend radius between 8.5 and 12 mm, which are used for edge filter wavelength measurements. Furthermore, when the bend radius of the optical fiber is less than 1 cm, the fiber can be applied to sensing.

Fiber loop sensors are sensitive to external physical parameters when the optical fiber is bent to a point smaller than the critical radius; they can be used to measure temperature, strain, and vibration. Because of their unique characteristics, fiber loop sensors can measure the vibration frequency of mechanical equipment, and since these sensors require minimal optical power, potential fire risk is low. Fiber loop sensors can also be applied to measure high- and low-frequency vibrations as well as to detect shift by the millimeter. Numerous existing physical models have been employed to predict optical waveguide bending loss; the most common method adopted in this process is the bending loss equation [1,2]:

$$2\alpha_B = \frac{1}{2}\left(\frac{\pi}{\gamma^3 R^e}\right)^{1/2} \frac{\kappa^2}{V^2 k_1^2(\gamma a)} \exp\left(-\frac{2\gamma^3 R^e}{3\beta_0^2}\right) \tag{1}$$

$$\gamma = (\beta_0 - k^2 n_{cl}^2)^{1/2} \tag{2}$$

$$\kappa = (k^2 n_{co}^2 - \beta_0^2)^{1/2} \tag{3}$$

$$V = ak(n_{co}^2 - n_{cl}^2)^{1/2} \tag{4}$$

$$k = 2\pi/\lambda \tag{5}$$

$2a_B$ represents the bending loss coefficient per unit length, where γ, k, and V denote the propagation constant; β_0 indicates the propagation constant for the leaky mode of the straight optical fiber; a symbolizes the core radius; R^e expresses the effective bend radius; n_{co} and n_{cl} respectively refer to the refractive indices of the core and cladding; and $K_{1(\gamma a)}$ is equivalent to the deformed first order-Bessel function of the second kind.

Figs. 1 and 2 respectively show the AFLVS structure and the practical AFLVS. A plastic card or tube is used to bend the optical fiber and construct a fiber loop sensor. Two wooden blocks are placed at an appropriate distance on a rubber sheet, and sheet metal is placed atop the two wooden blocks. The loop sensor is subsequently attached to the sheet metal, and the sensing platform for the AFLVS is complete.

Fig. 3 shows the power loss of two fiber loop sensors that possess distinct fiber loop diameters. The power loss curve shows numerous intermediate peaks, which are caused when light is reflected from the cladding-coating (jacket) and coating (jacket)-air junction and combines with leaked core light, generating the resonance peaks in the whispering gallery mode [1–3]. Although the two fiber loop sensors are composed of the same single-mode fiber, certain differences exist between their power loss curves (Fig. 3).

Whispering gallery mode has been used to develop several sensor applications because of its substantial sensitivity. Fig. 3 shows the maximal slopes of Fiber Loop Sensor 1 from diameters of 1.55 cm to 1.60 cm and Fiber Loop Sensor 2 from diameters of 1.57–1.62 cm, indicating that power within this range is easily affected, and, thus, possesses the highest sensitivity level. Conse-