Accelerometer Based on Polarization-Maintaining Microstructured Fiber in Sagnac Interferometer

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Abstract: A novel optical accelerometer based on Sagnac loop using high-birefringence polarization-maintaining photonic crystal fiber, was developed to improve the tradeoff between sensitivity and resonant frequency. Resonant frequency beyond 2,300 Hz and sensitivity of 29 pm/g were demonstrated.

OCIS codes: (060.2370) Fiber optics sensors; (060.2420) Fibers, polarization-maintaining; (120.3180) Interferometry

1. Introduction

Monitoring structural damage at an early stage is crucial in large civil and mechanical structures. Accelerometer is one of the most important sensing components in structural health monitoring systems for vibration measurements. Vibration is a mechanical oscillation moving periodically or randomly about an equilibrium point. When the driving frequency of an oscillation matches the system's natural frequency of vibration, mechanical resonance can lead to larger oscillation amplitude causing great damage to the structure. Vibration monitoring of large structures is essential to reduce the likelihood of structural failure.

Piezoelectric accelerometer is one of the most popular commercial accelerometers which employs piezoelectric elements to measure vibration and acceleration. However, electrical sensing devices are susceptible to electromagnetic interference. In contrast, optical sensing system is immune to electromagnetic fields and provides significant advantages such as long-term stability, high reliability, remote sensing, capability of multiplexing and so forth. Due to their unique optical properties, optical sensors based on fiber Bragg grating (FBG) are highly desirable in many applications and are widely used in vibration/acceleration sensing. Generally, commercial FBG-based accelerometers cannot operate at high frequency and their resonant frequency is typically less than 1,000 Hz [1, 2]. On the other hand, the sensitivity of FBG accelerometers can be as high as ~1300 pm/g, at the expense of a low resonant frequency of 60 Hz ($g = 9.8\ m/s^2$). There is tradeoff between the sensitivity and the resonant frequency of FBG-based accelerometers. Commercial FBG-based accelerometers with resonant frequency up to 700 Hz is available but with a much lower sensitivity of 16 pm/g [3].

Optical sensors based on interferometric techniques are well established and deployed in a wide variety of sensing applications as they are highly sensitive to measure environmental parameters [4]. Because of its simplicity comparing with other interferometric schemes, Sagnac interferometer, which is mainly composed of a fiber coupler and a segment of polarization-maintaining fiber (PMF) in a loop, attracts many attentions in a number of sensing applications. In addition, since the scheme is self-stabilized and does not require precise alignment of optical components, it is suitable for most in-field applications. The configuration of a Sagnac interferometer vibration sensor composed of two identical PMFs with their main axes orthogonally coupled to each other has been introduced [5]. Temperature-compensated vibration measurement of up to 1 kHz was confirmed but the brittle characteristic of the sensor rendered it unsuitable for practical sensing applications. The Sagnac loop structure has also been applied in dynamic acoustic vibration measurements where frequency response range from 30 Hz to 22 kHz with signal to noise ratio (SNR) from 9 dB to 43 dB was reported [4].

In this study, we propose an innovative approach to improve the tradeoff between the sensitivity and the resonant frequency of optical fiber accelerometer, based on PMF in Sagnac interferometric structure. The sensor head is composed of a section of PMF, a 3-dB coupler, an inertial mass and a base plate, and the technique employs birefringence of PMF to have good response to the mechanical vibrations. Resonant frequency up to 2.5 kHz was measured and relatively flat sensitivity of 29 pm/g was observed over a wide frequency range of 20-900 Hz.

2. Experiment

The PMF used to construct the accelerometer is a commercial fiber which has a core dimension of 4×7-μm, a cladding diameter of 125-μm, and outer diameter of 230-μm including an acrylic coating. The fiber core is surrounded by five layers of air-holes which are acting as cladding region along the fiber as shown in Fig. 1. The diameter of air-holes and the spacing between them are around 2 and 4 μm, respectively. To break the circular symmetry of the effective refractive index distribution (i.e., a strong birefringence), two large air-holes with diameter of 4.4-µm are introduced adjacently to the fiber core. The birefringence and attenuation of PMF are 8.9×10^{-4} and ~2 dB/km at 1550 nm, respectively.

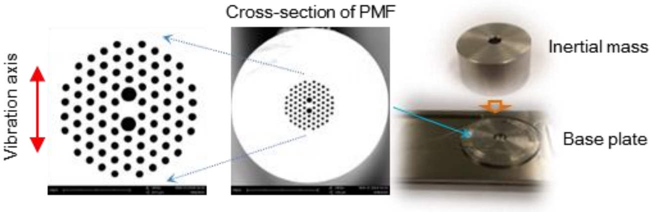

Fig. 1 Cross-sectional image of PMF and orientation of the fiber

The photo of the proposed accelerometer is shown in the inset of Fig. 2. The base plate and inertial mass of the accelerometer were made of stainless steel with the weights of 56 and 70 grams, respectively. The base plate has a rectangular shape with dimensions of 65 mm × 35 mm × 5 mm and the mass is a stainless steel cylinder with diameter and height of 25 mm and 15 mm, respectively. The PMF used in the accelerometer is 0.35-m long and was coiled into a circular shape with the largest diameter of ~ 21 mm. The acrylic coating was removed by dipping the PMF-coil into hot sulfuric acid. Both ends of PMF were manually spliced with fiber pigtails of 3-dB coupler inside a Sagnac loop using a fiber fusion splicer. The splicing loss was measured as ~1.2 dB/splice. The PMF-coil was firmly attached on stainless steel base plate and glued by a thin layer of epoxy resin adhesive (EPO-TEK 353ND). To ensure uniform strain distribution upon the fiber, the mass was placed on top of the PMF-coil. And then, the sensor package was heated up to 120℃ for 30 min inside an oven to cure the adhesive.

The orientation of the fiber was determined using a microscope and maintained in the coiled fiber. The orientation of fiber fixed on the base plate is shown in Fig. 1. The fast axis is aligned in the direction of the acceleration. Before gluing, the orientation angles of the fiber pigtails of the 3-dB coupler can be adjusted to obtain a high extinction ratio in the interference spectrum. The reflection spectrum of the accelerometer is illustrated in Fig. 3. The extinction ratio is over 10 dB, to ensure lower fluctuations in measured signal waveforms.

The accelerometer was mounted on top of a shaker platform as shown in Fig. 2 to measure its performance. The driven shaker (Bruel & Kjaer type 4808) provides acceleration levels up to 20 g and frequencies up to 2.5 kHz. The shaker was excited by a sinusoidal-signal generator with frequencies ranging from 20 Hz to 2500 Hz, in steps of 100 Hz. To ensure that the shaker provides the desired acceleration value, a conventional piezoelectric accelerometer (Bruel & Kjaer type 8305) was also attached under the shaker platform. The phase shift of output waveform of the accelerometer was recorded with an FBG-interrogator (Micron Optics si155) with data acquisition rate of 5000-Hz. Then, the time-dependent variable signals were converted as a function of frequencies by fast Fourier transform (FFT) analysis [6]. In our experiment, a very high-resolution interrogator permits to reduce small phase-measurement errors when measuring the vibration. Tests were performed at different frequencies for different acceleration values.

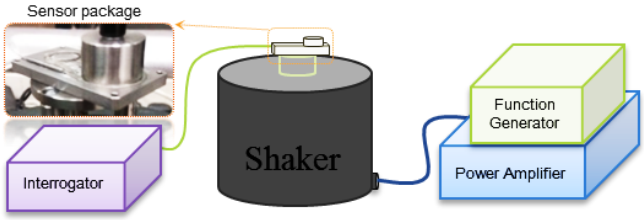

Fig. 2 Experimental set-up for the accelerometer

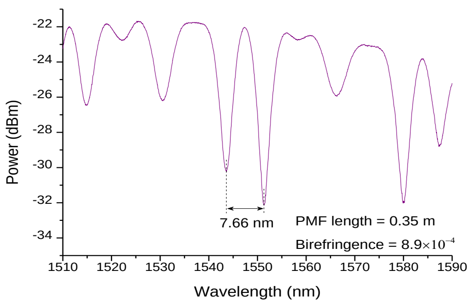

Fig. 3 Reflection spectrum of the fabricated accelerometer

3. Result and Discussion

A single frequency vibration in the range of 20–2,500 Hz was applied to the sensor head and the accelerometer's response was recorded at different vibration amplitudes. The measured sensitivity and operational frequency of two accelerometers constructed with PMFs without and with the acrylic protecting coating are shown in Fig. 4 and Fig. 5, respectively. Due to the limited frequency range of the shaker, the resonant peak cannot be observed in the frequency response curve in Fig. 4. A flat response occurs over a wide frequency range of 20–900 Hz, where average sensitivity is 28.8 pm/g. The "undesirable" frequency peak at 1400 Hz in Fig. 4 may be due to the impact of non-uniform mechanical stress applied to the fiber. This can be overcome by improving the process in securing the coiled fiber between the stainless steel pieces. Another accelerometer was constructed without removing the acrylic coating on PMF. Its frequency response from 20 to 2,500 Hz is shown in Fig. 5. The "undesirable" frequency peak has disappeared because the soft acrylic coating served as a buffer between the hard epoxy and glass fiber, allowing a more uniform mechanical stress applied to the fiber, at the expense of a much lower sensitivity. The resonance frequency of the accelerometer is 2,300 Hz. The average sensitivity of accelerometer in the frequency range of 20–900 Hz is just 1.4 pm/g.

These preliminary results indicate that the fiber coating materials, epoxy, and the process used to secure the fiber have significantly impact on the performance of the accelerometers.

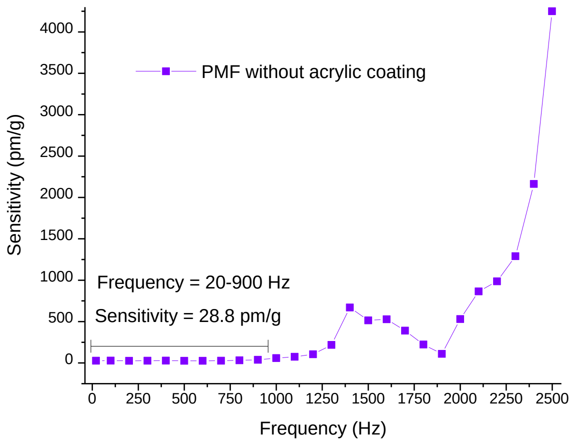

Fig. 4 Frequency response characteristic of the accelerometer constructed PMF without acrylic coating

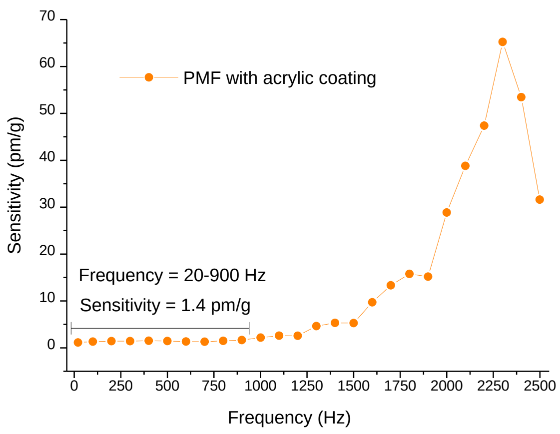

Fig. 5 Frequency response characteristic of the accelerometer constructed PMF with acrylic coating

For the accelerometer built using PMF without acrylic coating, the linear relationships of peak-to-peak wavelength shift as a function of acceleration at various frequencies are shown in Fig. 6. The accelerometer exhibits sensitivities varying from 26–4250 pm/g with excellent linearity (R^2) of 0.99998–0.99976. For lower excitation frequencies, the vibration amplitude was adjusted to give acceleration up to 20 g and it was gradually reduced when frequencies were higher. Figure 7 shows the time domain responses of the accelerometer at different excitation frequencies and their corresponding FFT plots. The output waveforms of the accelerometer are mostly sinusoidal and there are good agreements between the applied signals and the FFT results. The frequency peaks were measured to be at 99.94, 299.96, 599.92 and 900.10 Hz when applying the excitation frequency of 100, 300, 600 and 900 Hz, respectively. The measurement error is ~ 0.01%. According to FFT spectra, SNR of over 45 dB is obtained and it is quite satisfactory to improve the measurement performance and accuracy. Harmonics are observed at higher excitation frequencies. In Fig. 7 (d), harmonic at 1800 Hz was observed but with peak power at least 30 dB smaller than the excitation frequency of 900 Hz.

The amount of pre-compression on the coiled fiber can be adjusted by applying different forces on the mass during the epoxy curing process. Pre-compression allows the sensitivity, detectable frequency range and output interference spectrum of the accelerometer to be tuned. The sensitivity of the accelerometer is directly proportional to the weight of the mass at the expense of a lower operation frequency. The proposed accelerometer exhibits excellent performance in terms of sensitivity, linearity, and dynamic range. It is also simpler and relatively easy to manufacture. Moreover, the structure of the PMF can be modified by designing better air-hole arrangements and by protecting the fiber with polyimide coating in order to further improve the sensitivity, working frequency range and resonant frequency.

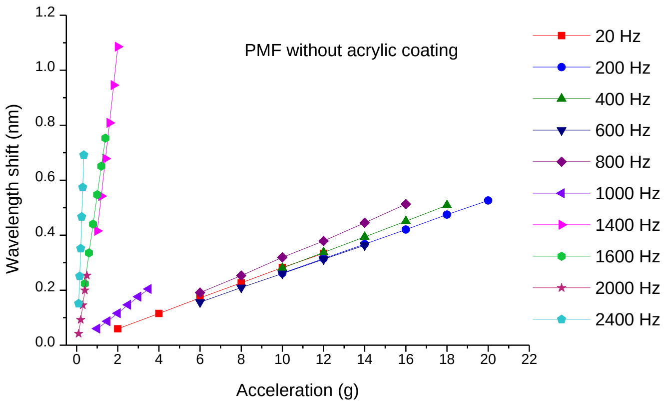

Fig. 6 Linear response of peak-to-peak wavelength shift versus acceleration in the excitation range of 0.1-20 g

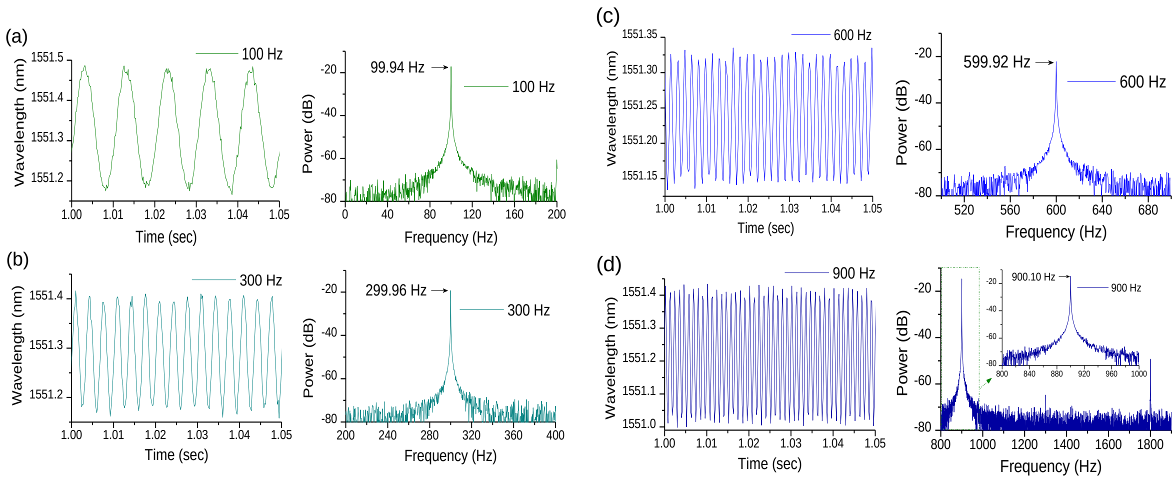

Fig. 7 Sinusoidal vibration and corresponding FFT spectrum of the accelerometer with 10-g acceleration at excitation frequencies of (a) 100, (b) 300, (c) 600, and (d) 900 Hz

4. Conclusion

A novel optical fiber accelerometer based on Sagnac interferometer constructed with a 0.35-m long polarization-maintaining microstructured optical fiber and a 3-dB coupler was successfully demonstrated. The tradeoff between sensitivity and resonant frequency was significantly improved over FBG-based accelerometers. The proposed accelerometer exhibits a resonant frequency of 2,500 Hz and can reach sensitivity of 29 pm/g over a relatively flat response from 20 Hz to 900 Hz.

5. Acknowledgement

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