# Cantilever optical vibrometer using fiber Bragg grating

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**Abstract.** A cantilever optical vibrometer using a fiber Bragg grating (FBG) is developed. The sensor head is made by attaching an FBG to a triangular beam to provide position-independent strain for the purpose of acceleration measurement. The vibrometer demonstrates a noise-limited acceleration resolution of $2.8\times10^{-4}$ g/$\sqrt{\text{Hz}}$ with repeatability error of less than 2.4%. 
[DOI: 10.1117/1.1615584]

Subject terms: fiber optic sensors; fiber Bragg gratings; optical fiber vibrometer.

Paper 020448 received Oct. 14, 2002; revised manuscript received Dec. 20, 2002; accepted for publication Jan. 13, 2003.

## 1 Introduction

It is often necessary to monitor or measure vibrations in applications such as high-power alternators in electrical plants and large rotating machines in petrochemical plants. The use of traditional electrical sensors is not preferred because of the existence of electromagnetic interference. Fiber optic sensors are best suited for these applications because of their immunity to an electric field. A particular type of fiber sensors, the fiber Bragg grating (FBG) sensors, has been intensively researched for the measurement of strain, temperature, and pressure.[1] The wavelength-encoded nature of FBG sensors makes them independent of fluctuating light power level and they can be easily multiplexed by using wavelength-division multiplexing (WDM) technology. Several types of FBG vibrometers have been reported in the literature.[2–4] Berkoff and Kersey[2] demonstrated the use of an embedded FBG transducer to measure acceleration, but it is sensitive to cross-axis excitation and the detrimental effects from transverse strain on the FBG, which induces birefringence splitting of its reflection peak. The problem of the cross-axis sensitivity could be minimized by using a cantilever beam type transducer[3] but it has lower measurement resolution because the signal was demodulated from the power variation of the reflected light of a chirped FBG. Another type of flexural beam type FBG transducer[4] has both advantages of low cross-axis sensitivity and higher measurement resolution but the strain induced on the FBG is nonuniform, therefore the physical length of FBG should be kept as short as possible to reduce the averaging effects imposed by its finite physical length and to minimize the strain gradient effect that induces spectral broadening. In this paper, we report a novel type of cantilever beam optical fiber vibrometer using an FBG to measure the acceleration of vibrating object. The design of the cantilever-beam-based sensor head ensures low cross-axis sensitivity and uniform strain applied to the FBG. A combination of an unbalanced interferometer and the phase lock loop method,[5,7] which has demonstrated high measurement resolution, is employed for the Bragg wavelength detection. The operation principle of the FBG vibrometer (FBGV) is described in Sec. 2. The experimental results are presented in Sec. 3 and a summary is given in Sec. 4.

## 2 Principle of Operation

The structure of FBGV is shown in Fig. 1(a). The FBG is attached to the bisector of an isosceles-triangul-shaped plastic cantilever beam. The lengths of the three sides of the triangul-shaped beam are 6.5, 6.5, and 3 cm, respectively. A circular metal mass is fixed at the bottom of the vertex of the beam. Theoretically, the structure of the FBGV can be treated as a spring-mass system, when a vibrating object is attached to the base of the FBGV, the motion of the vibrating object will be cause relative motion between the mass (at the vertex of the beam) and base, which results in strain being applied to the FBG. The value of the mass and the elastic property of the beam determine the relative magnitude of the strain applied to the FBG for a particular vibration or acceleration. The force applied on the mass ($F$) can be considered to be linearly proportional to the acceleration ($a$) of the object being tested:

$$F=Ga, \tag{1}$$

where $G$ is a constant. Assume that the thickness and the width of the beam are, respectively, $H$ and $w(x)=kx$, where $k$ is a constant. The strain along the bisector of the top surface can be deduced as[6]

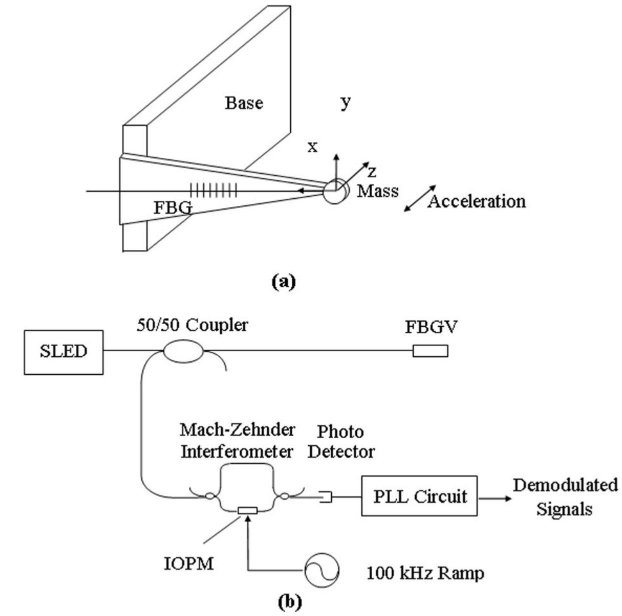


**Fig. 1** (a) Structure and (b) experimental setup of the FBGV: SLED, superluminescent light-emitting diode; IOPM, integrated optical phase modulator; FBGV, fiber Bragg grating vibrometer.

$$\epsilon(x)=\frac{H}{2E}\,\frac{M(x)}{i(x)}=\frac{H}{2E}\,\frac{Fx}{w(x)H^3/12}=\frac{6G}{EkH^2}a, \qquad (2)$$

where $M(x)$ and $i(x)$ are bending moment and inertia moment of beam section, respectively; and $E$ is Young's modulus of the beam material. We can see from Eq. (2) that the strain applied on the FBG is independent of position $x$ and therefore the spectrum of the FBG should not show any chirping characteristic in response to the vibration. This strain is transferred to the FBG with a coefficient $\eta$ and causes a shift in the Bragg wavelength[1]:

$$\Delta\lambda_B=\eta\lambda_B\left\{1-n^2\left[p_{12}-\frac{v(p_{11}-p_{12})}{2}\right]\right\}\epsilon=Ca, \qquad (3)$$

where $n$, $p_{11}$, $p_{12}$, and $v$ are the refractive index, components of the strain-optic tensor, and Poisson's ratio of optical fiber, respectively. We define $C$ as

$$C=6\eta G\lambda_B\left\{1-n^2\left[p_{12}-\frac{v(p_{11}-p_{12})}{2}\right]\right\}\Big/(EkH^2), \qquad (4)$$

where $\Delta\lambda_B$ is linearly proportional to the acceleration of the vibrating object. When the acceleration $a$ is a time-varying signal, the wavelength shift $\Delta\lambda_B$ will have a corresponding dynamic change. With the use of a combination of an unbalanced Mach-Zehnder interferometer (MZI) and a phase-locked loop (PLL) detection can measure this dynamic change in the Bragg wavelength shift $\Delta\lambda_B$ and therefore the value of the acceleration.

## 3 Experiments and Results

Experiments were conducted using a setup shown in Fig. 1(b). The light from an SLED with spectral width of 50 nm was used to illuminate the FBGV via a 50/50 coupler. The nominal Bragg wavelength of the FBG in the FBGV was 1545.0 nm. The full width at half maximum (FWHM) and the reflectivity of the FBG were about 0.2 nm and 90%, respectively. The mass placed on the vertex of the cantilever beam of the FBGV can be varied from 1 to 2.5 g. Light reflected from the FBGV was passed through the same coupler again and guided into an MZI. An IOPM was placed in one arm of the MZI and used to produce a serrodyne modulation function at a repetition frequency of 100 kHz. The peak-to-peak phase excursion of the serrodyne modulation was set to be $2\pi$ to facilitate heterodyne signal processing.[5] The serrodyne interferometric process converted the measurand-induced FBGV wavelength shift to phase difference variations between the two interferometer arms and further into phase shifts of the serrodyne signals at the interferometer output. The modulated output signal from the MZI was detected by a photodetector. To recover the vibrating signal of the FBGV from the photodetector, the PLL detection method was used.

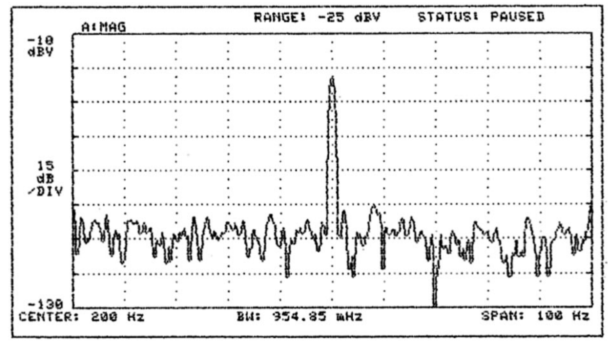


**Fig. 2** Frequency spectrum of the FBGV output when the peak value of the acceleration of the vibrating object is 0.177 g and the frequency is 200 Hz.

The performance of the FBGV was evaluated by attaching the base of the FBGV to a vibrating object (mechanical vibrator). For the purpose of comparison, an electronic vibrometer (model, Aihua AWA5933) was also attached to the object being tested to measure the peak acceleration of the object. Figure 2 shows the recorded output obtained from a dynamic signal analyzer when mass at the vertex was set to 1.5 g. The frequency of the dynamic signal was 200 Hz with a peak acceleration measured using the electronic vibrometer to be 0.177 g. The time-domain waveform can be see from an oscilloscope to be a sinusoidal signal at 200 Hz but is not shown here. The SNR is 56 dB at a bandwidth of 0.95485 Hz. The noise-limited resolution can be calculated to be $2.8\times10^{-4}$ g/$\sqrt{\text{Hz}}$.

To measure the repeatability of the FBGV, the peak value of the acceleration of the vibrating object was varied within a range of 0.023 to 0.238 g at frequency of 200 Hz with a constant step four times within 5 min. The outputs of the FBGV output were recorded and are shown in Fig. 3. The experimental data from the four scans were least-squares fitted to a linear equation and the standard deviation from this linear fit was found to be less than 1.02 mV. This indicates that the measured repeatability was less than 2.4% within the 42-mV measurement range.

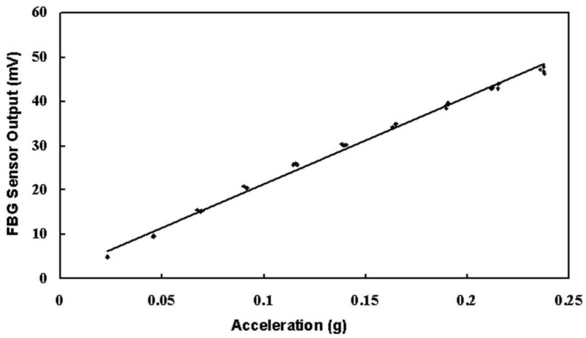


**Fig. 3** Relation between acceleration and output signal of FBGV.

It should be noted that response of the FBGV depends on the mass applied on the vertex. Figure 4 shows the frequency response of the FBGV for different values of mass placed on the vertex. The frequency response is relatively flat from 280 to 420 Hz and has a resonance peak around 200 Hz, corresponding to the resonance frequency of the cantilever-mass system. Figure 5 shows the FBGV output that was obtained from a dynamic signal analyzer when two approximately equal accelerations components of 0.047-g peak value at the frequencies of 180 and 220 Hz were applied on the tested vibrating object. The SNRs were both around 40 dB at a bandwidth of 1.9097 Hz. The noise-limited resolutions were found to be less than 3.4 $\times 10^{-4}$ g/$\sqrt{\mathrm{Hz}}$.

## 4 Conclusion

We reported a novel type of optical vibrometer design that uses a triangular beam with a mass placed on the vertex of the beam and an FBG attached to the bisector of the isosceles beam. The advantages of our vibrometer are the strain induced to the FBG in the sensor head due to vibration is uniform and this structure has lower cross-axis sensitivity. The use of an unbalanced MZI and PLL demodulation scheme enhance measurement resolution. The noise-limited acceleration resolution of this FBGV was found to be 2.8 $\times 10^{-4}$ g/$\sqrt{\mathrm{Hz}}$ and the repeatability is less than 2.4%. This type of vibrometer can be easily multiplexed by use of WDM because of the wavelength-encoded nature of the FBGs. All the FBGVs within the multiplexed system can in principle be demodulated by using the same demodulation unit (MZI+PLL), reducing the cost per FBGV.

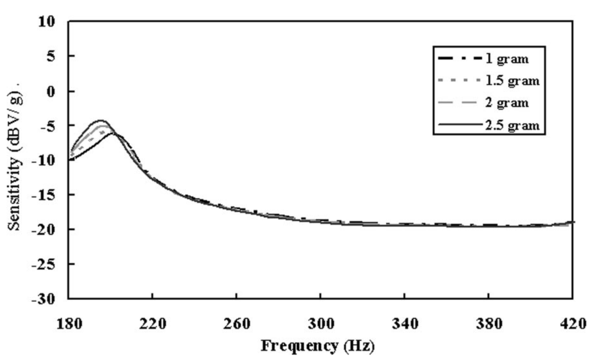


**Fig. 4** Frequency response of FBGV with varying mass.

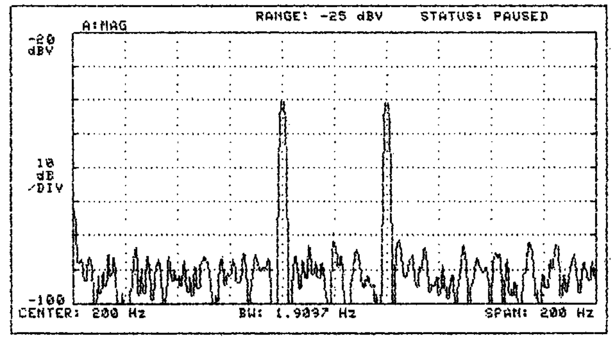


**Fig. 5** Frequency spectrum of the FBGV output when the vibrating object is excited by two sinusoidal signals at the same time. The two signals have frequencies of 180 and 220 Hz, respectively, and a peak acceleration of ~0.047 g.


### Acknowledgment

This work was supported by the Hong Kong SAR government through a CERG Grant No. PolyU5105/99E.


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Biographies and photographs of the authors not available.