MICROMACHINED, FIBER – OPTIC BASED ACCELEROMETER WITH SHUTTER MODULATION

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ABSTRACT

A highly sensitive shutter modulated fiber-optic accelerometer has been fabricated and characterized. Its structure is based on a mass suspended by two side-by-side cantilever beams. A vertical shutter at the free end of the mass can move vertically in the optical path between two multimode optical fibers. Cantilever beams, mass, shutter and optical fiber grooves are fabricated by advanced deep reactive ion etching (ADRIE). The accelerometer is characterized using a supra luminescent diode (SLD). A resonance frequency above 1 kHz and a measurement range of ±5 g are measured. To demonstrate the potential of using an economic light emitting diode (LED), an experiment with 2 µW input power was performed. It resulted in a noise equivalent acceleration of 2 mg.

INTRODUCTION

Many devices for industrial process, aerospace and military applications have to be able to withstand high electromagnetic fields. Sensors able to operate in these environments are often based on optical measurement methods. Intensity dependent optical sensors monitor the intensity of the light collected at one or several photo detectors after it has been influenced in some way. They require only simple measurement means and low spectral quality of the light source and therefore have the potential to employ LEDs as light source.

A great variety of micro-opto-mechanical accelerometers based on intensity modulation techniques have been published. They consist mostly of optical fibers combined with silicon microstructures [1,2] or fully integrated opto-mechanical microstructures [3,4]. These intensity modulation-based accelerometers can be separated into two categories. The first contains sensors whose response depends on a fiber or waveguide being bent or displaced, while the second contains those devices whose response is determined by a movable micromachined. Accelerometers in the first category often have the disadvantage that the acceleration direction is not determined in addition to a lack of sensitivity [2, 4]. Ollier [3] could overcome the drawback of the unknown acceleration direction with an integrated single mode input wave guide, a multi mode interference coupler and two output wave guides. Examples of accelerometers in the second category include one reported by Malki et al. [1] based on a mirror reflecting the light back into the optical fiber. A cantilever beam with the proof mass between the mirror and the fiber deflects the light beam, depending on the force applied on it. One of the advantages of devices such as these is that the acceleration direction is known. However, the mirror was not micromachined and had to be glued onto the substrate. The micromachined mechanical structure with the cantilever beam also was fixed to substrate by gluing.

Another interesting aspect is the quality of light of the light source used in intensity modulated sensor. Advantages of intensity modulation include the simplicity of the principle itself and the fact that no high spectral quality of the light source is required. Most of the optical intensity modulated accelerometers, however, are designed for use with of laser sources [2-4].

In this paper, we present a sensitive fiber optic based accelerometer which is easily fabricated on a single chip, and detects the acceleration direction, and which could use an LED as light source. Its structure is based on a mass suspended on two side-by-side cantilever beams. A vertical shutter at the free end of the mass can move vertically in the optical path between two multimode optical fibers, as shown in fig.1. With the ADRIE [5] technique, it is possible to etch a vertical shutter [6], together with the cantilever beams and mass in one single step. Alignment grooves for passive alignment of the optical fibers are also fabricated in the same step.

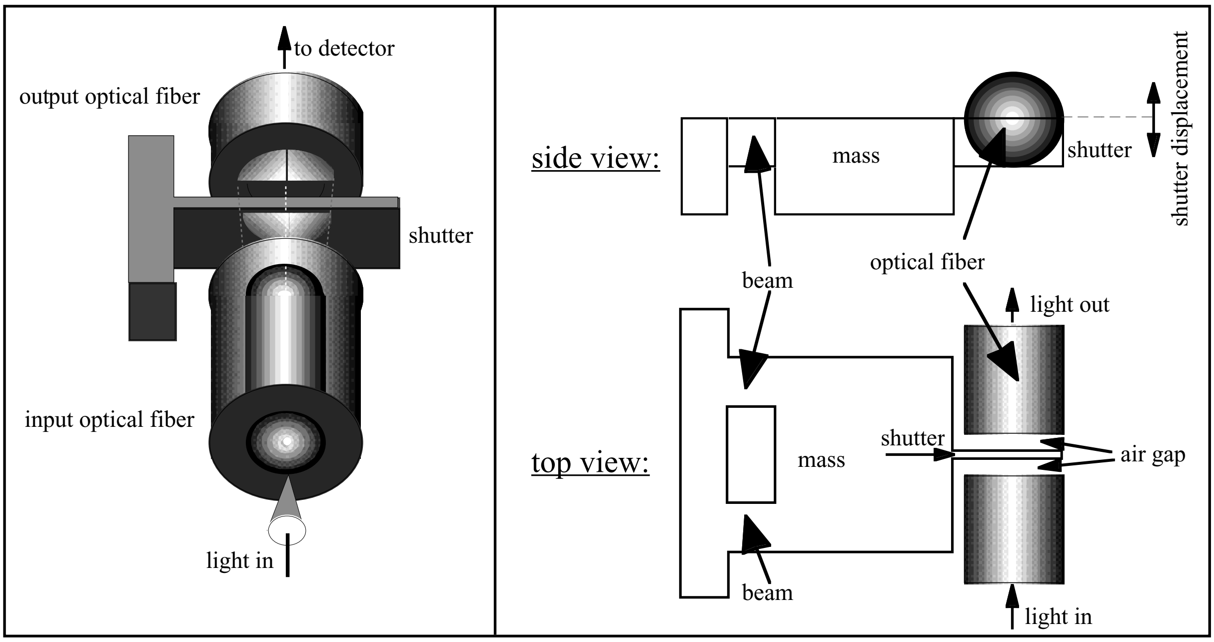

Figure 1: Optical displacement detection principle. Acceleration causes the vertical shutter to be displaced vertically. In the zero acceleration position, half of the light is coupled into the output fiber and the other half is blocked by the shutter. If the shutter moves up or down, less or more light is coupled into the output fiber. Signal intensity therefore also allows acceleration direction to be deduced.

DESIGN

In this study, the goal is to fabricate an accelerometer for electromagnetic machine vibration monitoring in the range of ± 2 g and a resonance frequency of around 1 kHz. Before designing the accelerometer, the micromachined optical shutter modulation technique (MOSMOD) was investigated on test structures.

For the shutter displacement experiment, the input fiber of the test structures was connected with a SLD source. The output-fiber is connected to a photodiode followed by a current to voltage converter. The maximum detected power in this experiment is 100 µW. Figure 2 shows the normalized voltage response on shutter displacements for a input fiber-to-shutter air gap of 10 µm. The air gap between the shutter and the output fiber was fixed at 5 µm (± 1 µm). Table 1 gives characteristics such as linear range and displacement sensitivity for three different air gaps between input fiber and shutter measured on different test structures. In the worst case, the displacement resolution is below 2.5 nm. The test structures proved (tab. 1) that the use of 50 µm core diameter multimode fibers resulted in useful linear displacement ranges above 5 µm. Full scale displacements of ± 2.5 µm can therefore be reached in the ideal case where shutters edge is exactly at the center of the optical fiber core at zero acceleration. But in practice the fiber diameter is known within ± 2 µm and

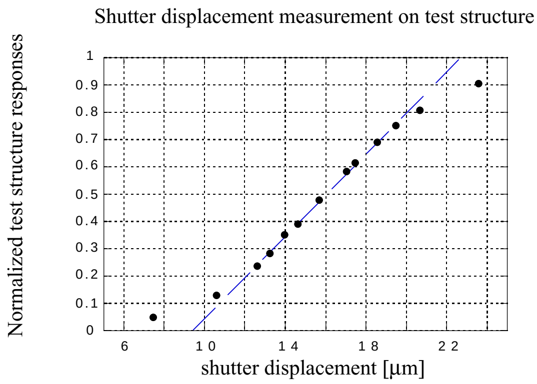

Figure 2: Measured test structure response. Shutter's top edge reaches the half height of the optical fiber at around 16 µm. The dashed line is the fit of the linear portion of the response.

TABLE I: Test structure characteristic

Input fiber - shutter / shutter – output fiber distance [µm],±1µm	Linear range [µm]	Displacement sensitivity [µW/µm]
2 / 5	6.18	8.4
10 / 6	6.87	7.4
18 / 5	8.82	6.17

the core diameter within ± 3 µm. From these data it is assumed that the core center can vary within ± 1.5 µm compared to the edge of the shutter. Full scale displacement of the shutter for sensing applications should therefore not exceed ± 1 µm.

The test structures used to investigate the MOSMOD technique were based on a vertical shutter movement. In practice it seemed easier to realize an experiment for vertical displacement and measurement than for horizontal. The accelerometer prototype presented in this paper is also based on a vertical shutter displacement principle. It has the advantage that it offers the planar mass surface as damping plate for a squeezed film damping. Of course the MOSMOD technique could allow also a horizontal detection direction. The test structures are based on an input and an output optical fiber. For practical reasons, one might desire only one optical fiber bonded to the micro-structure. This requires the detection of reflected light power from the shutter, which could be accomplished by connecting a fiber coupler between the light source and the input fiber. The drawback of the reflection method is its dependence on the optical mirror quality of the shutter.

The accelerometer was designed for a shutter displacement of approximately 0.35 µm under a vertical acceleration of 1 g. This gives a full scale displacement of ± 0.7 µm, which lies in limits discussed previously. The height of the optical shutter and depth of fiber grooves should ideally be half of an optical fiber diameter, say 62.5 µm.

FABRICATION

Double sided photolithography with 10 µm of AZ 4562 photoresist from Shipley is performed on a silicon on insulator (SOI) wafer containing a 61 µm thick top and 307 µm bottom silicon layer with a buried 2µm layer of oxide in between. The vertical shutter (Fig. 3), the fiber grooves (Fig. 4), the cantilever beams and the front side mass structure are fabricated by ADRIE. Back side etching to shape the mass and to liberate the moving part of accelerometer is also performed in this way. Fig. 5 shows the shutter and Fig. 6 the cantilever beams and a part of the mass viewed from the backside. The buried oxide layer serves as double-side etch stop. After stripping the photoresist and cleaning with piranha (conc.H_2SO_4 : 30%H_2O_2, 50:1) the remaining buried oxide is removed in a buffered hydrofluoric acid (BHF) bath. To have an optically sufficient shutter quality, a gold layer is deposited by e-beam evaporation. Finally, the fibers are inserted and bonded with UV-sensitive glue.

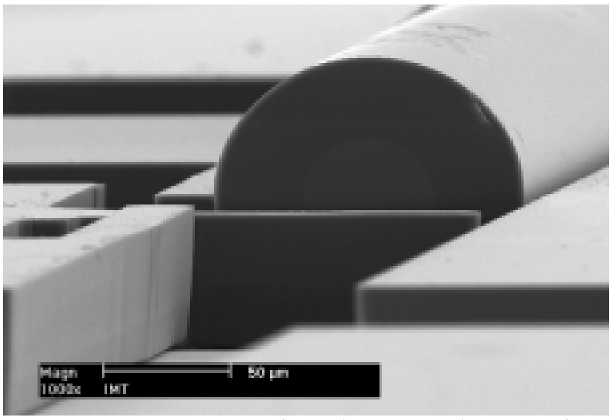

Figure 3: SEM picture of accelerometer shutter in front of a 125 µm diameter fiber with 50 µm core.

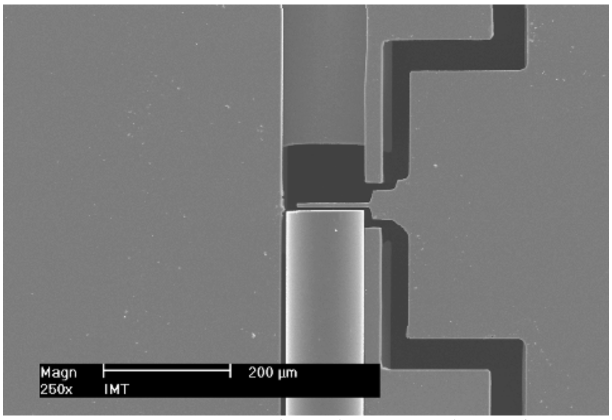

Figure 4: SEM picture of accelerometer shutter from top

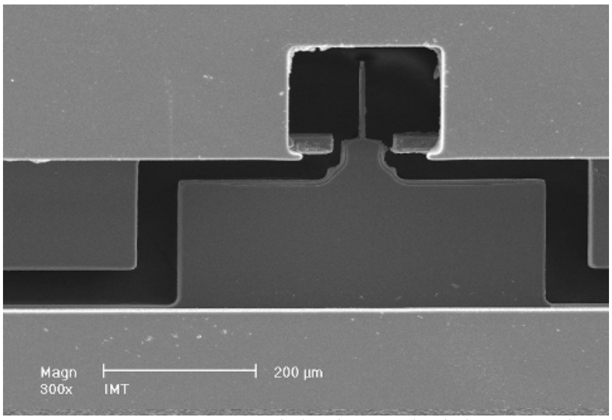

Figure 5: SEM picture of the free end of the mass from back side.

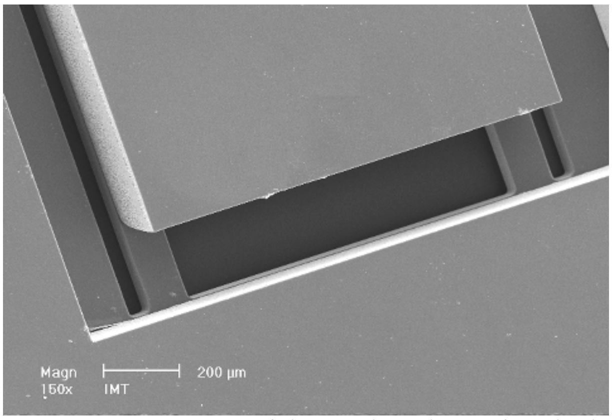

Figure 6: SEM picture of the cantilever beams from back.

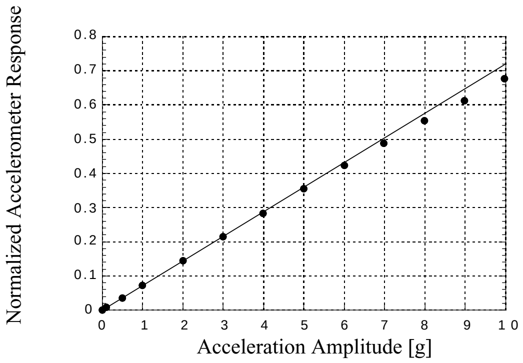

Figure 8: Amplitude response measurement at 133 Hz.

CHARACTERIZATION AND DISCUSSION

The characterization consists of two sets of experiments. In the first, set the frequency and amplitude response were measured using a lock-in amplifier. The noise equivalent acceleration is also measured. The second part involved demonstrating the use of an economic LED as next generation accelerometer light source.

For the characterization of the accelerometer, the input fiber was connected to a SLD source with a wavelength of 840 nm, The output fiber was connected to a photodiode followed by a current-to-voltage conversion circuit with a bandwidth of 3.5 kHz. Maximum detected power in this experimental part is 50 µW. The reference accelerometer and the prototype accelerometer were mounted on a vibration table. The amplitude of the accelerations was monitored by the reference accelerometer. The output signal of the prototype device was recorded using a lock-in amplifier. Figure 7 shows the result of the frequency response measurement. The measured resonance frequency of 1089 Hz corresponds well with the calculated value of 1079 Hz.

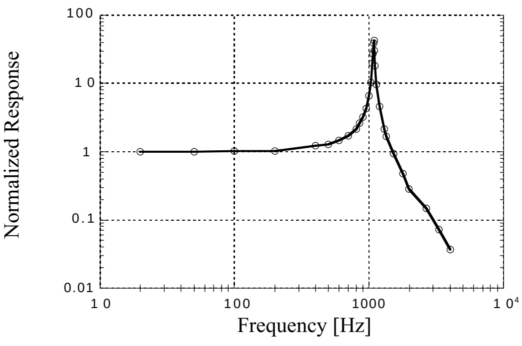

Figure 7: Frequency response measurement.

Amplitude response measurement was performed at 133 Hz, and shows a linear range of ± 5g (Fig. 8). The noise was measured when the vibration table was off. Its voltage standard deviation at the output of the basic current-to-voltage circuit with a bandwidth of 3.5 kHz corresponds to 5 mg.

The second part of the characterization consisted of a low input power experiment to simulate an LED light source. The SLD source couples 1.8 µW into the input fiber of the accelerometer. The photo diode amplifier had a bandwidth of 500 Hz. Fig. 9 shows the photo-diode output signal for three different acceleration values around 1 g at 133 Hz. The standard deviation of the acquired voltage is 1.25 mV which corresponds to an acceleration of 2 mg. The noise equivalent acceleration is therefore 90 $\mu gHz^{-0.5}$.

CONCLUSION

The combination of ADRIE and multimode optical fibers made possible the fabrication of a simple but sensitive fiber optic accelerometer machined on a single chip and capable of detecting acceleration direction. Its structure is based on a mass suspended by two side-by-side cantilever beams. A vertical shutter at the free end of the mass can move vertically in the optical path between two multimode optical fibers. This micromachined optical shutter modulation (MOSMOD) technique has been investigated and exhibited a displacement resolution below 2.5 nm and a linear range of 5 µm for a fiber core diameter of 50 µm. This compares favorably with a recent integrated waveguide accelerometer [4] which showed a displacement resolution of 10 nm.

The accelerometer was characterized using an SLD. A resonance frequency above 1 kHz and a measurement range of ±5 g have been measured. To demonstrate the potential of using an economic LED light source in next generation accelerometers, an experiment with less than 2 µW input power was performed. It resulted in a noise equivalent acceleration of 90 $\mu gHz^{-0.5}$ which corresponds to a resolution of 2 mg. The total absence of electronics, sensitivity, structural simplicity and the potential to use a LED light source makes this accelerometer a device having a broad range of applications.

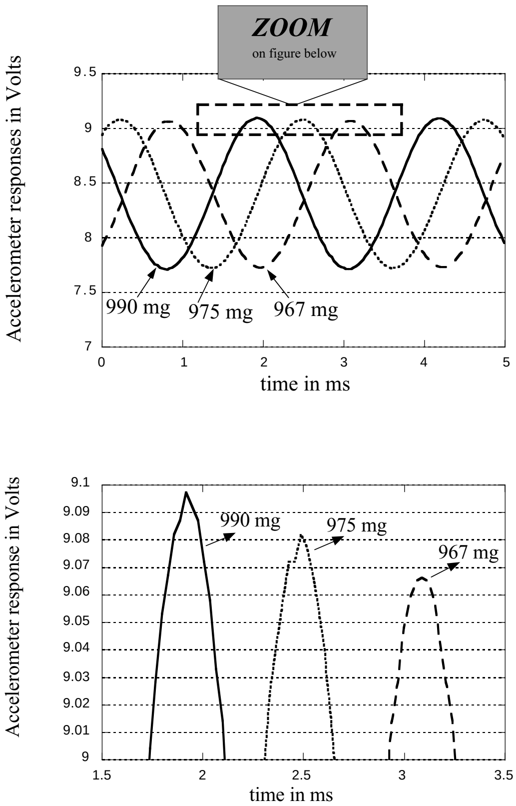

Figure 9: Photo diode amplifier response to three different acceleration amplitudes. The upper graph is zoomed and shown in the figure below.

OUTLOOK

The prototype accelerometer presented in this paper used fibers with a core diameter of 50 µm to obtain a useful range of 5 µm. Due to core and fiber diameter uncertainties, as well as errors on wafer thickness, a lower displacement range is practically useless. For future applications, however, a higher useful displacement range can be of interest. This goal can be reached by increasing the air gap between the input fiber and the shutter as shown in the experiments. However, it introduces coupling losses which must be avoided if an LED source is used. To increase the displacement range, it is therefore preferable and possible to use higher fiber core diameters. The MOSMOD technique makes possible displacement sensitivity in vertical as well as in horizontal direction. By using fibers with different core diameters, the displacement range and sensitivity can be adapted. Due to this flexibility, sensing devices other than accelerometers could be fabricated.

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