DEVELOPMENT OF AN OPTICAL MICRO AE SENSOR WITH AN AUTOMATIC TUNING SYSTEM

HIROSHI ASANUMA, HIRONOBU OHISHI, and HIROAKI NIITSUMA
Graduate of Environmental Studies, Tohoku University, Sendai 980-8579, Japan

Abstract

A prototype optical micro AE sensor, which has a mechanism for automatic tuning of the operating point, was fabricated using micro electromechanical systems (MEMS) technologies, and its performance was evaluated. The AE signal is detected by a interferometric pattern of returning lightwave from a Fabry-Perot interferometer (FPI) which consists of a half mirror at the edge of a optical fiber and a full mirror on a moving mass. The mechanical part of the micro optical AE sensor was designed to have a resonant frequency at 50 kHz. The linearity and sensitivity of this sensor is highly dependent on the initial gap length between the fiber and the moving mass because of non-linearity in the interferometric pattern of the FPI. To control gap length, we fabricated electrodes on the cover glass plate. This allows the initial gap to be automatically tuned by electrostatic force. Laboratory tests to evaluate performance of the AE sensor have demonstrated that the linearity, sensitivity and signal to noise ratio were improved by the automatic tuning.

Keywords: AE sensor, MEMS, Optical sensor, Fabry-Perot interferometer, Automatic tuning

1. Introduction

Technologies related to micro-electromechanical systems (MEMS) have progressed remarkably over the last decade and commercial products, which use the MEMS technology, are now widely available. Micro-sensors fabricated by the MEMS technology are one of the major and promising application areas of this technology. Micro-mechanical sensors, micro-acoustic and micro-seismic sensors, micro-medical sensors, and micro-optical sensors have been developed and their advantages over existing sensors have been demonstrated.

The authors have been developing microsensors mainly for geophysical/near-surface environmental measurement under the “Subsurface Microsensing Project” since 1993 [1]. Capacitive accelerometer, fiber sensors, optical hydrophone and ultrasonic sensors are studied in the project, and some of the sensors have now become commercially available [2, 3].

One of the major research areas currently under investigation in the project is the field of optical acoustic/seismic/ultrasonic microsensors using the principles of the Fabry-Perot interferometer (FPI) [4, 5], because of the simplicity in the principle and the availability of MEMS technologies for fabrication. The FPI is a variation of interferometers, where a multiply reflected lightwave at a gap of full and a half mirrors is outputted. The interferometric pattern (spectra) of the output changes associated with gap length. We have employed this property by fabricating a FPI which consists of a half-mirror at the fiber end and a full mirror on the moving mass/diaphragm and have detected displacement of the moving mass/diaphragm. Although the prototypes of the optical microsensors with FPI worked successfully [4, 5], we have found that
the precise control of the gap length presents a fabrication difficulty. In many cases, the authors inserted an optical fiber with a half mirror to the silicon/glass structure at the final stage of the fabrication, and the gap length is defined manually at this stage. The typical gap length of the FPI in the microsensors in our group is 20-40 μm, and the variation in the gap length is not negligibly small for the commercial use of the sensors where a laser with a single wavelength should be used to reduce the system cost.

Considering above mentioned problems, the authors had started to develop an ultrasonic/AE sensor which can automatically control its operating point to have the best performance. The concept, principles, fabrication process and results from laboratory tests are described in this paper.

2. Outline of the Autotuning Mechanism

The concept of the automatic tuning of the FPI sensor, which was employed in this study is shown in Fig. 1. The FPI consists of a half mirror at the end of the optical fiber and a full mirror on a moving mass, which is suspended by thin silicon beams. The interferometric pattern of the FPI changes with the reflectivity of the mirrors that is uniquely defined for each sensor, and the length of the gap which changes by externally applied acceleration. The typical initial gap length is around 20-40 μm, and it is determined by the manual process of inserting the fiber into the glass/silicon/glass structure. In the micro-accelerometer with an automatic tuning mechanism, an electrode is fabricated on a bottom glass plate, and an electrostatic force is generated by applying a voltage to it to change the length of the initial gap. The sensitivity and linearity of the sensor depends on the interferometric pattern of the FPI for a wavelength \( \lambda \) and this system automatically finds the optimum operating point by changing the gap length (see Fig. 2).

![Fig. 1: A schematic view of the optical micro-accelerometer with an electrode to control the initial gap.](image)
A block diagram of the prototype system incorporating automatic tuning is shown in Fig. 3. A wideband lightwave source (ASE: Amplified Spontaneous Emission) is used as an input of the lightwave to the sensor. The interfered lightwave at the sensor is then transmitted to an optical narrow-band filter using the FBG (Fiber Bragg Grating) [6]. The intensity of the filtered lightwave is converted to voltage at a photodiode (PD) and sent to both data display/acquisition as an output and to a PC with system control software. To start the system, the PC sends a control signal to the DC-DC converter and the optical response is collected for different gap lengths. The software finds the optimum operating point where the maximum sensitivity/linearity is obtained and then continuously applies a static voltage to hold this operating point.
3. Design and Fabrication of the Sensor

The mechanical part of this sensor is a resonant system in the first order. We have designed the prototype to have a resonant frequency at 50 kHz. Considering the damping effect in the sensor, which is mainly influenced by air damping in the gap of glass/silicon, we can design a system in the state of critical damping or over-damping for wideband performance. However, we decided to design the system to have strong resonance, suppressing the damping factor, because there are some unknown points in the behavior of the air damping at higher frequency and we preferred higher sensitivity rather than a flat frequency characteristic in this study.

![Image of sensor](image)

**Fig. 4: An external view of the sensor.**

The external form of the sensor is shown in Fig. 4, where top, bottom and side views of the sensor are shown. The sensor has a “sandwich” structure of glass/silicon/glass and has a dimension of 5 mm x 5 mm x 2.2 mm. A moving mass with an aperture of $1.96 \times 10^{-7}$ m$^2$, is suspended by 16 beams with a width of 20 μm.

The MEMS process mainly consists of a combination of standard techniques including photolithography, etching, and sputtering. A part of the process of the silicon structure is shown in Fig. 5. A technique of anodic bonding was used for the bonding of the silicon and glass parts. Almost all the process, except for the sputtering of a half mirror on the end of the optical fiber, can be realized by conventional MEMS facilities. Because a number of microsensors can be fabricated on a single silicon wafer, which has a typical size of 4”/8” in the industry, cost reduction and uniform performance of the sensors can be expected. A photo of the assembled sensor is shown in Fig. 6. The software for automatic tuning was developed using a commercial software package (LabView).

4. Evaluation of System Performance

The interferometric pattern of the fabricated sensor at different applied voltages to the electrode for the control of the gap length is shown in Fig. 7. It is seen that the interferometric
pattern has moved approximately 6 nm after applying 200V to the electrode. This shift corresponds to a change in the gap length approximately 0.18 μm. It is also seen that the interferometric pattern is distorted after applying 200V, suggesting that the silicon mass did not displace uniformly relative to the electrode.

Because of difficulties in precisely evaluating the absolute sensitivity in the frequency range of several tens of kHz, we inputted a sinusoidal wave from a PZT transmitter to a thin (t = ~20 mm) rock specimen and observed the output. Figure 8 shows the output from the optical sensor and that from PZT receiver for an input of 50-kHz sinusoidal wave. In this experiment, the automatic tuning was disabled as the objective was to prove that the optical sensor itself was working. It is seen from Fig. 8 that the transmitted signal is detected by both optical and
reference detectors. We interpret the distortion that appeared in the trace to have resulted from the effects of transmission of the acoustic signal in the heterogeneous rock specimen and from power instability of the optical source (ASE). Because our measurements recorded the sensitivity of the overall system, which is the sum of the sensor sensitivity and the sensitivity/gain of the processing circuit, it was not possible to determine the sensitivity of the sensor in isolation.

The waveform and power spectral density from the optical microsensor with and without the automatic tuning for an input of 40 kHz sinusoidal wave propagated through rock specimen is shown in Fig. 9. It is seen that the detected signal is more stable after the automatic tuning. The intensity of the spectra at 40 kHz is increased approximately 6 dB after the shift of the operating point by the automatic tuning. The signal to noise ratio around 40 kHz is approximately 50 dB, although higher contamination by noise, mainly from the optical source and photodiode, is seen in lower frequency.

5. Conclusions

This paper describes the principles, design, fabrication and evaluation of a micro-optical AE/ultrasonic sensor with a mechanism for automatic tuning. It has been demonstrated that the prototype of the sensing system successfully worked at the optimum operating point where the FPI had the best sensitivity and linearity.

The automatic tuning system brings additional merits to the improvement of sensitivity/linearity. The shift of operating point of the FPI allows the use of a laser working at a single wavelength, bringing a further cost reduction of the system since a tunable laser is now not required. If a wideband optical source is used such as the ASE in this study, an array of sensors could be realized because the interfered light wave could be multiplexed on one fiber.

There some points still to be investigated/improved in this system before commercialization. One is the improvement of the dynamic range. A system to compensate for the noise in
roduced by instability of the ASE will effectively work to suppress noise under 10 kHz. The use of an optical amplifier in the input line or a low-noise OE will further improve SNR around the operating frequency of the sensor. In the prototype we applied a maximum voltage of 200V, but this was insufficient to move the mass in a wide range. Further optimization of the design of the mechanical parts consisting of the moving mass, suspending beams and electrodes could improve the performance of the automatic tuning system.

Fig. 8: Outputs from optical and reference sensors for input of 50 kHz sinusoidal waves.

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References


Fig. 9: Trace and power spectral density from the optical micro-sensor without/with the automatic tuning for an input of 40-kHz sinusoidal waves.