Development of Fiber-optical Microsensors for Geophysical Use

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ABSTRACT

Technologies related to the Micro ElectroMechanical Systems (MEMS) has been remarkably progressed in this decade, and various kinds of microsensors have been developed using the MEMS technologies. Microsensors have a potential to drastically improve the geophysical instrumentation, because they have advantages in size, weight, sensitivity, mobility, and cost to the conventional sensors. Researchers in Graduate School of Environmental Studies, Tohoku University, Sendai, Japan, have been developing microsensors for geophysical use under the “Subsurface Microsensing Project” since 1993.

In this paper, the authors show principles behind a miniaturized capacitive accelerometer, fiber-optic hydrophone and optical accelerometer. A Fabri-Perot interferometer, which consists of a half mirror at the edge of optical fiber and a full mirror on diaphragm, is fabricated using the MEMS technologies for the detection of dynamic pressure in water and acceleration in the optical sensors.

1. INTRODUCTION

Technologies related to the MicroElectroMechanical Systems (MEMS) have made remarkable progress in the last decade. Various kinds of microsensors have been developed using MEMS technologies, which includes silicon processes and bonding techniques. Some types of microsensors have been commercially available for medical and industrial use. The micro sensors have the ability to drastically change the concept of the geophysical instrumentation, because they have the following advantages; (a) low cost is expected through mass production, (b) mobility in installation and in measurement, (c) optical microsensors have durability under harsh environments, and (d) high sensitivity and wide-band nature is realised through the small driving force needed for microsensors. Research on microsensors for subsurface use has become active worldwide in recent years 1, 2).

The authors have been developing microsensors and related technologies under the "Subsurface Microsensing Project" since 1993 3). The use of microsensors in geophysical measurements enables us to reduce cost for fabrication and installation/collection of sensors. It is also possible to realize an intelligent borehole, which is used for both production and instrumentation, by installing microsensors in the annulus or on the tubing. Intelligent logging tools can be built by installing various kinds of microsensors. The good potential of prototype of geophysical microsensors, such as capacitive micro accelerometer, optical interference micro accelerometer and micro sonde, which are fabricated from silicon and glass, has been previously reported by researchers in Tohoku University 4,5,6,7,8).

In this paper we report the concept and performance of prototypes of capacitive accelerometer, fiber-optic hydrophone and optical accelerometer with their design concept, fabrication provess and performance evaluation.

2. SILICON CAPACITIVE ACCELEROMETER

A conceptual structure and a photo of the fabricated silicon capacitive accerlometer fabricated by the authors are shown in Figure-1 and 2 respectively. This accelerometer has a size of 9mm×5mm×2.2mm. A moving mass suspended with beams are fabricated by MEMS techniques. The silicon plate is bonded between two glass plates using a anodic bonding. Electrodes for detection of displacement of the moving mass as a change in capacitance are sputtered on the glass plates. A non-evaporative

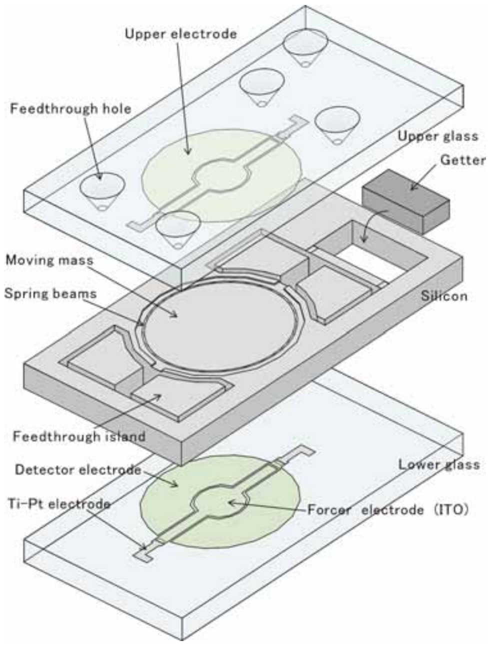

Figure-1: Structure of a silicon capacitive acceleroemter getter (NEG) was placed inside the cavity to reduce squeezed-damping effect which prevents the movement of the mass in higher frequency [9]. The sensitivity and bandwidth of the sensor are in a relationship of trade-off. Therefore, optimum design parameter was determined to have comparable performance with ommercially available downhole seismometer. A frequency characteristics of the accelerometer measured by a vibrator is also shown in Figure-3. The fabricated microaccelerometer had reasonably good performance as a seismic detector, although there is some difference in the designed and actual specifications. This difference was mainly due to difficulty to control a silicon process, and further trials to find better process parameters are underway. Investigation for electrical circuit with a low noise nature and a serveo is also on going. A commercial version of this micro-accelerometer is coming to the market in the autumn of 2003 from Akashi Co. Ltd., Japan.

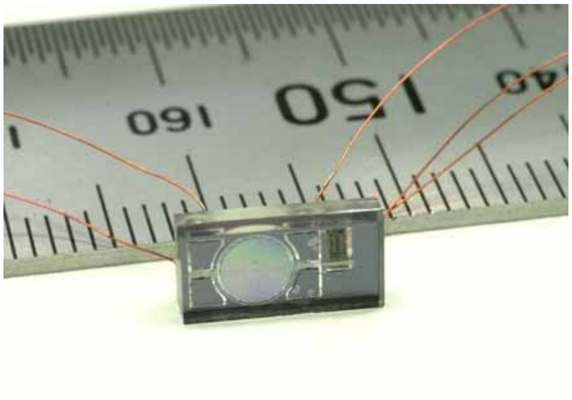

Figure-2: A photo of the silicon capacitive acceleroemter

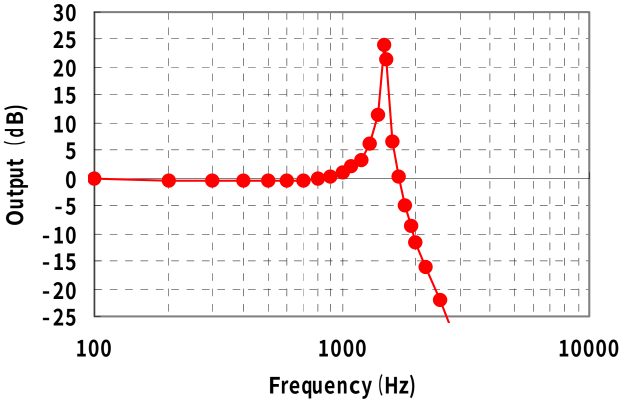

Figure-3: Amplitude characteristics of the silicon capacitive acceleroemter

2. OPTICAL HYDROPHONE

A photo of the prototype of the micro hydrophone fabricated by the authors is shown in Figure-4. The inside structure of the hydrophone, which was made from a silicon plate and reinforced glass, has a diameter of 5 mm and height of 3 mm. The internal structure is mounted in a metal case with a diameter of 9 mm and height of 13 mm for protection. It is designed to have a frequency response from approximately 100 Hz to 5000 Hz, and a sensitivity of -120 dB to -200 dB (0 dB is 1V/ P). This is a comparable performance with the piezoelectronic hydrophones that are commercially available. A Fabry-Perot Interferometer (FPI), which consists of a half mirror at the edge of the optical fiber and a full mirror on the diaphragm, is fabricated mainly by etching and anodic bonding. A laser beam with a wavelength of around 1550 nm is transmitted in the optical fiber and interferes at the FPI. By using the intensity of interference, the displacement of the diaphragm is detected.

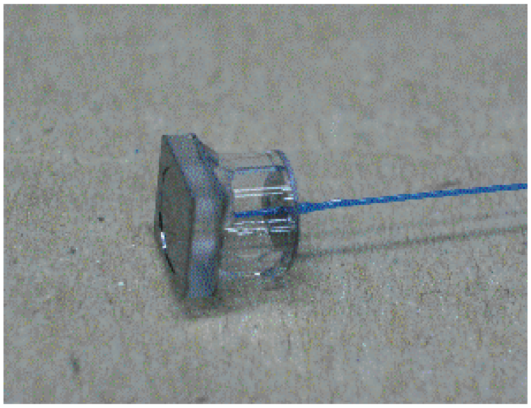

Figure-4:A photo of the optical hydrophone

The characteristics of the micro hydrophone was evaluated by a “Coupler Test Facility” of OKI Electronic Industry. The characteristics was instrumented from 1 Hz to 200 Hz using reference hydrophone. The optical micro hydrophone (Figure-5) showed a high pass characteristics as expected. The sensitivity of the micro hydrophone was approximately -192 dB at 200 Hz. The dynamic range of the hydrophone was estimated to be over 53dB. The noise level of the miro hydrophone was higher than the conventional ones, because of unstability in laser power and noise of O/E.

The micro hydrophone was modelled using the electro-mechanical equivalent circuit shown in Figure-6. The cavity, diaphragm and

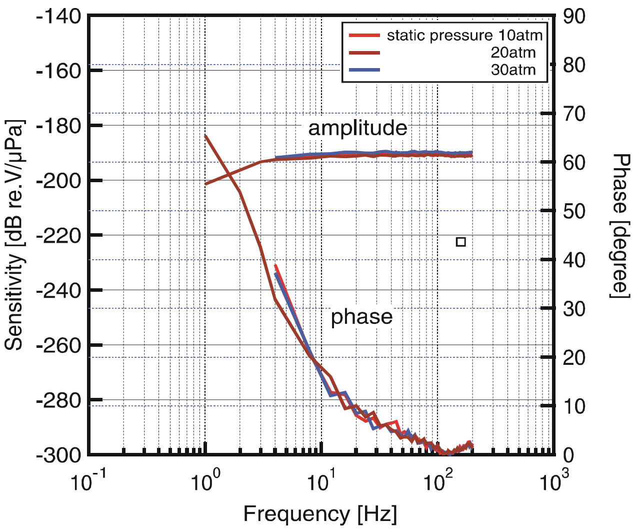

Figure-5:Amplitude and phase characteristics of the optical hydrophone groove are represented by impedance which are calculated from elastic constant of meterial/water, size, and water flow in the groove. The input voltage corresponds to the particle velocity of the water, hence, the displacement of the diaphragm is obtained by integrating the particle velocity.

The effect of the thin groove (φ10μm) is the most uncertain in the hydrophone. We, therefore, have tried to fit the frequency characteristics from the equivalent circuit to the experimental data by changing the size of the groove. We have fit characteristics from the model, although the size of the groove was larger than the designed one. This suggests that the other part of the hydrophone, possibly te coating of the fiber, transmits static pressure to the cavity 11).

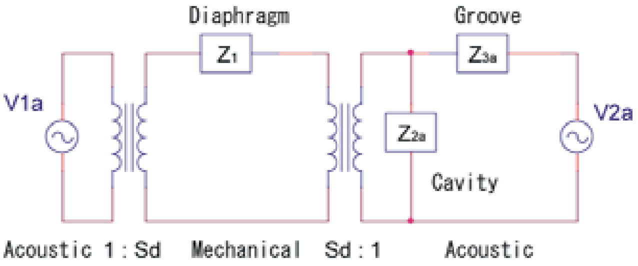

Figure-6: The electro-mechanical equivalent circuit of the optical microhydrophone.

3. OPTICAL ACCELEROMETER

The conceptual structure of the optical accelerometer is shown in Figure-7. A FPI is employed to the optical micro accelerometer as well as the optical micro hydrophone. The interference pattern (spectrum) of the returned laser signal changes associated with the displacement of the moving mass. A tunable laser is used as an input and intensity at a particular wavelength is used as an electrical output, although there are a lot of options to detect the change of the interference pattern. The accelerometer is designed considering the effect of spreading of the laser at a gap, frequency range (DC-1kHz), and higher sensitivity/linearlity.

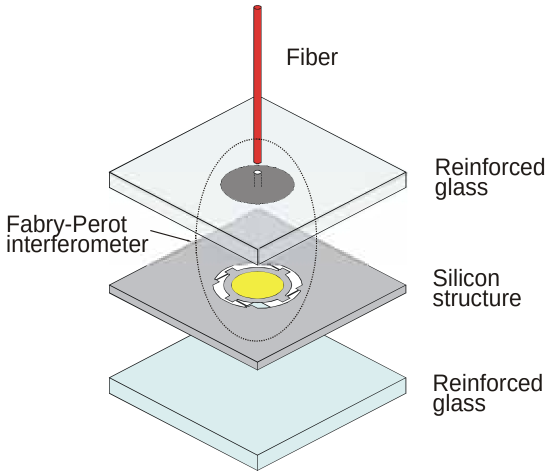

Figure-7: The conceptual structure of the optical micro accelerometer.

In the design of the second prototype, we have tried to make the process as simple as possible to have higher completion percentage. Nine accelerometers are fabricated on a 2cmX2cm silicon wafer and they are separated at the final stage of the fabrication. The advantage of the simple structure enables to fabricate using conventional MEMS facilities. Although we have to improve the control process of the initial gap, the micro accelerometer can be fabricated without a serious problem.

Because the gap between fiber and the moving mass is manually made, there are some divergence in the gap (±20%). The amplitude characteristics in Figure-8 shows that the sensor has flat response from DC to 1kHz as designed. The Q-factor of the resonance at 2.5kHz was lower than the designed because of the dumping effect of the thin air film between glass and silicon structure (squeeze film effect). The accelerometer was mounted to a shell and put in a test borehole on campus, and it detected artificial seismic wave from a downhole air gun.

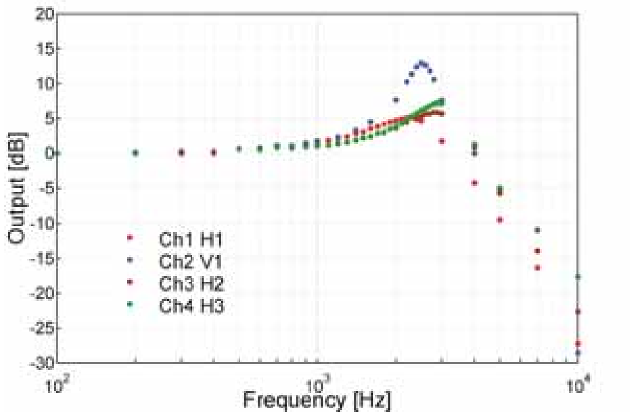

Figure-8: Amplitude characteristics of the optical micro accelerometer.

4. CONCLUSIONS

Outline of the development of a prototype of a micro downhole seismic detector with silicon capacitive accelerometers is described in this paper. The accelerometer fabricated with a silicon and glass plates had satisfactory performance as a seismic detector for geophysical use. The accelerometers are now assembled in a small sonde for a downhole use. It is demonstrated that this micro seismic detector has an ability to detect three dimensional motion of seismic waves in field.

A prototype of a miniaturized hydrophone/accelerometer was fabricated using MEMS technologies. A Fabry-Perot Interferometer was used to detect the elastic wave. The assembled hydrophone/accelerometer had a performance satisfying the initial design, although we intend to evaluate its performance in more detail.

The full passive nature of this optical micro hydrophone/accelerometer makes it possible to employ the sensors at high temperatures. The micro hydrophone/accelerometer has a size of less than 1/10 of the equivalent piezoelectronic ones in the market. An array of the micro hydrophone/accelerometer along with a optical telecommunication line is also realized by using a multiple fiber line or multiplexing. Detection of the distribution of pressure intensity in a borehole can be made using the micro hydrophone/accelerometer. The simple structure of this micro hydrophone/accelerometer enables us to fabricate it with the conventional MEMS facilities. Because of these advantages, the micro hydrophone/accelerometer would find various applications, including geophysical and marine measurement such as reflection/VSP/crosshole seismic surveys, microseismic measurement etc.

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