A SELF-EXCITED CHOPPER MADE BY QUARTZ MICROMACHINING AND ITS APPLICATION TO AN OPTICAL SENSOR

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ABSTRACT

We report the successful self-excited operation of the monolithic optical chopper made of quartz. The chopper is oscillated through piezoelectric strain induced by electric field between meandering electrodes on the flexible suspensions. The piezoelectric signal from the deformed suspension is detected to control the amplitude of oscillation at constant magnitude. We also employed this chopper in an optical sensor as a mechanical component to regulate the incident laser-beam, and demonstrated chopper-amplification and demodulation.

1 INTRODUCTION

Optical choppers have attracted arising attention as an application of Micro Electro Mechanical Systems [1]. We have developed a quartz chopper and reported the fabrication sequence, the scheme of piezoelectric driving, and mechanical characteristics in last *MEMS'93*[2] and *TRANSDUCERS'93*[3]. We selected quartz as a material for microfabrication because (A) piezoelectric effect of quartz is used to induce/detect the strain, and (B) quartz is anisotropically etched in hydrofluoric-acid based solution [4]. In this report we show the self-excitation of the chopper and operation of an optical sensor composed with this chopper.

We improved the driving circuit and succeeded in self-excitation. The oscillating frequency is automatically set to the mechanical resonance of the chopper, and the resonance is maintained against disturbance such as change in temperature and physical vibration. Furthermore, the amplitude of oscillation is also kept constant by a gain-controller. Thus we do not need an external oscillator nor need to adjust its frequency or amplitude.

We also composed an optical sensor with the quartz chopper, and could successfully demonstrated chopper-amplification and demodulation of the incident laser beam. This result confirms the feasibility of making a compact optical sensor that is composed of circuits, an optical detector, and a microfabricated chopper.

We believe this is the first report on successful operation of an optical sensor with a microfabricated chopper.

2 OPTICAL CHOPPER BY QUARTZ MICROMACHINING

Our goal is to make an optical sensor with a microfabricated chopper as illustrated in Fig. 1. The chopper is mounted on the substrate which has a detector and circuits.

Figure 2 shows an SEM view of the quartz optical chopper. The structure is made by anisotropical etching of quartz. The size is 6 mm × 7 mm in area, and 0.1 mm in thickness. The inside plate is supported by four folding suspensions; each one is 2 mm long and 50 microns wide. The suspension has electrodes for piezoelectric operation. As the inside plate oscillates horizontally, the incident light is regulated through the slits. The chopper is mounted on the silicon substrate (0.5 mm thick), fixed with glue, and packaged as shown in Fig. 3. We have a tiny through-hole drilled into the base-metal of the package in order to let the chopped light pass through to the detector underneath

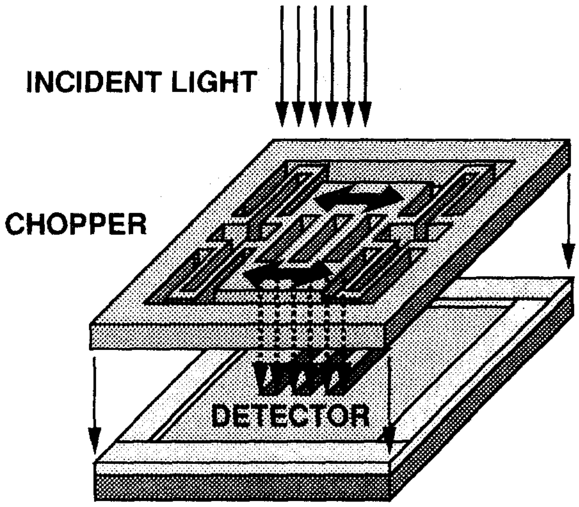


Figure 1: Concept of monolithic optical chopper

The incident light is regulated through the slit as the chopper plate oscillates horizontally.

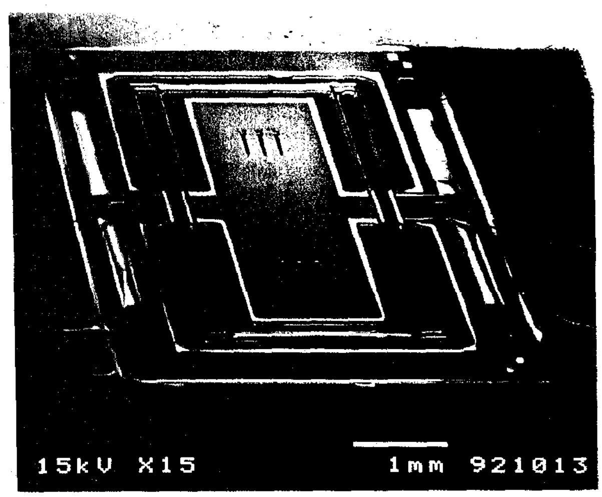


Figure 2: SEM view of the chopper

The size is 6 mm × 7 mm in area, 0.1 mm in thickness.

the package. Fabrication sequence and mechanical characteristics was reported in [3].

3 PIEZOELECTRIC SELF-EXCITATION

Self-excitation of the chopper is needed to maintain the resonance of the chopper against change in temperature. Moreover it is necessary to make the driving circuit, and thus the total system compact. Since quartz has piezoelectric effect, we could make a self-excitation system based on this effect: The chopper is oscillated through piezoelectric strain induced by electric field between

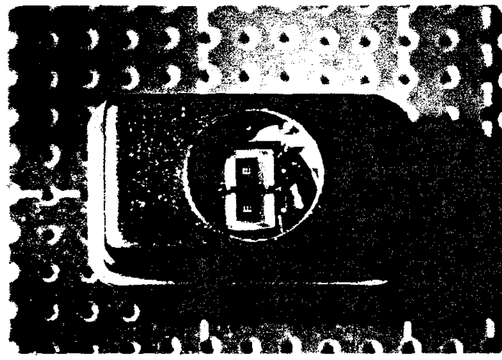


Figure 3: Packaged chopper

meandering electrodes on the flexible suspension. The piezoelectric signal from the deformed suspension is also detected through the same effect to control the resonant frequency and amplitude of the oscillation.

3.1 PIEZOELECTRIC DRIVE & DETECTION

In Fig. 4 we show a close SEM view of the electrode for piezoelectric operation. Note that electrodes are not on center but off center. They meander on the suspension so that we have distributed piezoelectric strain; this strain has an effect to bend the suspension in "S" shape. Intuitive way of finding this arrangement of electrodes discussed in our previous report [2]. We will also describe more sophisticated way using FEM analysis later.

We have two sets of electrodes on the surface of left and right-hand suspensions as shown in Fig. 5. Left-hand side electrodes are for piezoelectric drive, and right-hand side ones are for piezoelectric detection.

Since the chopper has High-Pass-Filter (HPF) and Attenuator (ATT) like characteristics between the drive and the detect-electrode as shown in Fig.6, driving voltage ($\sim$ 100V) leaks and superimposes over weak piezoelectric signal ($\sim$ mV). In Fig. 7(A) we show detected piezoelectric signal as a function of frequency. The background noise level of the signal is as much as 90 % of the peak intensity because of the leakage; this makes it difficult to keep the resonance by self-excitation. Therefore we arranged additional HPF and ATT circuits which emulate the parasitical characteristics of the chopper in order to compensate the unwanted leakage by subtraction as shown in Fig. 8. Thus we could suppress the background level under several percents of the peak intensity, and could detect the piezoelectric signal very clearly as shown in

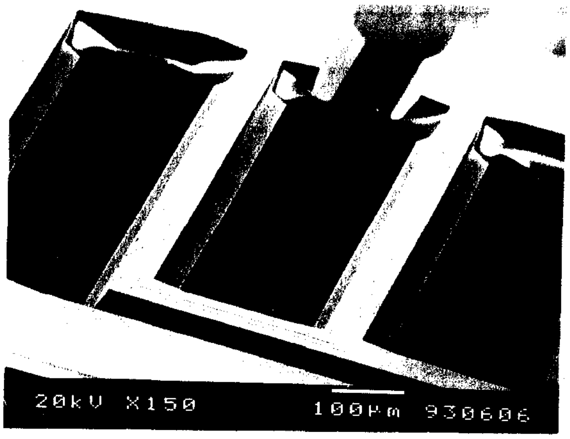


Figure 4: Close SEM view of the electrode

Each suspension is 2 mm long and 50 microns wide. There exists meandering electrodes for piezoelectric operation on the surface.

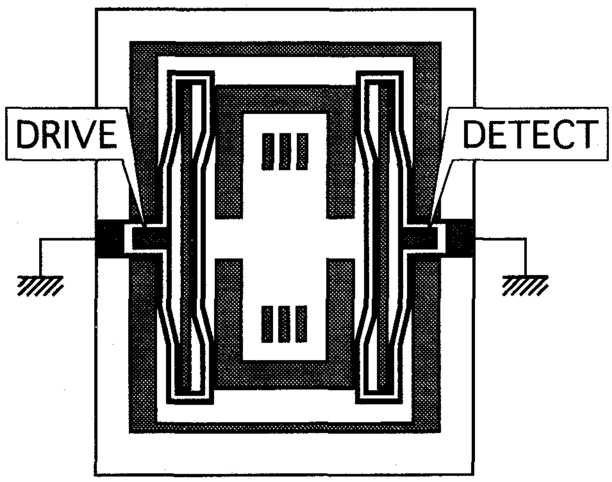


Figure 5: Electrodes in the chopper

Two sets of electrodes on the left and right-hand side suspensions. Left-hand side electrodes are for drive, and right-hand side ones are for detection, for example.

Fig. 7(B).

3.2 SELF-EXCITATION CIRCUIT

Even though we could detect the signal with high clarity, the problem still remains: Piezoelectric current generated by oscillating chopper is very small because (A) the resonant frequency of the chopper is as low as kHz, and (B) the electrical capacitance between electrodes are very small compared with that of lead wires. While detected piezoelectric voltage is as low

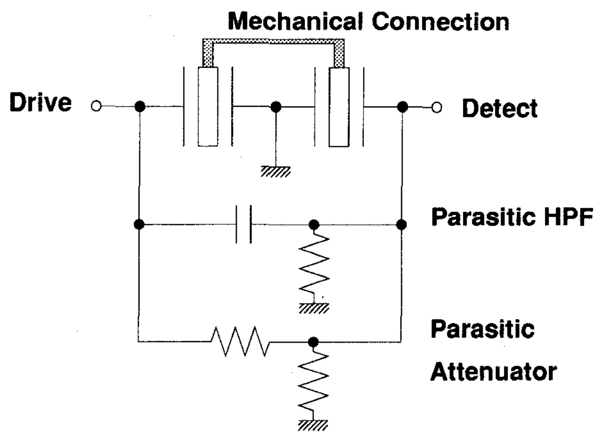


Figure 6: Equivalent circuit of the chopper

The chopper has parasitical characteristics in parallel: high-pass-filter and attenuator.

as mV, we need voltage as high as 100 V to drive the chopper. This implies that it is difficult to make a self-excitation circuit by typical positive feedback loop because we need impractical value of amplifier-gain of 10000. Therefore we counted on transformed phase-locked-loop (PLL) to assist self-excitation, and proved this scheme properly worked out.

In Fig. 9 we show PLL based self-excitation circuit. The PC (Phase Comparator) generates the control voltage in proportion to the phase difference between piezoelectric signal from the chopper and output from the VCO (Voltage Controlled Oscillator). This control signal is fed back to the VCO to lock its frequency at the mechanical resonant frequency of the chopper. We amplify the VCO's output by the series of pre-amplifier A1 and power-amplifier A2 to drive the chopper. While the gain of A2 is constant, that of A1 is controlled by the AGC (Automatic Gain Controller) in order to keep the amplitude of oscillation constant. In addition, an NLA (Non-Linear Amplifier) is inserted between the chopper and the PC in order to suppress higher modes of oscillation: Higher mode signals which are usually smaller than that of the first mode are attenuated by the NLA, and only the first mode's signal is amplified so that the PC locks the VCO's frequency. Therefore, both frequency and the amplitude of oscillation are controlled against disturbances such as external vibration or change in temperature and pressure. The robustness of the system is under investigation.

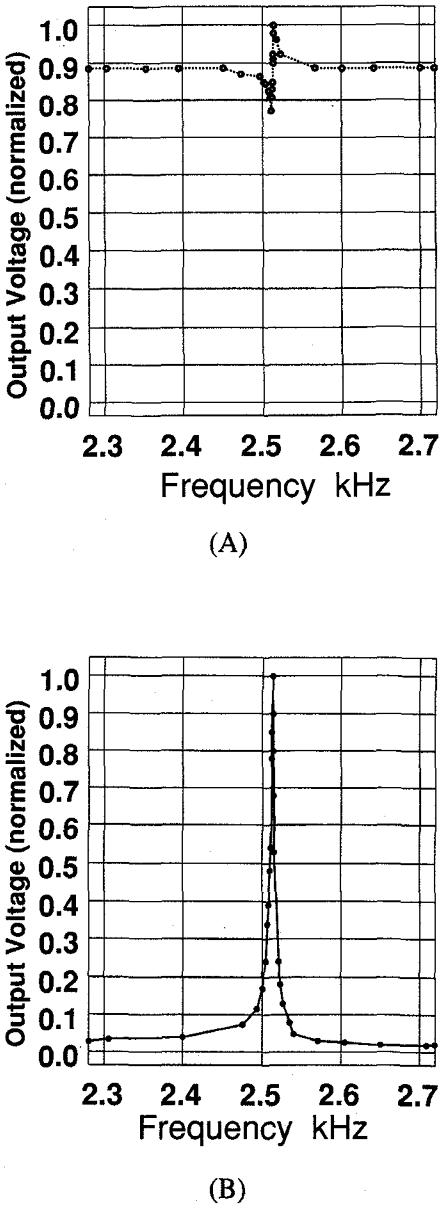


Figure 7: Frequency response of detected piezoelectric signal

(A) without compensation circuit
(B) with compensation circuit.
The clarity of peak intensity is improved by the compensation circuit.

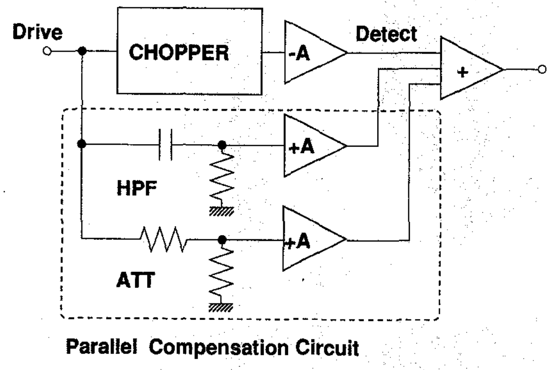


Figure 8: Leakage compensation circuit

Leakages from parasitic HPF and ATT are canceled out by subtraction with signals from additional HPF and ATT circuits.

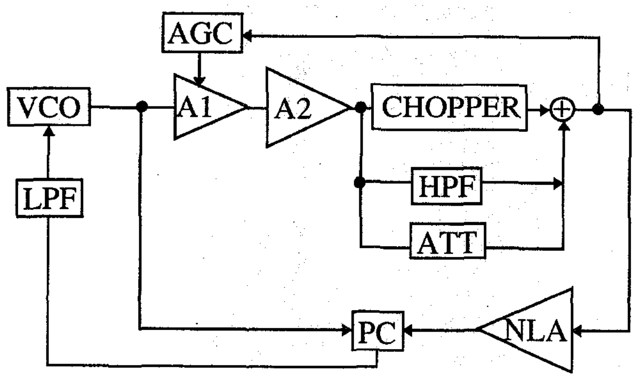
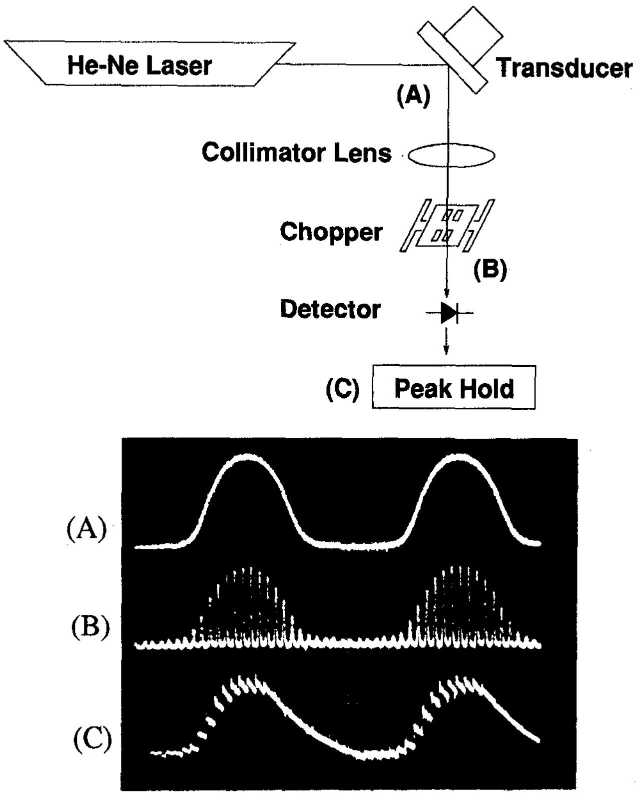


Figure 9: PLL based self-excited circuit
Detected piezoelectric signal is used to lock the resonant frequency and to control the amplitude.

4 OPTICAL SENSOR WITH QUARTZ CHOPPER

We successfully demonstrated a chopper-amplification type optical sensor using the quartz chopper. The diagram of the system is shown in Fig. 10, and traces of signals at corresponding points are also inset. The output from a He-Ne laser (5 mW) is modulated at 600 Hz by a transducer to make a incident signal light (trace (A), inset). The incident light is collimated by a lens and focused at the slit of the chopper. The focusing length is 20 mm, and focused beam is 50 microns wide. The incident light is regulated into alternating signal as the chopper slit oscillates at 2.4 kHz (trace (B), inset), and is detected by a silicon photo-diode located at 5 cm from the chopper. We also demodulated it by a peak-hold circuit (trace (C), inset). This result confirms the feasibility of making a compact optical sensor.

The demodulated signal does not completely reproduce the original signal because of large time-



100 mV / div, 1 ms / div

Figure 10: Optical sensing with quartz chopper

He-Ne output is modulated by the transducer and focused at the chopper slit. Chopped signal is detected and demodulated by the circuit. (inset: Wave traces at corresponding points.)

constant of the peak-hold circuit. However, it can be improved by replacing the peak-hold circuit with a sample-hold circuit.

5 DISCUSSION

Since piezoelectric effect is reversible, the distribution of piezoelectric polarization under certain strain has the same pattern but opposite direction as that of electric field which is required to deform the structure in the same shape. Simulating the deformation of a quartz Y-rod by FEM software ANSYS^{TM}, we obtained the distribution of the potential due to the piezoelectric polarization as shown in Fig. 11. This pattern is quite similar to the electrode arrangement we adopted (see Fig. 4).

We also looked for the ideal design of the electrode by simulating the piezoelectric strain caused by the electric field as a function of design-parameters: (A) the ratio of straight region over total electrode length and (B) the ratio of the gap between electrodes over half of suspension width. The result is illustrated in Fig. 12, and parameters we designed are also indicated. This shows that our arrangement is almost ideal and that there is little room for improvement. Thus we should change other design parameters in order to have larger displacement. If we see the chopper as a quadratic system with mass m, viscous damping coefficient c and elastic constant k, the resonant amplitude is $A \propto \frac{1}{k}Q$, where Q is the quality factor defined by $Q = \frac{\sqrt{mk}}{c}$. Since viscosity is caused mainly by air damping, c is proportional to the area of the chopper plate a. We have also $m \propto a$ because mass of the system is defined mainly by that of the chopper plate. Therefore, we obtain $A \propto \sqrt{\frac{1}{ak}}$. This shows that the amplitude is increased by (A) extending the suspension length, (B) reducing the suspension width, and (C) reducting the area of the chopper plate.

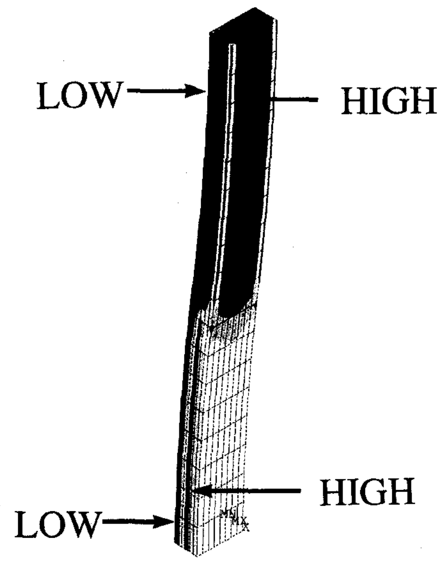


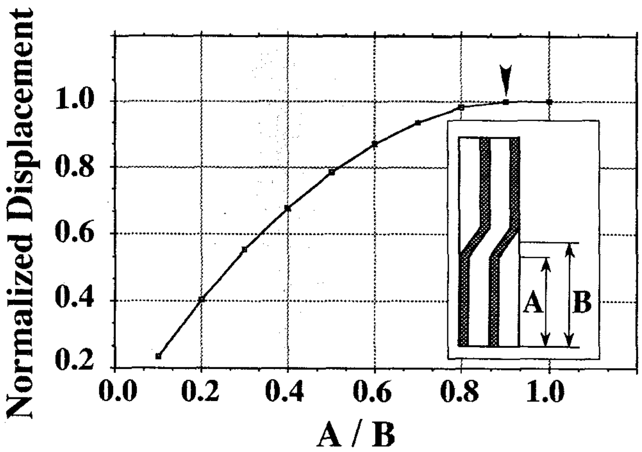
Figure 11: Polarization under strain

FEM analysis of polarization under external force. Electrode arrangement for piezoelectric operation is obtained by observing polarization under the strain.

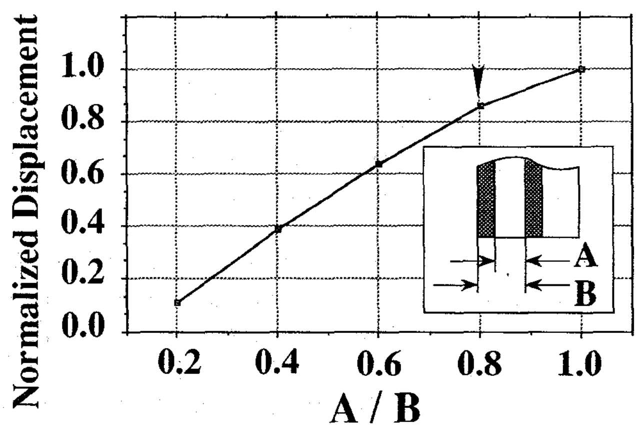
6 CONCLUSION

We succeeded to self-excite the microfabricated quartz chopper to maintain the resonance and to stabilize the amplitude of oscillation. We also demonstrated a chopper-amplifier type optical sensor with the quartz chopper.

We believe that this is the first report on successful operation of an optical sensor with a microfabricated



(A)



(B)

Figure 12: Normalized displacement as a function of design parameters for electrodes

(A) Displacement versus the ratio of straight region over total length

(B) Displacement versus the gap width between two electrodes

mechanical chopper.

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