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Development of SAW based gyroscope with high shock and thermal stability

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ABSTRACT

A novel surface acoustic wave (SAW)-based gyroscope with an 80 MHz central frequency was developed on a 128° YX $LiNbO_3$ piezoelectric substrate. The developed sensor was composed of a SAW resonator, metallic dots, and two SAW delay lines. A SAW resonator was employed to generate a stable standing wave with a large amplitude, metallic dots were used to induce a Coriolis force and to form a secondary SAW, and two delay lines were formed to extract the Coriolis effect by comparing the resonance frequencies between these two delay lines. Coupling of modes (COM) modeling was conducted to determine the optimal device parameters prior to fabrication. According to the simulation results, the device was fabricated and then measured on a rate table. When the device was subjected to an angular rotation, resonant frequency differences between the two oscillators were observed because of the secondary wave, generated by the Coriolis force, perturbed the propagation of the SAW in the sense element. Depending on the angular velocity, the difference of the resonance frequency was linearly modulated. The obtained sensitivity was approximately 172 Hz deg^{-1} s^{-1} at an angular rate range of 0–500 deg/s. Device performances depending on different mass weights and temperatures were also characterized. Good thermal and shock stabilities were observed during the evaluation process.

1. Introduction

On a spinning disc, a moving ball with a velocity v will deviate from a straight line and follow a curved path due to the Coriolis force acting on the ball at right angles to its direction of motion. The Coriolis force is expressed by $F_{\text{coriolis}} = 2m(v \times \Omega)$, in which m is the mass of the ball and Ω is the angular velocity of the disc. Almost all of the reported MEMS gyroscopes utilize this Coriolis force to measure the angular velocity of a spinning disc. Other types of gyroscopes exist, such as fiber optic gyroscopes, ring laser gyroscopes, and conventional rotating wheel gyroscopes, but these are too expensive and too large for use in most emerging applications [1–5]. In recent years, MEMS gyroscopes have received a great deal of attention for use in automobile safety systems, image stabilization, body movement monitoring, and smart weapons systems applications, because these devices provide a small size, high sensitivity, a low power consumption, and an easy integration with current CMOS electronics. Most of the currently existing MEMS gyroscopes have a single proof-mass suspended above the substrate; it is free to oscillate in two orthogonal directions. Owing to the suspended mechanical structure, the device is very sensitive to external shock and vibration. In addition, when a resonant vibration is applied upon the sense axis from the outside, the oscillating device cannot detect the Coriolis force. To obtain a high sensitivity, the MEMS gyroscope requires a matched resonant frequency between the drive mode and the sense mode. However, during fabrication, inevitable imperfections are generated, resulting in an unmatched resonant frequency. Normally, the resonant frequency matching in both the drive and the sense mode can be achieved by electrical tuning, but this requires additional power and control systems.

Compared with currently available MEMS gyroscopes, SAW based gyroscopes exhibit some unique properties, such as a superior inherent shock and vibration robustness, an easy resonance frequency matching between the drive and the sense mode, a low power consumption, and a fabrication simplicity. Some research groups have experimented with such SAW based gyroscopes with different designs and structures. Varadan et al. reported a 74.2 MHz MEMS-IDT SAW gyroscope and Kurosawa et al. depicted the effect of the dot array design on the gyroscope performance [6,7]. Lee et al. presented a micro rate gyroscope based on the SAW gyroscopic effect on ST quartz using the differential dual-delay-line oscillator configuration [8]. However, despite these meaningful works on SAW gyroscopes, they still suffer from low sensitivity and poor temperature stability due to the piezoelectric substrate which has large temperature susceptibility.

In this paper, we propose a new design for a SAW MEMS gyroscope with an operation frequency of 80 MHz. Fig. 1 shows the

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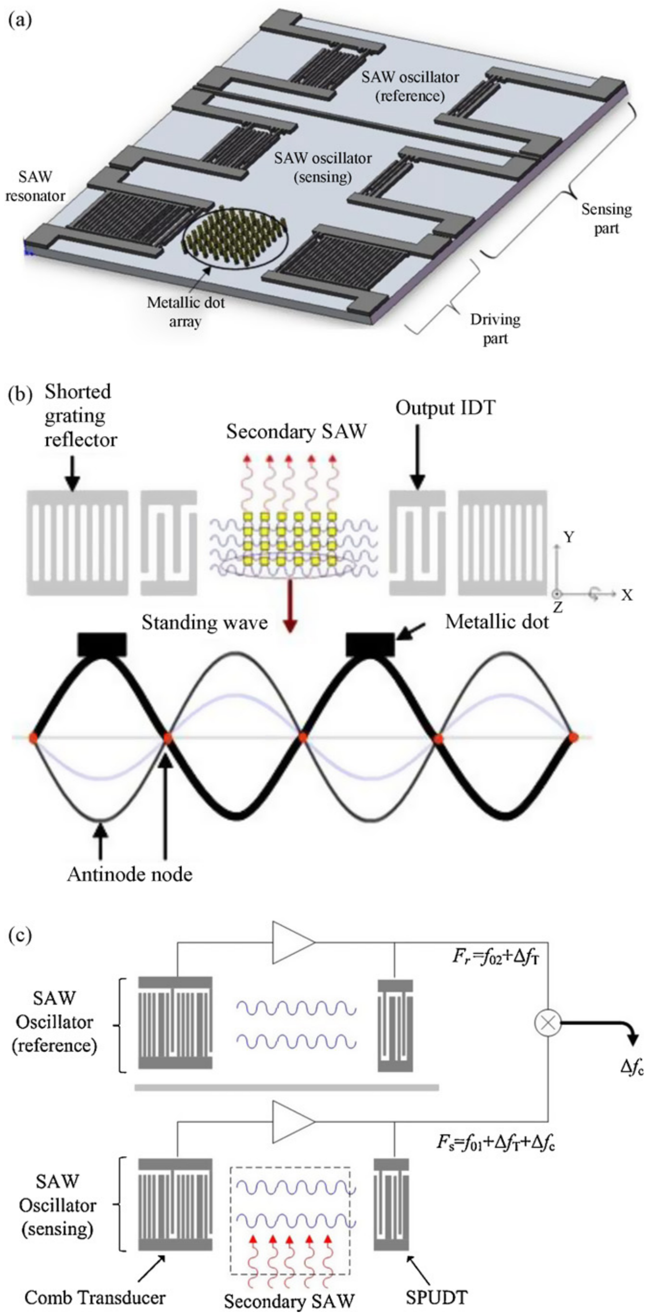

Fig. 1. (a) Entire view of the SAW gyroscope. (b) Magnified views of the driving part and (c) sensing part.

schematic diagram and the working principle of this SAW gyroscope. It consists of a two-port SAW resonator with a metallic dot array within the cavity, and two SAW delay lines in which one is used for a sensor element and the other is used for a reference element. A standing wave is generated at the two-port resonator. Metallic dots at an anti-node of the standing wave vibrate in the normal direction ($\pm z$-axis). When the substrate is subjected to an angular rotation, the Coriolis force acts on the vibrating metallic dots. The Coriolis force generates a secondary SAW in the orthogonal direction of the primary standing wave ($\pm y$-axis). The Coriolis force is proportional to the mass of the metallic dot (m), the vibrating velocity of the dot (v), and the rotational velocity of the substrate (Ω). This generated secondary SAW interferes with the Rayleigh SAW flowing in the sensing device, causing a change in the acoustic velocity of the sensing device, and thus it induces a shift in the resonant frequency. By measuring the resonant frequency difference between the sensor oscillator and the reference oscillator, we can detect the rotational velocity of the substrate.

To extract the optimal design parameters, coupling of modes (COM) modeling was carried out prior to fabrication. According to the resultant device parameters, the SAW gyroscope, with an 80 MHz operation frequency, was fabricated and then characterized on the rate table. The sensitivity, the linearity, and the thermal and shock stability were evaluated.

2. Optimal device design and simulation

2.1. Driving parts

2.1.1. Resonator

The driving part is composed of a two-port SAW resonator and metallic dots (Fig. 1(b)). The resonator has two IDTs for input and output, and two shorted grating reflectors. The input/output IDTs and reflectors have a symmetrical structure. The IDTs create SAWs that propagate back and forth between the reflectors and form a standing wave pattern within the cavity due to a cumulative reflection from the reflectors at the resonant frequency. This standing wave has a series of nodes (with a zero displacement in the z-direction) and anti-nodes (with a maximum displacement in the z-direction) at fixed points. A 128° YX $LiNbO_3$ was used as the piezoelectric substrate because it has Rayleigh wave propagation type and relatively high electromechanical coupling coefficient (K^2 = 5.56%). The wave velocities of the 128° YX $LiNbO_3$ in the x- and y-directions are 3961 m/s and 3656 m/s [9]. The high K^2 allows for a larger amplitude in the standing wave.

To form a stable standing wave and to improve the resonator performance, several design parameters need to be considered: the number of IDT finger pairs, the aperture length, the cavity length between two IDTs, the spacing between the reflector and its adjacent IDT, the number of metal stripes in the shorted grating reflector, and the operation frequency. The IDT metal fingers should be positioned exactly above the SAW standing wave maxima. The number of IDT finger pairs and the aperture length should be minimized to obtain a good resonator performance, but there is a trade-off in choosing the aperture length because a small aperture length enhances the acoustic beam diffraction. Five IDT electrodes were chosen, and the aperture length was set to $40\lambda_y$. A relatively large cavity length ($50\lambda_x$) between the input and output IDTs was designed to accommodate larger metallic dots. The minimum spacing between the reflector and its adjacent IDT was calculated to be $\lambda/8$. However, this can be troublesome in device fabrication. To overcome this fabrication limitation, and because the standing wave is periodic, the positions for both shorted grating reflectors were moved out by an integer number of the acoustic half-wavelengths. Thus, in our resonator design, the spacing was set to $5\lambda/8$. The number of metal stripes in the shorted grating reflector was set to 451 to obtain total reflection from the reflectors. The 80 MHz operation frequency was chosen because the employment of a lower operation frequency allows for a standing wave with larger amplitude.

To extract the optimal design parameters for the SAW device, coupling of modes (COM) modeling was used prior to fabrication. The COM model provides for an efficient and highly flexible approach for modeling of various kinds of SAW devices. Using the cascading relationships and the P-matrixes for the IDT and shorted grating reflectors, a SAW resonator modeling was performed. The COM equation for IDT is presented by 3×3 P-matrix representation, which deals with acoustic waves propagating in the forward (R) and reverse directions (S) and incorporates their coupling interaction