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A stable and highly sensitive strain sensor based on a surface acoustic wave oscillator

Chen Fu[a], Kijung Lee[a], Keekeun Lee[a], Sang Sik Yang[a,*], Wen Wang[b]

[a] Department of Electrical and Computer Engineering, Ajou University, Suwon 443-749, South Korea
[b] Institute of Acoustics, Chinese Academy of Sciences, Beijing 100080, People's Republic of China

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ABSTRACT

A stable and highly sensitive strain sensor based on a surface acoustic wave (SAW) oscillator is presented in this article. A 151 MHz SAW delay line was fabricated on a 128° YX $LiNbO_3$ substrate as the oscillator element. A cantilever beam with a tapered cross section was designed to provide a quasi-uniform strain testing platform and analyzed with a finite element method (FEM) model. Single-mode selection capability was achieved by using a comb configuration, and the triple transition interference (TTI) was suppressed by using a single phase unidirectional transducer (SPUDT). Prior to fabrication, a FEM/boundary element method (BEM) simulation was used to simulate and optimize the parameters of the SAW delay line structure. The RF test results of the fabricated SAW devices agree well with the simulation results. Further, the output frequency fluctuation of the developed SAW oscillator was shown to be only approximately 0.7 ppm in a temperature-controlled laboratory environment for stability tests. The measured sensitivity was evaluated to be 126 Hz/$\mu\varepsilon$, and good linearity was observed at strain values ranging from 0 to 400 $\mu\varepsilon$.

1. Introduction

There is a significant demand for strain micro-sensors in a wide range of applications for monitoring quality, safety, and reliability in aerospace, automotive, motor sport, and civil engineering fields. For real-time intelligent monitoring and control sensing in these applications, robustness, high sensitivity, and a wide dynamic measurement range are required. SAW sensors are highly attractive for performing different types of physical measurements because of their properties such as low power consumption, low cost, ease of fabrication, small size, and high sensitivity. In recent years, many SAW-based strain sensors have been proposed for machine diagnosis and failure analysis. Varadan et al. proposed a wireless, passive strain micro-sensor by utilizing reflective delay-line structures [1]. Donohoe and Stoney et al. also realized a wireless strain sensor on an AT-quartz wafer by using a SAW one-port resonator [2,3]. Konno et al. proposed wireless SAW oscillator strain gauge scheme [4]. Bruckner et al. proposed a SAW-based strain sensor on a langasite (LGS) wafer [5]. Nomura et al. reported a shear horizontal (SH) SAW strain sensor using both oscillator and reflective delay-line schemes [6]. Oh et al. developed a SAW strain sensor using an SH-SAW mode [7]. These SAW-based strain sensors have exhibited promising sensitivity characteristics when compared with industry-standard strain-gauge devices. However, these important studies on SAW strain sensors still primarily suffer from two unsettled problems: the inability to achieve both high sensitivity and stability and the absence of a systematic theoretical analysis.

In this article, we introduce a SAW strain sensor with a dual SAW delay line oscillator to obtain high sensitivity and stability. Further, the parameters of the SAW device mounted on a strain measurement structure are designed via a complete theoretical analysis of the SAW strain sensor. Finally, we fabricate and test the SAW strain sensor by using an oscillation circuit.

2. Design considerations

A cantilever beam is a well-known strain measurement platform that provides different desired strains as a function of the loads applied at the free end. A SAW strain sensor is attached on top of the cantilever beam, as shown in Fig. 1. In particular, we use a tapered cantilever beam to achieve uniform strain distribution along the beam. The dual SAW delay-line oscillator detection unit consists of two SAW devices with single-mode selection capability [6]. One device is fixed to the beam surface to convey the beam strain, whereas the other device is mounted loosely to be free from the beam strain and only senses environmental conditions such as

* Corresponding author. Tel.: +82 31 219 2488; fax: +82 31 212 9531.
E-mail address: ssyang@ajou.ac.kr (S.S. Yang).

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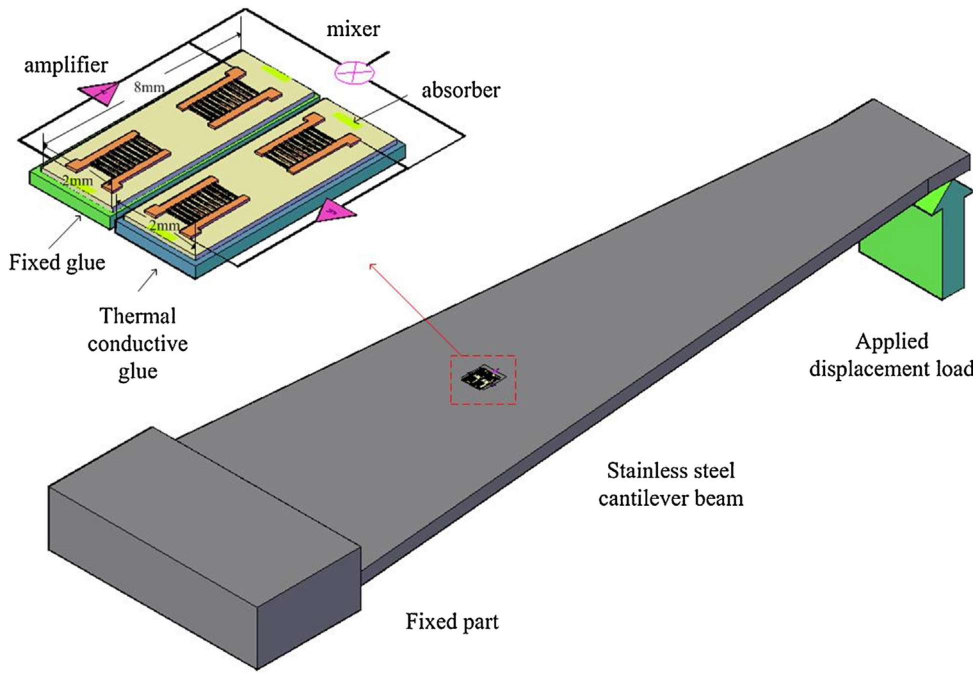

Fig. 1. Schematic diagram of the dual SAW delay line oscillator sensor mounted on the tapered cantilever beam.

temperature and humidity. By measuring the oscillation frequency difference between the sensor channel and the reference channel, the net strain response can be determined. The optimum design parameters of the SAW devices are determined by using a finite element method/boundary element method (FEM/BEM). In addition, the principles of SAW sensor response subjected to a load are investigated.

2.1. Cantilever beam with a tapered cross section

A tapered cantilever beam is used as the strain measurement platform in this study. A load is applied at the free end of the cantilever beam, as shown in Fig. 2(a), According to mechanics theory, the normal strain in the x-direction, ε_x at the position x distant from the fixed end on the top surface of the straight cantilever beam, is given by

$$\varepsilon_x = \frac{6PL}{Eh^3 w_1} \frac{1 - x/L}{1 - (1 - w_2/w_1)(x/L)} \quad (1)$$

where L, h, w_1 and w_2 denote the length, height, and the beam widths of the fixed and free ends, respectively. Here, E is the Young's modulus of the material, and P is the load applied at the free end. If the ratio w_2/w_1 is sufficiently small, a quasi-constant strain can be obtained. However, a configuration having a very small w_2/w_1 ratio is sensitive to manufacturing accuracy and increases the difficulty of applying loads at the free end. The strain distribution on the beam surface from the fixed end to the free end is calculated for different w_2/w_1 ratios and is shown in Fig. 2(b). The w_2/w_1 ratio was set to be 0.1 as a tradeoff between the approximate uniform strain and practical manufacturing considerations.

2.2. Single phase unidirectional transducer

Single phase unidirectional transducers (SPUDTs) are primarily employed to replace general SAW transducers to reduce bidirectional propagation loss [8] and to suppress triple transition interference (TTI) [9]. For strain-sensing applications, SAW devices do not require any sensitive or guiding film on the wafer surface. Therefore, SAW propagation attenuation is significantly lower in a strain sensor than in SAW chemical and biological sensors. Conversely, TTI is a major issue in the proposed SAW strain delay line because a relatively large delay-line area is expected. The TTI is induced by the acoustoelectric regeneration effect and may lead to unwanted ripples in the SAW response passband. Generally, two

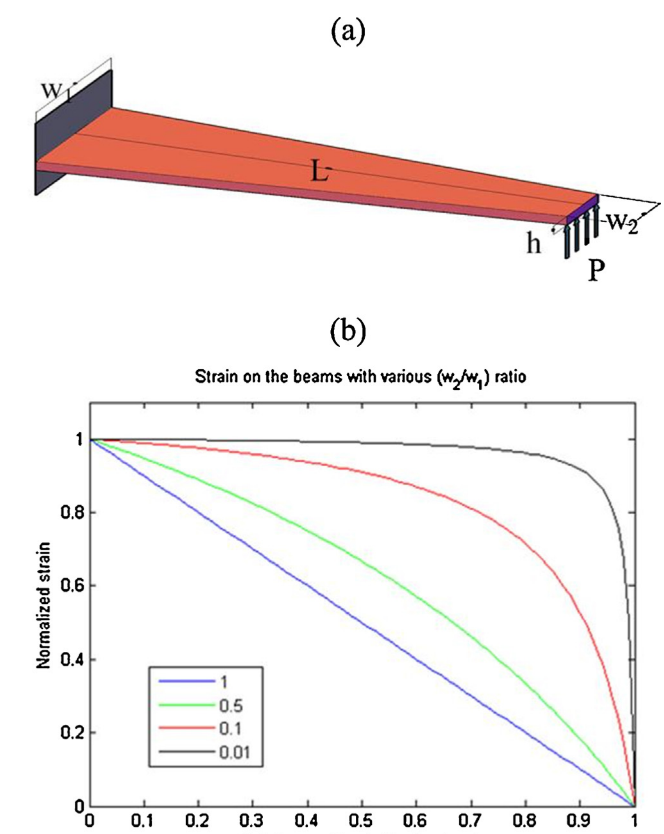

Fig. 2. (a) Schematic diagrams of the tapered cantilever beams. (b) Calculated strain distribution on the beam with different w_2/w_1 ratios.