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Optimal design on SAW sensor for wireless pressure measurement based on reflective delay line

Wen Wang *, Keekeun Lee, Insang Woo, Ikmo Park, Sangsik Yang

Division of Electronics Engineering, Ajou University, Suwon 443-749, South Korea

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Abstract

This paper presents optimal design on wireless pressure micro-sensor based on surface acoustic wave (SAW) reflective delay line. Using the coupling-of-modes (COM) analysis, the device was simulated, and the effect of reflector configuration and interdigital transducer (IDT) structure on the performance of the devices was studied. From the COM simulation results, a 440 MHz SAW-based pressure sensor based on a reflective delay line on 41° YX $LiNbO_3$ with shorted circuit grating reflectors and single-phase unidirectional transducers (SPUDT) structure was developed experimentally. Using the network analyzer, the SAW sensor was wirelessly characterized, and the experiment results were well matched with simulation data. Sharp reflection peaks, low insertion loss and few spurious signals between the peaks were observed. Obtained pressure sensitivity was 2.67°/kPa.

Keywords: Coupling of modes; Reflectors; SAW reflective delay line; SPUDT; Wireless pressure sensor

1. Introduction

Recently, SAW reflective delay line was used widespread as sensors for wireless passive sensing of various measurands like pressure, temperature, humidity, chemicals, etc. It is easy to provide the necessary delay time to suppress all environmental echoes; in contrast to delay line with two transducers, the propagation path is used twice, resulting in smaller chips. Fig. 1 shows the operating principle of such wireless SAW sensors system. A RF pulse is received by the contact antenna of the SAW sensor. The interdigital transducer (IDT), which is connected to the antenna, transforms the received signal into a SAW. Reflectors are placed in the propagation path of the SAW at which small parts of the SAW are reflected. The reflected waves are reconverted into an electromagnetic wave by the IDT and are transmitted to the reader unit through antennas. The sensor signal is determined by evaluating the phase shifts of the reflected impulses. Several groups have reported some successful SAW sensors based on the SAW reflective delay line [1,2]. However, such SAW sensors suffer from the high propagation loss (40–60), high level of spurious signal and relatively low signal to noise ratio. Hence, simulation and analysis to improve the performance of the SAW device is very important which is the focus of this paper.

This paper present the optimal design on the pressure micro-sensor based on the SAW reflective line, which is composed of one transducer and several reflectors, as shown in Fig. 1. In general, there are four types of configuration used for reflectors, such as IDTs, open circuit grating, shorted circuit grating and bar type. Using the coupling of modes (COM) model, the SAW devices were simulated and the effect of transducer structure and reflector configuration on the performance of the devices was studied. From the analysis results, a 440 MHz SAW sensor on $LiNbO_3$ based on the reflective delay line with low loss and few spurious signals was experimentally developed for wireless pressure measurement. Shorted circuit grating was used as the reflectors to reduce the spurious signal, whereas low loss was implemented by SPUDT structure which is to enhance the generated signal in the forward direction but reduce the signal in the reverse direction using the distributed reflection sources in the IDTs [3]. Then, using the network analyzer, the device was wire-

* Corresponding author.
E-mail address: wangwenwq@hotmail.com (W. Wang).

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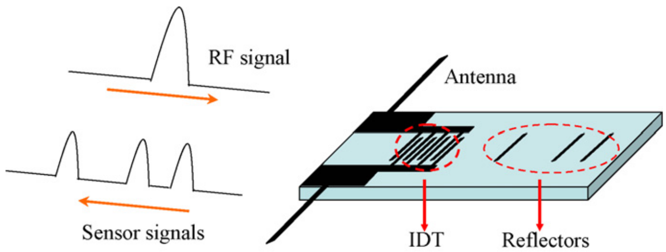

Fig. 1. Schematic diagram of the SAW-based pressure sensor.

lessly characterized, and experimental results were well matched with simulated data.

2. COM analysis

COM model provides an efficient and highly flexible approach for modeling various kinds of SAW devices [3]. For the SAW reflective delay line, COM model was used to analyze the IDT and reflectors respectively. Then, using the so-called mixed *P*-matrix and FFT program, the reflective coefficient S_{11} in time domain of the SAW device was deduced.

2.1. COM analysis for IDT

The COM equation for IDT deals with acoustic waves propagating in the forward and reverse directions and incorporates their coupling interaction, as shown in Fig. 2. $R(x)$ and $S(x)$ are slowly varying two acoustic wave amplitudes. Then, the 3×3 *P*-matrix representation is used to present the solutions to the COM equations [3]. The *L* is transducer length. The three equations in the COM modeling can be integrated, so that all parameters in the *P*-matrix can be evaluated as the following:

$$\begin{bmatrix} S(0) \\ R(L) \\ I \end{bmatrix} = \begin{bmatrix} P_{\mathrm{IDT11}} & P_{\mathrm{IDT12}} & P_{\mathrm{IDT13}} \\ P_{\mathrm{IDT21}} & P_{\mathrm{IDT22}} & P_{\mathrm{IDT23}} \\ P_{\mathrm{IDT31}} & P_{\mathrm{IDT32}} & P_{\mathrm{IDT33}} \end{bmatrix} \begin{bmatrix} R(0) \\ S(L) \\ V \end{bmatrix} \quad (1)$$

2.2. COM analysis for reflectors

Fig. 3 shows the configuration of various type reflectors. The COM analysis of the IDT type reflectors (Fig. 3(a)) was mentioned above, whereas for the shorted circuit grating reflector,

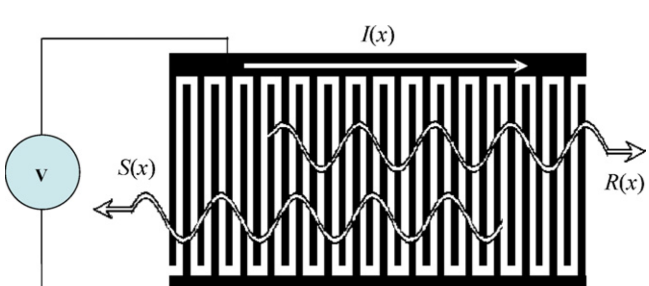

Fig. 2. SAW schematic and variables for COM theory of the IDTs.

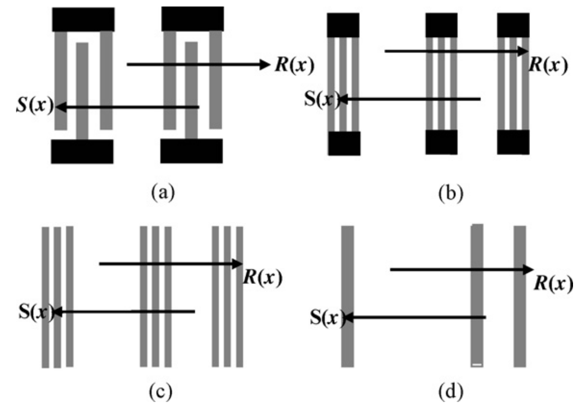

Fig. 3. Reflectors for the SAW reflective delay line: (a) IDT type, (b) shorted circuit grating reflector, (c) open circuit grating reflector and (d) bar type reflector.

as shown in Fig. 3(b), the COM equation is presented by

$$\begin{cases} \dfrac{\mathrm{d}R(x)}{\mathrm{d}x} = -i\delta R(x) + i\kappa S(x) \\ \dfrac{\mathrm{d}S(x)}{\mathrm{d}x} = -i\kappa^{*} R(x) + i\delta S(x) \end{cases}, \quad (2)$$

where the δ is the detuning factors, and κ is the reflectivity. The 2×2 mixed *P*-matrix was used to present the solutions to Eq. (2).

$$\begin{bmatrix} S(0) \\ R(L) \end{bmatrix} = \begin{bmatrix} P_{\mathrm{ref11}} & P_{\mathrm{ref12}} \\ P_{\mathrm{ref21}} & P_{\mathrm{ref22}} \end{bmatrix} \begin{bmatrix} R(0) \\ S(L) \end{bmatrix}. \quad (3)$$

Then, the COM equation for open circuit grating reflector, as shown in Fig. 3(c), is

$$\begin{cases} \dfrac{\mathrm{d}R(x)}{\mathrm{d}x} = -i\delta_{\mathrm{oc}} R(x) + i\kappa_{\mathrm{oc}} S(x) \\ \dfrac{\mathrm{d}S(x)}{\mathrm{d}x} = -i\kappa_{\mathrm{oc}}^{*} R(x) + i\delta_{\mathrm{oc}} S(x) \end{cases}, \quad (4)$$

where $\delta_{\mathrm{oc}} = \delta - 2|\alpha|^2/(\omega C)$, $\kappa_{\mathrm{oc}} = \kappa + 2\alpha/(\omega C)$ [4]. Similar to the shorted circuit reflectors, the open circuit grating reflectors can also be described as the 2×2 mixed *P*-matrix.

As for the bar type reflector, as shown in Fig. 3(d), it can be regard as a special open circuit grating reflector with unit length of $\lambda/4$ (only a finger for one reflector), where λ corresponding to the operation frequency.

2.3. COM simulation and discussions

Using the cascading relationships [5], the *P*-matrix for all the individual IDT segments and the transmission matrix between the IDT and first reflector can be cascaded and described as P_{TIDT}. The *P*-matrix for the reflectors is also cascaded as P_{Tref}. Therefore, the admittance matrix for the whole device can be expressed by

$$Y = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}, \quad (5)$$