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Wideband tunable Love wave filter using electrostatically actuated MEMS variable capacitors integrated on lithium niobate

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ABSTRACT

A tunable bandpass filters with low insertion loss, sharp cut-off characteristics, wide bandwidth and wide tunability is strongly expected for future reconfigurable and cognitive wireless systems. In this study, a wideband tunable filter with the center frequency of 1.08 GHz was fabricated by directly integrating Love wave resonators and electrostatically actuated MEMS variable capacitors on a 15° Y $LiNbO_3$ wafer. The Love wave resonators have an extremely large electromechanical coupling coefficient ($k^2 \sim 30\%$), providing wide bandwidth and wide tuning range. The 3 dB bandwidth was tuned from 146 MHz to 130 MHz by applying 15 V to one of the MEMS variable capacitors.

1. Introduction

In recent years, the number of wireless services for mobile communication is increasing. To access multiple wireless services at different frequencies, a recent mobile phone has a quite complicated wireless front-end, which is composed of many filters, amplifiers, mixers etc. To make a wireless system simpler and even flexible, a tunable/reconfigurable wireless front-end is expected [1]. Furthermore, a cognitive wireless system, which automatically selects the best frequency based on spectrum sensing, is required to solve frequency resource shortage problem [2]. A possible architecture of a tunable wireless front-end consists of tunable bandpass filters and a tunable LNA (low noise amplifier). The tunable LNA can be made using MEMS-based variable capacitors or inductors [3,4]. On the other hand, the tunable front-end filter is much more difficult to develop due to the following severe requirements. The front-end filter must have low insertion loss, sharp cut-off characteristics, required bandwidth and small size. An LC filter and a micro strip line filter can be tuned by MEMS variable capacitors [5–11], but cannot offer sharp cut-off characteristics due to their low Q factor.

Acoustic filters have much higher Q factor and smaller size compared with the LC filter and the micro strip line filter. To satisfy the other requirements, i.e. low insertion loss and required bandwidth, an electromechanical coupling coefficient (k^2) must be also high. At present, therefore, SAW (surface acoustic wave) and BAW (bulk acoustic wave) devices with a relatively high product of Q and k^2 are used for practical front-end filters. The resonance frequency of the SAW and BAW devices is basically determined by the dimensions such as IDT (interdigital transducer) pitch and film/plate thickness, and material properties such as Young's modulus and density, which are difficult to change widely. A relatively wider frequency tuning of ca. 1% was demonstrated at ca. 810 MHz by an acoustic filter using high-κ dielectrically transduced MEMS resonators [12]. A larger frequency tunability of ca. 5% was achieved by a length-extensional mode PZT (lead zirconium titanate) resonator with a relatively low resonance frequency of 20 MHz [13].

In this study, we prototyped a novel SAW-based tunable filter at 1 GHz using MEMS-based variable capacitors. To obtain a wide frequency tuning range, Love wave resonators with an extremely large k^2 were used, and electrostatically actuated variable capacitors were integrated with the Love wave resonators on a $LiNbO_3$ wafer. To our best knowledge, this type of tunable filter was first prototyped in this study. This paper reports the design, fabrication and preliminary test result.

2. Principle and design

2.1. Principle

Fig. 1 shows the electrical equivalent circuit of an acoustic resonator, where L_1, R_1 and C_1 are called motional inductance, motional resistance and motional capacitance, respectively, while C_0 is electrical shunt capacitance. The circuit impedance takes the

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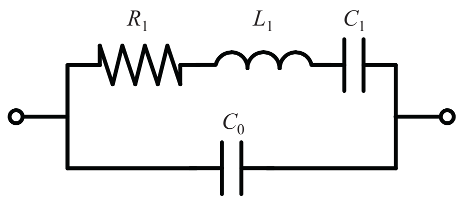

Fig. 1. Electrical equivalent circuit of an acoustic resonator.

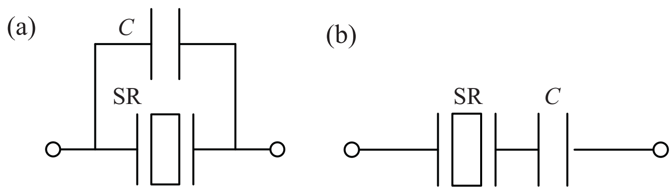

Fig. 2. Capacitor, C, connected (a) in parallel and (b) in series to a SAW resonator, SR.

minimum at frequency f_r called resonance frequency, which is given by

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_1}}, \tag{1}$$

while it takes the maximum at frequency f_a called anti-resonance frequency, which is given by

$$f_a = \frac{1}{2\pi\sqrt{L_1 (C_1^{-1} + C_0^{-1})^{-1}}}. \tag{2}$$

When a capacitor is connected in parallel to a resonator as shown in Fig. 2(a), the anti-resonance frequency decreases according to

$$f_a^e = f_a \sqrt{1 - \frac{1}{\gamma + 1} \cdot \frac{C}{C_0 + C}}, \tag{3}$$

while the resonance frequency does not change. In Eq. (3), γ ($= C_0/C_1 \approx k^{-2}$) is the capacitance ratio, and C is the capacitance of the additional capacitor. When C increases from 0 to ∞, f_a^e decreases from f_a to f_r. On the other hand, when a capacitor is connected in series to a resonator as shown in Fig. 2(b), the resonance frequency increases according to

$$f_r^e = f_r \sqrt{1 + \frac{1}{\gamma} \cdot \frac{C_0}{C_0 + C}}, \tag{4}$$

while the anti-resonance frequency does not change. Note that the resonance frequency without the additional capacitor is obtained by making the series capacitance infinity ($C \to \infty$). When C decreases from ∞, f_a^e approaches f_a from f_r.

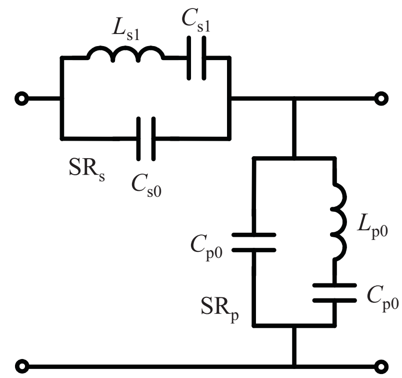

Fig. 3. Basic section of a ladder-type filter.

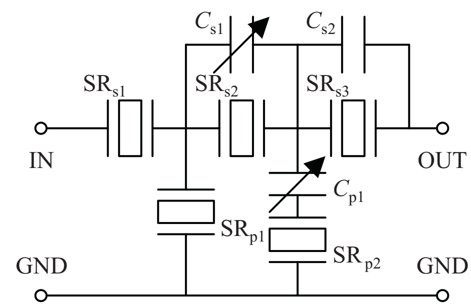

Fig. 4. Circuit diagram of a simple tunable filter composed of resonators and variable capacitors.

Let us consider a circuit shown in Fig. 3. Here, the resonance frequency f_r^s of the series element SR_s is chosen to coincide with the anti-resonance frequency f_a^p of the parallel element SR_p. Efficient signal transfer is possible through the filter at a frequency f_c ($= f_r^s = f_a^p$). On the other hand, the signal transfer is rejected at f_a^s and f_r^p. Thus, the filter exhibits a typical transmission characteristic shown in Fig. 5(a). Multiple sections are often cascade-connected with inversion for improving out-of-band rejection. A filter of this configuration is called ladder-type filter.

When we construct the ladder type filter using the units shown in Fig. 2(a) and (b) (see Fig. 4), f_a^s and f_r^p shift inside, i.e. the bandwidth is narrowed in comparison with the filter without the additional capacitors, as shown in Fig. 5(a). The position of f_a^s and f_r^p moves depending on the capacitance of the additional capacitor. On the other hand, f_c always stays in the filter passband, because f_r^s and f_a^p are invariant by the additional capacitors. Therefore, the bandwidth and the center frequency can be tuned by changing the capacitance of the additional capacitors, as shown in Fig. 5(b).

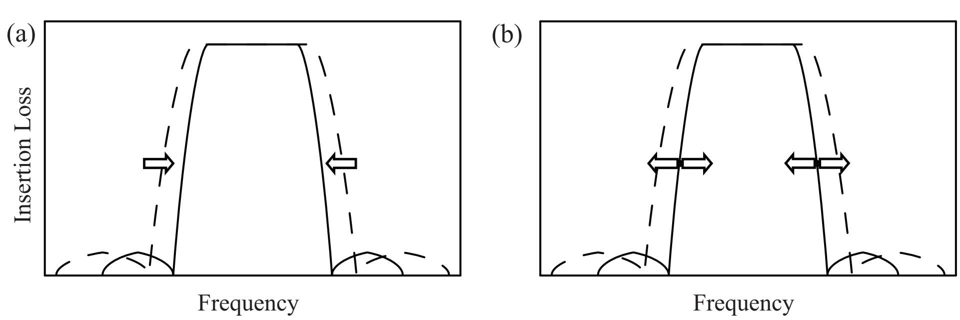

Fig. 5. Transmission characteristics of a tunable filter. (a) Bandwidth is restricted when capacitors are connected to a ladder type SAW filter e.g. as shown in Fig. 4. (b) Bandwidth is tuned when the capacitance of the additional capacitors are changed.