Paper VI

Non-synchronous resonators on leaky substrates

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VI

Non-Synchronous Resonators on Leaky Substrates

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***Abstract*—We study non-synchronous resonator structures on leaky-wave 42°-$LiTaO_3$ substrate. Such resonators have the resonance frequency in the center of the grating stopband where the reflectors effectively confine the acoustic energy inside the transducer. This can yield improved performance in the form of increased quality factors and reduced ripple. Two structures are presented: a double-resonance device in which a hiccup-type resonance arises with amplitude distribution concentrated around a distributed gap, and a non-synchronous short resonator with transducer pitch smaller than that of the reflectors. Experimental data for both device types are presented, and the possibility of using them as impedance elements in filter applications is briefly discussed.**

Keywords-surface acoustic waves; surface acoustic wave devices, surface acoustic wave resonators

I. INTRODUCTION

Resonator structures on substrates supporting leaky-wave surface acoustic waves (SAW) are widely used in ladder (impedance element, IE) filters [1]. In virtually all cases, the resonator structure is synchronous, consisting of an interdigital transducer (IDT) surrounded by two reflector gratings, all elements having the same period, with no breaks in the periodicity of the electrodes. The reasons for this are well-known: on leaky-wave substrates, gaps and other perturbations in periodicity can result in strong bulk-acoustic wave (BAW) scattering and deteriorate the resonator performance. A synchronous structure, having waves uniformly distributed along the IDT, has the maximal possible coupling and, thus, the maximal resonance-anti-resonance frequency separation, which is advantageous for ladder filter design. Despite their wide use, synchronous resonators have certain drawbacks. In a synchronous resonator, the resonance frequency is shifted to the left edge of the stopband, where the reflectivity of the reflectors is reduced. As an essential part of SAW energy is concentrated in reflectors, the coupling of the IDT to the resonance mode is reduced. That results in a decrease of quality factor (Q-value), or necessitates very long reflectors. In addition to this, on the left side of the resonance the reflectors are transparent, and the finite length of the structure can cause ripples to appear on the admittance curve. If such resonators are used as building blocks for a ladder filter, in some cases the ripples can ultimately be seen in the filter passband. Therefore it would be advantageous to use resonators in which the resonance is situated in the center of the grating stopband [1]. Because of the strong the reflectivity of the gratings, such resonators can have high Q-values and the ripple in the admittance curve is reduced.

In this paper, we study possibilities of non-synchronous (NS) resonators on leaky-wave substrates. The main problem to be overcome is the loss arising from BAW scattering at the breaks of periodicity between IDTs and gratings. On 42°-$LiTaO_3$ substrate used in this work, the propagation loss on free or metallized surface is higher than under a grating, which leads to additional loss in gaps [2]. We present two types of resonators: a hiccup-type resonator with long transducers, and a short NS resonator having a reduced pitch in the IDT. A detailed analysis of the operation and experimental results for both structures are presented, and the possibility of using them as impedance elements is discussed.

II. HICCUP-TYPE DOUBLE-RESONANCE RESONATORS ON LEAKY-WAVE SUBSTRATES

A hiccup-type structure with long IDTs and a $\lambda/4$ metallized gap on a leaky substrate was proposed in 1996 by Plessky et al. [3]. Although simulations promised excellent filter performance, experimental devices on 36°-$LiTaO_3$ showed unexpectedly high insertion loss in the passband and strong ripple on the transfer curve. We believe this to be due to losses occurring in the gap region, i.e., conversion into BAW and propagation loss. The structure has a strong hiccup resonance spatially situated in the gap region, so that losses in the gap are especially significant for the operation of the device. We study here a novel structure on leaky-wave 42°-$LiTaO_3$ substrate, depicted in Fig. 1, which has distributed gaps replacing the metallized gap [4, 5] in order to reduce BAW conversion and propagation loss. It has been shown [5] that distributed gaps significantly improve resonator Q-values on leaky-wave substrates. Theoretical values of Q-factor (Q≈600) obtained in [5] look very attractive and exceed typical values for synchronous resonators. However, these results are related to a structure with relatively short IDT.

The resonator structure shown in Fig. 1 consists of two long transducers with the number of electrode pairs greater than $1/K^2$ and $1/\kappa$, where K^2 is the coupling coefficient of the substrate and κ is the reflectivity per wavelength. The hiccup-type gap between the IDTs is replaced with a short electrode section having a reduced pitch (distributed gap). Although the structure is quasi-periodic with no visible perturbation in periodicity, we will use the term "hiccup resonator", introduced by P. Wright [6] for the synchronous structures with off-set close to $\lambda/4$ between two parts of the IDT. A strong hiccup resonance arises in the gap region, in addition to which there exists a "synchronous" resonance created in the long IDTs. Therefore, we call the structure a double-resonance (DR) device. In Fig. 2, the admittances of 3 experimental devices with varied pitch in the gap are shown. The hiccup resonance is situated in the center of the stopband at 1590 MHz, whereas the synchronous resonance takes place at the left edge of the stopband at 1545 MHz. Changing the pitch in the distributed gap moves the hiccup resonance without affecting the synchronous resonance frequency. Fig. 3 shows a coupling-of-modes (COM) model simulation of the amplitude distribution in such a resonator at synchronous and hiccup resonance frequencies, clearly showing that in the synchronous resonance, SAW energy is distributed in the long IDTs, whereas at the hiccup resonance frequency, a strong concentration of acoustic energy takes place in the gap region. Small losses in the gap can in effect destroy the hiccup resonance, dramatically degrading the performance [5]. Therefore, using a distributed gap is essential.

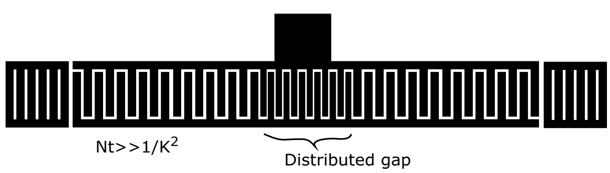

Figure 1. Schematic of the double-resonance structure. The gap between the long transducers is replaced with distributed gap.

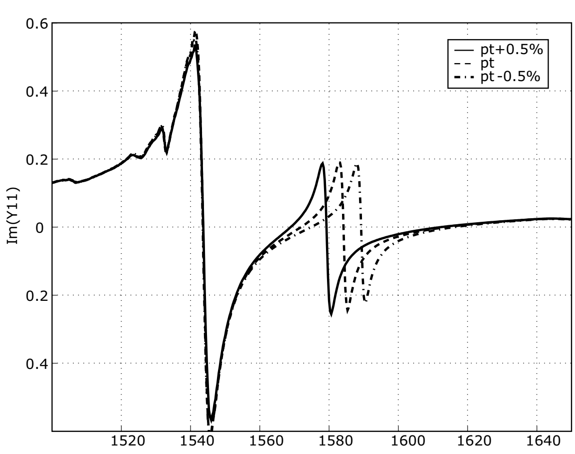

Figure 2. Imaginary part of admittance for 3 experimental DR resonators with varied pitch in the gap. Changing the pitch in the distributed gap shifts the position of the hiccup resonance occurring at 1590 MHz, not affecting the synchronous resonance at 1545 MHz.

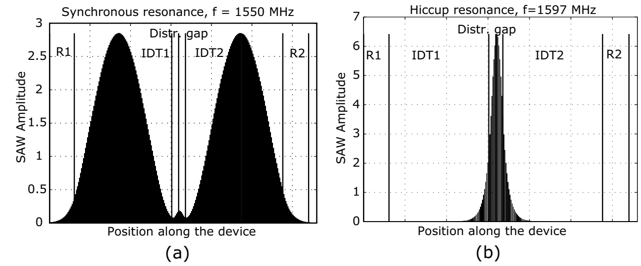

Figure 3. Amplitude distributions in a DR resonator; COM simulation. (a) At the synchronous resonance, acoustic amplitude is distributed in the long IDTs. (b) At hiccup resonance, amplitude is concentrated in the gap.

An interesting feature of the structure is that the hiccup resonance becomes "self-matched" if certain conditions are satisfied. As seen in Fig. 2, by changing the pitch in the distributed gap, the hiccup resonance frequency can be made to coincide with the anti-resonance point of the synchronous resonance. In such a situation, the synchronous resonance acts as a parallel matching inductance, canceling the static capacitance and making the hiccup resonance symmetric. In the ideal case there exist two anti-resonance points symmetrically on each side of the hiccup resonance, giving a possibility of placing a notch on each side of the resonance. An experimental example is shown in Fig. 4, with Fig. 4(a) depicting experimental response of a resonator and Fig. 4(b) showing the series-connection of the resonator, with simulations. Placing the notches can be a useful feature for a 2-port filter configuration (see companion paper in this Proceedings [7]). To observe self-matching, the parameters of the device must be chosen such that the anti-resonance and hiccup resonance frequencies coincide. In addition to this, the structure and the substrate material must be such that the anti-resonance point can be positioned in the center of the grating stopband, where the hiccup resonance takes place. In approximation, they must satisfy $1/K^2 \sim |\kappa|/\pi$.

The strength of the synchronous resonance is determined by the length of the long IDTs that have practically no effect on the hiccup resonance. However, self-matching can only be achieved if the synchronous resonance is strong enough, so that its anti-resonance frequency is in the center of the grating stopband. Experimental results for a DR resonator are shown in Fig. 4(a), and parameters for the device are collected in Table I. The Q-value of the hiccup resonance is better than that of the synchronous resonance occurring in the same device.

TABLE I. DEVICE PARAMETERS AND EXPERIMENTAL DATA OF A DR RESONATOR.

Aperture (µm)	110=43 λ
Number of fingers in long IDTs	95
Number of fingers in gap	14
Synchronous resonance frequency (MHz)	1544
Hiccup resonance frequency (MHz)	1589
Q-value of synchronous resonance	290
Q-value of hiccup resonance	565

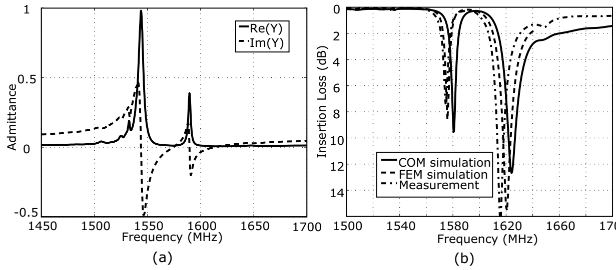

Figure 4. (a) Experimental admittance data for a DR resonator. Device parameters are summed in Table I. (b)Frequency response of a series-connected DR resonator. Anti-resonance points create notches on both sides of the resonance.

TABLE II. DEVICE PARAMETERS AND EXPERIMENTAL CHARACTERISTICS OF A NON-SYNCHRONOUS RESONATOR.

Aperture (µm)	146=72 λ
Number of fingers in reflectors	69
Number of fingers in IDT	45
Pitch in reflectors (µm)	1.02
Pitch in IDT (µm)	0.976
Resonance frequency (MHz)	2003
Q-value	582
Resonanace-anti-Resonance dist. (MHz)	44

III. NON-SYNCHRONOUS RESONATORS

To achieve resonance in the center of the stopband in a short resonator, we experimented with resonators consisting of a relatively short IDT surrounded with two reflector gratings. The structure is quasi-synchronous: the pitch in the IDT is reduced, but there are no distinctive gaps between the reflectors and the IDT.

The resonance arising in such a structure can be situated in the center of the grating stopband, as shown with simulations and experimental results in Fig. 5. The admittance curve of the non-synchronous resonator is smooth, having no ripple caused by the finite length of the reflectors. A standard synchronous resonator with similar parameters has strong ripple on the admittance, as FEM simulations in Fig. 5 show. To reduce this ripple, longer IDT structures are typically used in impedance elements. Fig. 6 shows experimental admittance curve for a one-port resonator. Parameter data and characteristic values are collected in Table II.

Simulated amplitude distributions in Fig. 7 indicate that at the resonance frequency, reflectors efficiently confine acoustic energy inside the transducer of the non-synchronous resonator (top row in Fig. 7), yielding a strong resonance in the structure (Fig. 7(b)). In a standard synchronous resonator (bottom row in Fig. 7), a considerable amount of SAW energy is leaking into the gratings in the resonance frequency (Fig. 7(a)).

The structure studied here can be considered as a classic resonator with two mirrors and the IDT filling the resonance cavity. Relatively small difference in the pitches allows to get the desired phase shift, providing a resonance close to the center of the stopband, simultaneously making the reflectors more efficient. On the other hand, the structure has no visible gaps, so that losses on transitions between the reflectors and the IDT are minimal. That makes the structure suitable for the widely-used leaky-wave substrates.

The position of the resonance in the center of the stopband ensures minimal losses on both sides of the resonance. Such an element should be advantageous in the design of ladder filters, at least as a series-connected impedance element.

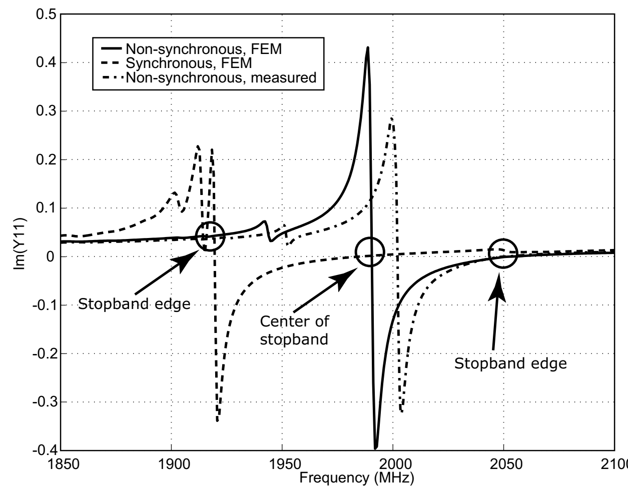

Figure 5. Simulated (FEM, solid line) and measured (dash-dotted line) admittance of a NS resonator. Dashed line shows the FEM simulation of a corresponding synchronous resonator. In the NS structure, the resonance occurs in the middle of the grating stopband and has no ripples. Amplitude distributions at frequencies indicated with circles are shown in Fig. 7.

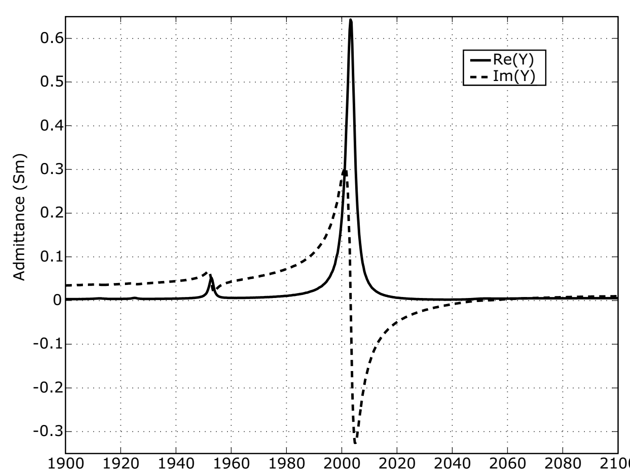

Figure 6. Experimantal admittance data of a non-synchronous resonator. Device parameters are summed in Table II.

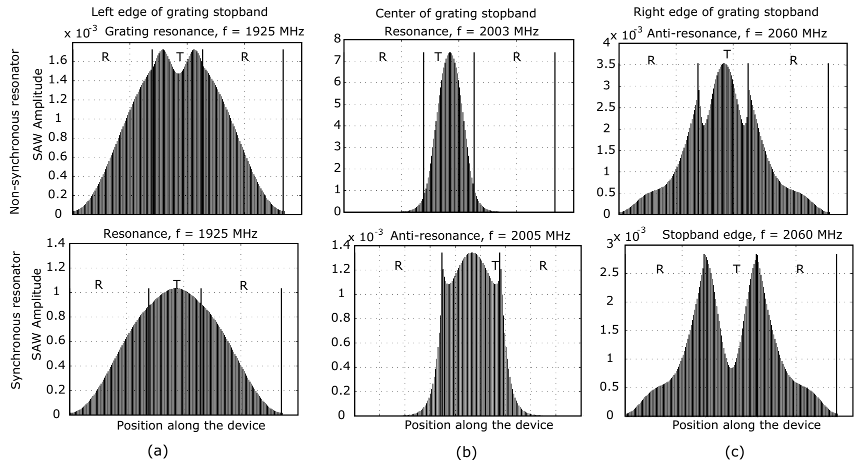

Figure 7. Amplitude distributions in an NS resonator (above) and corresponding synchronous resonator (SR, below) at the frequencies indicated by circles in Fig. 5, COM simulation. Vertical lines show element edges; R – reflector, T – transducer. (a) At the left edge of the stopband, the resonance frequency of the SR, a considerable amount of the acoustic energy is inside the gratings. (b) In the center of the stopband, resonance frequency of the the NS resonator, reflectors confine the acoustic field inside the transducer, resulting in a strong resonance mode. (c) At the higher edge of the stopband, reflectors start to leak. Note that the vertical scale is different for different frequencies.

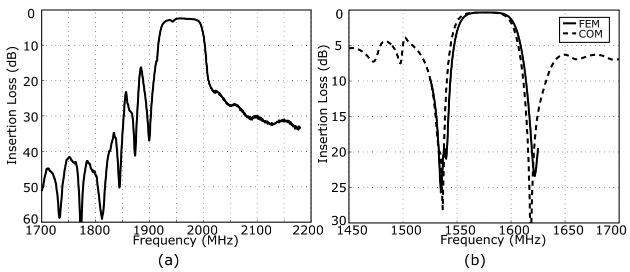

Figure 8. (a) Experimental frequency response of a CRF filter with a non-synchronous series resonator at the input. (b) Simulation of a 2-element IE filter response using DR resonators.

IV. NON-SYNCHRONOUS AND DR RESONATORS AS IMPEDANCE ELEMENTS

Double-resonance and non-synchronous resonators can be used as series elements in, e.g., coupled resonator filters (CRF), or as building blocks for IE filters. Fig. 8(a) shows an experimental frequency response for a CRF with a non-synchronous resonator connected in series to the input. The skirt at the high-frequency side of the passband is improved by the series element. In Fig. 8(b), simulated results for a two-element (1-section) ladder filter using DR impedance elements are shown. The resonators used as the IEs have short transducers in order to suppress the synchronous resonance.

V. DISCUSSION

Double-resonance and non-synchronous resonator structures presented in this paper feature a strong resonance taking place at a frequency near the center of reflector stopband. Such structures can have improved Q-values because the strong reflectivity of the reflectors confines the acoustic energy inside the transducer, and reduction in the ripple appearing on the resonator admittance. The hiccup resonance arising in a double-resonance device can also become self-matched, giving improved performance and a possibility of introducing a notch on both sides of the resonance.

In experimental devices we obtained very good Q-factors, although no optimization was performed to minimize losses. Non-synchronous resonators can be employed as impedance elements in ladder filters and other applications.

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