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SHORT COMMUNICATION

Design and Modelling of a Two-port Surface Acoustic Wave Resonator using Coupling-of-modes Theory

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ABSTRACT

In this present paper the coupling-of-modes theory has been used to design and simulate the characteristics of a two-port SAW resonator with shorted reflection gratings to define the resonance cavity. A resonator device at 150 MHz has been designed and fabricated on ST-Quartz. It is found that the simulated and experimental characteristics of the device are in close agreement. The results show that the SAW designs based on coupling-of-modes formulation are adequate for most applications.

Keywords: Coupling-of-modes theory, simulation studies, two-port SAW resonator, surface acoustic wave

1. INTRODUCTION

The design of surface acoustic wave (SAW) devices is based on: (a) signal theory (impulse response model), (b) field theory (finite element method (FEM), Green's functions, etc), and (c) network theory (P-matrix, coupling-of-modes (COM), equivalent circuit formulations, etc). The impulse response model allows for a first-order design since the inter digital transducer (IDT) impulse response $h(t)$ is directly related to the overlap and spacing of the electrodes as a function of position, with the time scale related to the position scale by the surface acoustic wave velocity v. The signal theory guidelines however, are not capable to account for many second-order effects like electrode reflections, spurious bulk acoustic wave (BAW) generation, wave diffraction, beam steering due to anisotropy of substrate, dispersion, electromagnetic feed through between IDTs, mechanical loading, charge distribution in electrodes - to name the most relevant phenomenon. The qualitative characterisation of these effects is taken into account the field theory approaches. Purely numerical simulators are used to describe the wave motion in the electrodes, and the piezoelectric substrate with the FEM and/or Green's function techniques. The device properties are derived directly from the material constants and device geometry. In the analysis the second-order effects are also fitted to simple, mostly analytic expressions depending on frequency, geometrical parameters such as metallisation ratio, and material parameters such as coupling coefficient, mass density, etc. Bond wires, chip layout effects, and package parasitics are evaluated in a similar manner. These simulators, though very accurate, require intensive computation and are consequently quite slow[1,2]. Several phenomenological models have also been proposed for modelling and analysis of SAW devices. These include the equivalent-circuit model, P-matrix model and the COM model. The equivalent-circuit model

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based on the Mason circuit was originally developed to describe the launching and detection of bulk acoustic waves[3]. The choice of model is generally dictated by the nature of the physical phenomenon relevant for the device performance. Also from the designer's point of view, the first requirement for a model is that it accurately predicts the device performance, saving cost and time-consuming design iterations. The P-matrix or COM-based models, which describe coupling between two waves propagating in opposite directions, are very accurate models needing only a limited number of physical parameters to analyse a device.

2. COUPLING-OF-MODES MODEL

The COM formalism is a particular branch of the highly developed theory of wave propagation in the periodic media. The approach has been widely used since 1950s in various problems related to optics and electromagnetism. The model was introduced to the SAW field by Suzuki and Haus. Subsequently, an analytic solution for uniform structures was found by Hartmann, Wright and others[4]. The advantages of this new modelling method are: (a) it retains much of the mathematical simplicity of the earlier impulse response model, (b) unlike the impulse response model, it accurately models the effects of distributed reflections inside the transducer, and (c) it results in closed form analytical expressions for many SAW transducer parameters that previously could only be calculated by numerical methods.

The COM model is based on the fact that the progressing and the counter-progressing waves couple with each other in the periodic structures and the amplitudes vary slowly in space. The waves are coupled due to surface perturbations, and can grow or diminish as they propagate. The model is particularly advantageous if multiple reflections are strong and essential for device operation. Hence, COM theory is a widely used tool for the analysis of SAW IDTs and SAW reflection gratings employed in a SAW resonator design. Using the coupled-mode theory, the relation among the two acoustical and one electrical port can be developed, and a simple distributed-parameter equivalent circuit representation can be developed. The two principal COM parameters needed for device analysis are the wave number perturbation and the coupling coefficient. For a particular substrate material and grating geometry, the values of these parameters need to be determined *a priori* either numerically or analytically[6,7].

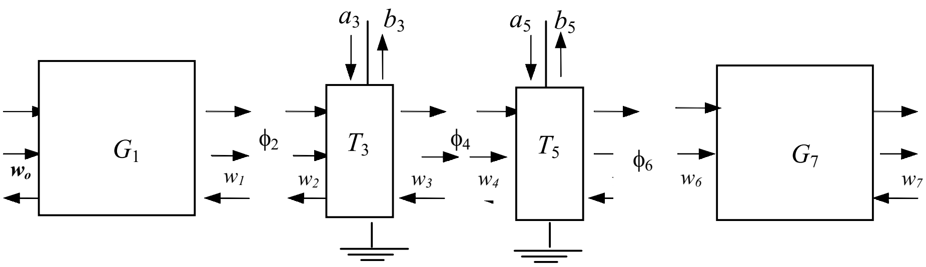
3. COM-BASED TWO-PORT SAW RESONATOR DESIGN

To model a two-port SAW resonator using COM theory, the SAW device may be divided into different segments, including the gratings, delay lines (inter-IDT gap and IDT to reflector gap) and input/output IDTs. By considering the coupling between the two forward and two backward travelling components, the coupled-mode theory is applied to derive the 2 x 2 transmission matrix relating to the acoustic wave amplitudes at the input and output of a surface wave grating. Then using the transmission matrices for the IDTs and the delay lengths, the external transmission through a SAW resonator is found by the matrix multiplication. The frequency response of the resonator is then obtained by calculating the transfer function b_5/a_3 and applying boundary conditions[8]. A schematic representation of the COM approach for the design of two-port SAW resonator is shown in Fig. 1.

4. DESIGN PARAMETERS AND EXPERIMENTAL PERFORMANCE

For designing a two-port SAW resonator, the important design parameters which need to be considered are the spacing between IDT and grating, separation between the reflection-gratings, and the inter IDT gap. These parameters control the standing wave pattern formation and the optimum performance of the resonant structure. Transduction is maximum when the IDT fingers are placed on the SAW standing wave maxima. For correct placement of reflection gratings, the phase of the reflected wave at the grating edge must be correctly identified.

The frequency response of the resonator will be symmetric about centre frequency when optimal reflection-grating spacing is employed[9]. Depending on the overall cavity length, however, spurious longitudinal modes can arise if the cavity lengths are large



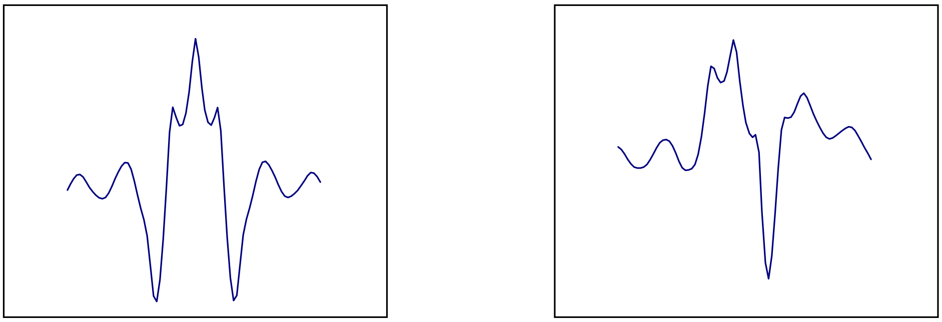
Overall Acoustic Transmission Matrix $[M] = [G_1][\phi_2][T_3][\phi_4][T_5][\phi_6][G_7]$

$S_{21} = b_5/a_3$

Figure 1. Coupling-of-modes approach for design of a two-port SAW resonator.

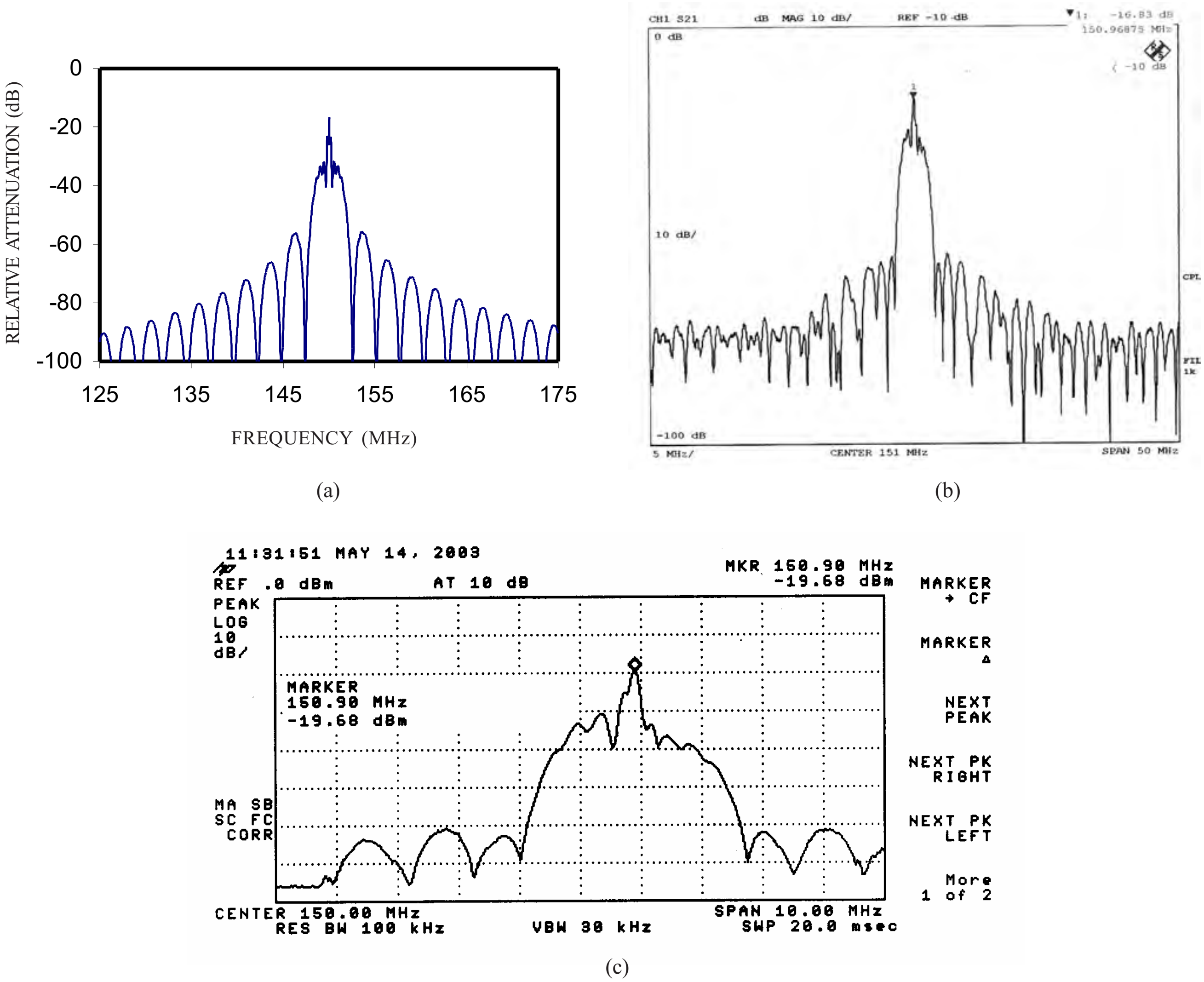
enough to support them. This multimode situation often occurs in two-port resonator design on ST-X quartz with low coupling. The spurious responses can be removed if the gratings are synchronously placed wrt IDTs. This, however, results in asymmetric response around center frequency and an increase in insertion loss. Frequency responses simulated for the two cases: (i) longitudinal modes in larger cavity length and (ii) no longitudinal modes with synchronous spacing, are shown in Fig. 2. The other important design parameters are the number of IDT fingers and the number of reflectors for optimum reflection.

The design parameters were optimised by adjusting the various parameters and using the coupled mode theory, a two-port SAW resonator at 150 MHz was designed and fabricated in-house on STX-quartz. The SAW cavity was defined by two shorted aluminium electrode reflectors having 274 electrodes at $\lambda_0/2$ periodicity in each, where λ_0 represents the surface acoustic wavelength at centre frequency. The cavity length was $499\lambda_0/2$. The input and output interdigital transducers had 58 and 81 electrode pairs with uniform acoustic aperture of $50\lambda_0$ and center-to-center separation of $165\lambda_0$. The distance of the IDTs from the reflectors was $15\lambda_0/2$. The resulting chip size was nearly 13 x 3 mm^2. The other parameters taken for the design and simulation included the unperturbed SAW velocity, $v = 3158$ m/s and the grating coupling coefficient $\kappa = 323$ m^{-1} according to COM model detailed by Smith[5]. Both the simulated and the experimental frequency responses of a device are shown in Fig. 3. The obtained insertion loss was nearly 19 dB as against the simulated loss of 18 dB. The experimental measurements were done using a vector network analyser (Rhode & Schwartz model ZVR) and spectrum analyser (HP 8951) without any impedance matching at the device ports.



(a) (b)

Figure 2. (a) Symmetric frequency response with optimal spacing, and (b) asymmetric frequency response with synchronous spacing.



(a)

(b)

(c)

Figure 3. (a) Simulated amplitude response, (b) experimental response showing resonance peak at 150.9 MHz, and (c) experimental response over a span of 30 MHz along with out-of-band attenuation (nearly 12 dB) limited by the delay line characteristics between input and output IDTs.

5. CONCLUSIONS

The experimental performance of the 2-port SAW resonator at 150 MHz designed using the coupling-of-modes formulation is in close agreement with the simulated characteristics. This shows that the coupling-of-modes design is adequate to correct distortions in SAW device performance that arise due to second-order effects during excitation, propagation, and reflection of piezoelectric surface acoustic waves. Accuracy of the results depends on the precision of material parameters used in the design, particularly the SAW velocity and coupling coefficient. Since in most situations, the rigorous analysis techniques are impracticable due to their complexity and computational slowness, the COM model with equivalent circuit parameters for interdigital transducers is adequate to yield satisfactory device performance.

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Contributors

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