DESIGN CONSIDERATIONS FOR HIGH PERFORMANCE ONE-PORT SAW RESONATORS ON QUARTZ

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Abstract — **The design of high performance SAW resonators requires detailed knowledge of the properties and characteristic behavior of their key constituents like the interdigital transducer (IDT) and the reflector gratings. This paper presents and analyzes various design considerations for high performance SAW resonators. Analytical models for a single design are used to simultaneously optimize the IDT and the reflectors. In addition, a novel theoretical condition for harmonic rejection inside the resonance cavity is presented. Our work demonstrates how the device performance can be improved by properly accounting for these design considerations and recommendations.**

Keywords : SAW Resonators, ST-Quartz, Interdigital Transducer (IDT), Reflector Gratings

I - Introduction

Since their first introduction in 1970 [1], surface acoustic wave (SAW) resonators (and filters) have been widely employed for a range of sensor or telecommunications applications such as the RF front-end of radio transceivers in mobile phones. Their small size, low cost high volume manufacturing process, ruggedness, wide accessible frequency range (10 MHz – 3 GHz), relatively high quality factor and high stability make SAW devices a preferred choice for many applications.

Early designs for SAW resonators, predominantly operating at relatively low frequencies (i.e., <300MHz), make use of simple models like the delta function model [2] or the impulse response model [3]. However, as the operating frequency increases many effects that are not considered in the models mentioned above may become significant. Examples of such effects are multiple reflections in both the reflector gratings and the interdigital transducer (IDT), the mass loading effect caused by the deposited metal strips of the IDT and the reflectors, and, the bulk scattering loss. Accounting for these effects is possible as will be shown in this paper, but will come at a price of a more complex analytical model.

Many works have been developed for the optimization of SAW resonator design [4-6]. However, all of these efforts are based on separate optimization approaches for certain device parameters without providing a comprehensive approach, which simultaneously considers the effects of the various device parameters.

In this paper, the basics of one-port SAW resonators are described, design considerations and trade-offs are given and a novel procedure for obtaining an optimized design is proposed. Design parameters addressed include the geometries of the IDT and reflector gratings, the substrate loading and any bulk scattering effects. Furthermore, novel conditions for the suppression of (higher) harmonics inside the resonance cavity will be introduced.

II – SAW Resonator Structure: Basics

The SAW resonator structure considered in this paper is shown in Fig. 1. It consists of a pair of reflector gratings, defining an acoustic cavity, and of an IDT, used to couple acoustic energy to the cavity. These components are produced on top of a piezoelectric substrate required for the function of the IDT. In this paper, an *ST*-cut quartz substrate with material properties as given in Table 1, is assumed.
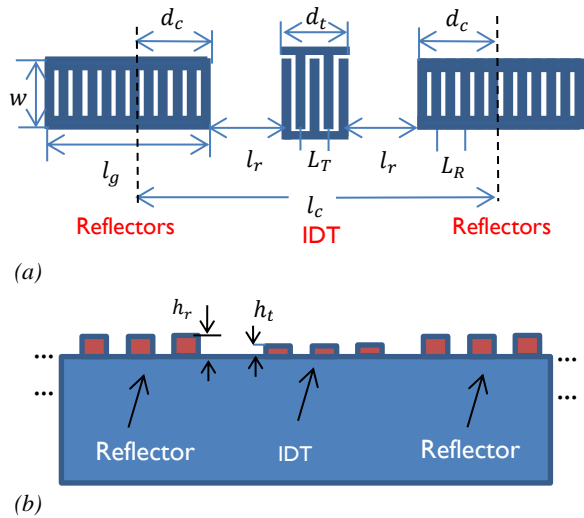

(a)

(b)

Figure 1: *Schematic of a one-port SAW resonator: (a) Top view; (b) Cross-Sectional view.*

The surface acoustic wave is excited by applying a proper electrical signal to the IDT. The reflector gratings are constituted of a set of metal strips, either shorted or open-circuited, and act within their stop band as mirrors reflecting the incident waves thus forming a resonance cavity with an effective length l_c. The distance d_c is defined here as the distance into the reflector gratings at which the SAWave has decayed to $1/e$ of its value in the cavity right before the reflector gratings. In this paper, the metal strips of the reflector gratings are shorted. However, the work here is still valid for open circuited strips or for reflection grooves thereby taking into consideration the reflectivity of each type [9].

Table 1 :*Relevant properties of ST-cut quartz.*

Material	Cut	TC [ppm/°C]	Coupling Coeff. k^2 [%]	speed v_f [m/s]
ST-Quartz	+42.75° rot. Y	0 at T=25°C	0.16	3157

All the simulations presented in this paper assume the following parameters and notations:

f_0: Target resonance frequency = 100 MHz
λ_0: Target resonance wavelength = v_f/f_0
f_c : Actual resonance frequency
N_{idt} : Number of IDT finger pairs $(=d_t/\lambda_0)$
RF : Mirror Reflection Factor $=\dfrac{total\ reflected\ power}{total\ incident\ power}$

III – Analytical Modeling

The Impulse Response (IR) model [3] and the Delta Function (DF) model [2] are the early methods used for the modeling and simulation of low frequency SAW devices (i.e., <300MHz). However, as the frequency goes up, the approximations used for these models, such as negligible internal reflections and negligible thickness, become no longer valid and potentially affect the device performance. This necessitates looking into more comprehensive models. These include the transmission line (TL) model, the coupling-of-modes (COM) model and the P-matrix model [6].

Figure 2 shows an example of the validity of neglecting internal reflections in the gratings. As shown, both the DF model and the TL model give roughly the same response for $Nr<1$, where N is the number of reflector gratings and r is the reflectivity per strip. However, for Nr near or larger than 1, the delta function model gives a reflection factor greater than 100%, something which is not realistic, thus illustrating the need for a more precise yet more complex model for the SAW simulations.
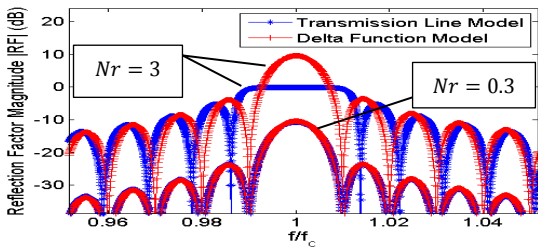

Figure 2: *Comparison of Reflection Factor magnitude response of reflector gratings with Nr <1 and Nr >1 evaluated for the two models: TL and DF.*

IV – Design Tradeoffs

A. IDT Design tradeoffs

The design of the IDT involves the determination of three parameters: electrode thickness (h_t), transducer length (d_t) and the finger pair period (L_T), all further explained in Fig. 1. The finger overlap width w of the IDT is of less importance and is primarily set to guarantee working on the Fresnel zone to avoid the diffraction effect [9]. Varying the thickness and/or the length of the

IDT mainly has an effect on the mass loading, on the radiation conductance magnitude and on the reflections from the IDT edges. The mass loading induces a frequency shift as a result of the "wave slowing" under the metalized regions where strong reflections can lead to high distortion [4]. While some effects, like the frequency shift (see below) can be compensated for, other factors pose a tradeoff to be made in the optimization problem. Figure 3(a) shows the effect of the thickness variation on the response of the IDT defined by the normalized radiation conductance [6] and simulated using the COM model. The radiation conductance is a measure for the electromechanical coupling efficiency. As the thickness h_t increases, the radiation conductance increases, yet the frequency response becomes more narrow and more distorted. Figure 3(b) also shows a similar tradeoff for the number of IDT finger pairs N_{idt} or the IDT length d_t through $d_t=N_{idt}*L_T$. Taking into account the maximum device dimensions set by the application requirements, the length and the thickness of the IDT are simultaneously determined in conjunction with the reflector design as shown below.
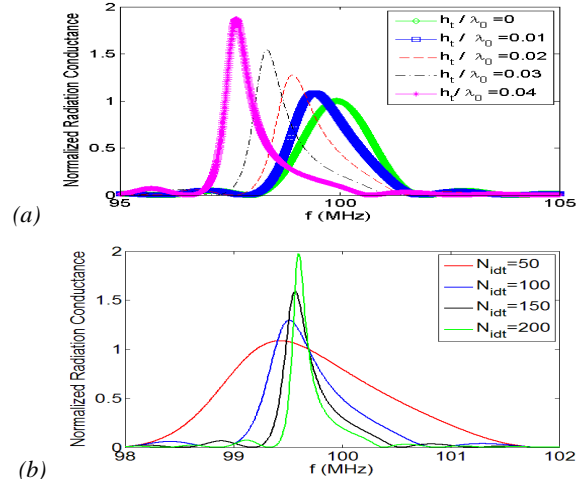

(a)

(b)

Figure 3: *Effect on the radiation conductance of (a) the electrode thickness h_t (for N_{idt} =50) and (b) the number of IDT finger pairs N_{idt} (for h_t/λ_0=0.01).*

B. Reflector Gratings Design tradeoffs

The design of the reflector gratings is the most crucial for a high quality factor SAW resonator. It involves three design parameters: metallic strip thickness (h_r), reflector length (l_g) and the finger pair period (L_R), all explained in Fig. 1. The response of the reflector gratings is shown in Fig. 4(a), and is represented by the magnitude of the reflection factor RF. The maximum RF is determined both by the resonance frequency and the quality factor, thereby assuming negligible material damping according to:

$$Q = \frac{l_c}{4\lambda_o}\frac{2\pi}{1-|RF|^2}(1+|RF|)^2 \qquad (1)$$

where λ_0 denotes the resonance wavelength.

Varying the thickness h_r and/or the length l_g of the reflectors mainly has an effect on the mass loading induced frequency shift, and further on the RF magnitude and the selectivity of the mirrors. The mirror

selectivity is reflected in both the bandwidth BW of the main lobe and the side lobe rejection, both shown in Fig. 4(a). Figure. 4(b) shows an example of the effect of varying the thickness h_r on the mirrors response. The optimization of both L_T and L_R should be done simultaneously as will be shown in Section V.
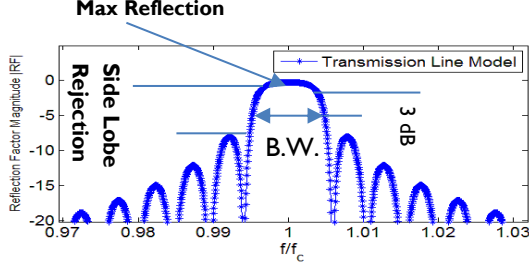

Figure 4(a): *Frequency response Reflection Factor magnitude of the reflection gratings evaluated for N=200 and $h_r/\lambda=0.01$.*
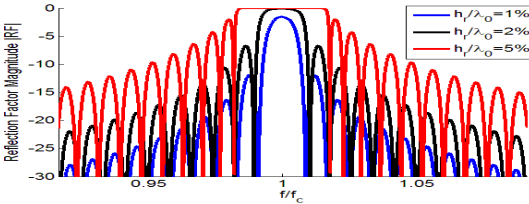

Figure 4(b): *Effect of reflection gratings thickness variation on Reflection Factor magnitude using the Transmission Line Model for N=120.*

V – Optimized Design

A. Optimized design of the reflectors

We start by choosing the reflector strip thickness h_r. Since the bulk losses are directly proportional to $(h_r/\lambda_0)^2$ the losses increase with increasing thickness h_r [7]. An optimum thickness h_r of the reflector strip for a given reflector length is one for which the bulk-mode losses are slightly smaller than the most limiting loss mechanism for the frequency range considered. In the lower frequency range ($f_0 < 300\,\mathrm{MHz}$), the material losses are fairly low, and extremely thin strips may be necessary ($h_r/\lambda_0 < 0.5\%$) to reach the material Q limit in the device performance. This would dictate very long arrays, and the overall device size may thus be the limiting factor. At much higher frequencies the material losses increase considerably, and it may be possible to have somewhat thicker strips and still keep the bulk-mode losses less than losses due to the material.

Having determined the thickness, the SAW velocity v_m under the metalized region can be calculated using the following formulas [9],

$$f_a = \frac{1}{2}\left(\frac{\lambda_0}{4v_m} + \frac{\lambda_0}{4v_f}\right)^{-1} \tag{4}$$

$$f_a = \frac{v_a}{\lambda_0} \quad , \quad v_a = v_f\,(1 - k'_{11}) \tag{5}$$

where, v_f is the SAW velocity at the free (not metallized) surface, v_a is the average shifted velocity, and k'_{11} is the self-coupling coefficient [9]. Given the two velocities, the new center frequency f_c can be calculated from [6],

$$f_c = 0.5\left(\frac{1}{\frac{\lambda_0}{4v_f} + \frac{\lambda_0}{4v_m}}\right) \tag{6}$$

Having calculated the new center frequency, the design problem is repeated with a modified target frequency $f'_0 = f_0 + (f_0 - f_c)$. Thus, when $L_R = \lambda'_0 = v_f/f'_0$ the center response of the reflectors will be aligned to the desired resonance frequency as illustrated in Fig. 5 for a specific case.
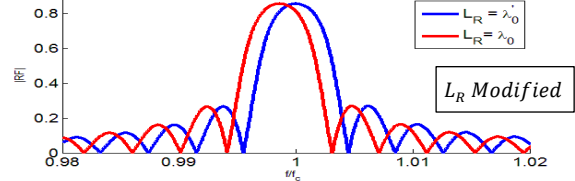

Figure 5: *Effect of reflector gratings period (L_R) modification for N= 120 and h_r/λ_0 =0.01.*

The determination of the length of the reflector grating l_g should then guarantee single mode operation inside the cavity as well as a high RF magnitude at resonance. The mode selectivity inside the cavity is initially done by choosing the length l_c of the cavity to be an integer multiple of half wavelengths ($\lambda_o/2$) of the desired mode. Since a single reflector is not used, properly spacing of the reflectors inside the array can also add to a better selectivity of the mirrors. However, this selectivity also induces nonzero phase response to the mirror response, which means that different frequencies are reflected with different phases. The phase condition of a mode reflected with an arbitrary phase $\phi(\omega)$ to survive in the cavity can be obtained from the analogy with a conventional cavity with two single mirrors on both sides as shown in Fig. 6, or formulated mathematically,:

$$\frac{2\pi}{\lambda}\frac{N_1\lambda_0}{2} = \frac{2\pi}{\lambda}\frac{N_2\lambda}{2} - 2\phi(\omega), \quad N_2 \le \frac{N_1\lambda_0}{\lambda} \tag{7}$$

or

$$\phi(\omega) = -\frac{N_1\lambda_0}{4v}\,\omega + \frac{N_2\pi}{2}, \quad N_2 \le \frac{N_1\lambda_0}{\lambda} \tag{8}$$

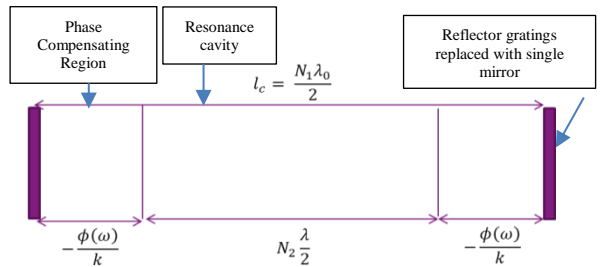where, $N_1\frac{\lambda_0}{2} = l_c$ and $k = \frac{2\pi}{\lambda}$

Figure 6: *Resonance cavity representation with reflector gratings replaced by an equivalent single mirror with similar frequency response.*
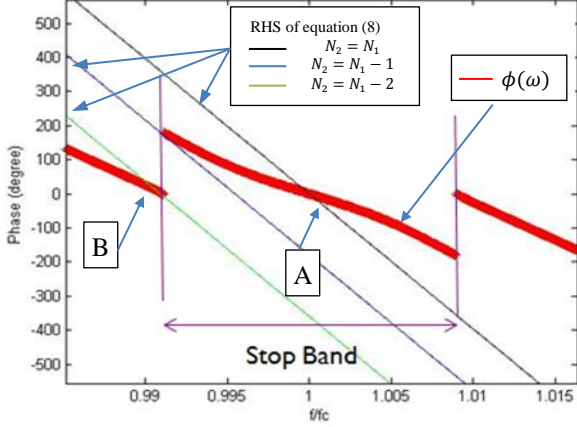
Figure 7: The phase response of the mirrors main lobe (stop band) together with the right hand side of eq. (8) for various values of the arbitrary integer N_2

If there exist an integer N_2 that satisfies (8), it will represent a "surviving mode" inside the cavity. The condition for having single mode operation then is to have the equality in (8) satisfied only once inside the reflector gratings stop band. Figure 7 shows the plot of both the LHS ($\phi(\omega)$) and the RHS of (8), where intersections (e.g. A & B) give the modes that will satisfy the condition. The greater the length of the reflector gratings l_g the less intersections we get in the stop band. Consequently, the length of the reflectors should be chosen so as to satisfy single mode operation (single intersection inside the main lobe), acceptable side lobe rejection and quality factor without violating the required maximum device dimensions.

B. Optimized design of the IDT

We start here by adjusting the finger pairs period L_T to coincide the IDT response with the reflector gratings response at the desired resonance frequency as shown in Fig. 8. According to [6], the condition on the periods in eq. (9) for high performance is given by

$$\frac{\left(1-k'_{11}-k'_{12}-\frac{k'_{12}}{(0.35q_T^2+0.3q_T+0.2)}\right)}{1-k'_{11}} < \frac{L_T}{L_R} < \frac{1-k'_{11}-k'_{12}}{1-k'_{11}} \quad (9)$$

where, $q_T = \pi k'_{12} N_{idt}$ and k'_{11} and k'_{12} are the self and mutual-coupling coefficient, respectively. The value of L_T (for a given L_R) is chosen in the middle of this range and where both peaks of the reflectors and the IDT responses coincide as shown in Fig. 8. Having these limits in (9), the electrode thickness and the IDT length are chosen such that these limits remain within the available fabrication tolerance. The IDT electrodes are chosen to be very thin to ensure low distortion effects resulting from the internal reflections, low bulk scattering and low mass loading to the substrate. However, as the thickness decreases the radiation conductance also decreases. The design criterion of choice is to minimize the thickness near the fabrication limits and next choose the IDT length as long as it increases the radiation conductance without violating the aforementioned fabrication limits of (9).
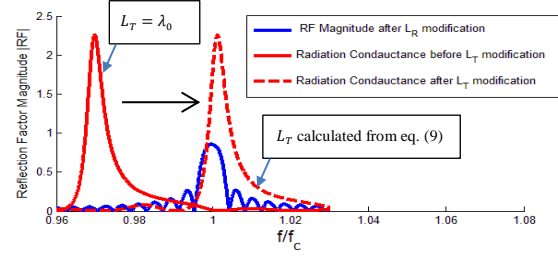

Figure 8: Effect of modifying the IDT finger pair period L_T for $N= 120$, $N_{idt}=50$ and $h_r/\lambda =0.01$

VI – Conclusions

Several design considerations and tradeoffs for high performance SAW resonators were discussed and recommendations for an optimized design were given. Matlab simulations were used to show the significance of some of the design tradeoffs. Various analytical models were used in conjunction with each other for device simulation. In addition, an optimal design approach for IDT and reflector gratings design was presented including the distortion effect, mass loading, in addition to a novel condition for harmonic suppression inside the cavity.

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