HIGH Q MICROWAVE ACOUSTIC RESONATORS AND FILTERS

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ABSTRACT

This paper presents recent experimental results and modeling obtained on high Q microwave acoustic resonators and filters for use in oscillators and other frequency control applications. Overmoded resonators have exhibited an FQ greater than 1×10^{14} Hz (e.g. Q=68000 at 1.6 GHz) with a strong inductive response suitable for one-port and two-port oscillator feedback circuits. Ladder filters fabricated with overmoded resonators have loaded Q's greater than 40000 with 76 KHz bandwidth at 1.6 GHz. Aluminum nitride films were use for transduction on Z-cut sapphire substrates.

I. Introduction

In microwave oscillator applications high Q resonators and filters are required as feedback elements in low phase noise designs. Microwave acoustic two-port devices using bulk or surface acoustic wave modes have been employed in microwave low phase noise oscillators [1-3]. These narrow bandwidth filters, often referred to as two-port resonators, are in delay line configurations designed to weakly sample the standing wave to effect a high Q response. The work reported here uses a different design approach employing individual high Q resonators in a ladder filter configuration to realize narrow bandwidth high Q filters.

Four forms of high Q microwave acoustic resonators and filters are shown in Fig. 1. The first resonator, Fig. 1a is a piezoelectric plate having suitable electrodes and traction free reflecting surfaces to form an acoustic resonator. The extent to which this is a high Q resonator depends on the degree of energy trapping in the structure. The primary loss mechanism is energy leaking into plate waves that radiate away from the electroded region. Typical dimensions of a thin film aluminum nitride resonator at 1 GHz are plate thickness of 5 micrometers and width and length (or diameter) of 0.5 mm. The films are therefore very thin compared to the resonator's lateral dimensions.

The second resonator, Fig. 1b, uses a piezoelectric film as a transducer to excite waves in a substrate having parallel surfaces. If the substrate is some number of wavelengths thick then the resonator operates at a large mode number and can exhibit a high Q impedance response. The resonant frequency is well above the primary plate frequency so the loss mechanism is due mostly to diffraction effects rather than plate wave excitation. A high Q response is obtainable with substrates having low intrinsic mechanical loss and with sufficiently high mode numbers that the piezoelectric film occupies a small fraction of the resonator volume and hence is weakly coupled to the standing wave.

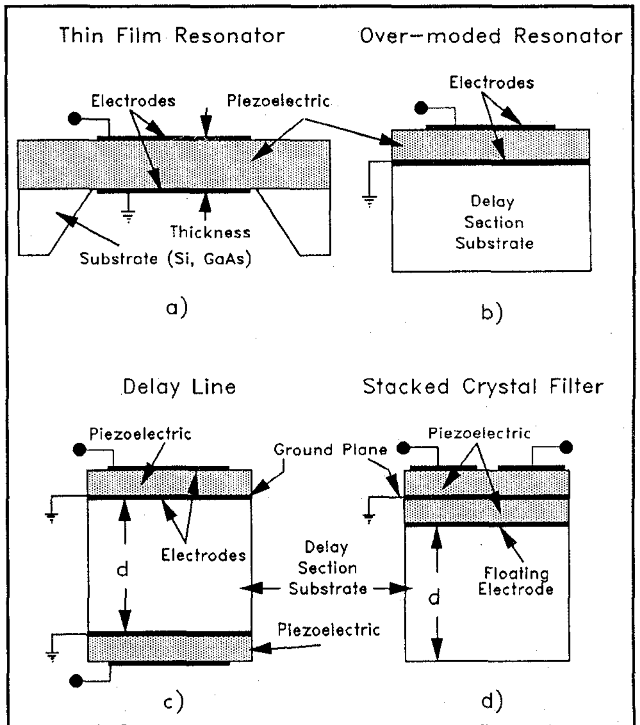

Fig. 1 a) One and two-port resonator configurations for microwave frequencies. a) A thin film fundamental mode resonator supported by the edges of a substrate. b) An overmoded resonator consisting of a thin film piezoelectric transducer fabricated on a low loss substrate having reflecting surfaces. c) A two-port resonator in the form of a delay line weakly coupled to the source and load to provide a large standing wave and high Q response. d) A stacked crystal filter having two layers of piezoelectric films. Two single section stacked are shown connected in series so as to bring the output electrode to the surface.

The advantage of an overmoded resonator over a thin film resonator is that substrates can be employed that have desirable properties, such as high intrinsic material Q and low temperature coefficients of delay, generally not obtainable in thin film fundamental mode resonators. At high mode numbers the piezoelectric film and associated electrodes are a small fraction of the resonator volume and

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the resonator Q is dominated by the substrate material. The overmoded structure is also mechanically rugged due to the finite thickness of the substrate.

An important property of the overmoded resonator is that multiple resonances occur at frequency intervals determined by the fundamental resonant frequency of the plate and transducer combination. For example, an overmoded resonator having a fundamental resonance of 10 MHz would have a mode number of 100 at 1000 MHz and resonances every 10 MHz over the passband of the transducer.

Two-port overmoded bulk wave resonators, essentially narrow band filters, have been studied in the two forms shown in Figs. 1. The first, Fig. 1c, is a conventional acoustic delay line configured so that the transducers are weakly coupled to the external source and load thus allowing significant standing waves in the delay line and a high Q resonance response [2]. The second two-port resonator, Fig. 1d, is configured as a Stacked Crystal Filter (SCF) having both driving and sampling transducers fabricated in tandem on one side of the crystal [4-7]. Narrow band multimode responses were reported for an overmoded SCF having bandwidth of 174 KHz at 1 GHz with a loaded Q of 8000 [8] on a spinel substrate.

The SCF configuration allows close proximity of filter input and output and a free surface for resonator trimming. The planar nature of the device is highly compatible with microelectronic processing and MIMIC chips and circuits.

An alternative approach to narrow band filter realization is to use the high Q overmoded resonators of Fig. 1b to implement a more traditional filter configuration. By using individual resonators to synthesize a desired filter response the task of resonator design is separated from filter design giving a wide latitude in obtainable filter characteristics. This paper will describe the one port overmoded resonator, Fig. 1b, and its use in a ladder circuit configuration to form narrow band two-port filters suitable for microwave oscillator control or other signal processing applications.

II. Overmoded Composite Resonator Modeling

The composite resonator consists of a piezoelectric plate with electrodes and a substrate as shown in Fig. 2. If the linear equations of piezoelectric elasticity are solved for the one dimensional case the electrical impedance at the electrodes may be found by a general expression;

$$Z = \left(\frac{1}{j\omega C}\right)\left(1 - K^2 \frac{\tan\phi}{\phi} Z_m\right) \qquad (1)$$

$$Z_m = \frac{(z_r + z_l)\cos^2\phi + j\sin 2\phi}{(z_r + z_l)\cos 2\phi + j(z_r z_l + 1)\sin 2\phi}$$

where z_r and z_l denote mechanical load impedances normalized by the piezoelectric film impedance. Here $\phi = kd/2$ is the phase across the piezoelectric film. All structures attached to the piezoelectric plate, including mechanical effects of the electrodes must be described in terms of a suitably normalized equivalent terminating impedance, as suggested in Fig. 2. The equivalent load impedance can be found by successive use of the transmission line equation,

$$Z_{in} = Z_0 \left\{ \frac{Z_l \cos\theta + jZ_0 \sin\theta}{Z_0 \cos\theta + jZ_l \sin\theta} \right\} \qquad (2)$$

Here Z_{in} is the input impedance, Z_0 the characteristic impedance, θ the phase across the delay section, and Z_l the load impedance attached to the line section.

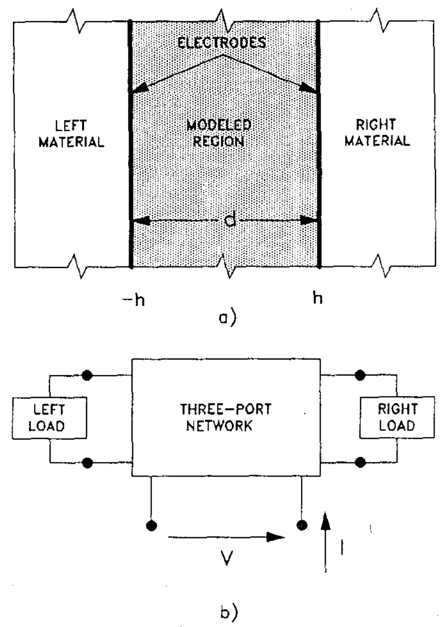

Fig. 2. Representation of the general one dimensional piezoelectric plate. a) Material configuration of piezoelectric material and external load materials. b) Circuit block diagram representation showing a three port network having arbitrary mechanical loads on left and right and an electrical port.

Impedance equation (1) was applied to an overmoded resonator consisting of an aluminum nitride film of 3 micrometers thickness, aluminum electrodes of 0.3 micrometers thickness and a Z-cut sapphire substrate of 635 micrometers (25 mils) thickness. From the computed series and parallel resonances the effective electromechanical coupling coefficient was calculated from

$$K_e^2 = \phi_r / \tan\phi_r \qquad (3)$$

where

$$\phi_r = \frac{\pi f_s}{2 f_p}$$

and f_s and f_p are the series and parallel resonant frequencies respectively.

Q is determined from;

$$Q = \frac{f}{2}\frac{d\phi_z}{df} \qquad (4)$$

evaluated at the resonant frequency where ϕ_z is the phase of the impedance z

Greater details for resonator modeling have been provided in the literature [9] along with ladder filter design using crystals [10].

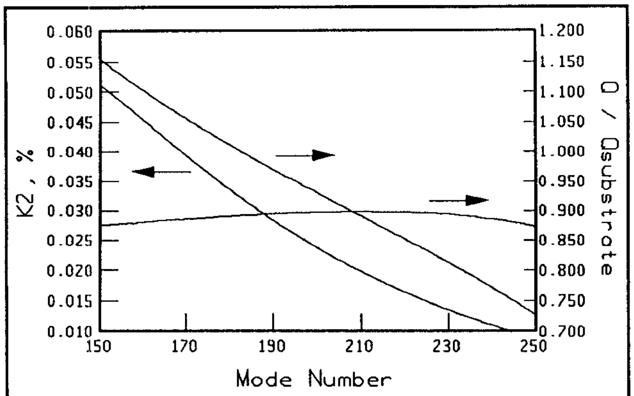

Fig. 3. Effective piezoelectric coupling coefficient and Q as a function of mode number for a fixed substrate thickness. The diagonal line Q accounts for 1/f frequency variation of material loss and the near horizontal line Q plot assumes material loss independent of frequency.

III. Experimental Results

Overmoded resonators were fabricated on sapphire substrates having nominal thicknesses of 380 and 635 micrometers (15 and 25 mils) polished both sides and diameters of 51 and 76 mm (2 and 3 inches) respectively. The transducers consisted of aluminum nitride c-axis normal films with circular electrodes of 0.3 micrometer thick aluminum. The aluminum nitride thickness was chosen to put the transducer in the center of the frequency range of interest for maximum excitation efficiency. The overall flatness of the 76 mm diameter substrate was better than the 51 mm substrate and produced cleaner resonator characteristics. The aluminum nitride thickness uniformity is better than one percent over the entire wafer.

Sapphire was chosen as the substrate material during these initial investigations because of its known high Q and ready availability in diameters to 76 mm optically polished on both sides.

All measurements reported here were done on a HP8753C network analyzer and 50 ohm microwave wafer probe station and at room temperature. The wafers contained approximately 600 resonators of different areas or 350 filters of various sizes and designs.

Figure 4 shows a Smith chart of one resonator at mode number 185. The effective coupling coefficient of the resonance is 0.019 percent for a K^2Q product of 12.2 and FQ product of 1.1×10^{14}. The minor loop in the capacitive region is due to spurious resonances from diffraction and non-parallelism of the resonator surfaces. The spurious resonances become very pronounced if the overall structure, including transducer, has non-parallel surfaces.

Determination of K^2 and Q were done by using (3) and (4) and a computer program to analyze the data. Resonant frequencies were defined as the points where reactance is zero. Q was computed over the entire frequency range and subsequently noted at the resonant frequencies. Maximum Q typically occurs slightly removed from the parallel resonant condition.

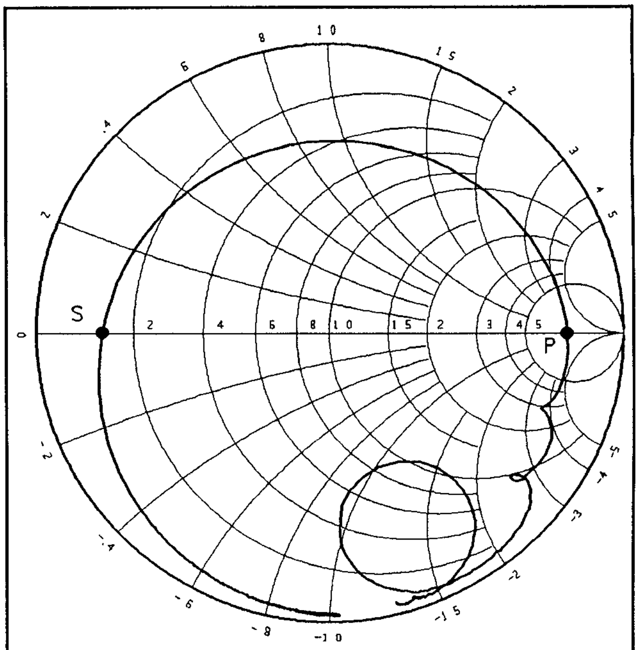

Fig. 4 Smith chart display of one resonance of a high Q overmoded resonator. The series resonant frequency at **A** is 1.60327 GHz and the parallel resonant frequency at **P** is 1.60339 GHz and the Q's are 47500 and 65700 respectively. A maximum Q of 68000 was obtained near parallel resonance. The sapphire substrate thickness of 650 micrometers (25.6 mils) produces a resonance spacing of 8.64 MHz. Therefore the resonator mode number is 185. The FQ product for this resonator is 1.1 x 10^{14}.

Resonators have been measured over a wide frequency range, corresponding to different mode numbers, and the FQ product is maintained through 2.8 GHz. Coupling coefficients showed variations expected from the initial modeling.

Overmoded resonators were fabricated into bandpass filters in ladder filter configurations having various numbers of series and shunt resonators. The filter is fabricated so that the series resonators are series resonant at the frequency where the shunt resonators are parallel resonant. Filters are designated as X/Y where X denotes the number of series resonators and Y the number of shunt resonators.

Shown in Fig. 5 is a 6/6 ladder filter having square electrodes and designed for 50 ohm source and loads at frequencies near 1.6 GHz. Because the individual resonators are overmoded, the filter shows the same multiple response every 8.64 MHz corresponding to mode numbers 184, 185, and 186. The filters low level spurious response, due to imperfect resonance, is apparent at levels below approximately -40 dB.

An expanded view of the filter for mode number 186 is shown in Fig. 6. The 3 dB bandwidth of the filter is 152 KHz and the loaded Q is approximately 30000 in mid-band rising to over 50000 at the band edge as the resonator is less efficiently coupled to the source and load.

The response for a 4/4 ladder filter, on the same wafer as the 6/6 filter in Fig. 5 and 6, is shown in Fig. 7. The design for the 4/4 allows for a somewhat narrower bandwidth of 76 KHz and loaded Q of approximately 40000.

The filters were designed for fundamental mode operation and therefore did not use resonators optimally configured for overmoded operation. Filters designed specifically for overmoded resonators are under investigation.

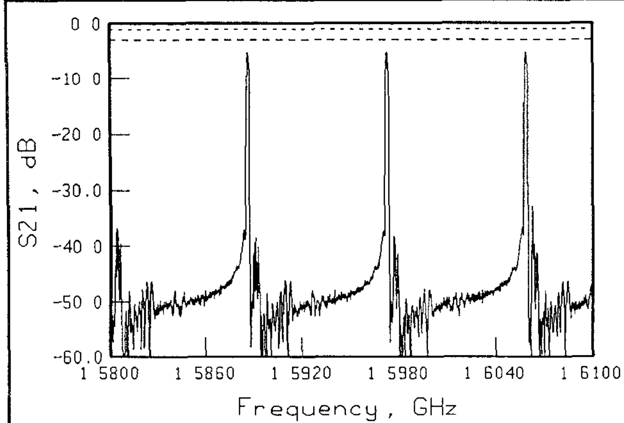

Fig. 5 Response of a ladder filter composed of 12 high Q overmoded filters on a sapphire substrate. The three responses, spaced 8.64 MHz, correspond to resonator mode numbers of 184, 185, and 186.

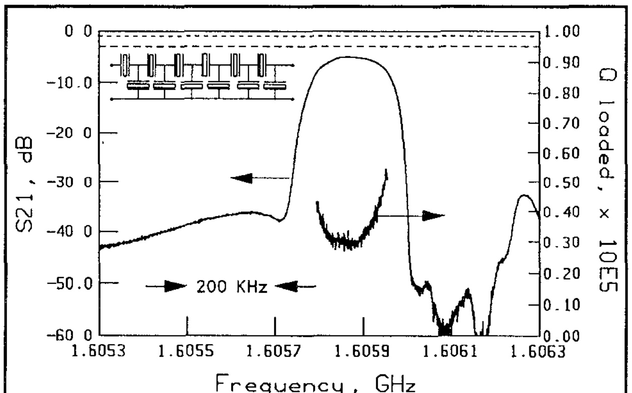

Fig. 6 Expanded plot of the center multi-mode filter response (mode number 185) of Fig. 5. The 3 dB bandwidth of the filter is 152 KHz (200 KHz per division on horizontal axis) and the loaded Q varies from 30000 in mid-band to over 50000 at the band edges. The mid-band insertion loss is 5 dB. The die size of the filter is 2.5 mm x 1.25 mm x 1.6 mm.

V. Summary and Acknowledgments

Modeling and experimental results were reported on overmoded high Q resonators and filters. Resonators have shown FQ products over 1×10^{14} Hz for aluminum nitride film transducers on Z-cut sapphire. Ladder filters containing up to 12 overmoded resonators showed bandwidths down to 76 KHz with loaded Q's over 40000 at 1.6 GHz.

This work was supported by the U.S. Government and an SBIR Phase II Contract from U.S. Army Research Laboratory, Ft. Monmouth, NJ.

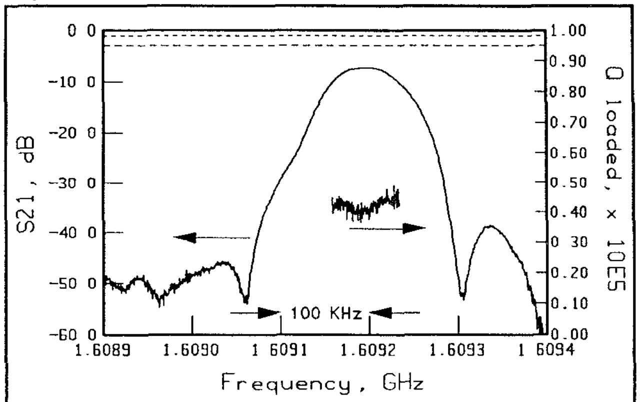

Fig. 7 Response of a 4/4 ladder filter of narrower bandwidth design and fewer basic resonator elements. The 3 dB bandwidth of the filter is 76 KHz wide (100 KHz per division on horizontal axis) and the loaded Q varies from 40000 in mid-band to over 50000 at the band edges. The mid-band insertion loss is 7 dB. The die size of the filter is 2 mm x 1.7 mm x 1.6 mm.

References

1. M.M. Driscoll, R.A. Jelen, and N. Matthews, "Extremely Low Phase Noise UHF Oscillators Utilizing High-Overtone, Bulk-Acoustic Resonators", IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39, No. 6, Nov. 1992 ,pp 774-779

2. D.S. Bailey, M.M. Driscoll, R.A. Jelen, and B.R. McAvoy, "Frequency Stability of High-Overtone Bulk-Acoustic Resonators", IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39, No. 6, Nov. 1992 ,pp 780-784.

3. T.E. Parker and G.K. Montress, "Spectral Purity of Acoustic Resonator Oscillators", Proceedings of the 1992 Frequency Control Symposium, 27-29 May 1992, pp. 340-348.

4. K.M. Lakin, G.R. Kline, R.S. Ketcham, and J.T. Martin, 43rd Annual Frequency Control Symposium, Denver, CO, pp. 536-543, May 31-June 2, 1989.

5. G.R. Kline, R.S. Ketcham, and K.M. Lakin, IEEE Gallium Arsenide Integrated Circuit Symposium Proceedings, Nashville, TN, Nov. 6-9, 1988, p. 313.

6. R.B. Stokes and J.D. Crawford, IEEE Microwave Symposium Digest, Albuquerque, NM, June 1-5,1992, pp. 157-160.

7. K.M. Lakin, "Equivalent Circuit Modeling of Stacked Crystal Filters", 35th Annual Symposium on Frequency Control Proceedings, Philadelphia, PA, May 27-29, 1981, p. 257-262.

8. G.R. Kline, R.S. Ketcham, and K.M. Lakin, "Low Insertion Loss Filters Synthesized With Thin Film Resonators", IEEE Ultrasonic Symposium Proceedings (1987), p. 375-380.

9. K.M. Lakin "Modeling of Thin Film Resonators and Filters", 1992 MTT Symposium Digest, Albuquerque, NM 2-4 June, 1992, pp. 149-152.

10. K.M. Lakin, G.R. Kline, and K.T. McCarron, "Thin Film Bulk Acoustic Wave Filters for GPS", 1992 IEEE SU Symposium, Tucson, AZ, Oct. 20-23.