A REVIEW OF SAW RESONATOR FILTER TECHNOLOGY

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Abstract

Every year worldwide many millions of SAW resonators are produced for a wide diversity of applications. These devices must be extremely precise in their frequency and yet, in general, very low in cost. What is often not appreciated is that the diversity of resonator designs is almost as great as that of their applications. This paper reviews for the reader a compendium of design approaches that have been proved to be successful in large-scale production. Many resonator configurations are presented and typical performance characteristics illustrated. New developments are also discussed. These include techniques for increasing coupled-resonator bandwidths $< 0.5\%$ *and weighting reflector banks to suppress close-in ripple. The trend towards high-coupling designs that do not require matching is also discussed, as are possible applications of new SPUDT technologies.*

1 Introduction

SAW resonators and coupled-resonator filters have typically received much less attention in the literature than have filters. Textbooks on SAW technology, for example, frequently have several chapters discussing aspects of SAW filter design, whilst SAW resonators if discussed at all, are quickly passed over with a few terse comments. The clear impression left with the reader is that SAW resonators are either of little economic importance or that their design and analysis is straightforward. In reality, neither of these conclusions is true.

The current annual market for SAW resonators is in excess of $30 million. In addition, there are now an extremely wide variety of SAW resonator design options available, each one with its own particular advantages and disadvantages. The richness of the resonator design portfolio, in fact, probably exceeds that available for SAW filter design. Most importantly, SAW resonator design like SAW filter design is not static. There are many exciting developments going on which keep the field very competitive and exciting to work in. In this paper we shall try to give the reader an overview of some important resonator topologies, their response characteristics, and some of the recent advances in the technology.

Because of its temperature stability, quartz remains the overwhelming material of choice for resonators. Recently, several new useful orientations for resonators on quartz have been identified. These are based on leaky-wave propagation, rather than the customary Rayleigh waves [1]. Significant advantages on these orientations are higher coupling and improved temperature dependence. New materials are also under development for SAW devices [2, 3, 4]. Some resonators have already been reported on these new materials [3]-[5]. Unfortunately, none of these new materials is as temperature stable as quartz. Thus, for the foreseeable future, quartz will undoubtedly remain the preferred material for most resonator applications.

Currently, no low-cost large-volume production technique exists for milling or etching grooves in quartz. We shall not, therefore, consider such structures in this paper. It is unfortunate, as resonators employing grooved reflector banks are preferred for oscillators which must have extremely low phase noise [6]. In addition, the ability to incorporate grooves and to recess the transducer electrodes adds a degree of freedom which can be used to great advantage [7]. With future advances in front-end process technology hopefully this situation will change.

2 One-Port Resonators

One-port, typically one-pole, resonators are used in oscillator applications. The most important criteria for these devices are: (1) cost, (2) frequency tolerance, (3) resonant conductance value, and (4) size. These four characteristics are all interdependent. As a result, a compromise must generally be made in deciding on the

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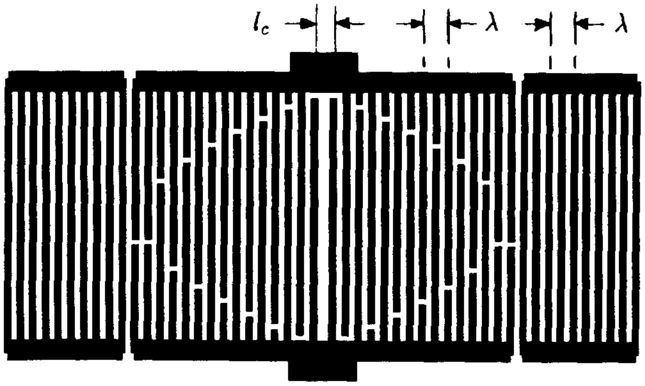

Figure 1: One-port one-pole synchronous SAW resonator.

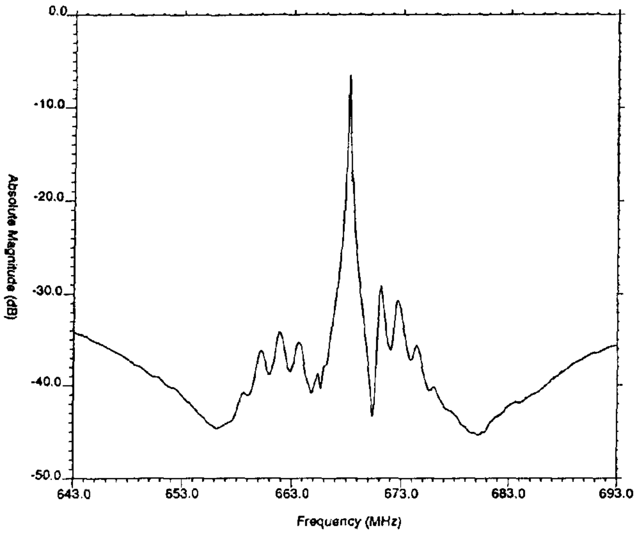

Figure 2: Parallel-inductor-tuned synchronous one-port response.

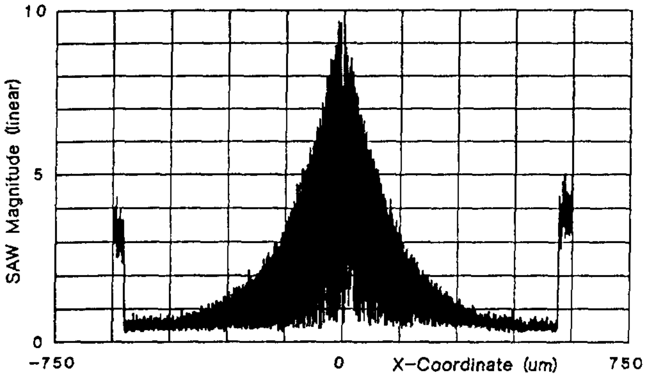

Figure 3: Acoustic energy profile in synchronous one-port.

resonator configuration most appropriate for the application. The most important initial decision to be made is whether the resonator should be of the "synchronous" or "non-synchronous" type.

2.1 Synchronous

A synchronous resonator is one in which the transducer electrodes form a periodic extension of the adjacent grating [8, 9]. Single-port or multi-port devices can be designed with this concept and single pole or multi-pole responses can be implemented. The great advantage of the synchronous resonator is its manufacturability. The center frequency of the resonator is essentially independent of the reflectivity of the electrodes, thus devices can be manufactured in large volume with a very small frequency deviation (±50 kHz). The disadvantage of the approach is a reduction in coupling, which is manifested by higher insertion loss or an increase in device area. In the most cases, however, this penalty is well worth the increase in manufacturing yields.

The device configuration of a one-port one-pole synchronous resonator is shown in Fig. 1. Note, that the resonant cavity is located in the centre of the transducer. Apart from this one discontinuity in the structure, all transducer and grating electrodes are entirely periodic. The transducer electrodes are typically apodized, as shown, to suppress transverse modes. The transmission response of such a resonator, tuned with a parallel inductor, is shown in Fig. 2. This device employed a beamwidth of 50λ and an overall length of $\sim 359\lambda$, where λ is the acoustic wavelength.

The critical parameter for a one-port resonator, for oscillator applications, is the conductance value at resonance. Ideally this should be as high as possible. It might be thought the conductance could be increased indefinitely, by simply increasing the active transduction region and overall length of the resonator. However, this turns out not to be the case. This is due to the synchronous nature of the transducer electrodes which results in the acoustic energy being tightly confined in the center of the resonator. A laser probe of the longitudinal acoustic energy profile in a one-port synchronous resonator is shown in Fig. 3. It clearly demonstrates how tightly the energy is confined to the center of the resonator. If a higher conductance is required, a non-synchronous structure must therefore be used.

2.2 Non-Synchronous

There are two basic variations of the non-synchronous one-port resonator. These are shown in Fig. 4 and Fig. 5. The resonator in Fig. 4 resembles the syn-

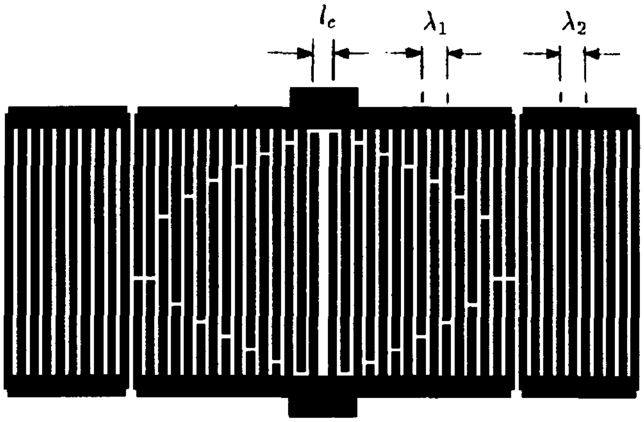

Figure 4: One-port resonator with center cavity.

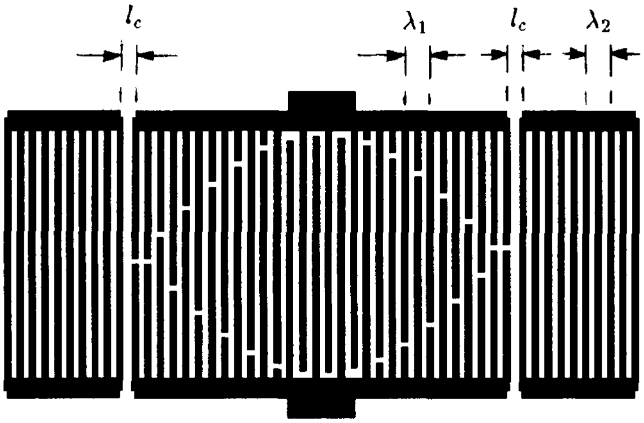

Figure 5: One-port resonator with external cavities.

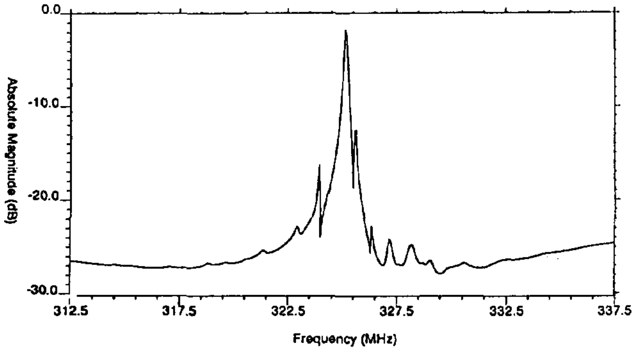

Figure 6: Parallel-inductor-tuned non-synchronous one-port response.

chronous resonator of Fig. 1. However, the center cavity is no longer $(2n+1)\lambda/4$, where n is an integer. Furthermore, the transducer and grating periods, in general, are different. In the alternate configuration shown in Fig. 5, the transducer is totally periodic with symmetric cavities and gratings at each end. Again, in general, the transducer and grating periods differ, and the cavities are not resonant at the exact center frequency of the resonator.

Both one-port resonator configurations in Fig. 4 and Fig. 5 can be optimised to achieve similar performance. Considerations of bulk-scattering losses and practicalities of writing an e-beam mask can affect the choice of which particular configuration is best suited for a given application. A much enhanced conductance, in comparison to the synchronous one-port, can be achieved with both structures, though at a price. The price is a small decrease in device yield. This is because the resonator frequency and response characteristics are now dependent on the reflectivity of the electrodes which was not the case with the synchronous designs.

In Fig. 6, the tuned transmission response of a non-synchronous one-port resonator is shown. Significant transverse mode resonances can be observed on the high side of the response. Typically they are more of a problem than in the synchronous designs. However, the conductance of the resonator is significantly higher than that of an equivalent synchronous one-port.

3 Two-Port Resonators

There are many varieties of two-port resonator structures in production. We shall review here the characteristics of those we have found to be most suitable to large-scale production. In addition, we shall discuss some recent advances in the technology.

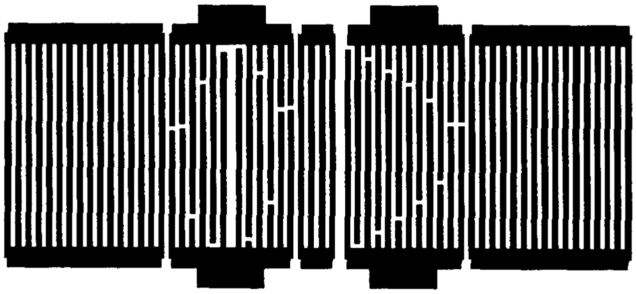

Figure 7: "Hiccup"/regular two-pole coupled resonator.

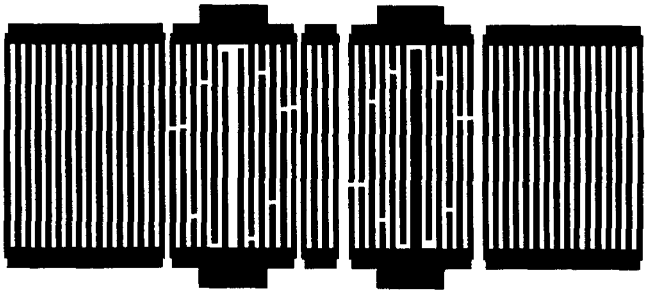

Figure 8: "Hiccup/conjugate-Hiccup" two-pole coupled resonator.

3.1 The Synchronous One Pole

For frequency-stabilization applications where only a one-pole response is required, the synchronous resonator in which the transducers are a periodic extension of the gratings is the most suitable for mass production. Millions of such resonators are manufactered by RF Monolithics alone every year. Identical considerations apply to the synchronous two-port resonator as were discussed for the one-port synchronous resonator in section 2.1. This structure has also been discussed in detail many times in the literature [8]-[11]. Thus, we shall not discuss it further in this review. Instead we shall proceed directly with a review of multi-pole configurations.

3.2 "Hiccup"-Based Designs

"Hiccup"-based multi-pole or coupled-resonators have proved to be extremely amenable to large-scale production [10, 11]. In this class of coupled-resonator the resonant cavities are internal to the transducers. Until recently the majority of such designs have been synchronous structures. As with the single-pole synchronous resonators, these resonators are relatively insensitive to changes in reflectivity which occur during the manufacturing process which results in high yields.

"Hiccup" transducers come in two varieties, one has a $+90^{o}$ phase discontinuity at the center while the other has a -90^{o} discontinuity. These transducers can be used in various combinations with each other or with a uniform transducer to achieve a wide range of coupled-resonator responses. Two of the most frequently used two-port two-pole configurations are shown in Fig. 7 and Fig. 8. Typical responses for these resonators are shown in Fig. 9 and Fig. 10. This class of multi-pole resonator has proved to be very flexible in its design characteristics and very producible in volume applications. Fractional bandwidths in the $>$ 0.1% to $<$ 0.3% range are readily obtainable and tuned insertion losses are typically in the 1 dB to 3 dB range. The bandwidth and insertion loss characteristics of the resonator are easily controlled by varying the lengths of the two transducers and the position of the cavity within each "hiccup" transducer. This type of resonator filter also allows considerable control in placement of the out-of-band rejection nulls [12]. For narrower fractional bandwidths, close in rejection levels of $\sim$30 dB are achievable. However, for the wider fractional bandwidths the close-in rejection may approach 10 dB.

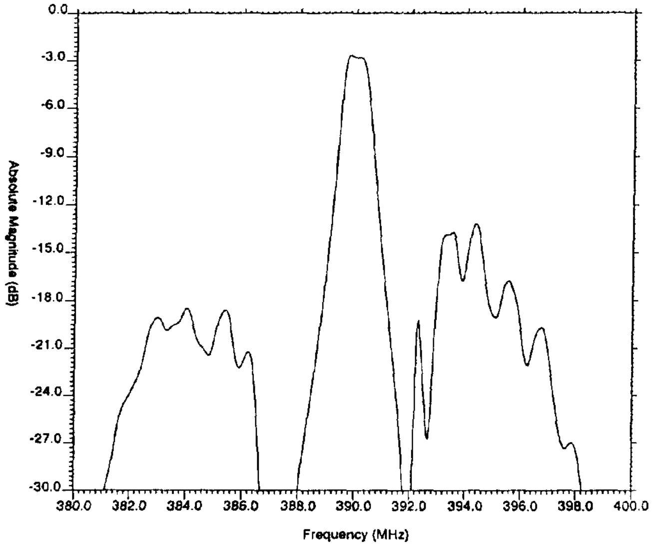

Figure 9: Typical response of "hiccup"/regular resonator.

Developments in resonators have recently been somewhat paralleling those in SAW filter technology. End users have been demanding lower insertion losses and re-

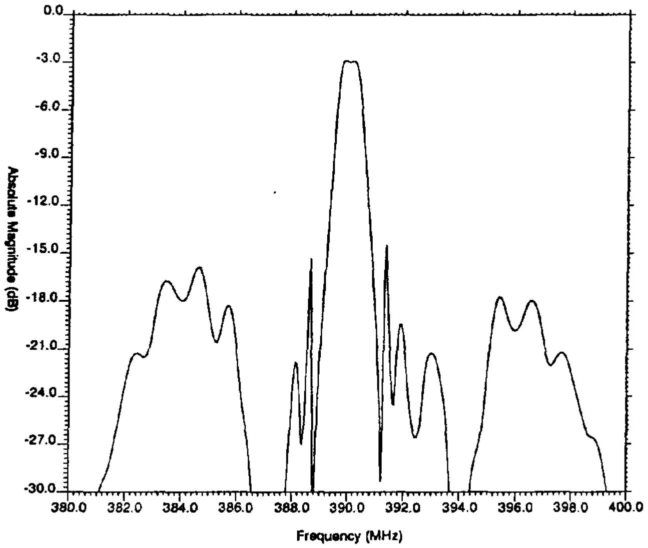

Figure 10: Typical response of "hiccup/conjugate-hiccup" resonator.

duced matching requirements. In response, we have developed more tightly coupled "hiccup"-based resonator designs which can achieve low insertion loss in a 50Ω impedance system without matching. The response of such a resonator is shown in Fig. 11. These resonators are slightly less manufacturing friendly as they are no longer synchronous designs. Transducer and grating frequencies are, in general, different. However, eliminating the need for matching elements with the resonator can result in a significant saving to the end-user.

3.3 NSPUDT Designs

Coupled resonators built on NSPUDT orientations (Fig. 12) achieve near symmetric frequency responses [10, 11, 13]. However, their major advantage is the wide fractional bandwidths that can be achieved with the technology. For example, bandwidths in excess of 0.4% can be obtained on quartz (Fig. 13). A disadvantage of the NSPUDT coupled-resonator is that the $sinc(N(f/f_o - 1))^2$ transmission pedestal, where N is the number of transducer electrode pairs, tends to be rather broad resulting in poor close-in rejection. For wide bandwidth designs, insertion losses are typically in the 3-6 dB range.

The measured tuned response of a rather novel NSPUDT coupled resonator is shown in Fig. 14. This device was novel in two respects. First, the outer ends of the gratings were withdrawal-weighted to suppress the close-in ripple which can be seen in Fig. 13. Second, the

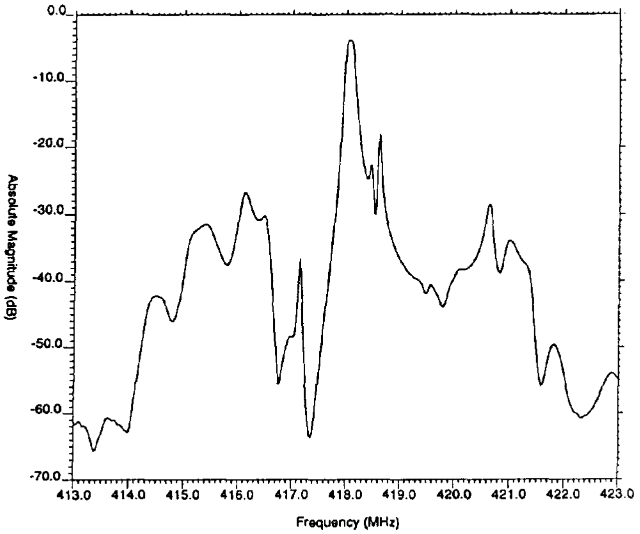

Figure 11: Untuned response of optimized "hiccup" resonator.

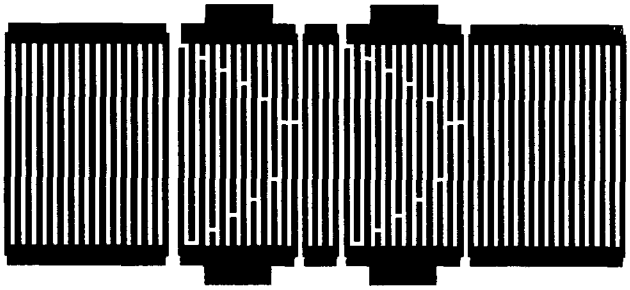

Figure 12: NSPUDT coupled-resonator.

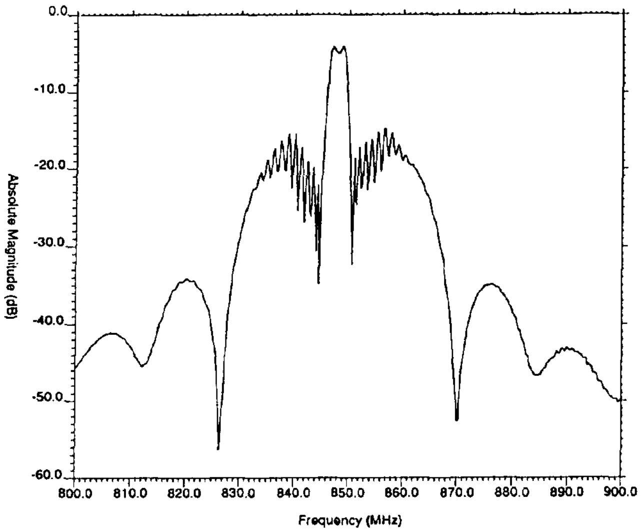

Figure 13: Wide bandwidth NSPUDT coupled-resonator.

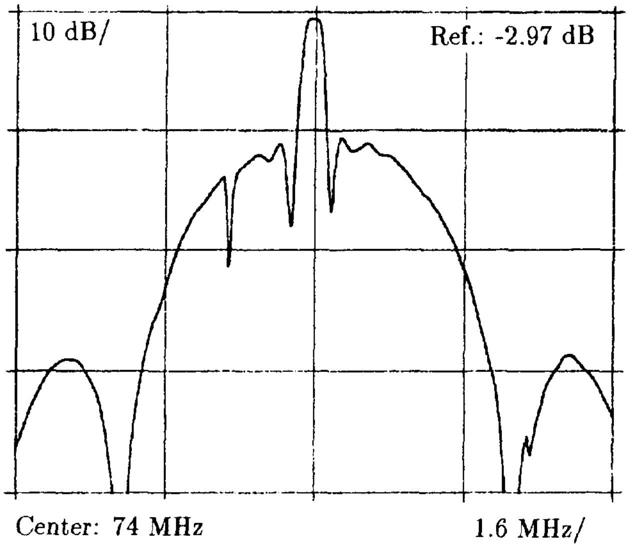

Figure 14: Novel NSPUDT coupled-resonator.

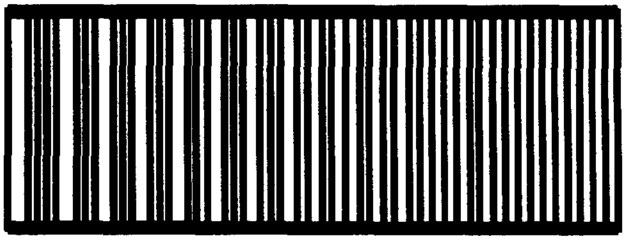

Figure 15: Withdrawal-weighted grating.

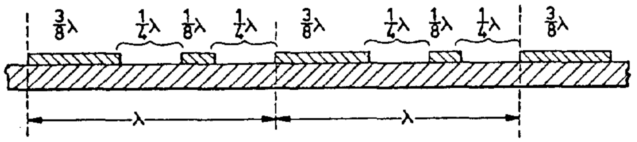

Figure 16: Electrode configuration with reduced reflectivity.

reflectivity of the transducer and coupler-grating electrodes was reduced by a factor of $\sqrt{2}$ to increase the bandwidth of the resonator.

Withdrawal-weighting of the reflector gratings is an alternative to tapering the ends of the gratings as was done in [13]. The withdrawal-weighting algorithm developed does not remove any electrodes from the gratings as this would result in a local velocity perturbation, requiring complex compensation [14]. Instead the electrodes are jitterred around in location to achieve the desired reflection weighting, as shown in Fig. 15.

The reduction in electrode reflectivity in the resonator was achieved by making the electrode widths alternately $\lambda/8$ and $3\lambda/8$ respectively, as shown in Fig. 16 [15]. The result was an increase in bandwidth accompanied by only a modest increase in insertion loss. The resonator had an insertion loss of ~3.6 dB and a 3 dB fractional bandwidth of 0.36%.

3.4 "2-Per-K0" Designs

NSPUDT resonator filters have a symmetric frequency response as in Fig. 13. To achieve a symmetric frequency response from a single-level structure on a conventional crystal orientation is more difficult. The problem is that the input conductance of a transducer with internal reflections is skewed by the reflections, in gen-

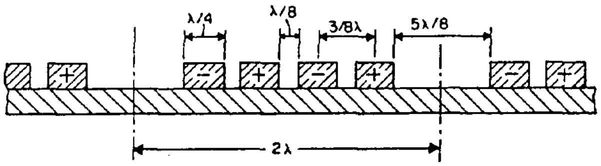

Figure 17: "2-per-K0" electrode configuration.

eral, to the low-frequency side [10]. One way to solve this problem is to employ transducers in the resonator that do not have any electrode reflections. An additional advantage of reducing or eliminating the transducer electrode reflections, as illustrated in 3.3, is that wider fractional bandwidths can be achieved for the resonator. To eliminate electrode reflectivity, split-electrode transducers have been used, as have transducers with recessed electrodes [7]. Both of these approaches, however, have serious drawbacks. First, the photomask and fabrication difficulties are significantly increased. This limits the upper frequency at which such resonators can be built. Second, the velocites in the transducer and grating regions are different. This velocity difference must be determined very precisely, frequently empirically, to enable the appropriate compensation to be made to the resonant cavity length. This compensation will then be strictly accurate only for one particular electrode thickness.

A new reflectionless electrode structure has been devised for implementing resonator filters with wide fractional bandwidths and symmetric frequency responses. The new electrode structure has no net distributed reflectivity and yet has essentially the same acoustic velocity as a reflective 2-per grating at the same frequency. This eliminates the need for any cavity-length compensation as discussed above with alternate approaches. The new transducer electrode configuration is shown in Fig. 17. We refer to it as a "2-per-K0" configuration [16].

The principle of operation of the "2-per-K0" transducer structure can be understood from the reflection phasor diagram in Fig. 18. Reflection phasors are shown for four adjacent electrodes in the transducer. Note that any four adjacent electrodes taken together have no net reflectivity. There is a slight penalty in coupling with the "2-per-K0" transducer compared to a standard 2-per transducer. There is also an increase in static capacitance. However, the transducer works well and enables resonator filters with fractional bandwidths > 0.6% to be built on quartz.

The untuned experimental response of a prototype resonator is shown in Fig. 19. The tuned response of the resonator is shown in Fig. 20. Note, that as expected this resonator, like the NSPUDT, has a near symmetric frequency response. The 3 dB fractional bandwidth of this resonator was 0.63% and the minimum insertion loss was 4.92 dB.

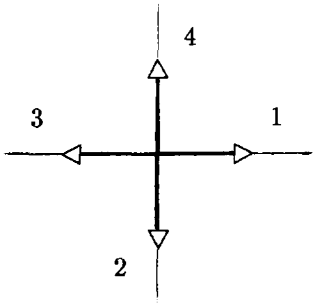

Figure 18: "2-per-K0" reflection phasor diagram.

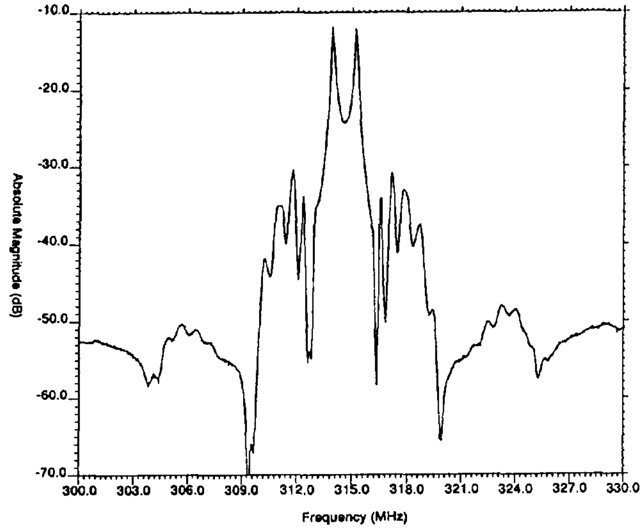

Figure 19: Experimental "2-per-K0" coupled-resonator untuned response.

3.5 Proximity-Coupled Designs

The proximity-coupled, or guided-mode, resonator filter was first demonstrated in 1975 [17]. The basic device configuration is shown in Fig. 21. The structure comprises two one-pole resonators, of the type shown in Fig. 5, laid out in close longitudinal proximity to each other. The proximity results in resonant energy in each of the two cavities being coupled together by virtue

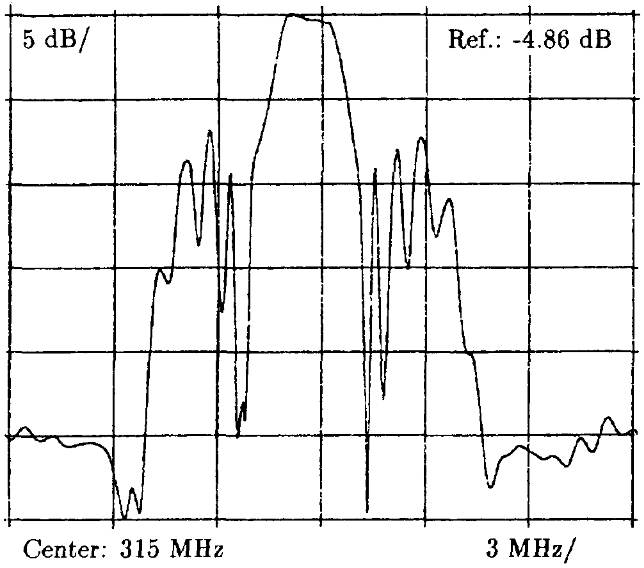

Figure 20: Experimental "2-per-K0" coupled-resonator tuned response.

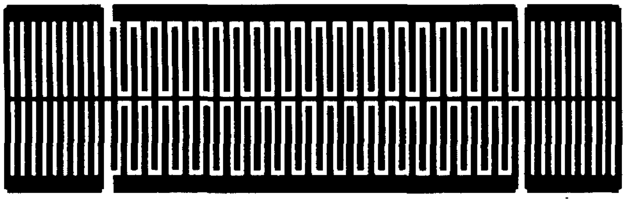

Figure 21: Proximity-coupled resonator.

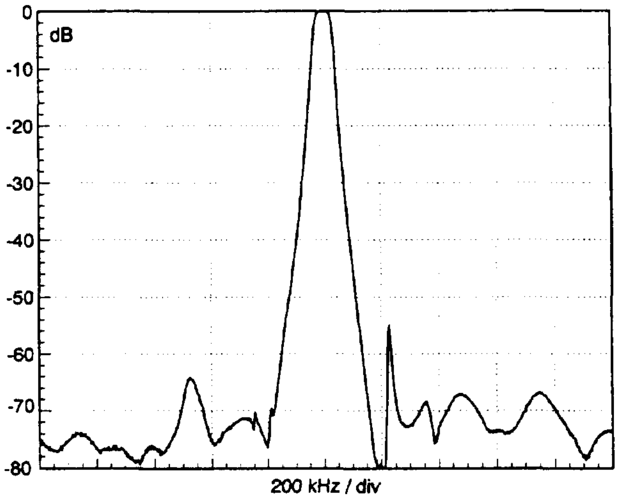

Figure 22: Proximity-coupled resonator filter response.

of the evanescent acoustic fields. If the beamwidths of each of the separate resonators are sufficiently small, typically a few wavelengths, there are only two guided modes in the overall structure, one symmetric and one anti-symmetric (Fig. 21). The velocity difference between the two modes results in a two-pole response. Four-pole responses are readily achieved by cascading two such resonators.

Proximity-coupled resonator filters are practical for fractional bandwidths <~0.1%. The most impressive characteristic of these devices is the very steep shape factors that they achieve. Fig. 22 shows the tuned response of a prototype proximity-coupled resonator filter on quartz. Note, that an ultimate rejection of 70 dB is obtained relatively close to the passband. The rejection characteristics of a proximity-coupled resonator are excellent because the input and output transducers are not in-line. Thus, away from the stopband of the gratings there is no coupling.

Very low insertion losses ~1-2 dB can be achieved with proximity-coupled resonators. In addition, because of the very narrow beamwidths of the devices, they are typically very small. These characteristics have made proximity-coupled resonators extremely popular for paging applications.

3.6 SPUDT Designs

I cannot close this review of resonator filters without mentioning a possible new direction that the technology might follow. Enormous progress has recently been

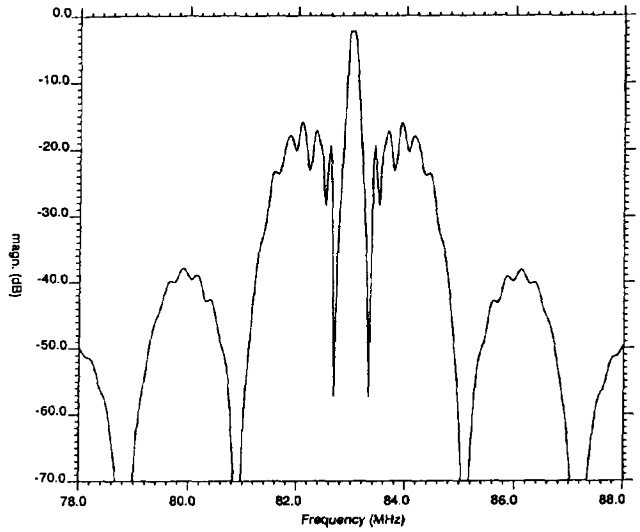

Figure 23: Theoretical tuned response of 2-pole SPUDT resonator.

made in the field of low-loss filters, especially on quartz. This technology is based on the Single-Phase Unidirectional Transducer (SPUDT). Many useful SPUDT configurations have been developed, but all rely on the same principle of operation. Transduction and reflection centers are implemented within the transducer with a separation of ±45°. In a filter, the purpose of the latter is to cause the transducer to be unidirectional. However, in a resonator, as was demonstrated with the NSPUDT configurations in section 3.3, this phase shift can be used to implement a symmetric frequency response. Unlike the NSPUDT, with which it is difficult to realise both ±45° phase shifts in the resonator, with most other SPUDT's both phase shifts can be easily implemented. This would allow the $\sin(x)/x$ response to be reduced significantly compared to those in Fig. 13 and Fig. 14. Furthermore, the local reflectivity in an SPUDT can be varied spatially with a great deal of control. This new degree of freedom opens up new possibilties for resonator filters. Fig. 23 shows a typical theoretical response for a simple two-pole SPUDT resonator.

3.7 Other Resonator Filter Technologies

It is not possible in a single review paper to cover all the developments currently taking place in resonator-filter technology. We have covered here most of those with which the author is familiar and which are currently in medium to large-scale production. Perhaps the most important resonator-filter technology we did not discuss is the "interdigitated-interdigital" style device, first proposed in [18]. An image-impedance interconnection of this type of resonator was then proposed in [19]. Since then, there has been enough additional work in this field to merit a dedicated review on the subject. The main advantages of this technology are that these resonators can be built at high frequencies (e.g. ~800 MHz) and that low insertion losses can be achieved. Both these characteristics make them suitable for RF filtering applications. In general, however, the passbands of such filters have high ripple and out-of-band rejection characteristics are relatively poor. It is very likely that this technology will soon see competition from SPUDT filters for some RF filtering applications.

4 Summary

This paper has attempted to present an overview of the current state of resonator-filter technology. A variety of resonator filter configurations has been presented and typical performance characteristics discussed. Hopefully, the reader may now appreciate, if he did not before, that the field is diverse and challenging. The field is not static as is often believed. Quite the contrary. Many new ideas are currently in development which should obsolete many of the devices being built today.

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