SAW FILTERS AND COMPETITIVE TECHNOLOGIES
A COMPARATIVE REVIEW

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Abstract

The current performance capabilities of SAW bandpass filters are reviewed and summarized for the frequency range of 30 MHz to 3 GHz. SAW coupled-resonators with up to 0.8% bandwidth, low loss transversal, and surface-skimming bulk-wave filters are included. SAW filter capabilities are compared with those of competing bandpass filter technologies in the same frequency range. These include bulk crystal, LC, cavity, helical, tubular, dielectric resonator, combline, interdigital, and stripline technologies. The following two needs are addressed: 1) SAW filter designers and marketers must be informed about the current capabilities of competing technologies, and 2) RF system designers need reference material to aid the efficient selection of optimum filters. Such reference literature is scarce and is often incomplete or obsolete.

Introduction

One of the most interesting and challenging characteristics of the SAW filter industry is its technical immaturity. Because of this relative immaturity, the capabilities of the technology are constantly improving. Simultaneously, advances are also being made in alternative filter technologies. Mature filter technologies gradually improve due to evolutionary advances in materials science, computer modeling, and mass manufacturing experience. New technologies (e. g., high temperature superconductors) often appear suddenly as the result of research not directly related to filters.

There are several consequences of this constant change: 1) The RF circuit/system design engineer must maintain a process of education regarding the available technologies; 2) The economics of filter market competition changes as the size and position of each market niche changes; and 3) both suppliers and customers of products containing RF filters can reap significant size/cost/performance benefits from the optimum application of the best available filter technology.

There are two intended audiences for this paper: 1) The RF circuit/system design engineer (i. e., the filter *customer*) and 2) the SAW filter industry (i. e., the *supplier*). The latter should benefit from knowledge of potential competition from advances in alternative filter technologies.

The goal of this paper is to at least partially fulfill the need for continuing education in current passive RF filter technology advances. In particular, SAW filter technology is compared with non-SAW technologies. This paper contains necessarily brief reviews of the current state of SAW and non-SAW filter technologies. Then, some emerging alternatives to SAW filters are examined as potential competition to the SAW industry.

SAW Bandpass Filters

The general capabilities of current SAW bandpass filter designs are covered here only in a basic manner. The three primary parameters of center frequency (30 MHz to 3 GHz), fractional bandwidth, and insertion loss are presented graphically. Additional parameters are only discussed as highlights of new and emerging SAW filter technologies.

The scatter plot of Figure 1 is based on the characteristics of approximately 325 SAW bandpass filters (BPF's) from eight different manufacturers. This sample is based primarily on practical, available devices that have been designed and constructed. Many appear in published catalogs and are available for sale. Only a handful is based on experi-

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mental devices, and are only included as representatives of new technologies.

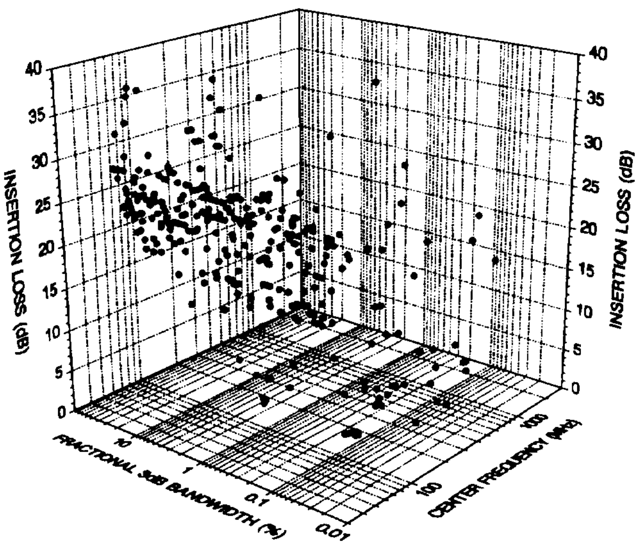

Figure 1: Sample of Extant SAW BPF Designs

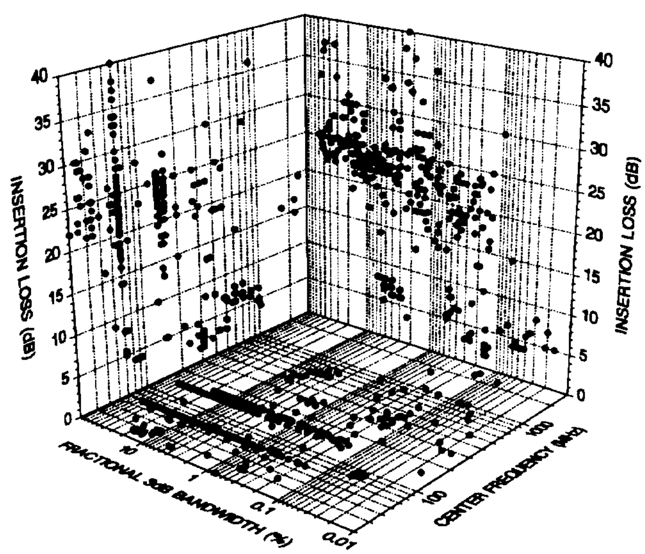

Figure 2: The scatter plot of Figure 1 projected onto 2-dimensional coordinates.

The scatter plot of Figure 1 is difficult to interpret. Consequently, this data is also shown in Figure 2 projected onto the three two-dimensional planes of bandwidth vs. frequency, loss vs. frequency, and loss vs. bandwidth. In this view, each data point appears three times.

The sample was not chosen "scientifically." Consequently, no accurate conclusions regarding distributions can be derived from it. However, it appears that the dense distribution of "high-loss" devices from 20 to 30 dB loss and 0.3 to 50% bandwidth is due to the maturity of this type of design. Also note the streaks due to the popularity of 70, 140, and 160 MHz receiver intermediate frequencies (IF's).

The performance capabilities of some of the major types of SAW BPF's are illustrated in Figure 3. Here, the various families are superposed onto the actual data points of Figure 2. For the purposes of this chart, "Int" = **Int**ernally tuned; "Ext." = **Ext**ernally tuned; "ML" = **Multi**level transducer (3-phase); "HL" = **H**igh **L**oss, bidirectional transducer; "LN" = **L**ithium **N**iobate; "LT" = **L**ithium **T**antalate; "Qtz." = ST **Quartz**. The region labeled "Qtz SPUDT" (transversal) also includes NSPUDT and other Coupled-resonators (CR's). Also not shown is 128° lithium niobate for the widest bandwidth high-loss transversal designs.

The bidirectional transducer "high-loss" and multilevel unidirectional transducer "low-loss" devices are generally well understood and fill a niche for specific requirements. That niche usually needs wide bandwidth, good shape factor, and a well behaved passband. The price that must be paid for this performance is insertion loss for the former and manufacturing and phasing complexity for the later. Since these designs have been in use for years, they are not addressed further.

CR SAW filters are finding increasing application where narrow bandwidth and low loss are required. There have been several recent advances with this type of filter that make it especially attractive for these applications. NSPUDT (**N**atural **S**ingle **P**hase **U**nidirectional **T**ransducer) and other techniques now yield in-line CR's with bandwidths up to 0.8%. Proximity (waveguide) coupling results in similar frequency and loss, with significantly improved sidelobe rejection and more limited bandwidths. The use of **s**urface **t**ransverse **w**aves (STW, surface-skimming bulk, or shear waves) allow CR's to function as high as approximately 2.5 GHz, fundamental mode. These and other enhancements are expected to significantly boost the usefulness of SAW CR's. [1-13]

Lithium tetraborate ($Li_2B_4O_7$) also shows promise as a new substrate material for SAW filters. UHF

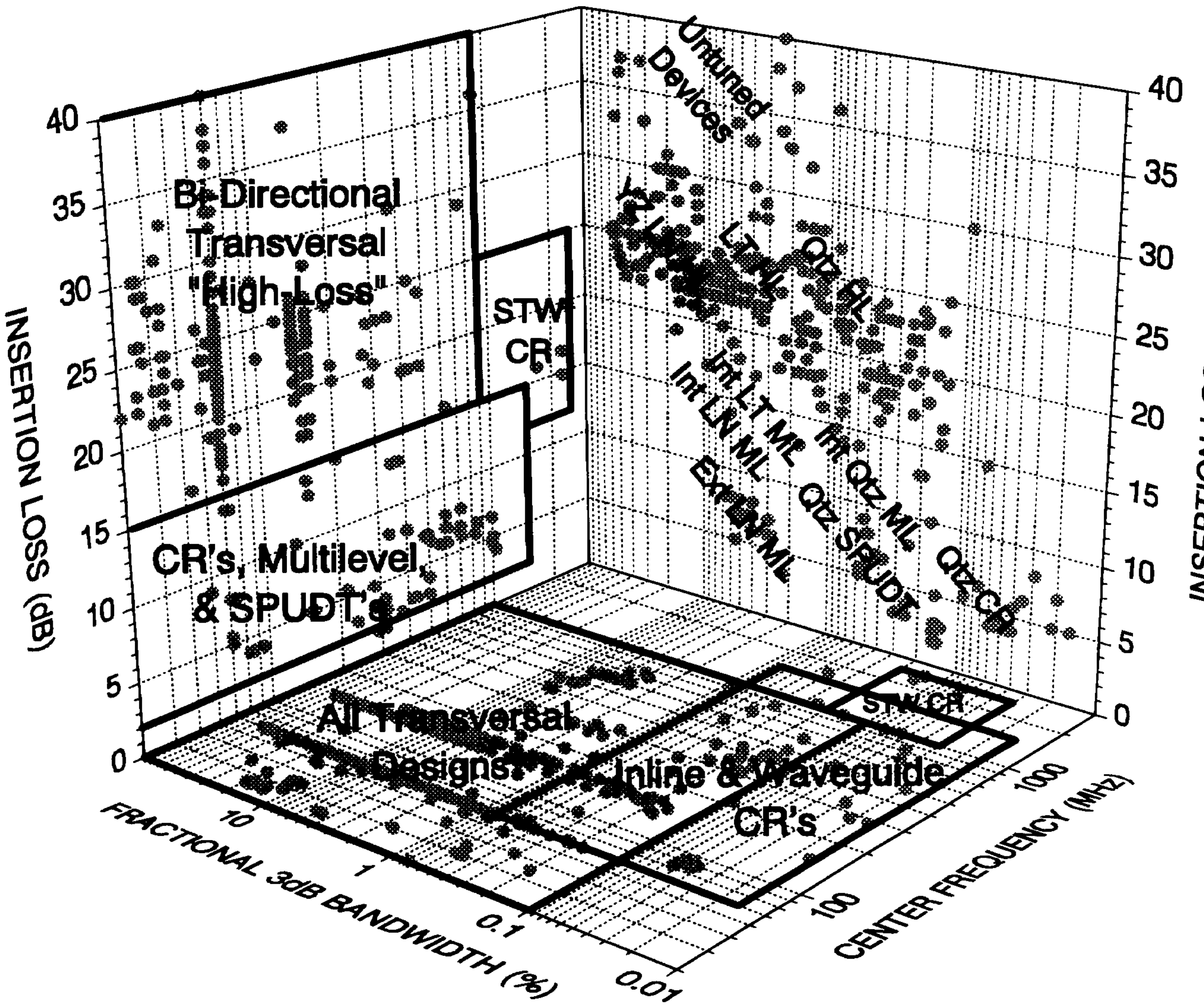

Figure 3: A generalized chart of common and emerging SAW BPF families superposed on the actual filter data points of Figure 2.

resonator filters have been demonstrated on this substrate. One of the chief advantages is the zero temperature coefficient. Insertion loss and bandwidth characteristics of such a filter should be similar to that of lithium tantalate. Disadvantages include lack of material availability and this material's solubility in water and acid which makes it incompatible with many current wafer processing techniques. [14]

Another very promising narrow-bandwidth transversal device type is the SPUDT filter. Much has been written in the literature and commercial devices are now available. This design achieves low loss with single level fabrication and a minimum number of impedance matching (tuning) components. An example of such a device, recently available commercially, is shown in Figure 4. The main drawback with SPUDT's is that bandwidth is limited to several percent. [15,16]

Other device types deserve mention, but have limited potential due to various drawbacks. Group type SPUDT's are capable of moderately low loss, but require the complexity of quadrature phasing. Interdigitated interdigital transducer (IIDT) devices offer low loss and simple matching, but require excessive substrate area due to the multiple transducers. [17-21]

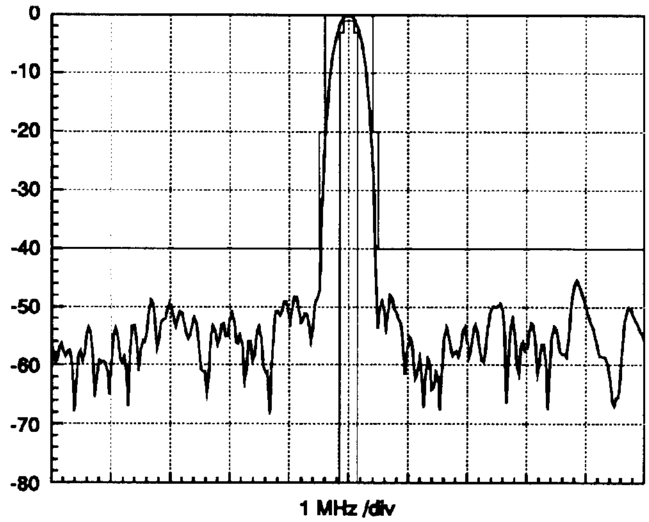

Figure 4: Example of a SPUDT filter at 71 MHz for GSM cellular telephone IF applications. (Ref. insertion loss = 5.5 dB.)

Harmonic SAW and/or STW filter designs have usually been considered to be of limited usefulness due to high insertion loss. However, current work with UDT's may make these devices more practical for frequencies between 1.5 and 2.5 GHz. [22]

Conventional Non-SAW Filters

Bulk acoustic wave (BAW) crystal filters, discrete and monolithic, are widely used. Topologies include ladder for narrower and lattice for wider bandwidths. They offer excellent Q, selectivity, ultimate rejection, temperature stability, and the narrowest bandwidths of the filter types considered here. Key disadvantages include spurious responses, limited power handling, the generation of intermodulation products, and a lack of ruggedness under shock and vibration. HBAR (high overtone bulk acoustic resonator) technology has the potential for competing with SAW CR's, but has not proven practical except in very specialized applications. [18,23]

The conventional, lumped-element LC filter has been improved considerably in the past decade by the development of smaller components with higher Q at high frequencies and by CAD techniques. This type of filter has tremendous design flexibility and practically no lower frequency limit or upper bandwidth limit. Additional advantages include good power handling and insertion loss at the lower frequencies and small size at the higher frequencies. Disadvantages include poor Q at high frequencies, moderately high unit costs, and only fair temperature and vibration characteristics. This filter is a good choice for many lower frequency and wider bandwidth applications. [24-26]

Combline filters are essentially the same as LC filters but with the inductances distributed instead of lumped. This permits higher Q, higher frequencies, and less shock and vibration sensitivity than LC filters. Practical frequencies range from 300 MHz to well over 10 GHz. The most practical bandwidths range from 3% to 20% with 1% to 50% possible. Advantages include low insertion loss (typically under 1 dB), and high power handling capability (up to several hundred watts). Disadvantages include high recurring unit cost and large size at lower frequencies.

Interdigital filters are similar to combline filters, but consist entirely of distributed reactances. Frequency, Q (up to 5500), and bandwidths are all somewhat higher than combline filters, but the size is also somewhat larger. The practical limits of frequency are 500 MHz to well over 10 GHz. Bandwidths of 5% to 80% are practical. Loss, power handling, advantages, and disadvantages are very similar to those of combline filters.

Suspended substrate stripline and/or microstrip bandpass filters can be implemented in a variety of ways but are usually a printed implementation of the interdigital filter described above. This type of filter is feasible down to 100 MHz, but is not usually considered practical below 1 GHz due to size. The primary limitation is low Q.

Tubular filters consist of direct-coupled or capacitively-coupled resonator sections installed in a tube. Practical frequencies range from 15 MHz (with large size) to about 8 GHz. Bandwidths range from 1% to 80%. Advantages include low loss, high power handling at lower frequencies, virtually no spurious responses, and little or no NRE charges for custom designs. Disadvantages include large size and unit cost at lower frequencies.

Cavity-resonator filters are usually implemented with helical, coaxial, or waveguide resonators. Coaxial filters are available in frequencies from 30 MHz to over 10 GHz and helical filters from below 10 MHz to 2 GHz. Size is excessive for both at the lower ends of their frequency ranges. Practical helical filter bandwidths range from 0.2% to 20%. Practical coaxial filter bandwidths range from 0.2% to 3.5%. Advantages include excellent Q (up to 10,000), good selectivity, and low loss. The primary disadvantages are often size and cost. [27,28]

YIG (**y**ttrium **i**ron **g**arnet) filters possess the very useful characteristic of tunability. However, there is no significant overlap with SAW technology.

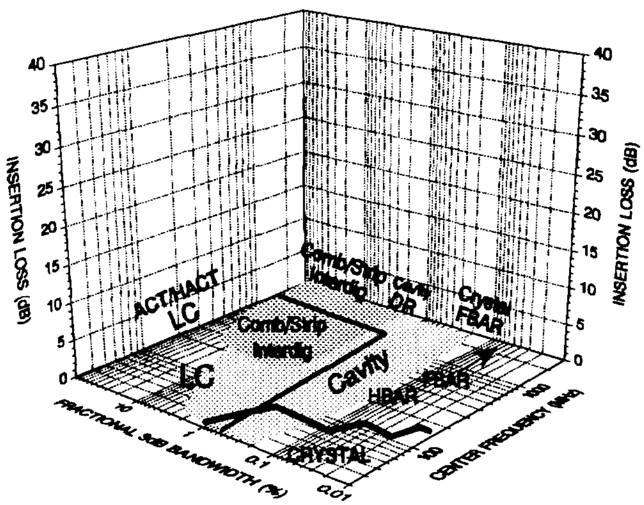

Figure 5: Overview of Non-SAW BPF's on the same scale as SAW plots. (Note: most IL ≤ 5 dB)

Important Non-SAW Developments

Although active filters are beyond the scope of this paper, much progress is being made in MMIC (**m**icrowave **m**onolithic **i**ntegrated **c**ircuit) designs. At the higher frequencies (smaller sizes) transversal filters can be implemented. The combination of lumped and transversal elements permit some advantages of both with a size much smaller than possible with transversal techniques alone. Active elements are now being used to increase equivalent resonator Q's in small structures ("Q recovery"). These techniques are primarily of importance above 3 GHz. However, the SAW industry should expect to encounter this technology more often as SAW filters continue to move higher in frequency and active techniques become more practical below 3 GHz. [18]

Much has been published on ACT and HACT (**a**coustic **c**harge **t**ransport and **h**eterojunction ACT respectively). Although these devices utilize SAW's they are covered here in the non-SAW section since they are not in the mainstream of the SAW BPF industry. These devices are capable of performing many signal processing functions in addition to transversal bandpass filter functions. Frequencies range from DC to about 500 MHz. Programmability makes them especially useful and flexible in certain applications. The use of GaAs (gallium arsenide) makes them compatible with GaAs MMIC's. In spite of the capabilities, cost and complexity are limiting factors that do not make this technology competitive with standard SAW filters. [18,29]

Dielectric **r**esonator (DR) filters have been available for many years. However, advances in materials have resulted in much more compact sizes and better temperature stability than in the past. Consequently, DR filters are becoming more price and size competitive at lower frequencies. Also, SAW devices continue the upward trend in frequency and power handling. So, the SAW industry should expect more direct competition between these two technologies in the future. They are available for center frequencies from less than 500 MHz to over 10 GHz. Practical bandwidths range from about 0.1% to over 50% with insertion losses in the range of 1 to 5 dB. Power handling can be several hundred watts for the lowest frequency devices.

The combination of low loss, wide bandwidth, and good power handling makes DR's ideal for many transceiver duplexer applications. Principal applications below 3 GHz are cellular telephone duplexers and L-band satellite receiver filters. [18]

Film **b**ulk **a**coustic **r**esonator (FBAR) or thin **f**ilm **r**esonator (TFR) filter technology is one that offers the high Q and narrow bandwidth of conventional crystal filters, but at higher frequencies. Optimum frequencies range from VHF to UHF. The full capabilities of this technology are not yet fully established. However, this type of crystal filter should fill the void in the high frequency, narrow bandwidth portion of the capability chart shown in Figure 5. This puts this technology in direct competition with the better SAW CR designs. It should not be ignored by the SAW industry. [18]

Finally, much fanfare has surrounded the recent advent of "high temperature" superconductors. The potential impact is significant for nearly all the filter types discussed in this paper. Although exciting and promising, "high temperature" at this time means liquid nitrogen instead of liquid helium. Consequently, the application of this technology is presently limited to very specialized applications (e. g., space communications). Unless or until further breakthroughs in *room* temperature superconductors, superconductivity is not expected to have any significant impact on the SAW industry in the foreseeable future. [30-33]

Conclusions

Conventional, established bandpass filter types were reviewed using SAW and non-SAW technologies. Recent developments and current trends were examined with an emphasis on potential competition between SAW and non-SAW devices.

Current important trends in SAW BPF technology involve low insertion loss (<10 dB) at wider and wider bandwidths (now to >1%) with economical, single-level designs. The other trend is upward in frequency with 2.5 GHz expected to soon become practical in narrowband CR devices with existing photolithography resolutions.

As SAW filters move up in frequency, more competition is expected from DR filters. DR filters are also getting smaller which makes them practical at lower frequencies. Also, TFR/FBAR crystal filters may become a serious competitor to narrow bandwidth SAW filters in the 1 GHz area.

These developments create more choices and alternatives for the RF system designer. They also result in greater competition among manufacturers that have not previously considered themselves competitors. In both cases, these developments should be considered as opportunities.

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References

1. W. J. Tanski, "Multipole SAW Resonator Filters: Elements of Design and Fabrication," *Proceedings IEEE Ultrasonics Symposium*, 1981, pp 100-104.
2. T. F. O'Shea, "SAW Resonator Filters with Optimized Transducer Rejection," *Proceedings IEEE Ultrasonics Symposium*, 1981, pp 105-110.
3. P. C. Meyer, D. Gunes, "Design and Fabrication of SAW Multipole Filters," *Proceedings IEEE Ultrasonics Symposium*, 1983, pp 66-71.
4. M. B. King, L. W. Heep, J. C. Andle, "1500 MHz Coupled Resonator Filter," *Proceedings IEEE Ultrasonics Symposium*, 1987, pp 127-130.
5. M. Tanaka, T. Morita, K. Ono, Y. Nakazawa, "Narrow Bandpass Filter Using Double-Mode SAW Resonators on Quartz," *Proceedings IEEE Frequency Control Symposium*, 1984, pp 286-293.
6. B. Horine, S. Gopani, "Narrowband SAW Filters For IF Applications," *Proceedings RF Technology Expo 90*, November 1990, pp 227-241.
7. L. A. Coldren, R. L. Rosenberg, "SAW Resonator Filter Overview: Design and Performance Tradeoffs," *Proceedings IEEE Ultrasonics Symposium*, 1978, pp 422-432.
8. A. Coon, *Capabilities and Applications of SAW Coupled-Resonator Filters*, RF Monolithics Application Note No. 23, December 1990.
9. P. V. Wright, "Low-cost High-Performance Resonator and Coupled-Resonator Design: NSPUDT and Other Innovative Structures," *Proceedings 43rd Annual Symposium on Frequency Control*, 1989, pp 574-587.
10. P. Zibis, "UHF Low Loss SAW Filters for Front End Applications," *Proceedings IEEE Ultrasonics Symposium*, 1986, pp 293-297.
11. G. Riha, "Saw Devices for Communications Systems," *Proceedings IEEE Ultrasonics Symposium*, 1989, pp 241-250.
12. Y. Ebata, H. Satoh, "Current Applications and Future Trends for SAW in Asia," *Proceedings IEEE Ultrasonics Symposium*, 1988, pp 195-202.
13. P. Dufilie, J. Hodé, J. Desbois, "A Low Loss High Performance Filter Structure," *Proceedings IEEE Ultrasonics Symposium*, 1988, pp 127-130.
14. M. Ohmura, H. Abe, K. Miwa, H. Saito, "A 900 MHz SAW Resonator Filter On $Li_2B_4O_7$ Crystal," *Proceedings IEEE Ultrasonics Symposium*, 1990, pp 135-138.
15. J. C. Andle, "Doubly Rotated Orientations of Cut Angles for Quartz Crystal for Novel Surface Acoustic Wave Devices," U. S. Patent No. 4,670,680, June 1987.
16. C. S. Hartmann, B. P. Abbott, "Overview Of Design Challenges For Single Phase Unidirectional SAW Filters," *Proceedings IEEE Ultrasonics Symposium*, 1989, pp 79-89.
17. D. P. Morgan, P. Durrant, "Low Loss Filters Using Group-Type SPUDT Transducers," *Proceedings IEEE Ultrasonics Symposium*, 1990, pp 31-35.
18. A. Ballato, S. V. Krisnaswamy, D. Malocha, B. Miller, "UHF and Active Filter Technology" Workshop at IEEE MTT-S International Microwave Symposium, Boston, Massachusetts, June 10, 1991.
19. N. Mishima, M. Takase, S. Mitobe, Y. Ebata, "IIDT Type SAW Filter Using Acoustic Reflection Cancel Condition With Solid IDT," *Proceedings IEEE Ultrasonics Symposium*, 1989, pp 31-35.
20. K. Anemogiannis, S. Berek, H. Zotti, "GHz Low-Loss SAW Filters Employing Standard Fabrication Process," *Proceedings IEEE Ultrasonics Symposium*, 1990, pp 129-133.
21. O. Ikata, Y. Satoh, T. Miyashita, T. Matsuda, Y. Fujiwara, "Development Of 800 MHz Band SAW Filters Using Weighting For The Number Of Finger Pairs," *Proceedings IEEE Ultrasonics Symposium*, 1990, pp 83-86.
22. R. Huegli, "GHz Filters With Third Harmonic Unidirectional Transducers," *Proceedings IEEE Ultrasonics Symposium*, 1990, pp 165-168.
23. M. D. Howard and R. C. Smith, "Quartz Crystal Filters: A Review of Current Issues," *Proceedings RF Technology Expo 90*, March 1990, pp 275-288.
24. E. Christian, *LC Filters: Design, Testing, & Manufacturing*, John Wiley & Sons, New York, 1983.
25. B. G. Malcom, "The Current State of the Art of Miniature L/C Filters," *Proceedings IEEE Ultrasonics Symposium*, 1985, pp 38-42.
26. R. Levy, "Design Considerations for Lumped-Element Microwave Filters," *Microwave Journal*, February, 1988, pp 183-192.
27. A. I. Zverev, *Handbook of Filter Synthesis*, John Wiley & Sons, New York, 1967.
28. G. L. Matthaei, L. Young, E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, Artech House, Dedham, MA, 1980.
29. S. Olson, E. Garber, D. Streit, W. Jones, D. Ko, B. Meadows, "Heterojunction Acoustic Charge Transport For Transversal Filter Applications," *Proceedings IEEE Ultrasonics Symposium*, 1990, pp 221-224.
30. J. A. Curtis, S. J. Fiedziuszko, S. C. Holme, "Hybrid Dielectric/HTS Resonators And Their Applications," *IEEE MTT-S International Microwave Symposium Digest*, 1991, pp 447-450.
31. J. A. Curtis, S. J. Fiedziuszko, "Miniature Dual Mode Microstrip Filters," *IEEE MTT-S International Microwave Symposium Digest*, 1991, pp 443-446.
32. S. Talisa, M. Janocko, J. Talvacchio, C. Moskowits, "Present And Projected Performance Of High-Temperature Superconducting Filters," *IEEE MTT-S International Microwave Symposium Digest*," 1991, pp 1325-1328.
33. R. V. Snyder, "All The World Is A Filter," *IEEE MTT-S International Microwave Symposium Newsletter*, June 1991, pp 5-10.