ACOUSTIC SURFACE WAVE ANALOG FILTERS

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Abstract

While the basic principles of surface wave device operation have been described previously, this paper describes the unification of this modeling information into a design synthesis procedure. Also, the excellent performance of the resulting devices is discussed. Emphasis is given to bandpass filters. The major advantages of acoustic surface wave filters are small size, low cost, reproducibility, wide dynamic range, high Q, great design flexibility, good temperature stability, and a center frequency range which extends from HF to L-band.

I. Introduction

A new analog filtering technique using acoustic surface wave propagation on piezoelectric substrates has recently become a reality. The basic operation principles of these filters differ from conventional filters in that a traveling wave, transversal filter technology is used whereas the more conventional filters use a resonator technology (i.e., "poles" and "zeros" are not useful terms for describing surface wave filters). The basic principles of operation and prototype device performance have been described previously.[1,2,3] This paper describes the unification of this modeling information into a design synthesis procedure and also the resulting high performance devices which were designed. This work required the solution of practical engineering problems such as packaging, crosstalk, parasitic capacitance and resistance, electrical matching, and fabrication tolerances. Also involved are more sophisticated problems such as design optimization and reduction of distortion effects.

The flexibility of this type of device allows one to realize a wide range of signal processing functions including pulse compression filters, correlation filters, delay lines, bandpass filters, and other specialized filters requiring unusual bandpass or phase characteristics. Bandpass filters will be emphasized here because they have received less attention in previous publications than some of the other filters. The major advantages of acoustic surface wave filters are small size, low cost, reproducibility, wide dynamic range, high Q (low propagation loss), great design flexibility, good temperature stability, and a center frequency range which extends from HF to L-band.

II. Bandpass Filter Design

Although the procedure to be discussed below is specifically aimed at bandpass filter design, similar procedures are used in designing other filters.

The starting point for the design is to ascertain the desired values or acceptable ranges of values for certain device specifications such as center frequency, bandwidth, sidelobe level, shape factor, insertion loss, phase and amplitude ripple, size, and input/output impedance.

The first major design decision is usually choice of the substrate to be used. Although numerous substrates have been used in experiments, practical considerations such as cost, ease of fabrication and polishing, temperature sensitivity, reproducibility, and reliability of the metallization, usually limit the choice to either quartz or lithium niobate. The choice is then further facilitated by using curves such as that shown in Fig. 1 which shows the minimum achievable insertion loss for a two transducer filter on various substrates as a function of the filter's fractional bandwidth. The ST quartz is the zero temperature coefficient cut of quartz, HC quartz corresponds to the cut with the highest coupling factor achievable on quartz, and the lithium niobate curve corresponds to the standard Y-cut, Z propagating configuration. It might appear from this figure that lithium niobate is the optimum material for most devices but unfortunately other considerations limit its usefulness so that quartz is the most popular material. For example, the temperature sensitivity of lithium niobate is high (90ppm/°C) whereas a range of temperature sensitivities from 0 to 35 ppm/°C are available on quartz. Also, the higher coupling lithium niobate suffers from severe electrode reflection distortion which results in unacceptable performance for devices with more than 40 or 50 electrodes. Techniques are being investigated for reducing this distortion and temperature sensitivity but actually, the lower coupling coefficient of quartz is ideal for many complex device functions and thus it is by far the most useful for the majority of applications.

The minimum inpulse response length which will satisfy the desired fractional bandwidth, shape factor, sidelobe and bandpass ripple requirements can be determined either by means of curves which show the performance of whole families of optimized waveforms or by means of optimization-search computer routines. By applying a suitable cushion for slight overdesign and space between the transducer arrays, one can determine the minimum required substrate length for this particular device.

Once the device length is known, one can calculate the minimum allowable beamwidth (A_{min}) based on beam-spreading considerations.

$$A_{min} \simeq \sqrt{2\lambda L(1-2b)}$$

where L is the length of the device, λ is the surface wave wavelength at the center frequency, and 1-2b is an anisotropy correction factor for the particular substrate which is used.[4]

With knowledge of the beamwidth, device fractional bandwidths and the type of substrate, one can calculate the approximate input and output impedance of this minimum size device. If the size constraint (if any) allows a larger device to be built, one can increase the beamwidth or the device length (or both) and achieve a more desirable impedance level which in turn can have important effects on parasitic loss and matching network losses. For example, the minimum size design for a 168 MHz low shape factor filter to be described later had an impedance of 18 K ohms in parallel with 1.5 pf. Parasitic capacitance in the package would more than have doubled the suseptance thereby aggravating an already severe matching problem. By using dispersive transducer arrays (with opposite dispersion in the input and output to result in an overall nondispersive device) and by increasing the beamwidth, the impedance was lowered to 1.5 K ohms in parallel with ~ 20 pf and an acceptable matched insertion loss of ~ 14 dB was obtained.

Thus an impedance level/size tradeoff is done at this point, and the beamwidth and array dispersion ratios are fixed. The general features of the array design are determined (although the exact finger locations have not been specified). An analysis is usually done at this point to calculate the probable effects of various distortion effects. For example, distortion due to electrode reflections, triple transit echoes, and bulk mode responses are of primary interest here. If the effects are too severe, some compensation is added to the design to reduce the effects to a reasonable level.

The substrate thickness and metallization thickness can be chosen and, based on the knowledge of the general array features, the connecting pads are designed. Approximate parasitic capacitance and resistance can thus be calculated as well.

A rough package design is next completed and the parasitic inductance and capacitance can be approximately determined. By adding these values to the approximate transducer impedance values, one can approximately find the impedance of the packaged filter.

Input and output matching networks are designed for this impedance and their effect on the amplitude and phase response of the filter is calculated. This is subtracted from the desired overall filter transfer function to obtain the desired transfer function of the surface wave filter. This transfer function is inserted into a transducer weighting optimization program which specifies the exact details of the array layouts and also generates the data for a computer controlled artwork generator. The artwork is photoreduced to produce photomasks for defining the desired electrode patterns. For L-band devices, the output data is used to program a computer controlled E-beam machine.

The packaging design includes careful consideration to reduce parasitics and distributed electromagnetic effects and special attention is given to crosstalk reduction. An equivalent circuit shown in Fig. 2 has been derived which adequetly describes the various crosstalk mechanisms. In this figure, R_A and R_B represent series parasitic resistance on the input and output, C_C is the crosstalk capacitance, C_1 and C_2 are the static capacitance of the interdigital arrays, G_{r1} and G_{r2} represent the acoustic radiation conductances (which have both real and imaginary components), L_1 and L_2 are the self inductances of the arrays and the bonding leads, M is the mutual inductance, R_1 and R_2 represent series parasitic resistance on the ground side of the arrays and R_C represents the parasitic resistance on the ground side which is common to both arrays. As shown here, the arrays are assumed to be driven from unbalanced lines. A similar model would also apply for a balanced drive. Figure 3 shows comparisons between experiment and theoretical predictions for the magnitude of the crosstalk on two "dummy" surface wave filters fabricated on fused quartz.

Surprisingly, the extremely small mutual inductance is the most serious crosstalk source in most devices. Packaging layouts are designed for the reduction of this effect. The capacitive crosstalk and resistive crosstalk are easily minimized by standard techniques.

After the packaged device is obtained, a detailed set of impedance measurements are made and the matching network is slightly redesigned to account for the actual impedance which is obtained. The type of matching network which is used varies but simple configurations like autotransformers, L networks and Pi networks are commonly used. The critical element is the inductance which is realized either with slug tuned coils, toroidal coils, tunable H cores, air core coils, shorted transmission line stubs, or strip line stubs depending on the frequency of the device.

The results of this design procedure lead to the high performance devices which are discussed below.

III. Device Performance

Numerous bandpass filters have been designed, packaged, and matched over the past several years. Table I summarizes some of the more notable ones. The following ranges of performance have been demonstrated by various different filters: amplitude ripple of less than ± 2.5 dB and phase ripple less than ± 1.5°, sidelobe rejection of 45 dB with ultimate rejection in excess of 60 dB, shape factors from 1.2 to ~ 5, bandwidths as low as 90 KHz and as high as 37% of the center frequency. Insertion losses as low as 4 to 6 dB are obtained with certain filters but 8 to 14 dB are more typical values. High yield fabrication has been demonstrated up to 300 MHz and experimental device fabrication up to 1.5 GHz.

Figure 4 shows the frequency response for a 7% fractional bandwidth amplifier module which uses a surface wave filter for bandpass shaping. The filter is centered at 168 MHz with a 12 MHz 3 dB bandwidth and a 15 MHz 40 dB bandwidth. The filter has a 14 dB midband insertion loss while the single stage amplifier integrated into the same package exhibits a gain of 20 dB. The extremely steep skirt response could only be obtained by using state-of-the-art design optimization techniqes. Temperature studies have been done on the module and the device center frequency showed less than 200 KHz drift over a temperature range of -55°C to 125°C with no perceptible change in the bandpass shape. The deviation from linear phase was less than 10° across the entire bandwidth. The overall package volume is less than 0.7 inches^3.

A relatively extensive design and development effort has been completed on a 300 MHz center frequency, 2.5 MHz bandwidth surface wave filter for use in a receiver front end. Figure 5 shows the response of the electrically matched filter with a midband loss of 6 dB and a sidelobe level of 45 dB. The low insertion loss was obtained by use of a 3-transducer configuration with the outer arrays connected in parallel. This configuration also has inherent multiple transit suppression resulting in extremely low amplitude and phase ripple. By proper electrical design of the filter package, direct electrical crosstalk has been suppressed in excess of 70 dB in spite of the extremely small filter size (0.3" x 0.12" x 0.02"). Volume production has been demonstrated for this device as illustrated in Fig. 6. A two-inch slice of quartz is shown onto which 63 of these filters have been deposited using standard IC production facilities. The interdigitated finger line widths for this filter are 2.25 microns. Thus, this device represents obtaining extremely high resolution over a fairly large area.

IV. Conclusion

The current and projected capabilities of surface wave bandpass filters are given in Table II. Current results with experimental devices indicate that the projected performance column is in reach. The advantages of this filtering technology (small size, low cost, reproducibility, temperature stability, low propagation loss, wide dynamic range, etc.) coupled with the tremendous design flexibility make possible a whole spectrum of new systems functions especially in the VHF and low microwave frequency range.

References

1. Tancrell, R.H., and Holland, M.G., "Acoustic Surface Wave Filters," Proc. IEEE, 59, 3 (March 1971), pp. 393-409.
2. Smith, W.R., et al., "Analysis of Interdigital Surface Wave Transducers by Use of an Equivalent Circuit Model," IEEE Trans. on MTT, 17, 11 (November 1969).
3. Jones, W.S., Hartmann, C.S., and Sturdivant, T.D., "Modified Equivalent Circuit Model for Ultrasonic Surface Wave Interdigital Transducers," 1971 International Microwave Symposium, Washington, D.C., Paper IV-5.
4. Slobodnik, A.J., and Szabo, T.L. "Design Data for Microwave Acoustic Surface Wave Devices," Ibid, Paper IV-2.

TABLE I. SURFACE WAVE BANDPASS FILTERS

Bandpass Filter Receiver Applications	Center Frequency (MHz)	Bandwidth (MHz)	Insertion Loss (dB)
PRC-95	10.7	0.4	20
FM-IF	10.7	0.25	14
Pulse-IF	21.4	0.09	8
FM-Data	25.0	0.4	8
IF	40.0	0.25	8
TV-IF	45.0	3.5	25
Spread Spectrum	168.0	12.0	14
Front End	300.0	2.5	6

TABLE II. SURFACE WAVE BANDPASS FILTER CAPABILITIES

Parameters	Current	Projected
Center Frequency	10 MHz - 1.0 GHz	1 MHz - 2 GHz
Bandwidth	50 KHz - 0.4 f_o	20 KHz - 0.8 f_o
Min. Insertion Loss	6 dB	2-3 dB
Min. Shape Factor	1.2	1.2
Sidelobe Rejection	45 dB	65 dB
Ultimate Rejection	60 dB	80 dB
Deviation from Linear Phase	± 1.5°	± 1.0°
Amplitude Ripple	± 0.25 dB	± 0.1 dB

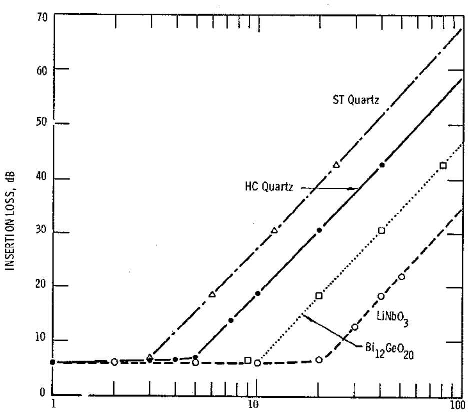

FIG.1. FRACTIONAL BANDWIDTH (PERCENT)

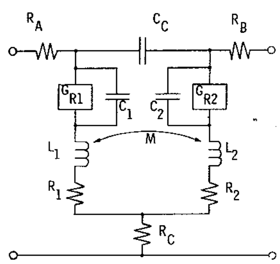

FIG.2. EQUIVALENT CIRCUIT OF A SURFACE WAVE FILTER INCLUDING CROSSTALK EFFECTS.

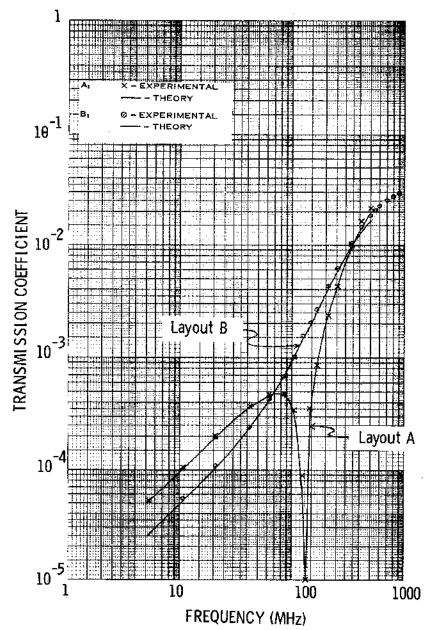

FIG. 3. MAGNITUDE OF CROSSTALK FOR TWO DIFFERENT CONFIGURATIONS.

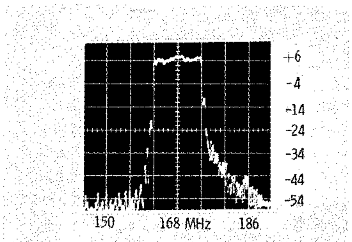

FIG. 4. 168 MHz, 12 MHz BW AMPLIFIER MODULE.

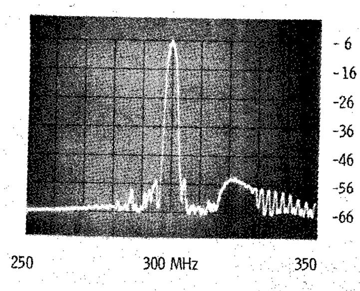

FIG. 5. 300 MHz, 2.5 MHz BW FILTER I.L. = 6 dB.

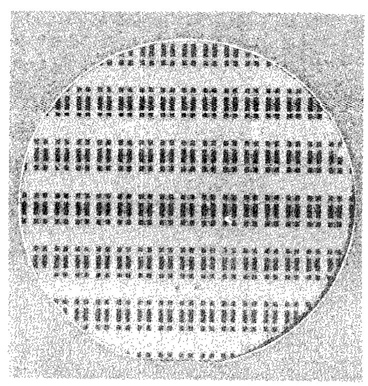
FIG. 6. 300 MHz BANDPASS FILTERS ON A PROCESSED QUARTZ SLICE.