X-Band Thin Film Acoustic Filters on GaAs

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***Abstract*—The Semiconductor Bulk Acoustic Resonator (SBAR) is composed entirely of thin films, piezoelectric aluminum nitride (AlN) and metal electrode films (primarily aluminum). It is fabricated on gallium arsenide (GaAs) wafers by depositing the thin film layers on top of the wafer and then etching away the GaAs from below, leaving a thin membrane supported by its edges. SBAR resonators and filters can be fabricated as part of the HBT or MESFET Monolithic Microwave Integrated Circuit (MMIC) processes, offering the high selectivity associated with acoustic resonators and filters to the MMIC designer. This paper describes performance of a recent 1-pole SBAR filter which has only 6.1 dB insertion loss at 7.8 GHz (2nd harmonic) and 7.5 dB insertion loss at 11.6 GHz (third harmonic), with fractional bandwidths less than 1%. Also described are 2-pole (1.4% bandwidth) and 4-pole (1.8% bandwidth) Chebyshev monolithic SBAR filters at 2.4 GHz, demonstrating flat passbands and good rejection. These results demonstrate that SBAR technology is practical for monolithic filters in MMICs at frequencies up to X-band.**

I. Introduction

With MMIC technology, active circuitry has been shrinking rapidly. However, off-chip filters have remained large and complex and are a barrier to overall system miniaturization. Crystal resonators, SAW resonators, and SAW filters provide outstanding performance as discrete devices. Unfortunately, they are relatively large compared to MMICs. And because they are constructed from special piezoelectric materials, they cannot be integrated on-chip. Also, they cannot perform at frequencies typical of MMICs (e.g., X-band), so that frequency down-conversion and up-conversion is often necessary specifically to take advantage of their high performance.

Semiconductor Bulk Acoustic Resonators (SBARs) are membrane acoustic resonators fabricated directly on GaAs wafers, and can be produced as part of the GaAs wafer process. The acoustic resonance is produced by longitudinal acoustic waves travelling perpendicular to the plane of the wafer. At TRW, we are currently making SBARs with piezoelectric aluminum nitride (AlN) films sputter-deposited onto GaAs wafers. Until recently, our development centered on devices at a few GHz, because we expected acoustic losses to be excessive a higher frequencies, such as X-band. Material acoustic losses per microsecond should be proportional to frequency squared, so we expected losses at higher frequencies to be much greater than what we observed at low frequencies.

Recently, we attempted to fabricate SBAR filters working at around 10 GHz in order to test the limits of application for these devices. We were surprised to measure performance almost as good as what we measure at much lower frequencies. Our 2-port stacked filter gave only 6 dB loss at 7.8 GHz and 7.5 dB loss at 11.6 GHz. Isolation remains high, nearly 30 dB at the 11.6 GHz resonance. The thinner AlN films seem to be of as good or better quality than our thicker films, and processing the parts with thinner films was not more difficult.

With this filter, we have demonstrated for the first time that the SBAR acoustic filter is practical for on-chip filtering directly at X-band frequencies or higher. Thus, it should be an attractive option for MMIC designers.

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II. History

A number of investigators have been making thin film acoustic resonators and filters on semiconductor substrates for at least 13 years [1]–[5]. The piezoelectric films are usually AlN or ZnO, and the semiconductor substrates have been both Si and GaAs. Many of the earlier devices were made using a stop-etch technique in which a small thickness of silicon was left as part of the acoustic path. This gave a smooth surface and enough thickness to provide good resonators below about 1 GHz without requiring excessive thickness in the electrodes or piezoelectric thin films.

TRW has been working on devices of this type and other high-frequency bulk resonators for about nine years. TRW is particularly interested in higher frequency filters on GaAs for integration into MMIC devices. For this, we developed a process to fabricate AlN resonators on GaAs without including any GaAs in the acoustic path. Because the membrane is so thin and has such a high acoustic velocity (10 400 m/s), its fundamental response is very high, typically well over 1 GHz.

III. Structure

At TRW, we fabricate SBAR piezoelectric acoustic resonators at high fundamental frequency by completely etching away the GaAs under the AlN and metal electrode layers, leaving a membrane typically several micrometers thick which is supported only at its sides. The fundamental resonant frequency is, of course, mostly determined by the AlN membrane thickness, since it makes up most of the acoustic path. The resonating region is typically rectangular, with side lengths on the order of a few hundred micrometers or less. The area of the SBAR determines its electrical impedance.

The resonator structure can be a one-port resonator, consisting of a single AlN layer with electrodes on both sides as in Fig. 1(a), or a more complex structure, such as the two-port resonator (also called the SBAR Stacked Crystal Filter, or SCF) shown in Fig. 1(b). The one-port resonator behaves like a simple crystal resonator, with the equivalent circuit of

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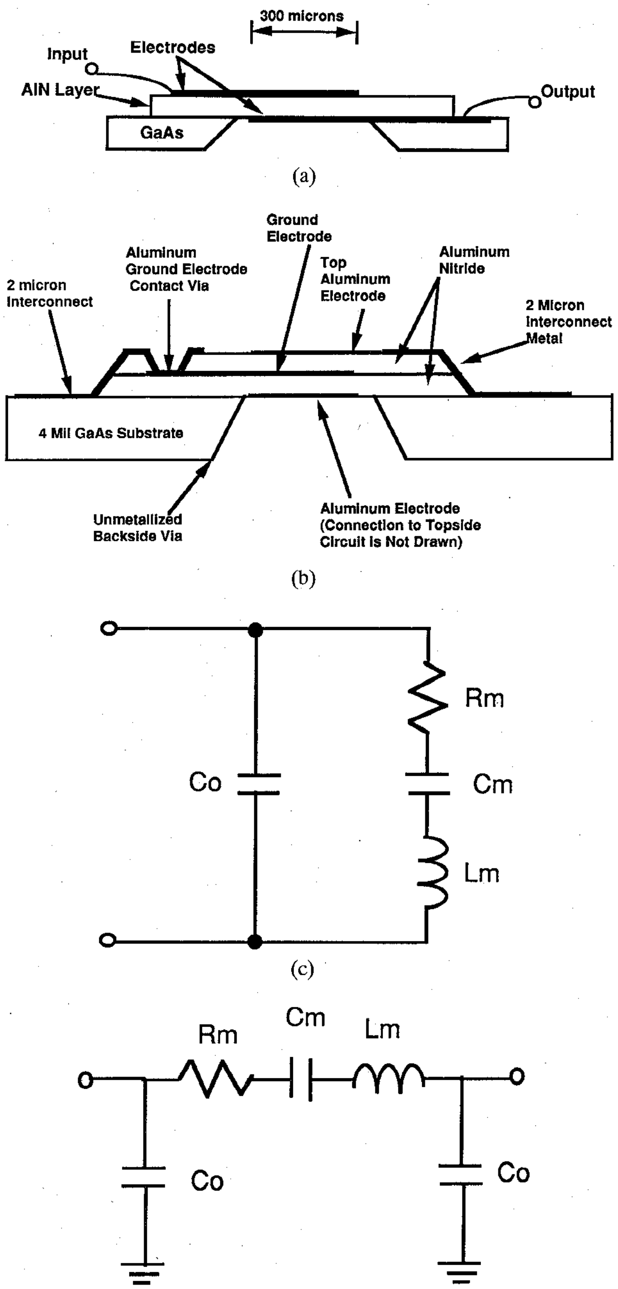

Fig. 1. One-port and two-port SBAR resonators and their equivalent circuits: (a) one-port SBAR resonator, (b) two-port SBAR resonator (also known as SBAR Stacked Crystal Filter), (c) equivalent circuit of one-port SBAR resonator, (d) equivalent circuit of two-port SBAR resonator.

Fig. 1(c). In the two-port resonator, the piezoelectric layer is split into two halves, with metal electrode layers at top, middle, and bottom. Typically, the middle electrode is grounded, so it helps to electrically shield the top electrode from the bottom electrode. This structure serves as a one-pole filter when the RF input signal is applied between the top and middle (ground) electrodes, and the output consists of the voltage between the bottom and middle (ground) electrodes. The equivalent circuit of this two-port structure at each of its resonances is essentially the simple LCR circuit shown in Fig. 1(d). The insertion loss of this filter at 1–2 GHz, measured at 50 ohms, is 2–3 dB. Isolation, measured by wafer probe, is typically 40 dB. The bandwidth of this two-port stacked structure is typically about 0.5%.

The layer thickness for the X-band SBAR filter which is the subject of this paper are shown in Fig. 2. The two AlN layers are each 4500 angstroms thick. The electrodes are primarily Al (with 2% Cu.) The bottom electrode is 780 angstroms, the middle electrode 800 angstroms, and the top electrode 2200 angstroms thick. The combined membrane thickness is therefore 1.278 micrometers. The resonating area

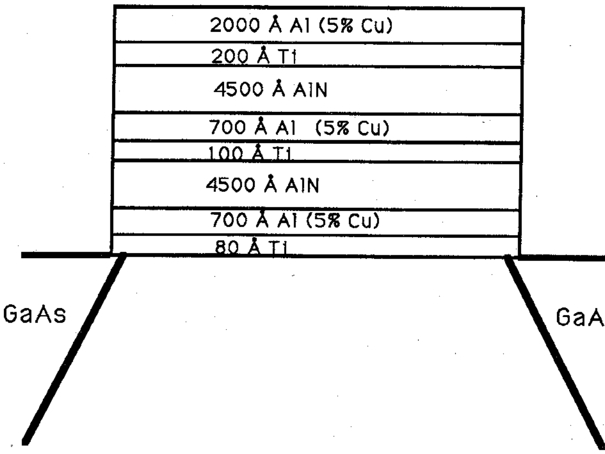

Fig. 2. Structure of the X-band two-port SBAR resonator.

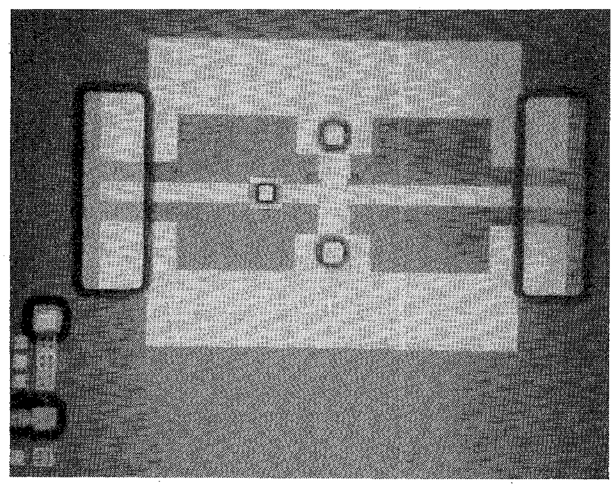

Fig. 3. Photograph of the X-band two-port SBAR resonator.

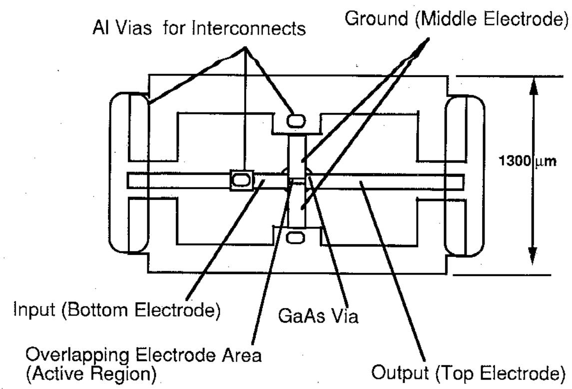

Fig. 4. Guide to the photograph of Fig. 3, showing dimensions.

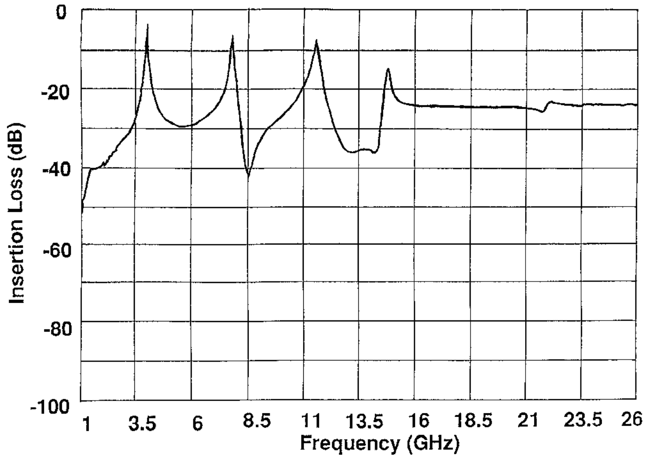

Fig. 5. Measured insertion loss of the X-band two-port resonator, from 1 to 26 GHz.

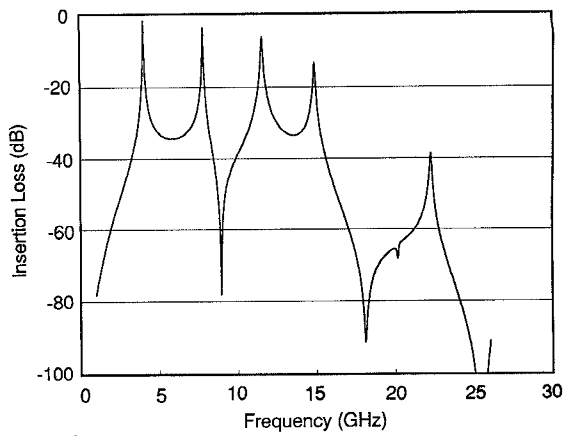

Fig. 6. Simulation of the insertion loss of the X-band two-port resonator, from 1 to 26 GHz.

is rectangular in the plane of the wafer, 30 micrometers by 105 micrometers.

A photograph of the complete X-band SBAR filter is shown in Fig. 3, and a drawing identifying its dimensions and construction are shown in Fig. 4.

Our SBAR process is completely compatible with our HBT and MESFET processes. HBT or MESFET wafers begin the SBAR process after top metal processing of the active circuitry, prior to thinning. The remaining process then consists of SBAR top metal processing (electrode and AlN layers), HBT backside processing, SBAR backside processing, and dicing. Thus, the SBAR filters are photolithographically defined on every chip as desired. We previously reported an HBT/SBAR filter-amplifier chip giving 14 dB gain at 1023 MHz with a 5 MHz bandwidth in a chip 3.2 × 3.2 millimeters [6].

IV. Fabrication

The key to SBAR fabrication is the deposition of the AlN. We deposit the AlN in a Varian S-gun sputtering system, by sputtering aluminum in a nitrogen atmosphere. If the system is sufficiently clean, the AlN grows consistently with high coupling. With proper wafer alignment, it grows with its c-axis perpendicular to the chip's surface. With these controls, we are able to consistently grow high quality AlN films for longitudinal bulk wave excitation. This longitudinal wave has a velocity of 10 400 meters per second. Its coupling coefficient is about 2%, as determined by comparison of our measured SBAR characteristics with Mason model simulations.

TABLE I

Response	Frequency	Insertion Loss
fundamental	4.03 GHz	3.7 dB
2nd harmonic	7.78 GHz	6.1 dB
3rd harmonic	11.56 GHz	7.5 dB
4th harmonic	14.81 GHz	14.6 dB
6th harmonic	22 GHz	24 dB

V. Performance

The insertion loss of the X-band SBAR filter, measured at 50 ohms from 1 to 26 GHz on a wafer prober, is shown in Fig. 5. The loss is low at the fundamental, 2nd, and 3rd harmonics, as shown in Table I.

Because the interfaces between the metal electrodes and the aluminum nitride cause partial acoustic reflections, the harmonics are not evenly spaced. The 2nd harmonic is 1.93 times, and the 3rd harmonic 2.87 times, the fundamental frequency. Higher harmonics are considerably suppressed.

The passband responses are typical of one-pole filters, having narrow 3 dB bandwidths but wide skirts. The extension of the SBAR to multipole filters, in analogy to multipole crystal filters, is an obvious way to achieve better filter shapes.

Note that the "close-in" rejection is about 27 dB at the third harmonic, 23 dB at the second, and 26 dB at the fundamental. The next section of this paper will show that up to the fourth harmonic, the limited rejection is predicted and is due to an overlap of the 1-pole harmonic responses, and is not due to electromagnetic feedthrough. An indication of the feedthrough level is given by the null at 8.5 GHz, which is lower than −42 dB.

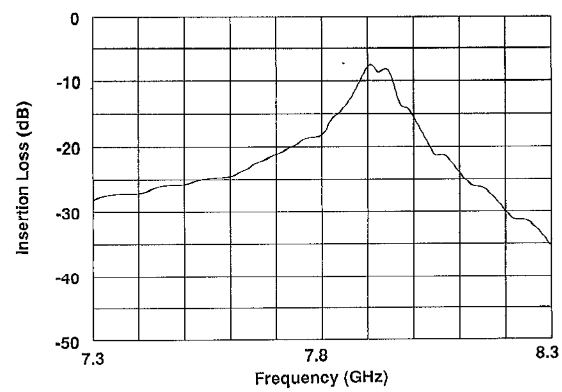

Fig. 7. Measured insertion loss of the X-band two-port resonator, 2nd harmonic.

TABLE II

Harmonic	Frequency (GHz) Meas.	Frequency (GHz) Sim.	Insertion Loss (dB) Measured	Insertion Loss (dB) Simulated
fundamental	4.03	4.03	3.7	1.9
2nd harmonic	7.78	7.79	6.1	3.8
3rd harmonic	11.56	11.54	7.5	6.3
4th harmonic	14.81	14.88	14.6	13.3
6th harmonic	22.	22.24	24.	38.6

VI. Simulation

The performance of the SBAR filter can be simulated using one-dimensional Mason equivalent circuit models [7]. These equivalent circuits can then be characterized using standard circuit analysis software. The Mason model is more complex than the simple LCR equivalent circuits shown in Fig. 1(c) and (d), but includes all harmonics in a single circuit (the LCR equivalents work only for a single harmonic) and is derived directly from the thickness of the piezoelectric and electrode films and their physical properties.

Initial Mason model simulations of this device represented each electrode as pure Al with the total electrode thickness given earlier, ignoring the fact that they are partly made of Ti and that the Al contains Cu. An AlN propagation loss of 14 dB per microsecond per GHz squared was assumed. Predicted resonances were too low and without exactly the right spacing. In order to give agreement with measurement, the layer thicknesses used in the model were perturbed until resonant frequencies very close to measurement were predicted using the same approach, when the layer thicknesses were modified in order to put the resonances in the right place (AlN thickness 4087 angstroms, top electrode thickness 2089 angstroms, middle and bottom electrode thicknesses 672 angstroms.)

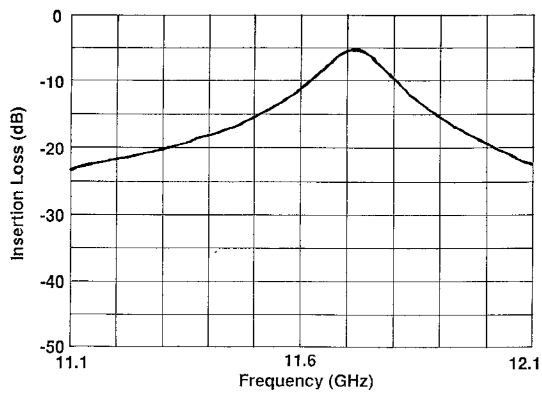

Fig. 8. Measured insertion loss of the X-band two-port resonator, 3rd harmonic.

The resulting simulation is shown in Fig. 6. The simulation shows insertion losses within 2.3 dB of measurement at the fundamental, second, third, and fourth harmonic. It also shows why higher harmonics were not clearly observed and also shows the weak 6th harmonic. The measured loss for the 6th harmonic, however, was much less than predicted. The simulation also shows that the limited rejection between harmonics has a simple acoustic basis, although the rejection is deeper in the simulation than in the measurement. Note that the simulation in Fig. 6 shows characteristics with up to 100 dB loss, while the corresponding characteristics in Fig. 7 (measured) are covered up by electromagnetic feedthrough ranging from about 50 dB loss at the lowest frequencies to about 24 dB loss at the highest.

The simulated versus measured passband properties are shown in Table II.

Narrowband measurements of the 2nd and 3rd harmonics are shown in Figs. 7 and 8 (not the same devices as Fig. 6), with simulations in Figs. 9 and 10. Agreement between the measured and simulated characteristics is fairly good. Simulated bandwidths for the fundamental through 4th harmonic are 0.82% (not shown), 0.60%, 0.95%, and 0.69% (not shown) respectively.

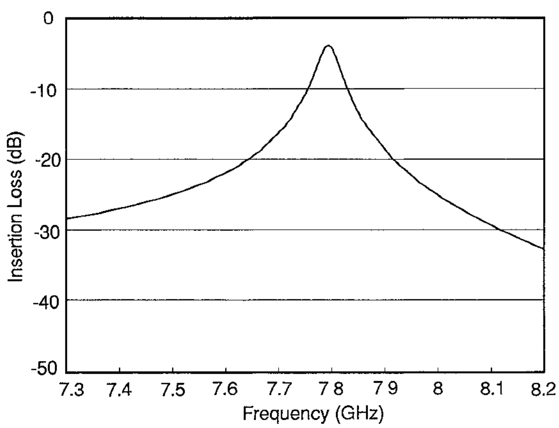

Fig. 9. Simulated insertion loss of the X-band two-port resonator, 2nd harmonic.

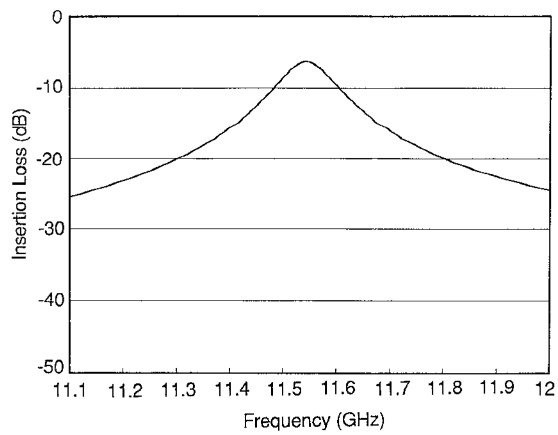

Fig. 10. Simulated insertion loss of the X-band two-port resonator, 3rd harmonic.

VII. Multipole Filters

Single-pole 2-port SBAR resonators have limited applications because their passbands are not flat. However, the 1-pole SBAR devices can be combined into multipole filters in a number of ways to produce more useful filter characteristics.

Recently, we have fabricated monolithic 2-pole and 4-pole Chebyshev multipole filters, by cascading the 2-port SBAR resonators with shunt coupling spiral inductors. This configuration is shown schematically in Fig. 11. The complete 4-pole filter is shown in Fig. 12. Input and output shunt inductors, necessary to provide a true 50-ohm match, were omitted here to save chip area.

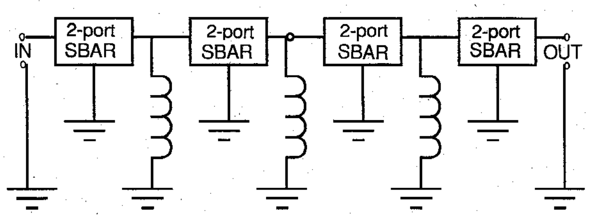

Fig. 11. Schematic illustration of a monolithic 4-pole Chebyshev filter made of 2-port SBAR resonators and shunt coupling spiral inductors.

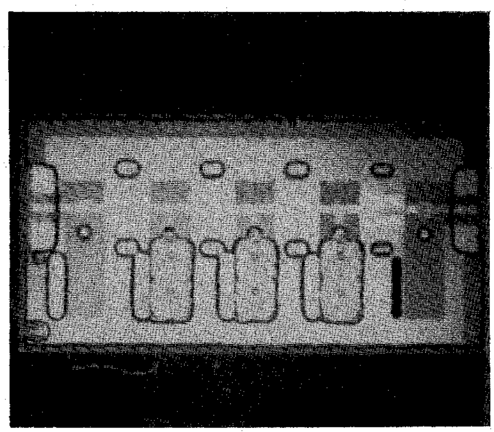

Fig. 12. Photograph of a monolithic 4-pole SBAR Chebyshev filter on GaAs at 2430 MHz.

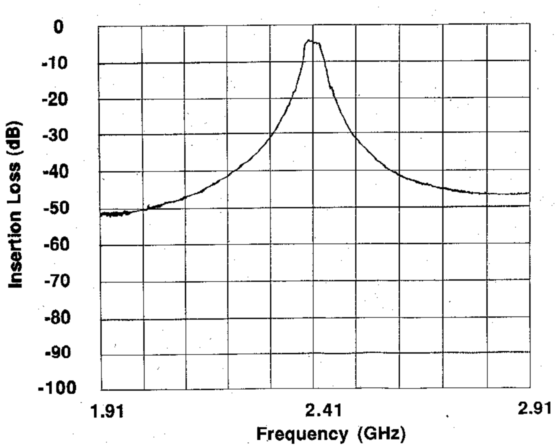

Fig. 13. Measured characteristics of a monolithic 2-pole SBAR Chebyshev filter on GaAs at 2430 MHz.

The measured filter characteristics of the 2-pole (1.4% bandwidth) and 4-pole (1.8% bandwidth) filters, which are centered at about 2430 MHz, are shown in Figs. 13 and 14. For comparison, the calculated characteristics of ideal Chebyshev filters centered at the same frequency (with a nominal 40 MHz, or 1.6% bandwidth) are shown in Figs. 15 and 16. Although passband ripple exceeds the theoretical 0.5 dB, the passbands are fairly flat and the rejection characteristics are quite similar to theoretical. The measured 4-pole characteristics in Fig. 14 differ from the ideal results in Fig. 16 primarily only in the 8.5 dB insertion loss and the electromagnetic feedthrough floor at about 40 dB below the passband.

VIII. Application

Integration of SBARs into MMICs is attractive where small size and simplicity of assembly is very important. Single-pole SBAR resonators may find application in oscillators or as filters to "clean up" the noise around a fixed-frequency local oscillator tone. Multipole SBAR resonators may find use as IF filters in receivers.

The SBAR devices themselves are quite small. The 2-port SBAR resonators (Stacked Crystal Filters) function well as single-pole filters without additional matching components.

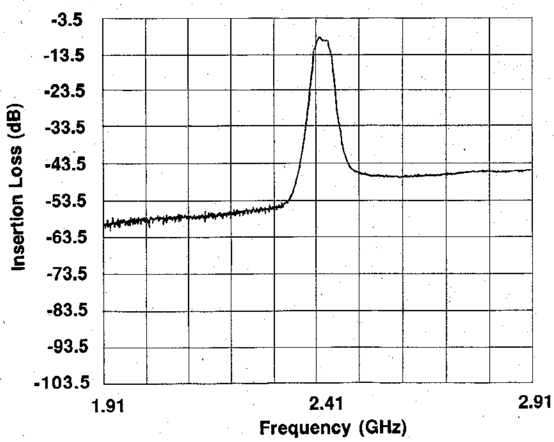

Fig. 14. Measured characteristics of a monolithic 4-pole SBAR Chebyshev filter on GaAs at 2430 MHz.

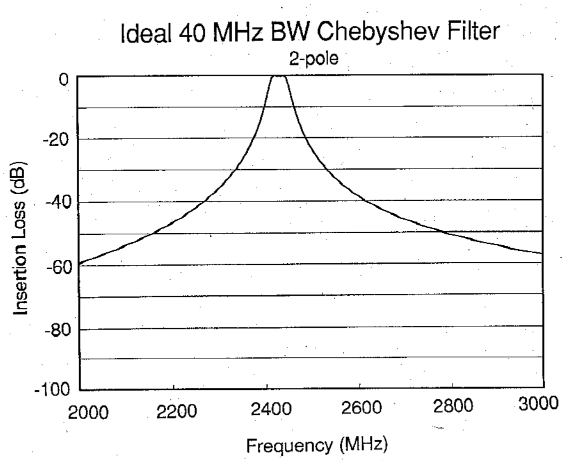

Fig. 15. Calculated characteristics of an ideal 2-pole Chebyshev filter at 2430 MHz, with 40 MHz bandwidth.

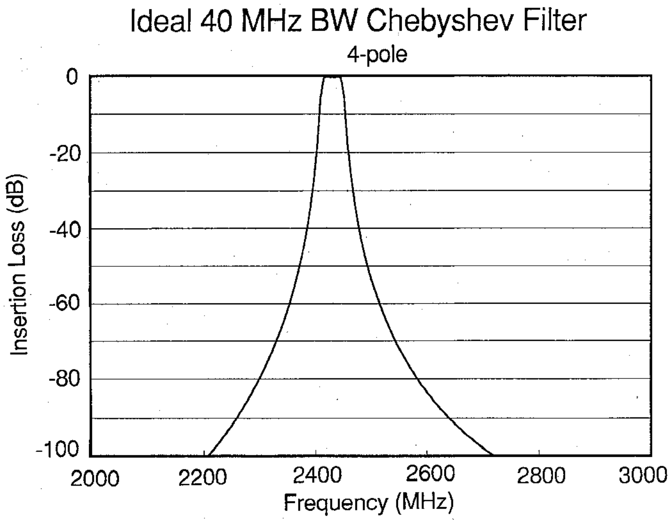

Fig. 16. Calculated characteristics of an ideal 4-pole Chebyshev filter at 2430 MHz, with 40 MHz bandwidth.

TABLE III

Harmonic	Signal Freq (GHz)	Passband Center (GHz)	Suppression (dB)
fundamental	4.03	4.03	0
2nd harmonic	8.06	7.79	24.2
3rd harmonic	12.09	11.54	19.7
4th harmonic	16.12	14.88	34.8

They can find application when low loss filtering at a single frequency is required, in analogy to a 1-pole bulk crystal or a 1-pole SAW resonator.

A number of multipole SBAR filter configurations can be conceived, which should provide better filter shapes with bandwidths from about 0.5% to at least 2%. These multipole filters can be applied to narrowband applications where transmission line filters are less attractive.

Simple SBAR filters such as the one reported here have many harmonics with low insertion loss. The uneven spacing of the harmonics, however, is a big advantage for many applications. This can be seen by an example, using the simulation of the X-band SBAR device for convenience. If the harmonic passband center frequencies were simple multiples of the fundamental, then a tone passed by the fundamental passband would have its harmonics passed by the harmonic passbands. Because the harmonics are not evenly spaced, this does not happen. If a tone appears in the center of the fundamental passband, its harmonics miss the filter's harmonic passbands, and are suppressed relative to the passbands' centers as shown in Table III.

Acknowledgment

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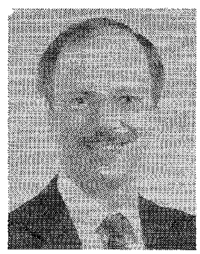

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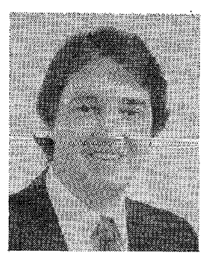

Jay D. Crawford was born in Highland Park, Michigan. He received a B.S. degree in Physics from San Diego State University in 1990.

In 1984 he joined the Microwave Acoustics Department as a technician working primarily on SAW devices. Since receiving his degree in 1990, his primary responsibility has been developing the fabrication process for SBAR devices. He is a member of the technical staff of the Microwave Acoustics Department.