

# WIDE BANDWIDTH LOW COST SAW NOTCH FILTERS

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*Abstract - Surface Acoustic Wave (SAW) Notch Filters have been fabricated in the past with limited success. A prevailing problem has been stopband null depth and bandwidth versus a reasonably broad passband response. Typically, notch filters developed in the past have achieved either one or the other. Notch Filters using the Single Phase Unidirectional Transducer (SPUDT) SAW notch element have achieved good null depth and null bandwidth, but have had little success in achieving a broad passband response [1]. Other filters, used in the CATV industry, have achieved very good broad passband responses, but have produced notch bandwidths that are too narrow to reliably operate over a large temperature range. SAW notch filters of the past have been physically large, at times over 17 mm in length and therefore required expensive packaging. Also, these filters have required large and expensive tuning components to achieve the desired performance. The physical size requirements resulted in circuits that were limited in applications.*

*In an effort to solve these problems, a new approach has been considered where a SAW element was optimized for high input impedance at the notch center frequency  $F_0$ . A Coupling of Modes (COM) model was used to predict the performance of the notch element and the notch network [2]. The results are presented along with experimental data. The result was a SAW notch element under 7 mm in length that could easily fit in a TO-39-5 package. Tuning for this notch network required only two small surface mount inductors. Typical passband performance was less than -7.0 dB from 350MHz to 1.5Ghz. Lower passband loss can be achieved when higher quality inductors are used. Typical notch performance was -40dB over a bandwidth of over 95KHz at design notch center frequencies ranging from 375 MHz to 450 MHz. Maximum null depth at the design center frequency exceeded -55dB.*

## PERFORMANCE PARAMETERS

Several electrical performance parameters are critical for a notch filter. The notch depth at the the notch center

frequency,  $F_0$ , should be many decibels (dB) below the passband level. Along with this specification, the stopband should be wide and at a level many dB below the passband of the filter. This wide notch bandwidth allows for aging, temperature drift, and set-on for manufacturing variation and has typically been the most critical electrical attribute of notch filters. The -3dB bandwidth should also be narrow enough to avoid distortion to adjacent frequencies that the filter should pass [1]. Finally, the passband should have a broad frequency spectrum and have low loss. For the filter described in this presentation, the desired specification goals for the above parameters were a total notch depth of more than -60 dB, a stopband width of approximately 100 kHz at -40 dB, a -3dB bandwidth of 0.500 MHz and a passband loss of less than 5dB from 350 MHz to 1500 MHz.

## LC NOTCH FILTERS

Discreet component notch or bandstop filters are common in many applications [1]. One popular LC configuration shown in Figure 1 is called a T-type band elimination filter [3]. This circuit is designed as a high pass filter and a

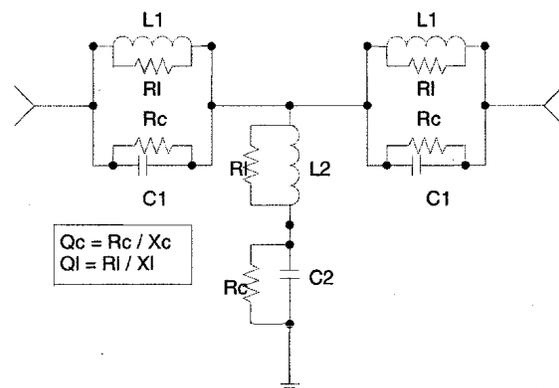


Figure 1: T-Type Notch Filter

pass filter connected in parallel. The stopbands of each filter overlap in the range of the frequencies to be eliminated. To obtain the notch performance comparable to the goals stated above, a solution for the necessary

capacitor (C1 and C2) and inductor (L1 and L2) values was found at a chosen  $F_0$  of 420 MHz. Using a circuit simulation program, the values for C1 and C2 were found to be 4.575 nF and 4.575 fF respectively and the values for L1 and L2 were found to be 31.385 pF and 31.385 uH respectively. Also, the required values of Q for the components as defined in Figure 1 were found to be 18,000 for L1 and L2 and 36,000 for C1 and C2 [4,5]. Figure 2 exhibits the theoretical performance of this T-Type notch filter applying discrete inductors and capacitors using a circuit simulation program. Clearly, discrete components with such inductance, capacitance, and Q values cannot be found to build the T-type configuration at 420 MHz. Thus, to meet the required specifications, alternative notch filter components are needed.

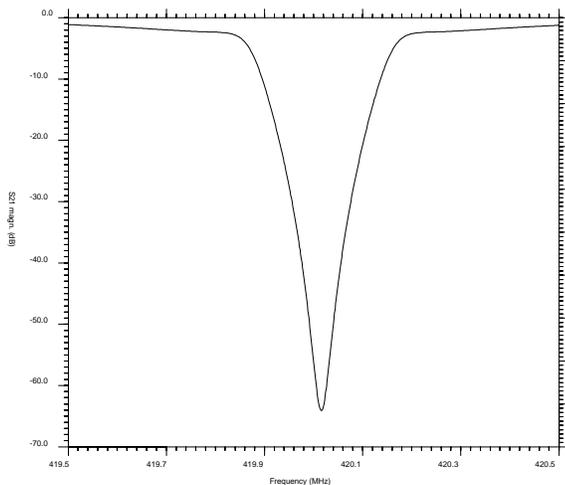


Figure 2: Simulation of T-Type Notch Filter

### PREVIOUS SAW BASED NOTCH FILTERS

One alternative is a notch filter design incorporating SAW transducers. Previously, SAW notch filters have incorporated the Single Phase Unidirectional Transducer (SPUDT) SAW Notch Element or SNE. The SPUDT SNE can be designed to provide a constant admittance over a specified frequency range [1]. Also, the susceptance is constant over the same frequency span as that of the “valley” of the conductance response. One possible circuit configuration uses the SNE in parallel with a conventional reference impedance with both connected to a phase reversing transformer. At the SNE frequency, the resistance of the SNE equals the resistance of the reference impedance and the signal is cancelled by means of the transformer. While this notch circuit provides good stopband performance, the passband may

not be wide enough for some applications. Also, the cost of the circuit and the SAW device itself can be prohibitive in many applications. Depending on  $F_0$ , the SAW device die can be as large as 17 mm. These large die also require large, expensive packaging. The tuning components themselves can be expensive, particularly the transformer. Also, the packaged die, transformer, and other tuning components take up a sizeable amount of physical space, which is one of the key limiting parameters in many applications.

Other circuits using the SNE are Bridged-T filters [1]. These circuits are physically similar to the discrete component T-type configuration in Figure 1, but use the SNE’s as tuned admittance elements. Also, a notch circuit using a Quadrature Hybrid Coupler has been developed [1]. These circuits require multiple SNE’s and extensive tuning, again raising the total cost and increasing the size of the complete circuit.

### 2-PER SAW IMPEDANCE ELEMENT

Keeping in mind the size and cost restrictions imposed by communications applications today, a less expensive, smaller alternative notch circuit was developed. SAW devices have been previously designed for a designated admittance response at the resonant frequency, such as the above mentioned SNE. However, a SAW device can also be designed to have a maximum impedance response at a designated anti-resonant frequency. This brings to mind the two LC tank circuits in the series sections of the T-type notch filter in Figure 1. Ideally, each of these parallel resonant tanks would appear as an open circuit at the resonant frequency being applied to them, assuming infinite Q values.

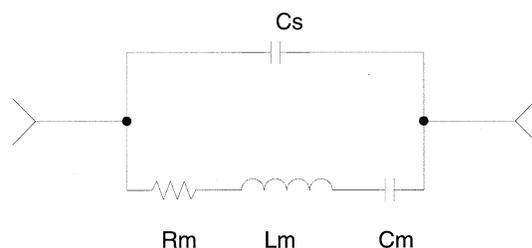


Figure 3: 1-Port Resonator Equivalent Circuit

These tank circuits appear electrically similar to the equivalent circuit of a Two Electrodes per Wavelength, or “2-Per”, SAW One-Port Resonator as shown Figure 3 [7]. Therefore, using a SAW design CAD program and a Coupling of Modes (COM) analysis program, a 2-Per

SAW resonator was designed. The SAW device was designed for maximum real impedance at the desired notch center frequency,  $F_0$ , of 420 MHz. The motional inductance,  $L_m$ , the motional capacitance,  $C_m$ , and the static capacitance,  $C_s$ , were found to have values of 48.56  $\mu\text{H}$ , 2.95 fF, and 3.66 pF respectively, with Q values for the motional components found to be 500,000 and the Q value for  $C_s$  found to be 100,000.

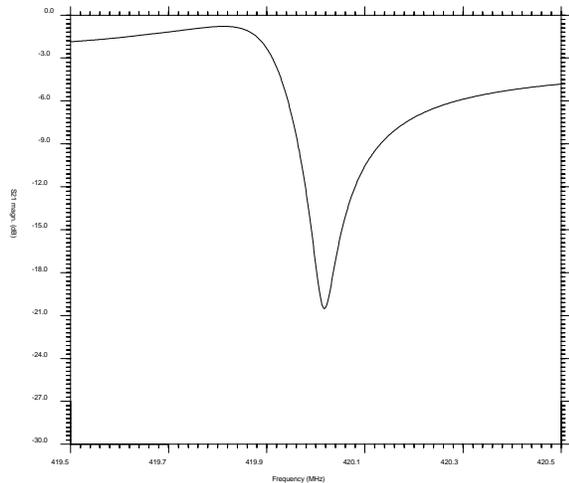


Figure 4: S21 Simulation of 2-Per SAW Impedance Element

Figure 4 shows the simulated transmission response of the SAW device. The peak is due to the series resonant circuit formed by  $L_m$ ,  $C_m$ , and the small motional resistance,  $R_m$ , and appears at the series resonance as a high conductance. The null is due to the parallel resonance of  $C_s$  with the equivalent inductance of the series branch composed of the motional components at the parallel resonant frequency. The Q of the resonance produced by this tank circuit is 11,494 [4]. At the parallel resonant frequency, the real part of the impedance of the SAW transducer is maximum. This null frequency corresponds to the desired notch frequency.

## TWO ELEMENT SAW NOTCH FILTER

A circuit similar to that of the T-type circuit of Figure 1 was developed using two of the SAW devices described above with these devices essentially replacing the tank circuits. However, the real impedance of the SAW is at a maximum of 950 ohms when the device is capacitive, due to the  $C_s$  of the SAW. Thus, the T-type circuit had to be modified. The series resonant circuit in shunt between the two tank circuits is replaced with a single inductor, as seen in Figure 5. This inductance resonates with the  $C_s$  of the SAW devices so that the circuit appears to have a nominal

75 ohm real impedance to the source over a wide passband, with the exception of the notch response.

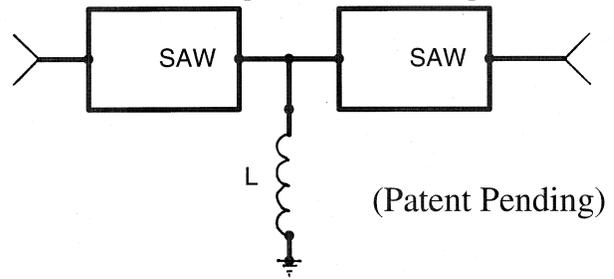


Figure 5: Two Element SAW Notch Filter

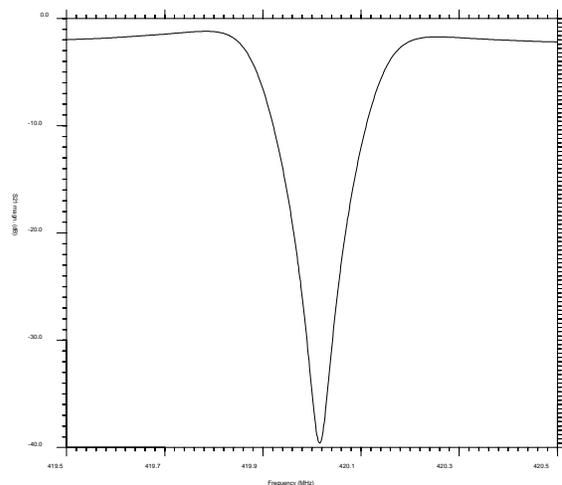


Figure 6: Theoretical S21 Response of Two-Element SAW Notch Filter

Figure 6 shows the transmission performance of the Two Element SAW notch filter, as generated by the circuit simulation program using a COM analysis for the SAW. The notch filter has a total notch depth of over -35dB, a -20dB stopband width of over 100 kHz, a -3dB bandwidth of less than 280 kHz, and a passband loss of less than -3dB. Figure 7 shows the input impedance on a Smith Chart. The circuit starts by appearing to the source as a nominal 75 ohm impedance on the low side of the passband. The circuit then quickly becomes inductive and the impedance increases rapidly until it crosses the real axis again at 950 ohms, corresponding to the maximum attenuation for the notch filter. The null depth at this frequency, which is the  $F_0$  of the filter circuit, is at a maximum. From this point, the circuit quickly becomes capacitive and the impedance rapidly decreases until returning to the nominal 75 ohms on the high side of the

passband. It should be noted here that the response can be rotated about the center of the Smith Chart by adding electrical delay. In fact, the response can be rotated 180 degrees so that the maximum impedance point described above becomes a maximum admittance point.

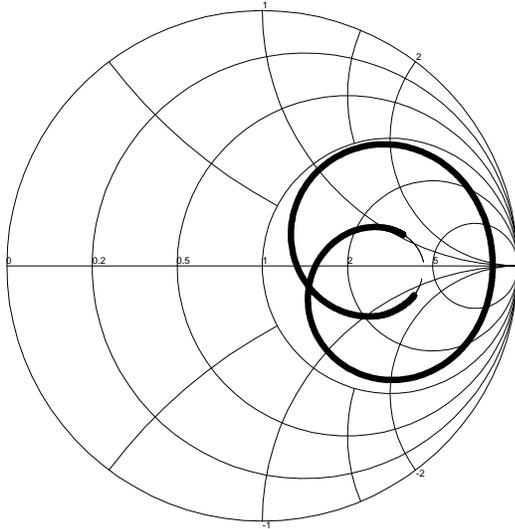


Figure 7: Theoretical S11 Response of Two-Element SAW Notch Filter

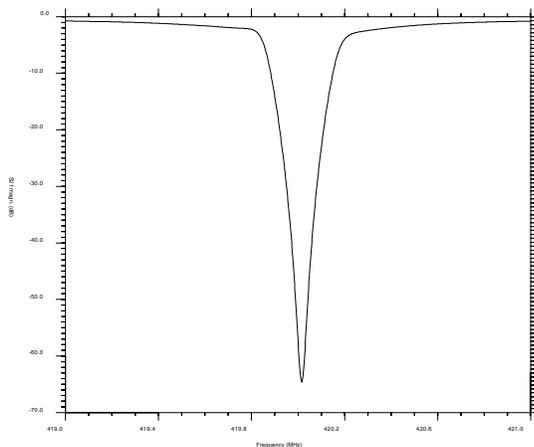


Figure 8: Theoretical S21 Response of Four Element SAW Notch Filter

#### FOUR ELEMENT SAW NOTCH FILTER

As was stated before, more attenuation over a bandwidth wide enough to compensate for temperature drift is

desired. The performance of the above mentioned circuit may not be adequate for many applications. Simply cascading two of the Two SAW Impedance Element filters shown in Figure 6 provided improved performance. When cascading two of the Two Element sections together, concern may be expressed that the tuning inductance between each SAW device pair may have to change. However, this was found to have negligible effect. In addition, no significant change was found in the inductance value needed for each section.

Figure 8 shows the simulated performance of the Four Element SAW Notch Filter. Total notch depth is greater than -60 dB below the passband with a -3dB bandwidth of less than 370 kHz. This circuit also has a -40dB stopband width of approximately 86 kHz. The loss in the passband is less than 5 dB from 350 MHz to 1.5 GHz.

#### EXPERIMENTAL RESULTS

The SAW devices developed for this notch circuit were designed to be small, easy to produce in large quantities, and inexpensive to manufacture. Two SAW 2-per resonators were fabricated on a single die. Each element was designed for a frequency of 420 Mhz. The metal used in the fabrication of these devices was a two percent Aluminum Copper alloy. The substrate was 39 degree rotated Y-cut quartz. The die dimensions were 6.40 by 1.40 mm. The package type used was the TO-39-5.

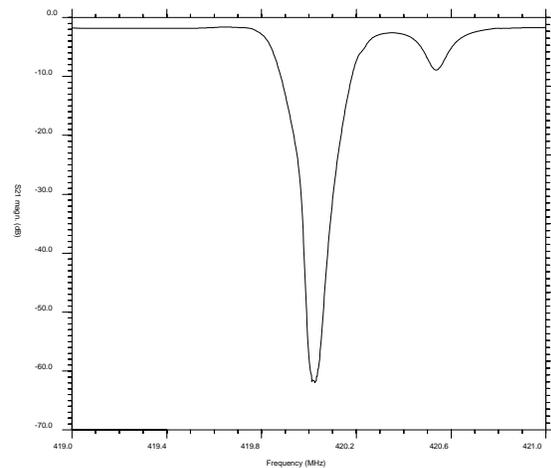


Figure 9: S21 Response of Prototype Four Element Notch Filter

Figure 9 shows the transmission performance of the prototype Four Element SAW Notch Filter circuit. For this prototype, commercially available surface mount inductors

with Q values of approximately 55 at  $F_0$  were used for the shunt tuning inductors. The total null response is greater than -60dB with a -3dB bandwidth of less than 410 kHz. Figure 9 also displays what was stated before as the major advantage of this notch circuit, the wide stopband width. The width of the -40dB stopband is exactly 100 kHz. Along with this, the total notch frequency variation over a temperature range of -40 to +60 degrees Celsius was 46 kHz. Comparing this variation to the -40dB notch bandwidth of 100 kHz, a reasonable set-on for production variation is obtained. The passband loss is less than 5dB, with the exception of bulk modes at 1.6 and 1.8 times  $F_0$ , and the 2-Per response occurring approximately 520 kHz higher than  $F_0$ . The bulk modes are no greater than -6.0 dB and the 2-Per response is approximately -9.0dB.

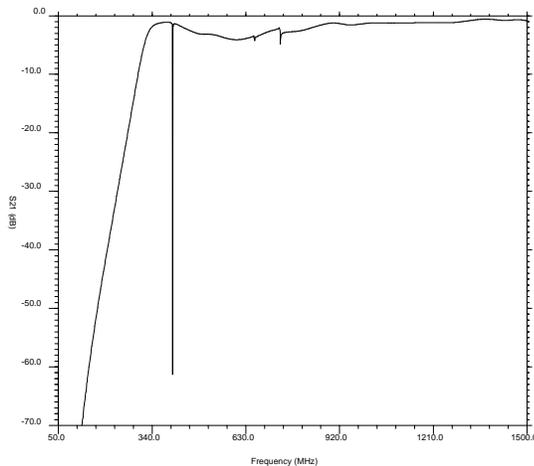


Figure 10: S21 Response of Prototype Four-Element SAW Notch Filter over a Wide Frequency Span

### LIMITATIONS

One limitation of this circuit is that it is also a high pass filter. As shown in Figure 10, the Four Element circuit has a cutoff frequency of approximately 332 MHz. While it is often desirable to have a notch filter perform as an all pass circuit from DC to above 1 GHz, the performance of this filter is acceptable for many applications. If inductors of appropriate values are connected in shunt across each pair of SAW elements, the lower frequencies will be passed down to 50 MHz. However, doing this will adversely affect the null depth substantially. Higher performance can be achieved with higher Q value tuning inductors.

### CONCLUSIONS

To develop these SAW Notch Filters, different options were explored. Designing a notch element for maximum admittance at the desired notch frequency,  $F_0$ , was considered and explored, but found to be too expensive due to increased die size. Developing a SAW impedance element to “block”  $F_0$  proved to be more successful. For this entire development, size of the SAW elements themselves and the circuit were of great importance. It was found that using a simple 2-Per SAW resonator as an impedance element provided an excellent solution for a low cost, wide stopband width notch filter circuit design.

The Four SAW Impedance Element Notch Filter proved to be the best development for the cost, size, and performance. The die size and therefore the package size was kept small and inexpensive. The tuning approach for optimum filter performance was simply impedance matching the equivalent RLC circuit of each SAW element in the filter at  $F_0$ . Therefore, the tuning components necessary for optimum filter performance were two surface mount inductors, keeping the cost of the complete circuit low. This development achieved a notch filter with a broad, low loss passband and a deep null with a -40dB bandwidth of approximately 100 kHz.

### REFERENCES

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