High Dielectric Constant Strip Line Band Pass Filters

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Abstract—**High dielectric constant ($K = 38$) strip line was employed to realize selective band-pass filters. Seven-pole gap coupled filters centered at 6.04 GHz and 8.28 GHz were designed for 140 MHz 3-dB bandwidths. The data shows excellent agreement without the need for tuners. Miniaturization of high performance filters has been demonstrated. This technique is applicable to MMIC based microwave systems.**

Introduction

THIS PAPER describes the design and construction of strip line band-pass filters using high-dielectric constant ($K = 38$) substrates. This work was undertaken to develop miniature filters with sharp selectivity amenable to low cost printed circuit fabrication techniques. Miniature filters are becoming increasingly important for use with MMIC-based hardware. Many microwave systems using MMIC based technology also require selective filters. These systems will not realize their miniaturization potentials unless the sizes of the filters are reduced together with the MMIC based RF assemblies. The choice of propagation media for this effort is balanced strip line. The substrate material is composed of zirconium tin titanium oxide [(ZrSn)TiO4] and possesses a dielectric constant of 38. The loss tangent of the material as quoted by the manufacturer is 0.0001. This corresponds to a dielectric quality factor of the order of 10 000. The material is also very stable with temperature, demonstrating a temperature variation of 6 ppm/°C. This material is extensively used to form dielectric resonator filters which provide high Qu resonators for very narrowband ($<1\%$) applications. Such filters also require non-printed circuit techniques for their realizations. For bandwidth designs which are in the range of 1% to 20% lower Qu media are tolerable and this is the niche that the authors believe their work addresses. It should be pointed out, however, that the possibility of combining this work with high temperature superconducting techniques provides a means of eliminating the chief cause of Qu degradation and permits the performance of superconducting versions of this type of filter to be comparable in performance to dielectric resonator filters. Additionally, using this material is thought, by the authors, to be the first such application in balanced high-K strip line. The filter type chosen for this present application is Cohn's gap-coupled design [1]. This particular design was chosen because of its eventual application in the design of compact multiplexers.

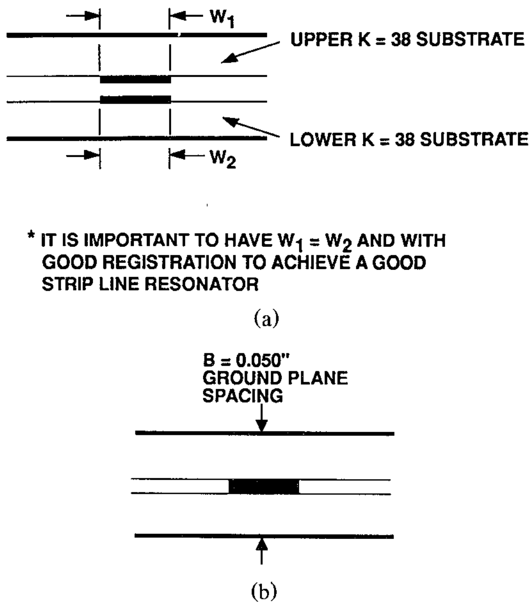

Fig. 1. Strip line cross section. (a) Two halves of a strip line.* (b) Two halves sandwiched together.

Technical Discussion

To demonstrate feasibility, $K = 38$ substrates were used. Such filters typically operate over bandwidths of the order of 10% or less. The effects of dissipation are generally more crucial for narrowband designs. Thus, the choice of materials with unloaded quality factors (Qu's) which meet the necessary requirements is an important consideration. The intended filter design would be unacceptable if dissipation effects were at too high a level. Fortunately, this is not the case. The low loss nature of the material is adequate for the intended purpose. Conductor losses also limit the Qu and they vary with the choice of transmission line. Strip line was chosen since it offered adequate performance electrically and reasonable mechanical requirements. Fig. 1 shows the strip line cross section. The impedance level is typically found to be in the 10 to 20 Ω range. The conductor losses for strip line are acceptable

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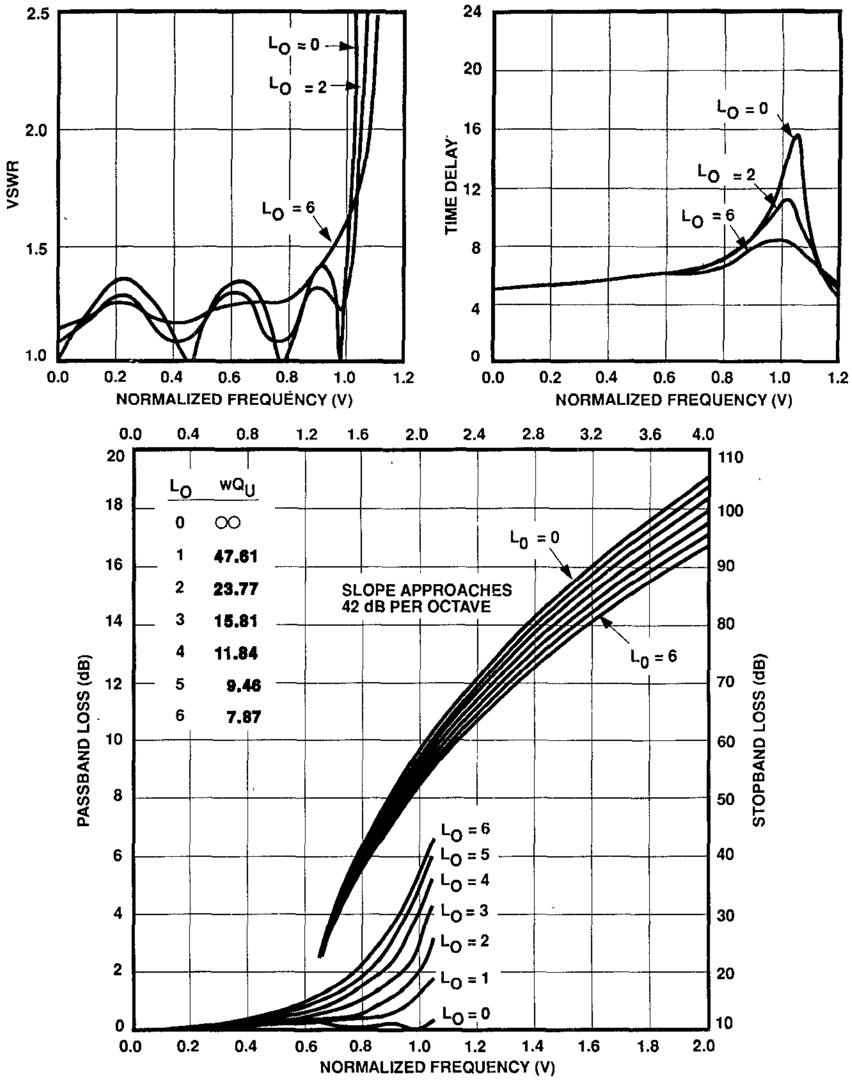

Fig. 2. Design information for lossy seven pole filter.

for these impedance levels. The conductor losses may easily be estimated with the use of data provided by Cohn [2]. Filter performance for the given conductor and dielectric dissipation may be estimated from design curves provided by Sleven [3]. The final consideration in the design involves consideration of higher order modes. The waveguide cutoff frequencies are lowered with the presence of higher dielectric constant substrates. They are, however, still high enough for useful operation at the frequencies of interest. In fact, higher frequency operation is possible with the use of higher mode suppression techniques which are themselves easily implemented. Feasibility has been demonstrated in two designs. The filters have center frequencies of 6.04 GHz and 8.28 GHz with 140.0 MHz bandwidths.

Design Example

A design example for the 6.04 GHz filter will now be discussed as a means of illustrating some of the points covered qualitatively in the preceeding discussion. The designs proceed with the use of a computer program which was composed specifically for this design task. The program consists of Cohn's design equations [1]. The formulations that were used to predict the capacitive gap discontinuities were those of Oliner [4]. Before proceeding with the use of the program, however, we must make some preliminary loss estimates from the material that is available in Sleven [3] or in [5]. Since we desire a 3.0 dB bandwidth of 140.0 MHz including the presence of dissipation and since the bandwidth contracts from the lossless prototype due to dissipation, then we must choose a wider bandwidth, initially, for the lossless prototype. For this particular design we will choose 170.0 MHz as the ripple bandwidth of our lossless prototype. The ripple bandwidth for the lossless prototype corresponds to a normalized frequency of unity. This is shown in Fig. 2 for $L_o = 0.0$ dB. As the loss increases to $L_o = 6.0$ dB, the bandwidth will contract with the 3.0 dB bandwidth for the lossy filter falling at a normalized frequency which corresponds to 0.82. Thus, the estimate for the bandwidth contraction has been obtained. The choice of 170.0 MHz is determined from the material shown in Fig. 2 for the

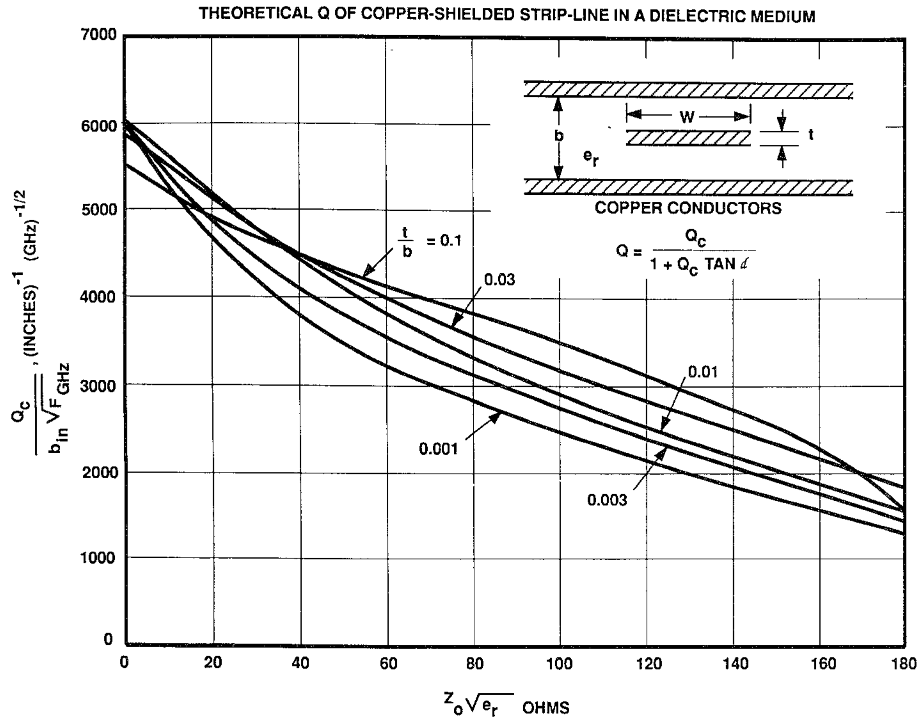

Fig. 3. Unloaded quality factor of strip line geometry assuming perfect conductors and lossless dielectric. (Reprinted from S. B. Cohn, "Problems in Strip Transmission Line," *IRE Trans. on MTT*, March 1955).

TABLE I
Design Program Sample Run Showing Input and Output Data

Input Data			
Design of N-Pole Gap-Coupled Filter, Version 8/4/89			
Enter FO and bandwidth (MHz): ZO, ZG and ZL (Ω) 6040 170 10 50 50			
Enter no. of poles (N, 2-10): G-values: G1 thru GN + 1			
7 1.1811 1.4228 2.0966 1.5733 2.0966 1.4228 1.1811 1.0000			
Enter Keff: Gnd pl. spac., total len. and max gap (mil) 38 50 1600 200			
Output Data	Line No.	Length (mil)	Gap (mil)
FO (MHz) = 6040.00	1	135.70	20.97
Bandwidth (MHz) = 170.00	2	136.14	35.21
Line impedance (Ω) = 10.00	3	136.13	39.55
Generator impedance (Ω) = 50.00	4	136.12	40.30
Load impedance (Ω) = 50.00	5	136.13	40.30
Effective dielectric constant = 38.000	6	136.14	39.55
Ground plane spacing (mil) = 50.0	7	135.70	35.21
Total filter length (MIL) = 1600.0			20.97

graph for an $n = 7$, 0.1 dB, Tchebychev low-pass prototype. For 6.0 dB of loss the normalized frequency axis predicts contraction to 0.82 at 3.0 dB. This translates into a lossless prototype which has to be (1/0.82) times wider. Hence 140.0 MHz/0.82 = 170.0 MHz. Referring, again, to the graph we see that for 6.0 dB of loss the product of the fractional bandwidth (w) and the unloaded quality factor (Qu) is 7.87. From this the Qu is estimated to be approximately 400. Now with this information in hand we choose the most convenient characteristic impedance which will help to achieve this Qu in strip line. We first make an initial assumption that about half of the ideal Qu is realizable. Thus, we require a Qu of 800 or better on Cohn's graph shown in Fig. 3. Impedance values greater than 30 Ω will force Qu values below 800 as shown in Fig. 3. From Cohn's graph it is seen that impedances in the range of 10 Ω to 30 Ω are a reasonable range to work in with higher Qu's being at lower impedance levels. Before making the final choice for the impedance, the higher order modes that are possible for various geometries for the impedances in the quoted range will need to be examined. The cutoff for the TE_{10} mode in the dielectric loaded waveguide is given by $c/(2a)$, where c is the velocity of light in the medium of the dielectric. For a guidewidth of $a = 0.100$ in. A cutoff frequency of 9.6 GHz is expected. This is compatible with a frequency of operation of 6.04 GHz over a 140.0 MHz bandwidth. Since the width of a connector tab is roughly 0.050 in for the input

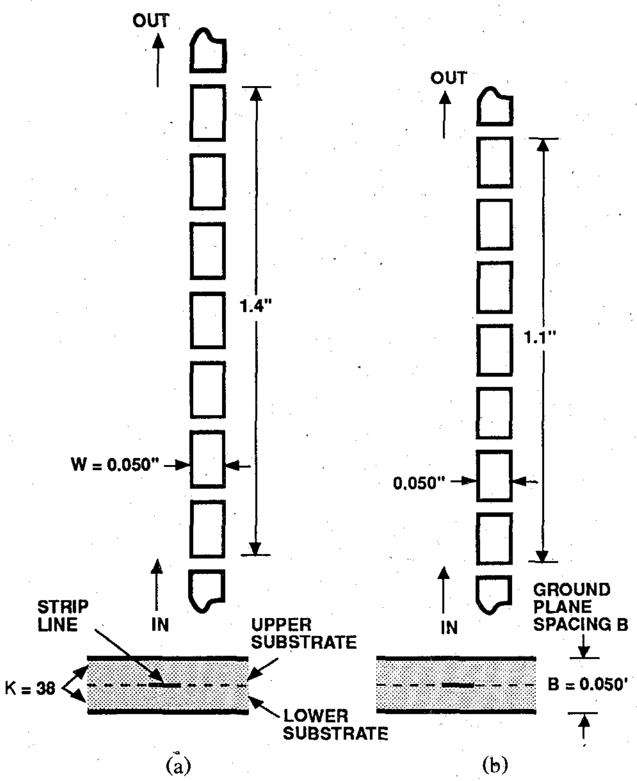

Fig. 4. Strip line patterns using $K = 38$ substrates. (a) 6.04-GHz filter/cross section. (b) 8.28-GHz filter/cross section.

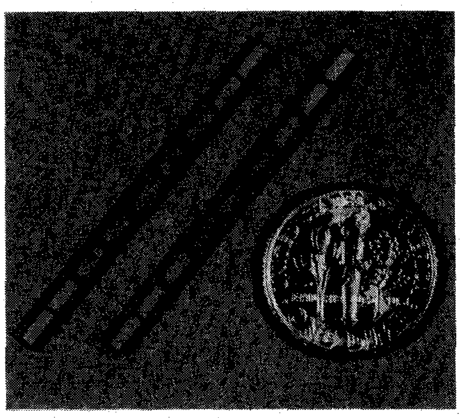

Fig. 5. AIL Systems Inc. developed 6-GHz, 7-pole band-pass filter using $K = 38$ strip line.

and output connectors, we would like to maintain a 0.050 in linewidth in order to minimize discontinuities. For a 0.050 in linewidth and a 0.050 in ground plane spacing we find that the impedance is 10.6 Ω. This is the range of the best Qu that is available. So we choose a 10.6 Ω operating impedance. Now that the significant parameters have been chosen we are now ready to make use of the design program. Typical inputs to the program include the element values for the Tchebychev prototype and the impedance level choices. Also included in the input data is the center frequency and the design bandwidth of the lossless prototype. A sample run is shown in Table I. The circuit layout is shown in Fig. 4 and a photograph of the actual substrate halves is shown in Fig. 5. Further details of the circuit construction are given in the next section.

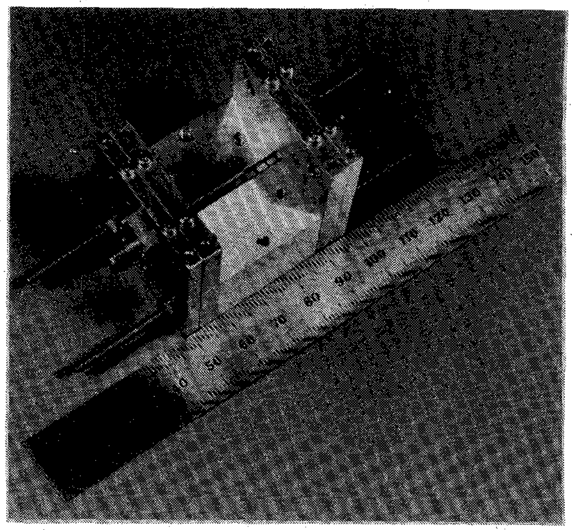

Fig. 6. Test fixture.

Processing and Construction

The construction of the test filter will now be discussed. Since the dielectric constant of the material is high, the higher order waveguide modes are lowered over those in air filled guide for the same guidewidth. Being a half a ground plane spacing away from the side wall allows us to proceed under the open strip line assumption to better than 1% accuracy. These circumstances are used to our advantage in the present design because it allows us to place the side walls close to the strip in order to guard against higher models. Also, continuing with the open strip line assumption allows us to make use of the abundance of design information and design experience that is available for strip line. However, if we were to bring the side walls in closer than half of a ground plane, we would then have to make use of shielded strip line. This would have an added advantage of pushing out the higher order modes by making the guidewidth smaller. Certainly, this could be the subject of future experimentation. However, for the present we will proceed with a half ground plane spacing. For the present design a ground plane spacing of 0.050 in and a guidewidth of 0.100 in was used. The width of the center conductor was also 0.050 in resulting in a characteristic impedance of 10.6 Ω. To transform the impedance level to 50.0 Ω requires the use of quarter-wave transformers. The impedance transformation was done in two steps to reduce discontinuities. A quarter-wavelength of line was used in each transition. The first transformer off the filter was built using Duroid 6006 material, which has a dielectric constant of 6.15. The ground plane spacing here was selected so as to maintain a 0.050 in linewidth and therefore minimizing discontinuities in the center conductor. The next transformer section was constructed using Duroid 6002 material, which has a dielectric constant of 2.94. Again, the ground plane

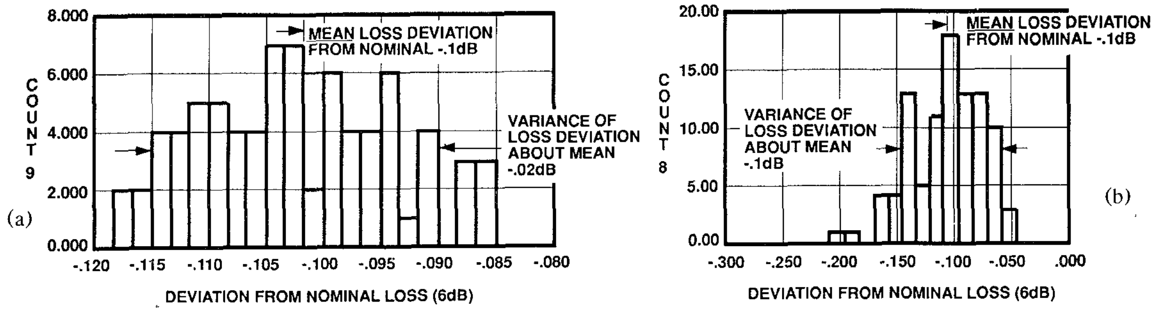

Fig. 7. Tolerance study of high accuracy photo etching process. (a) Deviation in dB from nominal midband loss (6 dB) due to changes in line width. (b) Deviation in dB from nominal midband loss (6 dB) due to changes in line length.

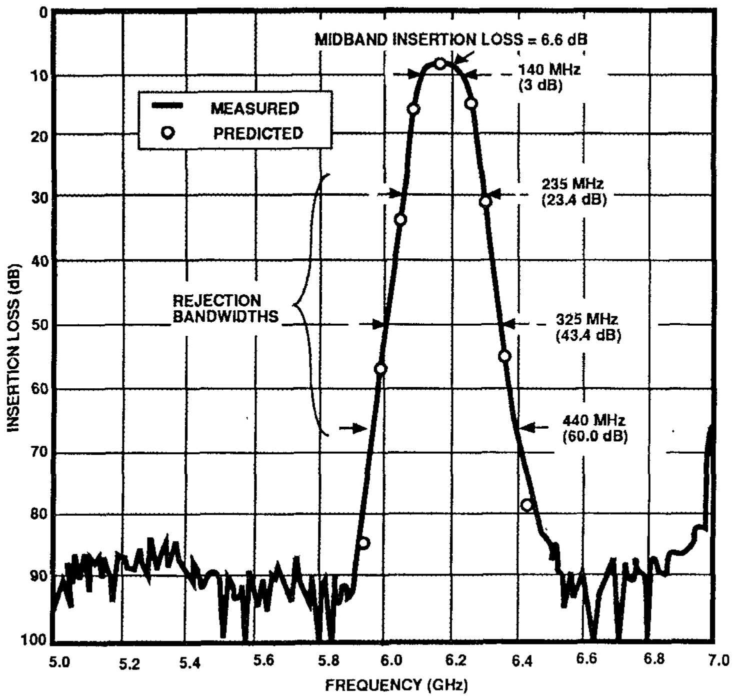

Fig. 8. Measured response of a seven resonator miniature strip line band-pass filter.

spacing was chosen in order to maintain a 0.050 in linewidth. The steps in the ground plane themselves produce discontinuities. Some tuning of these discontinuities was required. This tuning was accomplished with tabs on the center conductor at the discontinuity. Tuners were not required on the gap capacities or on the resonators in the remainder of the filter. Since the high-K material is somewhat brittle, one method of cushioning the substrate in the test fixture is to make use of Comeric® metal impregnated elastomers. This in addition to leaving the metal backing on the other substrates provided good ground contact while providing for stress relief on the high-K substrate. A photograph of the test fixture is shown in Fig. 6.

Manufacturability and Tolerance Analysis

The filters were found to be manufacturable with a high yield. This is attributed to the high accuracy photolithographic etching process that was used in their fabrication. This qualitative conclusion is confirmed with statistical analysis of the various dimensional variables. The variables of most interest are the changes in linewidth and the changes in linelength of the resonators. The linewidth changes are important in the quantification of the effect of registration errors for the two halves of the strip line. Length changes are also important because they determine the tuning frequency. Gap variations are statistically dependent on the linelength statistics and thus will not be treated as an additional degree of freedom. The etching process that was used to fabricate the strip line boards for the filter is accurate to 0.04 mil (1 μm). Statistical analysis of the filter model using a standard normal distribution with this level of variation showed mean deviations of 0.1 dB in the midband insertion loss of 6.0 dB with a variance of 0.02 dB in the case of width variations and a variance of .1 dB in the case of length variations. This is true for 85.0% of the samples studied. This agrees qualitatively with our experimental findings. The results are summarized in the histograms shown in Fig. 7.

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Experimental Results

Experimental data for the 6.04 GHz filter discussed in the design example is given below. A schematic diagram and the physical layout are shown in Fig. 4 and Fig. 5, respectively. The measured insertion loss response is shown in Fig. 8. It agreed very well with the predicted response with dissipation as found in [2]. The predicted dissipation was 6.0 dB as estimated from a Qu of 400.0. A filter centered at 8.28 GHz was also designed and fabricated with equally good results. The comparison between the predicted response and the theoretical response was made on the basis of the measured loss and measured bandwidth as they were compared to the performance estimates made on the basis of the material in [3]. These results were obtained without the need for tuners. The material in [3] allows one to estimate the unloaded Q factor. This factor was then estimated from Cohn's formula for the Qu of strip line. The measured Qu was found to be approximately half of the predicted value of 800.0. Achievement of about 50.0% of the theoretical Qu is expected, when working with imperfect conductors. Improvements in achieved Qu may be realized with the use of gold plating on the conductors or any other scheme which improves their approximation of the ideal. The achievement of the maximum Qu was not an immediate goal, however, and as a result this was considered to be a good practical result. The designer is now able to estimate the Qu for future filter designs based upon the ground work laid out by the present experiment. Additionally, the Qu levels that are realizable for this type of filter were found to be in useful ranges.

Summary and Conclusion

The practical implementation of high-K strip line band-pass filters has been demonstrated. The unloaded Q, choice of operating impedance and the role played by higher order modes has been both analytically and experimentally considered. It has been found that experiment and theory are in good agreement and allow for the use of the present results in predicting performance levels for use in future designs. High yields were achieved and are supported with statistical analysis. Such filters are expected to find applications in frequency multiplexers as well as in individual circuits, particularly with MMIC-based systems where there is a high premium on miniaturization. The containment of each filter in its own shielded channel also makes it suitable for multiplexer applications. Also, many of the high temperature superconducting resonators having high Qu properties are formed on high dielectric constant substrates such as lanthanium aluminate ($K = 24$). Thus, the design and fabrication techniques discussed herein are applicable to the area of superconducting filters as well.

Acknowledgment

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Mitchell Marcelli, photograph and biography not available at the time of publication.