A Novel Technique for Tuning Dielectric Resonators

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Abstract—**This paper presents a novel technique for the tuning of high dielectric resonators at microwave and millimeter wave frequencies. The resonator is tuned by coupling it to a section of non-resonant microstrip line. An experimental band-reject filter with a Q of 550 was tuned using this technique. The resulting tuning range of the filter was over 18 times its bandwidth. This technique makes it cost effective to tune dielectric resonators over a relatively broad range while maintaining a high Q characteristic.**

I. Introduction

THE expanding use of microwave and mm wave frequencies in commercial satellite, mobile communication, and consumer products, calls for size, weight, and cost reduction in microwave and mm wave filtering. In applications where performance requirements dictate a high Q implementation, dielectric resonator filters are a welcome alternative to waveguide filters. Dielectric resonators can achieve unloaded quality factors (Q_o) comparable to waveguide resonators, but at a substantially lower weight and smaller volume. Dielectric resonators are also compatible with a microstrip environment, which eliminates the need for microstrip to waveguide adapters. In theory, the resonant mode and the dimensions of the dielectric resonator along with the relative dielectric constant (ϵ_r) completely determine the resonant frequency (f_o) [1]. In practice, however, the exact in-circuit resonant frequency can not be accurately predicted due to thermal expansion, and the dimensional tolerances of both the resonator and its placement in the circuit. Therefore, some type of tuning is generally required to attain the desired frequency response.

One traditional method for tuning dielectric resonators employs a tuning screw or dielectric slug which can be brought in close proximity of the resonator to perturb the electric field [1]. The tuning screw or slug simply adds some shunt capacitance to the resonator, causing a slight downward shift in resonant frequency. At frequencies above about 20 GHz, the mechanical tolerances required for accurately tuning a dielectric resonator by this traditional method get extremely tight, making this approach impractical for low cost high volume production.

Optical and magnetic techniques have also been suggested [1], [4] to tune dielectric resonator oscillators. These methods can be adapted to filtering applications, but they add a significant amount of complexity and cost.

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A simpler approach is to use a resonant microstrip structure coupled to the dielectric resonator. An example of this type of tuning has been reported by Farr [4] in which the microstrip tuning structure was placed on top of the dielectric resonator. In this approach, the microstrip line is terminated with a varactor diode and the tuning is achieved electronically by changing the bias of the diode. One problem with this technique is that the resonator must be very loosely coupled to avoid severe Q degradation. However, loose coupling means that the frequency range over which the resonator can be tuned will be small. Also as will be discuss in this paper, the available tuning range of the varactor diode structure is very limited. Other microstrip circuit tuning techniques [5], [6] lack both versatility and accuracy.

The approach examined here employs a section of non-resonant microstrip line coupled to the dielectric resonator to add reactance as shown in Fig. 2(a). The value of reactance added to the dielectric resonator is then adjusted by simply offsetting the position of the resonator with respect to the center of the microstrip line. Offsetting the position of the dielectric resonator can be done using an automated assembly process. By correctly choosing the length of the microstrip tuning line, a known range of reactances can be added to the resonator. In applications such as oscillators, where the position of the resonator must remain fixed, the tuning line can be etched on a separate substrate and placed next to the dielectric resonator as shown in Fig. 2(b). Since the range of reactance added to the resonator is predefined, the tuning range, rejection, and overall resonator Q can be controlled. Therefore, this tuning method allows the use of dielectric resonators in volume production at higher microwave and millimeter wave frequencies without degrading Q and without adding significant cost and complexity to the design.

This paper presents an experimental study of this new tuning method. The tuning range of the dielectric resonator coupled to both open circuited and short circuited microstrip lines, and the effects of tuning on the quality factor are investigated. Section II of this paper describes the theory of the new tuning method, develops a model which has been used to predict the dielectric resonator's frequency response and tuning capability, and presents tuning predictions. Results of two experimental filters are summarized in section III. Section IV is the conclusion of the paper.

II. Theoretical Predictions

A. Model Development

A common method of magnetically coupling a dielectric resonator to a microstrip line is to simply place the resonator

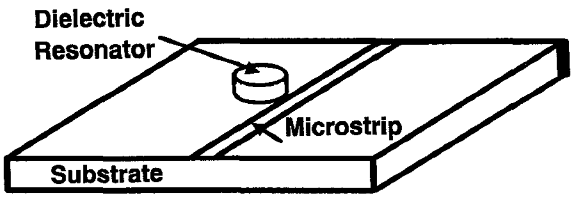

Fig. 1. A dielectric resonator coupled to a microstrip line.

on the substrate near the line as shown in Fig. 1. Normally, the desired resonant mode is the $TE_{01\zeta}$ mode which can be modeled as a high Q lumped element series resonator with a mutual inductance between the resonator and the microstrip line. This gives a dielectric resonator coupled to a microstrip line a band-reject frequency response. Coupling between the resonator and microstrip lines is modeled as a transformer in which the mutual inductance (m) can be related to the coupling factor (B) by the following equation [2]:

$$m = \frac{1}{\omega_0}\sqrt{2BR_rZ_0} \tag{1}$$

where ω_0 is the nominal untuned resonant frequency of the dielectric resonator, Z_0 is the characteristic impedance of the microstrip line to which the resonator is coupled, and R_r is the equivalent resistance of the resonator using a series resonant model. The coupling factor B is a function of the dielectric resonators proximity to the microstrip line, height relative to the microstrip line, and other physical factors such as the dielectric constant of the resonator, the dielectric constant microstrip substrate, and the presence of other structures such as a ground plane, cover, or cavity walls. For a particular application, B is best determined experimentally by using the relationship between the loaded Q (Q_L) and unloaded Q (Q_o):

$$Q_o = (1 + B)Q_L \tag{2}$$

Determination of the coupling factor will be discussed further in the experimental section of this paper. Also, Q_o and Q_L can be used to find the dielectric resonator equivalent circuit including the self inductance L, and series resistance R_r using (3) and (4).

$$Q_o = \frac{R_r}{\omega_0 L} \tag{3}$$

$$Q_L \approx \frac{Z_0}{\omega_0 L} \tag{4}$$

A circuit simulator such as EEsof's Libra is used to predict the rejection and frequency response of the filter. Additional detailed information, upon which the model is based, is available in [1].

B. Tuning

To simplify dielectric resonator tuning at high microwave and millimeter wave frequencies, a new tuning technique has been developed. The new approach, shown in Fig. 2, employs a non-resonant section of a microstrip line to modify the resonant frequency. As mentioned above, this section of the microstrip line adds reactive loading to the resonator. Because the input admittance of the tuning line seen by the dielectric resonator is a function of the resonators position on the line, the value of the reactance added to the resonator can be adjusted by simply offsetting the resonator with respect to the center of the tuning line. Since the range of reactance added to the resonator is determined by the length of the microstrip line, the tuning range, rejection, and overall resonator Q_L can be controlled.

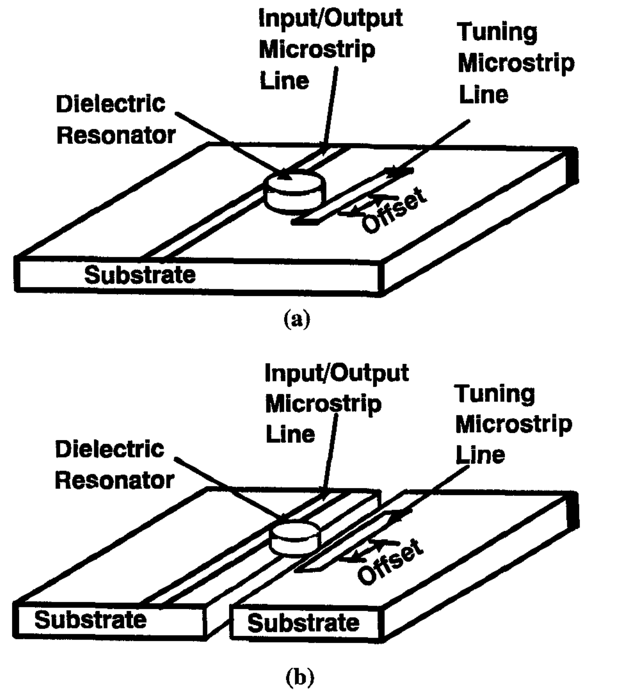

Fig. 2. Dielectric resonator tuning with: (a) the tuning line on the same substrate (b) the tuning line on a separate substrate.

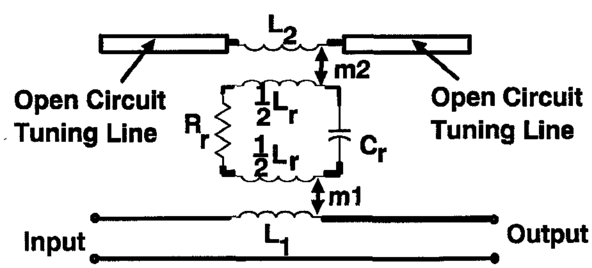

Fig. 3. Modified model of a dielectric resonator with microstrip tuning.

The new tuning technique requires that the standard dielectric resonator model be modified to include the additional tuning line. The new model is shown in Fig. 3. Once again, a series resonant circuit with a high unloaded Q is used to model the resonator. The self inductance L in equation 3 has been split equally into two series inductors in which one is used for each transformer model. L_1 and L_2 are relatively small values of inductance which act as lumped element approximations to account for the phase shift through the distributed coupling region. The values of circuit elements used in the simulations were based on measurements of a dielectric resonator coupled to a single microstrip line as shown in Fig. 1.

Fig. 4 shows the frequency shifts predicted by the model for a $3/4\lambda$, 50-ohm microstrip tuning line with both ends open circuited. This choice of tuning line length will be discussed in Section C. In these simulations, a dielectric resonator with a nominal resonant frequency of 8870 MHz and Q_o of 2000 was used. The mutual inductance of the coupled model was assumed to be constant. The substrate material was 0.025 in.

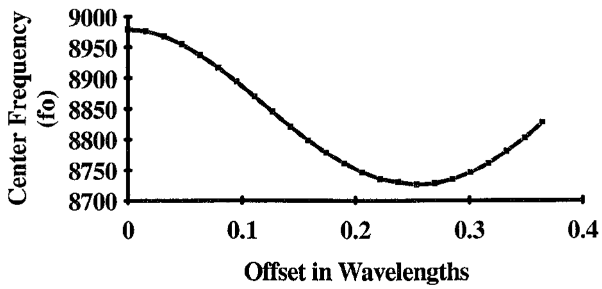

Fig. 4. Filter center frequency VS dielectric resonator offset.

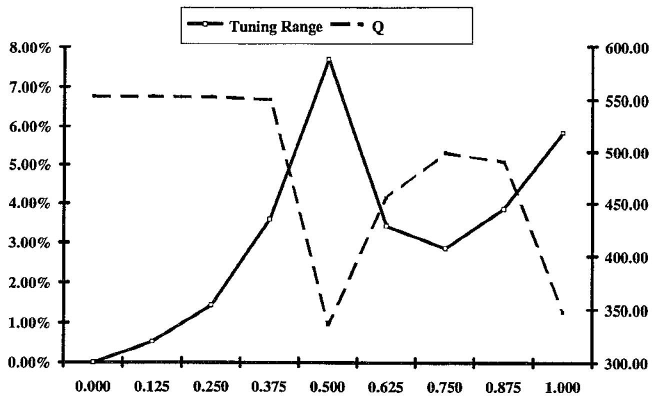

Fig. 5. Q and tuning range vs length for open circuited microstrip tuning lines.

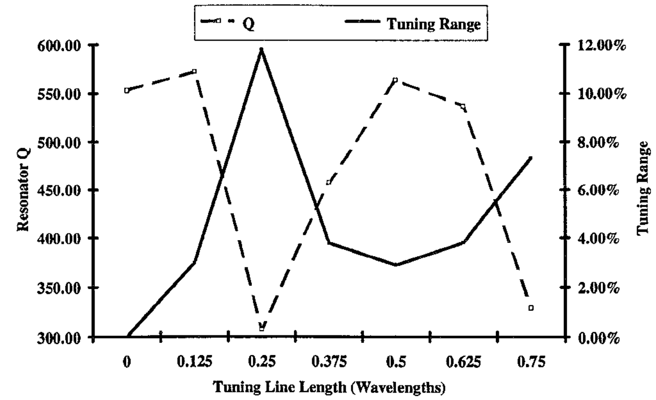

Fig. 6. Q and tuning range vs length for microstrip tuning lines open circuited at one end and short circuited at the other end.

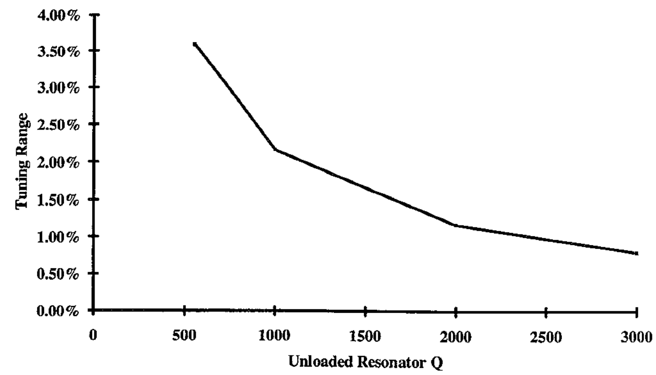

Fig. 7. Available tuning range versus unloaded dielectric resonator.

thick with a relative dielectric constant of 6.15, and a loss tangent of 0.0012. The simulations have shown it is possible to tune the resonator between 8725 and 8975 MHz. The highest frequency corresponding to the resonator at the center of the tuning line, and the lowest frequency corresponding to the dielectric resonator offset from the center of the tuning line by $\lambda/4$.

C. Predictions

The new dielectric resonator model mentioned above has been used to predict the available tuning range, rejection, and resulting Q_L for various microstrip tuning lines. Fig. 5 shows the tuning and Q_L versus the length of a tuning line that is open circuit at both ends. Once again, the dielectric resonator has an unloaded Q_o of 2000, and the substrate properties are the same as described earlier. The resonator Q_L remains relatively constant until the microstrip tuning line length approaches a multiple of $\lambda/2$ (resonant length). At these resonant lengths, even though the tuning range is maximized, the Q_L is severely degraded. Since a high Q_L characteristic is one of the primary advantages of using dielectric resonators, resonant microstrip tuning lengths should be avoided.

The above simulations were repeated using a microstrip tuning line that was short circuited at one end and open circuited at the other end. The same substrate and dielectric resonator properties were used in this second set of simulations. The results of the second set of simulations are plotted in Fig. 6. This time, the graph shows severe Q_L degradation at microstrip tuning line lengths of $\lambda/4$ and $3/4\lambda$ (resonant lengths). Therefore, as with the open circuited tuning line, resonant lengths of microstrip tuning lines should be avoided.

The simulation results in Figs. 5 and 6 can be used to judiciously choose tuning line length for maximum tuning without unacceptable Q degradation. As mentioned above, simulation results for both open and short circuited tuning lines show that resonant lengths result in significant performance degradation. The resonator Q_L's drop by a factor of two when using a resonant microstrip tuning line. The reduction in Q_L also results in the total rejection of the band-stop filter being greatly reduced. To avoid these problems with resonant tuning structures, the tuning line must be coupled very loosely to the dielectric resonator. Loose coupling ultimately results in much less tuning range. Farr *et al.* [4] report achieving tuning ranges of only 0.75% for a dielectric resonator with a Q_o of 1000 using a resonant tuning technique. Model predictions shown in Fig. 7 indicate that a non-resonant ($3/4\lambda$ open circuited at both ends) tuning line can achieve greater than 2.2% tuning with a Q of 1000. Therefore, a non-resonant microstrip tuning line is far more desirable because it provides more tuning range, higher Q, and more rejection. Another advantage of non-resonant tuning lines is that no in-band spurious responses are predicted. As the length of the tuning line gets close to a resonant length, a spurious mode resulting from the interaction of the dielectric resonator and the near resonant microstrip tuning line is observed. The additional spurious response is usually very close to the desired band making it particularly troublesome.

For microstrip tuning line lengths shorter than the first resonant length ($\lambda/2$ for a tuning line open circuited at both ends, and $\lambda/4$ for a tuning line open circuited at one end

TABLE I
EXPERIMENTAL AND THEORETICAL RESULTS OF MICROSTRIP TUNING

	Tuning Line Length	Tuning Range	f_{min} (GHz)	Offset @ f_{min} Wavelengths	f_{max} (GHz)	Offset @ f_{max} Wavelengths	Rejection (dB)	Loaded Q
Modeled	0.710	2.80%	8.76	0.250	9.00	0.000	22.08	438
Measured	0.710	3.40%	8.68	0.250	8.98	0.000	21.80	392

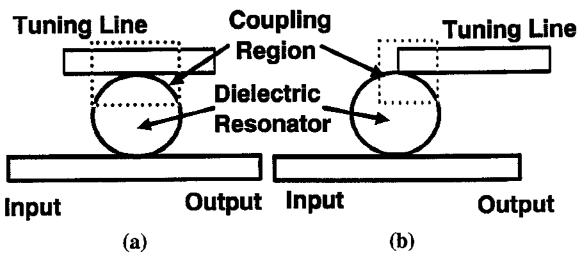

Fig. 8. Geometry of a dielectric resonator coupled to: (a) the center and (b) the end of a microstrip tuning line.

TABLE II
MEASURED COUPLING FACTOR (B) VARIATION WITH RESONATOR POSITION

B	15.1	12.9	14.5	4.5
Offset	0	0.125	0.25	0.375

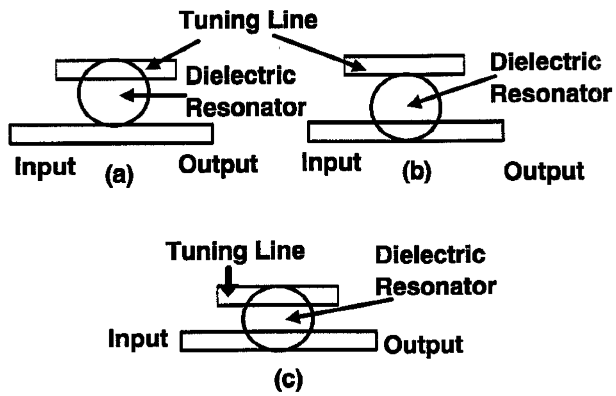

Fig. 9. Experimental setup for measuring the coupling factor (B) for different positions of the dielectric resonator.

and short circuited at the other end), simulations predicted that maximum tuning requires positioning the resonator at the end of the tuning line. However, when the resonator is at the end of the tuning line, the coupling area decreases significantly as shown in Fig. 8. With a smaller coupling area at the end of the microstrip tuning line, tight coupling can not be achieved. Simulations predict that for maximum Q_L and maximum tuning range, the coupling should be as tight as possible. Therefore, line lengths that require coupling at the end of the tuning line for maximum performance (lines of less than the first resonant length) should also be avoided.

Eliminating the previously mentioned undesirable choices for tuning line lengths, the simulations predicted that the best performance would be achieved with a non-resonant microstrip tuning line of about $3/4\lambda$ with both ends open circuited, or a non-resonant microstrip tuning line of about $\lambda/2$ with one end short circuited and the other end open circuited.

III. EXPERIMENTAL RESULTS

A. Microstrip Tuning

Based on the simulation results presented in the previous section, an experimental band-reject filter with a tuning line length of $3/4\lambda$ was built and tested in order to verify the new tuning technique. The experimental filter was fabricated using the same substrate and dielectric resonator that was modeled in Section II. The actual length of the microstrip tuning line was slightly shorter than the desired $3/4\lambda$, as the board was originally etched for a 9.2 GHz filter. The results of the experiment are summarized in Table I.

With the experimental filter, a tuning range of 3.4% was achieved. This was a larger tuning range than predicted by the model, the Q_L was lower than expected, and there was less rejection than predicted. These experimental results all correlate with a tuning line that is shorter than the desired $3/4\lambda$. Another difficulty in the experiment was that the placement of the resonator on the line was done manually, not by a more accurate automated process. Because of the manual placement there is a great deal of uncertainty as to the exact position of the resonator relative to the microstrip tuning line. In general the experimental results have shown that this tuning method is a viable alternative to more complex tuning mechanisms. Using this method, a significant increase in tuning range was achieved for the experimental filter without significantly degrading Q_L. The experimental results also verify that the model can predict rejection, Q_L, and tuning range with reasonable accuracy.

B. Coupling

The coupling factor (B) between the dielectric resonator and the microstrip lines was found experimentally using the ratio of the loaded and unloaded quality factor as in (2). The value of B varied with the position of the dielectric resonator. However, as shown in Table II, measurements indicated that the value remained relatively constant except when the resonator was placed near the end of the tuning line. With the dielectric resonator near the end, coupling is significantly lower due to the smaller coupling area. Thus, there was no advantage in using tuning lines shorter than the first resonant length since these lines would require coupling at the end of the line for maximum tuning range.

The effect of coupling on achievable tuning range was also experimentally verified. The following three different coupling combinations were investigated in the course of the experiment:

1) strong coupling to the tuning line and loose coupling to the input/output line (Fig. 9(a)).
2) loose coupling to tuning line and strong coupling to the input/output line (Fig. 9(b)).
3) strong coupling to both the tuning line and the input/output line (Fig. 9(c)).

TABLE III
EXPERIMENTAL AND THEORETICAL RESULTS OF VARACTOR TUNING

	Tuning Line Wavelengths	Offset Wavelengths	Varactor Tuning	Rejection (dB)	Q
Modeled	0.5	−0.125	0.30%	24.17	563
Measured	0.5	−0.125	0.34%	23.96	540

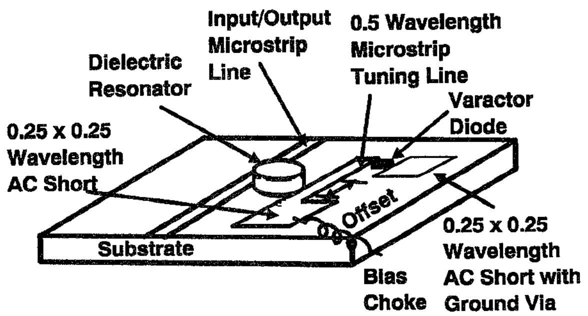

Fig. 10. Filter used for electronic tuning experiments.

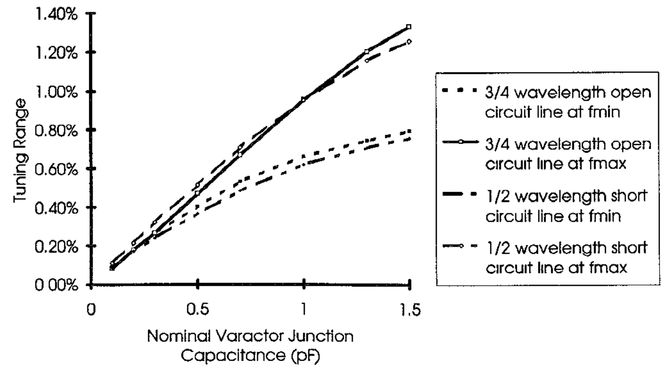

Fig. 11. Available electronic tuning of two experimental filters.

As predicted by the simulation, strong coupling to both lines is desired for maximum tuning range and rejection. In addition, simulations indicated that if tighter coupling between the dielectric resonator and the microstrip lines could be achieved, an even larger tuning range would result. For these reasons, the strongest achievable coupling was used in the filter experiments.

C. Varactor Tuning

Since the new tuning method depends on the physical placement of the dielectric resonator there is some error due to positioning accuracy. To provide a method of fine tuning the filter, and to explore the possibility of temperature compensating the filter, a second experimental filter was fabricated. The second filter was implemented using a $\lambda/2$ microstrip tuning line with an equivalent RF short circuit at one end, and a varactor diode at the other end as shown in Fig. 10. With the second experimental filter a tuning range of 0.34% was achieved electronically by adjusting the varactor diode bias. This was in addition to the 2.9% tuning achieved by adjusting the dielectric resonator position. The varactor diode equivalent circuit was added to the model to predict filter performance. Filter measurements are compared with model predictions in Table III. The performance including rejection and $Q_L$of the filter was not compromised by the addition of electronic tuning capability. This is due to the fact that the diode quality factor was very high ($Q_D = 8000$). Simulations also showed that the tuning range of the second experimental filter was substantially affected by its non-ideal grounding (RF shorts used in the filter consisted of $\lambda/4$ square metal plates for both the varactor and the microstrip tuning line). Therefore, the tuning range could be increased by better RF grounding in the filter circuit. The electronic tuning range can be increased by increasing the junction capacitance of the varactor diode. However, varactor diodes with large junction capacitance usually have low Q_D which may degrade the performance of the filter. Fig. 11 shows the amount of additional tuning predicted for the two experimental filters presented.

IV. CONCLUSION

A new method of tuning dielectric resonators has been developed and presented. In this technique, the dielectric resonator is coupled to a non-resonant microstrip tuning line and the offset is chosen to control the added reactance. The main advantage of this technique is the ease of tuning through a planar network. The new tuning method greatly simplifies the implementation of dielectric resonators in high volume production circuits by eliminating the need for the design of a complex mechanical tuning structure. This new tuning method also allows use of dielectric resonators at much higher microwave and mm wave frequencies where mechanical tolerances previously made tuning them expensive and impractical. A model to predict the performance of the new tuning method has been developed and experimentally verified. In general the measured Q_L of the experimental filters were slightly lower than the model predicted due to additional losses in the test environment. Coupling effects were also investigated and correlated to the model. Additional experimentation with varactor diodes indicated that electronic tuning may be useful for fine tuning and temperature compensation. Theoretical and experimental results presented here indicate that by using the new technique, it is possible to tune dielectric resonators over a much wider band and still retain a high Q characteristic.

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