

A Varactor Tuned RF Filter

Andrew R. Brown, *Student Member, IEEE*, Gabriel M. Rebeiz, *Fellow, IEEE*

Abstract—An electronically tunable filter at 1 GHz is presented. The filter uses a suspended substrate design and commercially available varactors for filter tuning. The filter has a 60% tuning range from 700 MHz to 1.33 GHz with a low insertion loss (better than 3 dB from 1-1.33 GHz). This paper discusses the effects of the varactor series resistance and the electrical length of the distributed resonator on the overall resonator quality factor and filter insertion loss. The IIP3 (input 3rd order intermodulation product intercept point) was measured to be better than 17 dBm across the entire tuning range.

Keywords—Tunable Filters, Frequency control

I. INTRODUCTION

LOW-LOSS, tunable frequency filters are often used as tracking filters for multiband telecommunication systems, radiometers, and wideband radar systems. Typically, tracking filters are mechanically tuned by adjusting the cavity dimensions of the resonators or magnetically altering the resonant frequency of a ferromagnetic yttrium-iron-garnet element [1], [2]. Neither of these approaches can easily be miniaturized or produced in large volumes for wireless communication products. The filters must be custom machined, carefully assembled, tuned, and calibrated. An alternative to the mechanically tuned and YIG filters is based on solid state varactor diodes. Varactor filters have previously been developed using 2-3 pole filters [3], [4], [5]. However, the effects of the varactor series resistance and electrical length of the distributed portion of the resonator have not been investigated.

An electrically tunable, capacitively-loaded interdigital filter is presented in this paper. The tuning element is a reverse-biased varactor diode. The resonators of the tunable filter are shortened interdigital fingers with varactor diodes at the ends. The coupling is carefully controlled by the geometry of the fingers and the tuning is performed by changing the bias on the varactor diodes. Since both the interdigital fingers and the diodes are carefully controlled and fabricated in batch, this filter can easily be produced in large quantities. The varactor controlled tunable filter based on a suspended substrate stripline technology. The suspended substrate allows for a very low effective dielectric constant resulting in very wide, low-loss transmission lines.

II. CENTER FREQUENCY OF A VARACTOR LOADED TRANSMISSION LINE RESONATOR

The design of a varactor-loaded interdigital filter is similar to the capacitively loaded comb-line filter presented in Matthaei [1], but is adapted for the interdigital topology. The interdigital filter is a symmetric filter of coupled resonators. The first finger at the input and output port is a shorted line that acts as an impedance transformer for the filter. This is the only line

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A. R. Brown and G. M. Rebeiz are with the Radiation Laboratory, Department of Electrical Engineering, University of Michigan, Ann Arbor, MI, 48109. E-mail: mscout@engin.umich.edu, rebeiz@engin.umich.edu

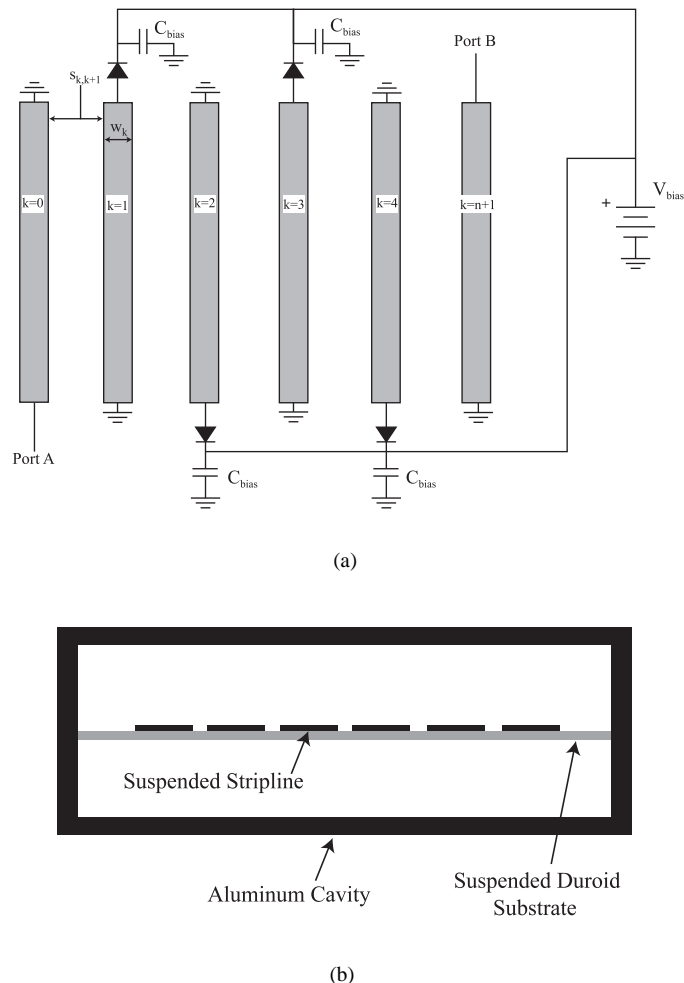


Fig. 1. (a) Topology of the varactor loaded interdigital bandpass filter, and (b) cross section of suspended substrate stripline.

with a fixed termination. The interior coupled lines are shorted at one end and loaded with varactor diodes at the other end (Fig. 1). To allow for biasing, large capacitors are added (C_{bias}). When the bias voltage is changed, the thickness of the depletion region of the varactor diodes changes. This alters the capacitance of the varactor tuning the resonant length of fingers. The width and separation of the interior lines are determined only by the bandwidth of the normalized filter response function, and is independent of the center frequency. The center frequency of the filter is determined by the resonant lengths of the lines which is tuned by the varactors. The tuning range for the filter is limited by the fixed lengths of the input and output finger lengths, the internal impedance of the filter, the range of capacitance of the varactor diodes, and the electrical length of the fingers.

The electrical length of a single finger, θ , without the capaci-

tive loading is given by:

$$\theta(V_{bias}) = 2\pi fl\sqrt{\epsilon_{eff}}/c \quad (1)$$

where f is the frequency, l is the length of the fingers, ϵ_{eff} is the effective relative dielectric constant (approximately 1.05 for membrane supported microstrip) and c is the speed of light. If the finger is loaded by a shunt capacitance, the effective length of the transmission line increases. If the amount of capacitance added increases the overall effective length to $\pi/2$, and the transmission line is shorted at one end as in the case of the interdigital filter, then the capacitively loaded transmission line behaves as a quarter-wave resonator. In order to achieve resonance, the reactance of the transmission line and the varactor must cancel ($X_{Varactor} + X_{T-Line} = 0$). By using a lossless transmission line approximation ($X_{T-Line} = Z_{ak} \tan \theta$ where Z_{ak} is the intrinsic impedance of the k^{th} finger), the necessary capacitance is given by:

$$C_{var} = \frac{1}{Z_{ak} 2\pi f_0 \tan \theta_0} \quad (2)$$

where f_0 and θ_0 are the frequency and electrical length of the finger at resonance. Conversely, the resonant frequency of the varactor loaded finger for a given capacitance is:

$$f_0(V_{bias}) \approx \frac{1}{Z_{ak} 2\pi C_{var}(V_{bias}) \tan(\theta_0(V_{bias}))} \quad (3)$$

where f_0 , C_{var} , and θ_0 are now functions of the bias voltage. Note that this is a transcendental function since the value of $\tan \theta_0$ is also a function of f_0 . From equation 3, a larger tuning range is obtained by making Z_{ak} small. An internal impedance of 60Ω was chosen. This is a relatively low impedance line while still maintaining a reasonable conductor width for loss considerations.

The resonant frequency (equation 3) was solved graphically for the upper and lower tuned center frequencies as a function of physical length of the transmission lines assuming a varactor with a capacitance range of 0.2-1.0 pF (Fig. 2). This is a typical varactor value for an X-Band tunable filter. This can be scaled in frequency by the transmission line physical length and the capacitance value. According to Fig. 2, the length of the transmission line segment should be as short as possible for the widest tuning range. However, the series resistance of the varactor has a stronger influence on the quality factor of the resonators as the transmission line section decreases where the quality factor is taken as the combination of the transmission line segment and the varactor.

III. QUALITY FACTOR OF A VARACTOR LOADED TRANSMISSION LINE

The quality factor of the resonant fingers is a function of the intrinsic impedance, the line length, the attenuation of the line, and the series resistance of the varactor. The resonator can be viewed as a short transmission line in parallel with a varactor to ground as in Fig. 3 where R_s is the series resistance of the varactor and α is the loss of the transmission line. It is necessary to define two different definitions for quality factor; namely, the

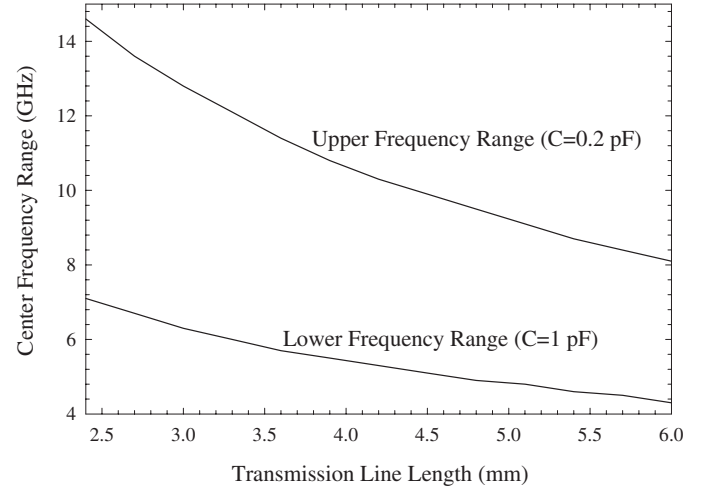


Fig. 2. Theoretical resonant frequency tuning range for a varactor with a capacitance range of 0.2-1.0 pF as a function of transmission line physical length.

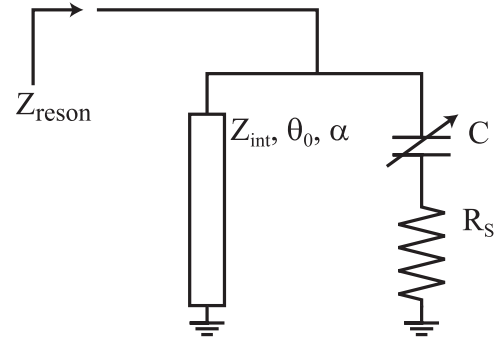


Fig. 3. Model of a varactor loaded transmission line resonator.

transmission line quality factor and the overall resonator quality factor. The transmission line quality factor is the unloaded Q of the transmission line without the varactor loading. The overall resonator quality factor is the unloaded Q of the transmission line with the varactor loading. The input impedance of the shorted transmission line alone is:

$$Z_{line} = Z_{int} \frac{\tanh(\alpha l) + j \tan(\beta l)}{1 + j \tan(\beta l) \tanh(\alpha l)} \quad (4)$$

The input impedance of the varactor alone including the series resistance is:

$$Z_{cap} = \frac{1}{j\omega C} + R_s \quad (5)$$

$$= -j \frac{\omega_0}{\omega} Z_{int} \tan \theta + R_s \quad (6)$$

The total impedance can be found by taking the parallel combination. The 3 dB bandwidth can be determined by finding the bandwidth where the magnitude of the impedance falls by a factor of $\sqrt{2}$ giving the reciprocal of the overall resonator unloaded quality factor. As the filter tunes, the electrical length of the transmission line changes altering the overall resonator quality factor. Fig. 4 shows the resulting overall resonator quality factor as a function of resonator electrical length and diode series

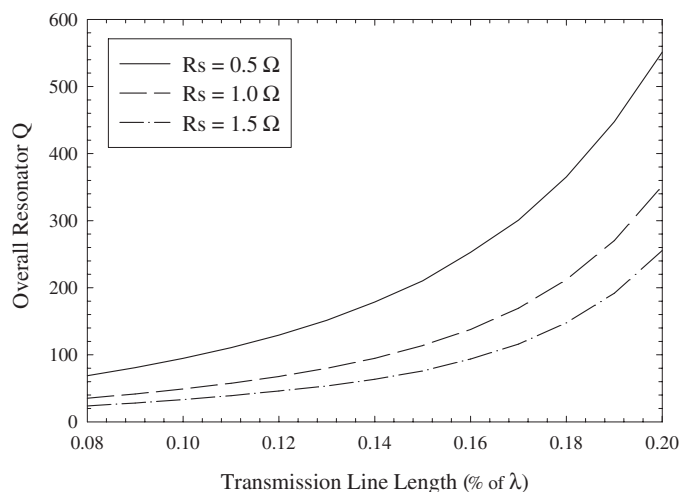


Fig. 4. Overall resonator quality factor as a function of transmission line length for a transmission line quality factor of 1030.

resistance. As the transmission line becomes electrically short, the transmission line quality factor has a decreasing effect. For wavelengths where the line is less than 0.1λ , the transmission line quality factor is not very significant, and the varactor series resistance controls the overall resonator quality factor. As the transmission line portion becomes electrically longer, the overall resonator quality factor is strongly dependent on the transmission line quality factor, showing the advantages of the suspended substrate transmission lines. However, this comes at the expense of the tuning range. Based on equation 3, the tuning range for a given capacitance ratio decreases considerably with increasing electrical length.

IV. RF TUNABLE FILTER

The RF tunable filter was fabricated on $127\ \mu\text{m}$ RT/Duroid¹ with a dielectric constant of 2.2. The circuit was suspended over an aluminum cavity. The depth of the cavity was 4 mm with an attached 4 mm top shielding cover. The finger length is 0.13λ at 1.25 GHz (3.1 cm) with an internal impedance of $60\ \Omega$ and a filter bandwidth of 16% with a ripple of 0.2 dB. The line widths and gaps are summarized in the Table 1 where w_k is the width of the k^{th} filter finger and $g_{k-1,k}$ is the gap between fingers $k-1$ and k . The transmission line quality factor for this structure is 1030 at 1.25 GHz.

The varactors are BB811 RF Variable Capacitance Diodes² with a series resistance of about $1\ \Omega$ and a junction capacitance from 1 pF to 8.8 pF over a 30 V bias range³. The varactors are biased equally with a 75 pF capacitor from the bias line to ground to provide an RF short for the varactor and an open circuit for the bias (see Fig. 1). The predicted tuning range is from 660 MHz to 1.6 GHz (83% tuning range) with all varactors biased equally in parallel (Fig. 5).

¹RT/Duroid is a product of Rogers Corporation, Rogers, CT.

²BB811 RF Variable Capacitance Diodes are a product of Phillips Semiconductor, Sunnyville, CA.

³Device parameters based on manufacturer supplied data.

TABLE I
RF TUNABLE FILTER FINGER DIMENSIONS

Finger, k	w_k	$g_{k-1,k}$
0	9.63 mm	
1	5.97 mm	0.25 mm
2	7.11 mm	2.87 mm
3	7.11 mm	3.51 mm
4	5.97 mm	2.87 mm
5	9.63 mm	0.25 mm

The measured response of the filter showed a 60% tuning bandwidth from 700 MHz to 1.33 GHz (Fig. 6). The filter input matching is good with a return loss of better than -10 dB over the tuning range up to 1.3 GHz. At center frequencies below 1 GHz, the bandwidth is reduced and the insertion loss increases. The reduced bandwidth is due to the bandwidth of the impedance inverter network of coupled lines at the input and output of the filter. The increase in insertion loss at the low end of the tuning range is due to the decrease in overall resonator quality factor as the electrical length of the transmission line portion becomes shorter.

The theoretical insertion loss assuming a 16% bandwidth, 0.2 dB ripple Chebyshev 4-pole filter was calculated based on the modeled overall resonator quality factor with a varactor series resistance of $0.5\ \Omega$ and $1\ \Omega$ from Fig. 4 and is plotted on Fig. 6a. There is a good agreement with measured and calculated insertion loss. For center frequencies above 1 GHz, the insertion loss is less than 3 dB in the passband. The series resistance of the varactor diode is the major limiting factor in the filter insertion loss. Still, the tuned RF filter performance is comparable to state-of-the-art YIG and mechanically tuned filters at only a fraction of the material and assembly cost.

Finally, the filter was measured under large signal tests. With a single large signal tone, the input power was increased to 20 dBm without reaching a 1 dB compression point.

The 3rd order intermodulation intercept point was measured under different bias conditions. In all cases, both signals and their associated 3rd order mixing products were within the passband of the filter (two fundamentals separated by 2 MHz). This is a worst case situation in that the filter has no effect on attenuating mixing products due to the nonlinearities of the varactors. The results of this are shown in Table II. In all cases, the input IP3 was better than 17 dBm.

TABLE II
INTERMODULATION MEASUREMENTS

Bias	f_0	Input IP3
5 V	720 MHz	24.0 dBm
7.5 V	830 MHz	28.1 dBm
10 V	970 MHz	17.9 dBm
15 V	1130 MHz	18.5 dBm
20 V	1220 MHz	23.0 dBm

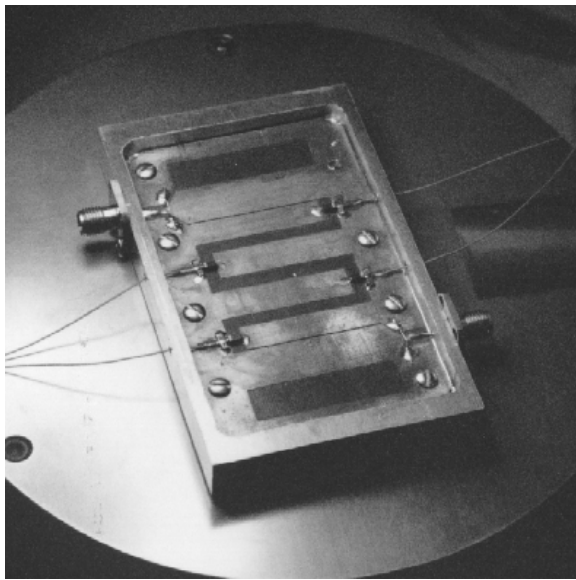


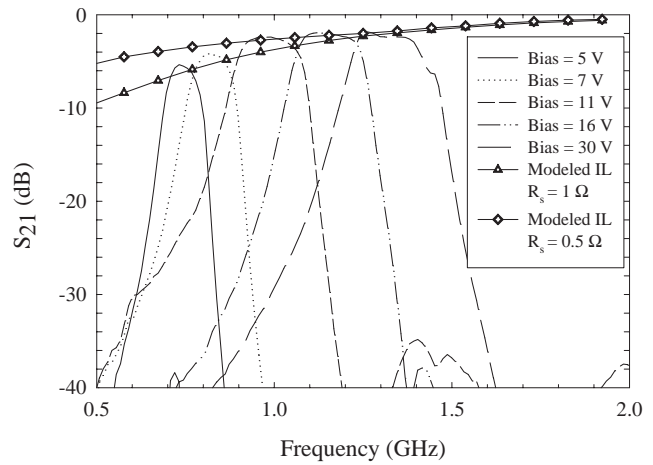
Fig. 5. The RF varactor tuned bandpass filter.

V. ACKNOWLEDGEMENTS

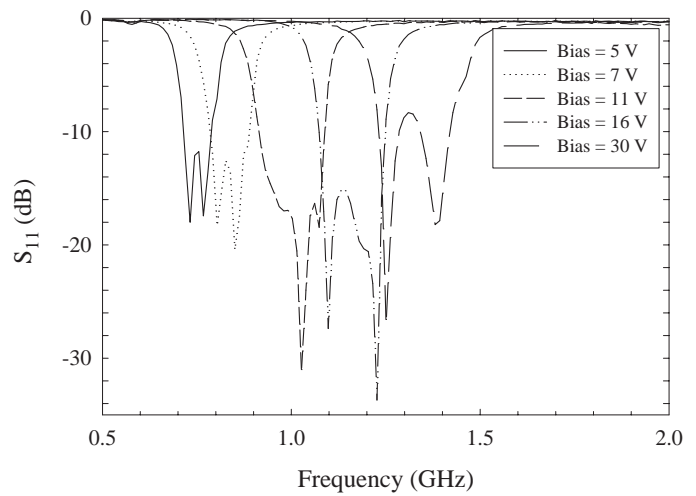
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(a)



(b)

Fig. 6. RF tunable filter (a) measured insertion loss and (b) return loss for various bias levels.

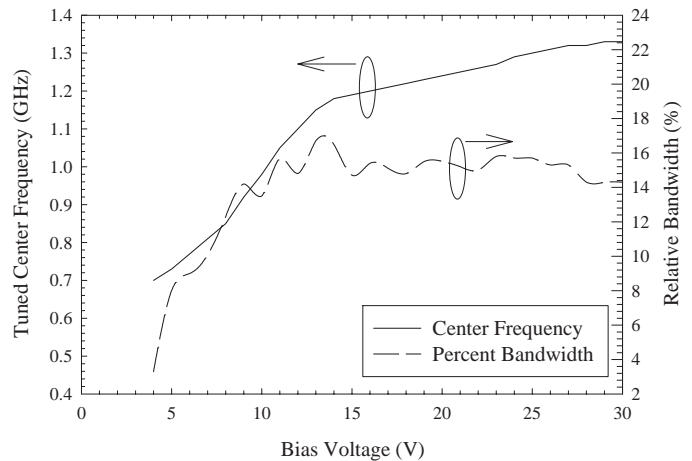


Fig. 7. Measured center frequency and relative bandwidth as a function of bias voltage.