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Design and Simulation of Tunable Ka Band Filters with Graded Barium Strontium Titanate (BST) Varactors

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Tunable Ka band filters based on graded barium strontium titanate (BST) have been investigated in terms of their associated parasitics, tunability, and temperature dependence of capacitance. The simulation results show that increase in parasitic resistance from 0.05 ohm to 1 ohm increases the insertion loss from 0 db to 25 db. The simulation results also show that, with 60% tunability for graded BST capacitors, the center frequency of the filter can be tuned from 29.489 GHz to 45.144 GHz. In addition, the bandwidth shift becomes temperature independent when the graded BST capacitor is biased at an electric field of 3e7V/cm.

Keywords: Ka band, BST, tunability

INTRODUCTION: TUNABLE FILTERS, PARASITICS, TUNABILITY, AND TEMPERATURE DEPENDENCE

Tunable Filters

Tunable filters are one of the important modules for future communication systems. A tunable filter can replace a bank of conventional filters [1, 2]. In addition, it also gives the flexibility to tune its performance after packaging. A variety of tunable devices such as p-n junction varactors, GaAs MESFETs, MEMS and ferroelectrics have been used to implement tunable filters [2,7,8]. Low loss, compact filters with ferroelectric varactors can be used effectively

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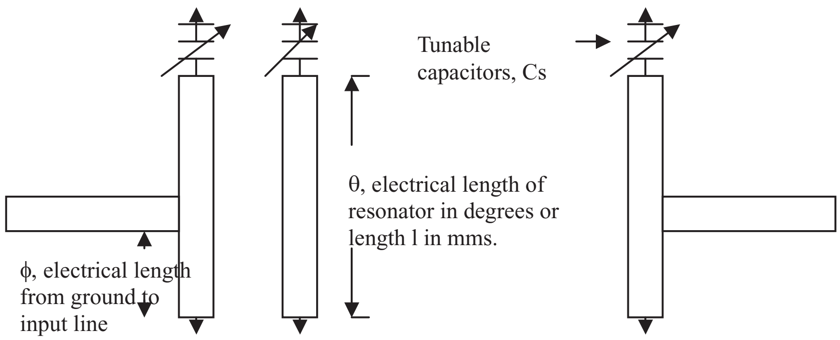

Figure 1. Schematics of distributed type band pass filter.

for highly integrated multiband/multifrequency communication systems. Recently, graded BST has attracted the attention of many investigators because of their large tunability and nearly temperature independent dielectric constant [3–5]. Generally, there are two topologies for the implementation of the filters depending on the type of resonators used: a) Distributed type and b) Lumped Element Type. Distributed type generally uses transmission lines as shown in Fig. 1 [1]. The resonating frequency is controlled by the metal-ferroelectric-metal (MFM) capacitors attached to the resonators. These types of filters show smaller change in frequency (tuning range) with the tuning voltage because of the reduction in variable capacitance due to the significant non-variable capacitance associated with the transmission line. Figure 2 is the schematic of

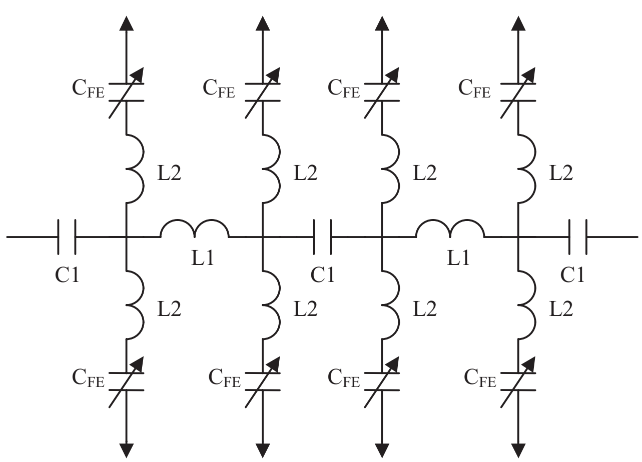

Figure 2. Schematic of lumped element band pass filter without incorporating parasitics.

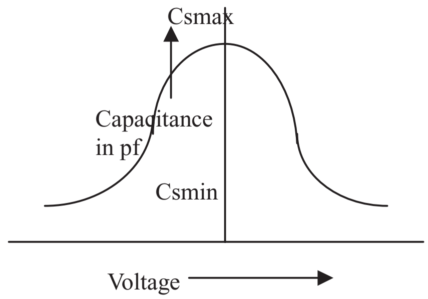

Figure 3. Capacitance versus voltage characteristics of a typical BST Capacitor.

tunable lumped element band pass filter for frequencies in the Ka band region [2]. In this paper, we are reporting the simulation results of lump element filter implemented with tunable ferroelectric capacitors.

In Figure 2, C_{FE} represents the tunable ferroelectric capacitor. The characteristics of a typical ferroelectric capacitor is shown in figure 3 and their typical structure with electrical equivalent circuit is shown in figure 4.

The parameters of the ferroelectric capacitors that can effect the filter characteristics are

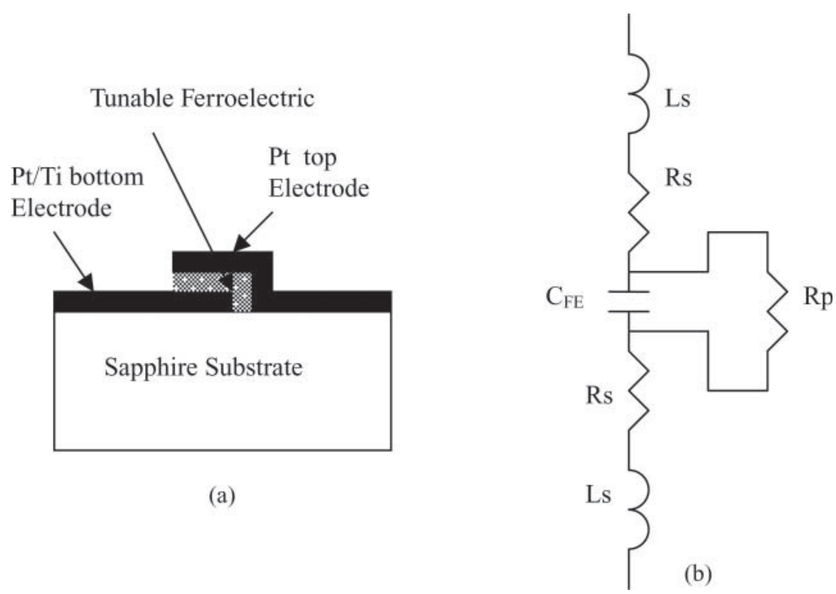

Figure 4. (a) Structure of tunable capacitor (b) Electrical equivalent circuit incorporating series resistance (Rs), and inductance (Ls) of top and bottom electrodes, as well as Rp, which is the parallel conductance of the tunable capacitor C_{FE}.

a. Parasitics associated with the capacitor ("Q" factor)
b. Tunability
c. Temperature dependence.

Effect of Parasitics of Capacitors on Performance of the Filters

Figure 4 shows the parasitics associated with a parallel plate capacitor where Rs is the series resistance and Ls is the series inductance and Rp is the resistance due to dissipation factor [8].

Figure 5 shows the insertion loss and return loss characteristics of the filter. Filter simulation was performed incorporating series resistance of the tunable capacitor (neglecting the series inductance). Figure 4a shows the schematics of the tunable device used for simulation. For all the tunable ferroelectric capacitors 300 fF is capacitance assumed for simulation. When the simulations were performed without incorporating the series resistance, the maximum return loss was about 37 db in the pass-band. The insertion loss was negligible since the resistance in the circuit was zero ohms. This also corresponds to a Q factor of infinity for all the components.

The variation of insertion loss and return loss in the pass band with series resistance of BST capacitors is shown in Fig. 6. With increase in the series resistance, the insertion loss in db increases linearly from nearly 0 db to 25 db with increase in resistance from 0 ohms to 1 ohm. The maximum return

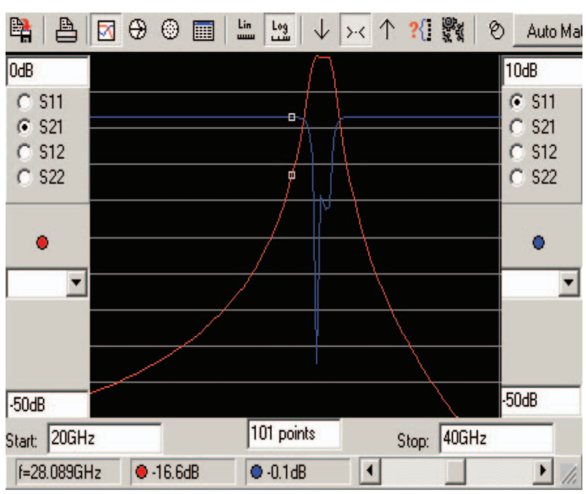

Figure 5. Simulated response of Ka band filter, showing the insertion loss and return loss. (See Color Plate XII)

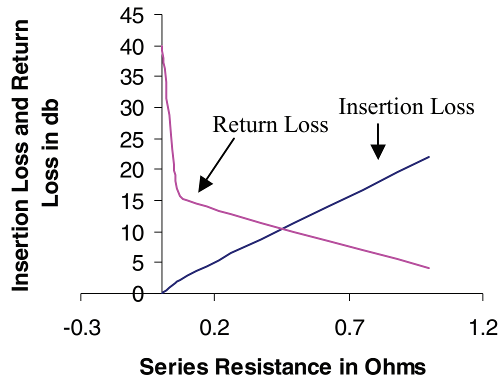

Figure 6. Variation of maximum insertion loss and return loss with series resistance. (See Color Plate XIII)

loss in the pass band decreases rapidly initially when the series resistance increases from 0 ohm to 0.05 ohms. Further increase in series resistance shows a linear decrease in return loss. Therefore, the lowest possible series resistance is essential to obtain low insertion loss and high return loss for the filter.

Effect of Tunability on Filter Response

The following are the parameters to be considered in the design of tunable filters:

a. Lower Center Frequency (minimum) f1
b. Upper Center Frequency (maximum) f2
c. Instantaneous Bandwidth, ΔBL min
d. Instantaneous Bandwidth maximum, ΔBL_{max}
e. Rejection at $\pm 10\%$ of center frequency.
f. Insertion loss
g. Return Loss

For simulation purpose, the zero bias capacitance of the tunable capacitor was assumed to be 300 fF. For a parallel plate capacitor configuration as shown in Fig. 4, this corresponds to an effective area of 25 micron^2 for a ferroelectric of thickness 220 nm, permittivity 300. A tunability factor of 60% is assumed for simulation. For a ferroelectric capacitor of capacitance 300 fF with a series resistance of 0.05 ohms, the response of the filter is shown in Fig. 7. The bandwidth of this filter is 1.335 GHz. The lower -3 db frequency is

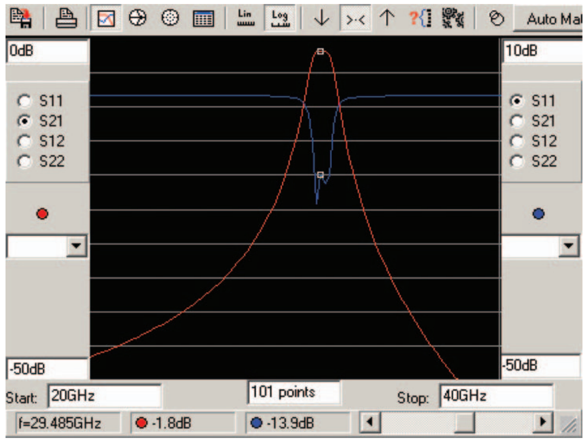

Figure 7. Zero bias response of the filter. (See Color Plate XIV)

28.87 GHz and upper −3 db frequency is 30.105 GHz. The center frequency is 29.487 GHz. The attenuation at 10% of center frequency is 31 db.

For 60% tunability, if the zero bias capacitance is 300 fF, the minimum capacitance is 120 fF. Figure 8 shows the response of the filter for this case. The maximum insertion loss is 0.5 db and the maximum return loss is 31 db. The bandwidth of the filter in this case 4.375 GHz, lower −3 db frequency is 42.956 GHz, and upper −3 db frequency 47.33 GHz. The center frequency of

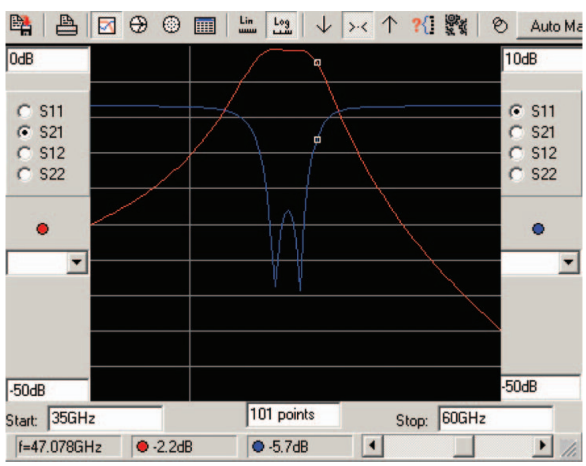

Figure 8. Response of the filter for 60% tunability of the ferroelectric capacitor. (See Color Plate XV)

Table 1
Temperature dependence of Filter Characteristics for graded BST.

Electric Field Volts/Meter	TCC parts per thousand in the temperature range 40−(−10)°C	Lower and upper 3 db pass band frequency in GHz with 10°C change in temperature at 20°C	3 db Band Width in GHz with 10°C change in temperature at 20°C	Shift in frequency 3 db with reference in GHz with 10°C change in temperature at 20°C
0	−4.4	29.530–30.826	1.296	+0.107
1e7	−3.5	29.4–30.66	1.260	+0.071
2e7	−1.8	29.18–30.408	1.228	+0.039
3e7	+0.12	28.919–30.105	1.186	−0.003
Experimental Work by Cole at al	−2.5	29.261–30.508	1.247	+0.058

the filter is 45.144 GHz. The attenuation at 10% of center frequency is about 13 db.

Effect of Temperature Variation of Capacitance

The capacitance of ferroelectrics such as BST is sensitive to temperature and this will give rise to temperature dependent characteristics of tunable filters.

Table 2
Temperature dependence of Filter characteristics for monolithic BST Composition 60-40.

Electric Field Volts/Meter	TCC parts per thousand in the temperature range 40−(−10)°C	Lower and upper 3 db pass band frequency in GHz with 10°C change in temperature at 20°C	3 db Band Width in GHz with 10°C change in temperature at 20°C	Shift in frequency 3 db with reference in GHz with 10°C change in temperature at 20°C
0	−1.72	29.160–30.385	1.225	+0.036
1e7	−1.45	29.121–30.342	1.221	+0.032
2e7	−.95	29.057–30.273	1.216	+0.027
3e7	−.67	29.015–30.224	1.209	+0.020
Experimental Work by Cole at al	+0.83	28.830–30.006	1.176	−0.011

Graded BST hetero structures offer the opportunity to minimize the temperature dependence of capacitance.

Recently, Cole et al reported the temperature coefficient capacitance (TCC) for uniform and graded compositions of BST. The experimental studies by Cole at all shows the TCC of about −.921 at a temperature range from 20 C to 90°C and −.716 at 20−(−10)°C. The TCC was also calculated at a temperature of −10°C to +40°C for graded BaxSr1-x TiO3 with composition variation parameter from x = 0.6 to .9) with electric field. Table 1 shows the TCC for capacitors for graded BST (60-40 to 90-10) with electric field based on the simulation results. This table also shows the shift in band width (defined with respect to 3 db) of the filter with 10C change in temperature at 20 C. The shift in band width is minimum at an electric field of 3e7 V/cm. Table 2 shows the characteristics of the filter for monolithic BST. Comparison of Tables 1 and 2 shows that graded hetero structure with electric can result in tunable filter with nearly temperature independent characteristics.

CONCLUSIONS

The simulation of Ka band shows that the series electrode resistance of capacitors plays an important role in the performance of the filter. The electrode resistance has to be kept as low as possible (less than 0.05 ohms) to minimize the insertion loss. The simulations also show that 60% tunability can be used to design filters with center frequency variation from 29.487 GHz to 45.144 GHz. The shift in bandwidth of the Ka band filter with temperature is insignificant for tunable graded BST capacitor biased at an electric field of 3e7 V/cm.

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