

**Development of low-loss tunable filters using
ferroelectric BST capacitors and GaAs varactors**

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This report presents the design of several tunable filters using different tuning elements such as ferroelectric BST capacitors or GaAs varactors. Several topologies are fabricated and measurements are presented.

The first filter presented in this report operates at Ka-band. It consists of a combination of cross coupling resonators loaded by BST capacitors and built on a sapphire substrate. Insertion loss of 5.7 dB to 4.6 dB is achieved at 33 GHz and 36.9 GHz, respectively, resulting in a tuning of 11.2%.

The second section presents three different filters. The two first filters are similar but operate at different frequencies depending on the values of the SMT components. The first filter is a third-order lumped components-based filter operating at 550 MHz. Five BST varactors and 3 SMT inductors allow a very large tuning of 45%. Insertion loss is only 2.7 to 2.1 dB in the [457-663] MHz frequency range while return loss is better than 12.8 dB. The second operates at 1000 MHz. Insertion loss is 2.9 to 2.1 dB and return loss is better than 16 dB in the [870-1273] MHz range, resulting in a high tuning of 46%. As for the third filter, it consists of an asymmetric CPW topology using 3 BST varactors and 3 SMT inductors. The frequency tunes from 927 to 1441 MHz, i.e. a tuning of 55%. Insertion loss varies from 3.3 dB to 2.7 dB while return loss is better than 21 dB.

The filter presented in the third section is a bandstop filter operating between 510 MHz and 1760 MHz. This filter, consisting of two metal layers, is easily fabricated on a 25-mil Duroid substrate and uses two SMT varactors. This filter allows a very huge tuning of 245%. Measurements are in very good agreement with simulations.

Finally, the fourth section presents a compact size multi-layer filter operating at [850-1150] MHz. This filter presents two transmission zeros. The compact size is achieved by folding the resonator on both top and bottom metal layers.

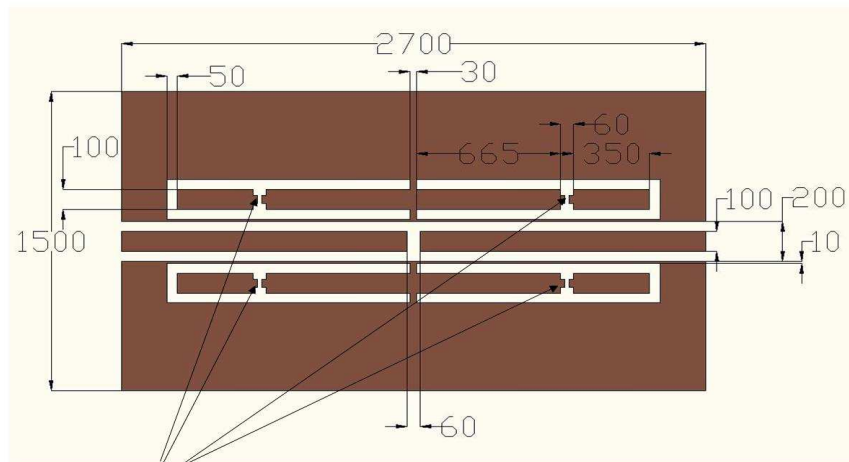
I. Ka-band BST Tunable Bandpass Filter

I. 1/ Topology:

This Ka-band tunable bandpass filter is composed of four CPW cross-coupling quarter-wavelength resonators, which are loaded with BST thin film varactors located in the gap at the end, as shown in Fig.1. The filter is built on a 430- μm thick sapphire substrate ($\epsilon_r = 10$). The total size is 2.7 mm \times 1.5 mm.

Ka-Band Tunable Bandpass Filter

Dimensions in μm



4 BST varactors (20~60 fF assuming a serie resistance 4 Ohm)

Space for varactors: 20 μm \times 40 μm

Fig. 1 - Layout of the Ka-band BST tunable bandpass filter.

I. 2/ Performance:

This structure shows a quasi-elliptical band passfunction. It exhibits good performance including low insertion loss in its passband and high out-of-band rejection level in both lower and upper stopbands. Furthermore, there exists two transmission zeros in its stopband and their positions can be controlled by adjusting the coupling between two resonators. By changing the value of the loaded BST thin film varactors, the electrical length of the resonators can be varied, as well as the center frequency.

Table. 1 Simulated performance of the Ka-band BST tunable bandpass filter for different values of capacitances.

C_{VAR} (pF)	f_0 (GHz)	Insertion Loss (at f_0)	BW (3dB)	Tunability
20	36.9	4.61	3.6	11.2%
60	33	5.74	2.9	

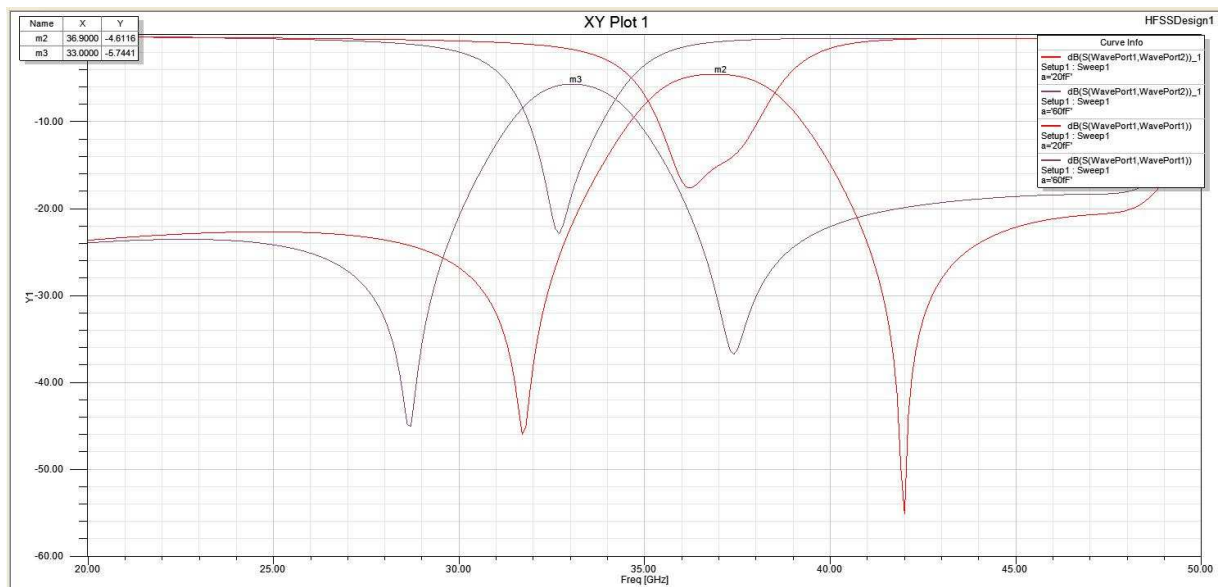


Fig. 2 - Simulation results of the designed Ka-band BST tunable bandpass filter.

II. Low frequency lumped BST tunable bandpass filter

A) Third order lumped BST tunable bandpass filter

II. A) 1/ Topology:

This filter is a coplanar waveguide third order lumped BST tunable bandpass filter composed with five BST varactors and three SMT inductors. The substrate is sapphire and is 430 μm thick ($\epsilon_r=10$). The total size is 6.3 mm \times 3.7 mm.

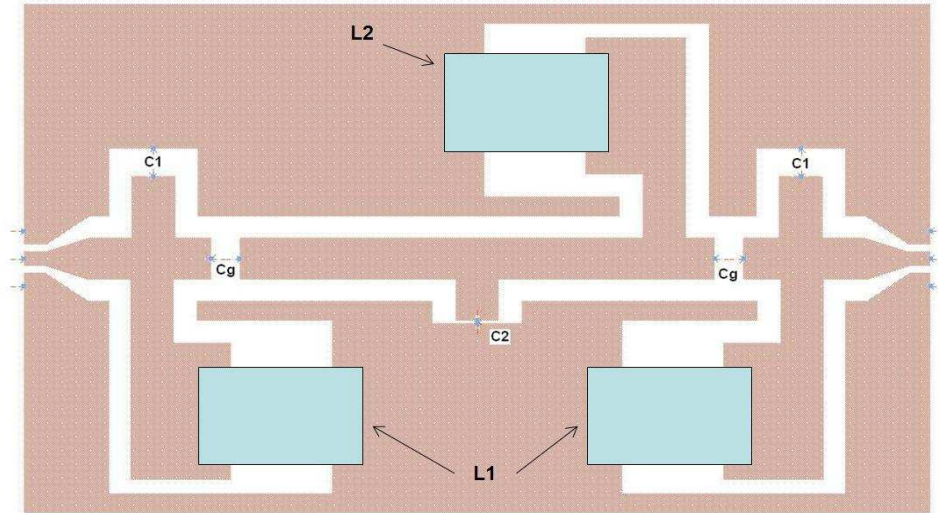


Fig. 3 - Schematic of the third order lumped BST tunable bandpass filter.

II. A) 2/ Performance:

Using different values SMT inductors can achieve different operating frequencies:

- i) 550 MHz: $L1 = 16 \text{ nH}$ / $L2 = 27 \text{ nH}$ (Varactor series resistance $R = 2 \Omega$)

Table 2 - Simulated performance of the 550 MHz lumped BST tunable bandpass filter for different values of capacitances.

C1/C2/Cg (pF)	3/0.3/0.5	5/0.6/1	6/0.9/1.2	6/1.2/1.2
f0 (MHz)	663	522	475	457
BW (3dB)	7.2%	12.8%	13.9%	12.7%
Insertion Loss (at f0)	2.715 dB	2.148 dB	2.221 dB	2.421 dB
Return Loss (at f0)	12.872 dB	17.283 dB	17.869 dB	16.229 dB
Tunability	45%			

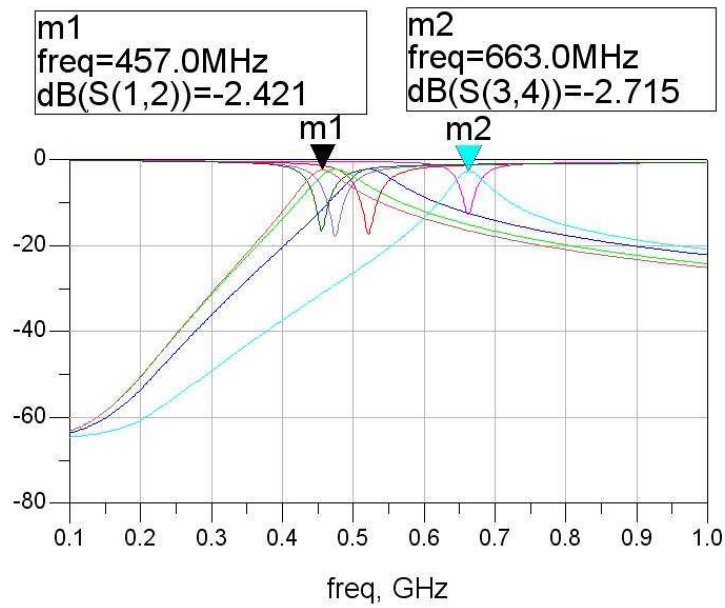


Fig. 4 - Simulation results of the 550 MHz lumped BST tunable bandpass filter.

ii) 1000MHz: $L1 = 4.3 \text{ nH}$ / $L2 = 8.7 \text{ nH}$ (Varactor series resistance $R = 2 \Omega$)

Table 3 - Simulated performances of the 1000 MHz lumped BST tunable bandpass filter for different values of capacitances.

C1/C2/Cg (pF)	3/0.3/0.3	4/0.3/0.6	4/0.6/0.6	5/0.9/0.9
f0 (MHz)	1273	1102	1018	870
BW (3dB)	5.3%	12.2%	10.7%	15.2%
Insertion Loss (at f0)	2.913 dB	2.149 dB	2.326 dB	2.364 dB
Return Loss (at f0)	16.025 dB	27.836 dB	26.562 dB	23.929 dB
Tunability	46%			

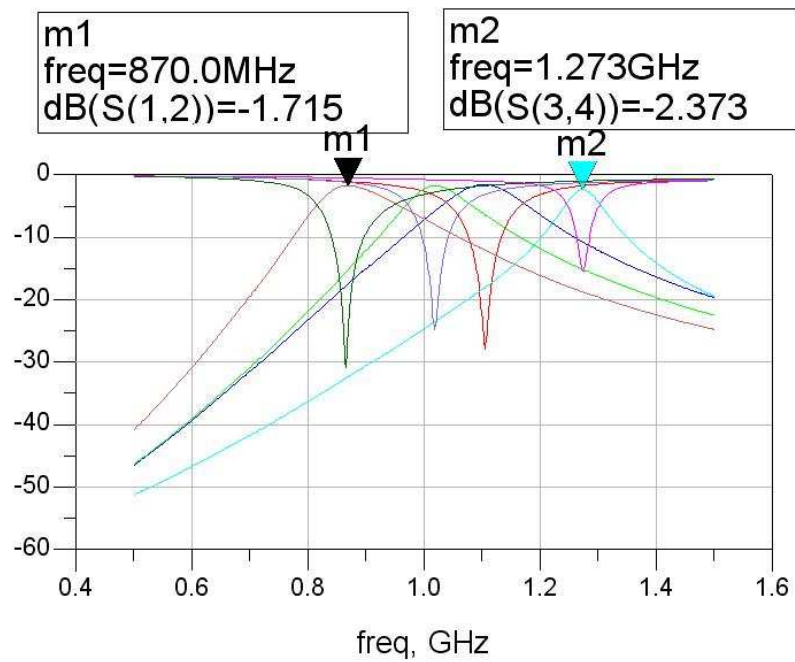
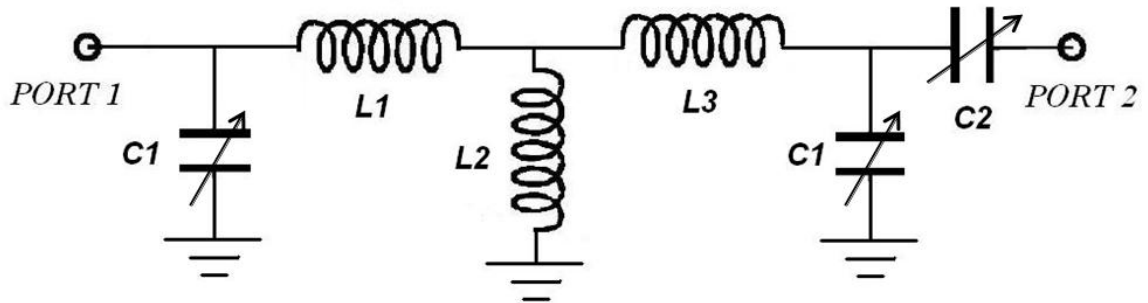


Fig. 5 - Simulation results of the 1000 MHz lumped BST tunable bandpass filter.

B) Modified magnetically coupling lumped BST tunable bandpass filter

II. B) 1/ Topology:

This filter is a modified magnetically coupling with three SMT inductors and three BST varactors. The circuit topology and layout are shown in Fig. 6 and Fig. 7 respectively. The total size is 8.4 mm × 3.3 mm. Substrate: 430- μ m thick sapphire ($\epsilon_r = 10$).



C1 : Frequency Tuning
C2 : Magnitude Compensation

Fig. 6 - Circuit topology of the modified magnetically coupling lumped BST tunable bandpass filter.

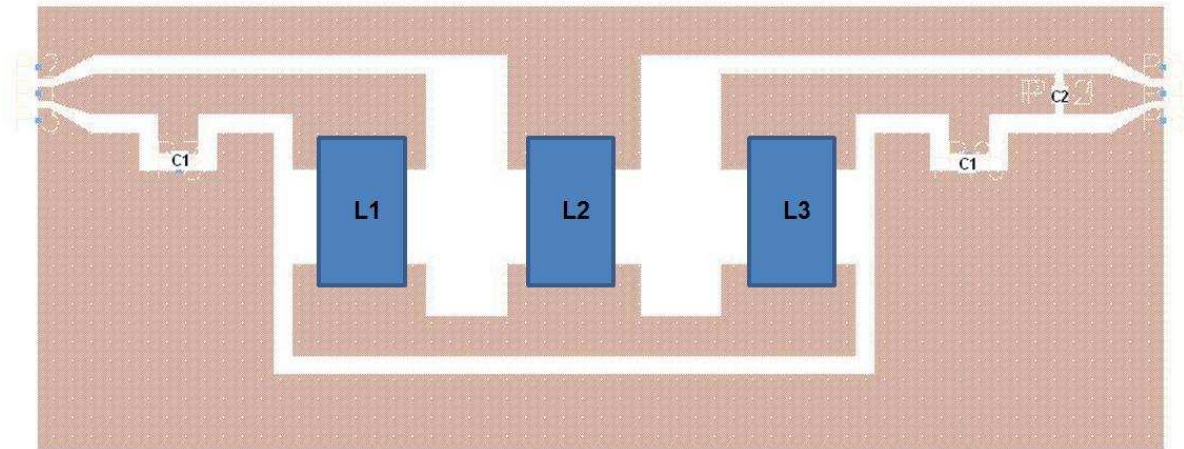


Fig. 7 - Layout of the modified magnetically coupling lumped BST tunable bandpass filter.

II. B) 2/ Performance:

L1 = 9.1 nH

L2 = 1.8 nH

L3 = 5.1 nH

(Varactor series resistance $R = 1 \Omega$)

Table. 4 Simulated performance of the modified magnetically coupling lumped BST tunable bandpass filter with different varactor capacitances.

C1/C2 (pF)	2.4/0.6	1.6/0.4	0.8/0.2
f0 (MHz)	927	1103	1441
BW (3dB)	10.1%	9.1%	6%
Insertion Loss (at f0)	2.738 dB	2.828 dB	3.280 dB
Return Loss (at f0)	21.897 dB	24.757 dB	33.059 dB
Tunability	55%		

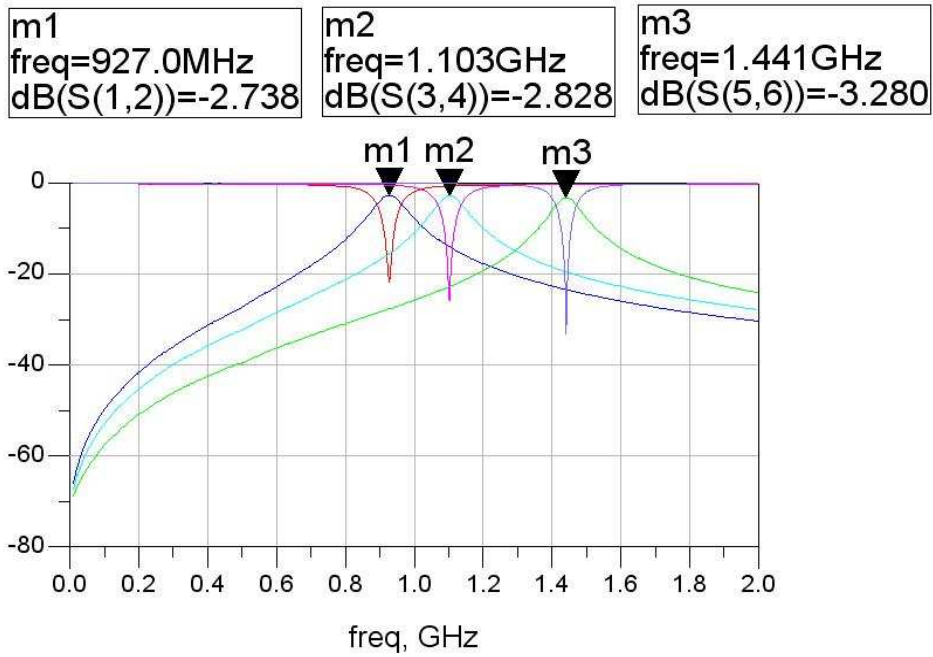


Fig. 8 - Simulation results of the modified magnetically coupling lumped BST tunable bandpass filter.

III. SMT varactor Tunable Bandstop Resonator

III. 1/ Topology:

Coplanar waveguide bottom-side meander line loaded with two SMT varactors, as shown in Fig.9. The substrate is a 25mil RT/duroid 6010.2LM ($\epsilon_r=10.2$). The total size is 20 mm \times 20 mm.

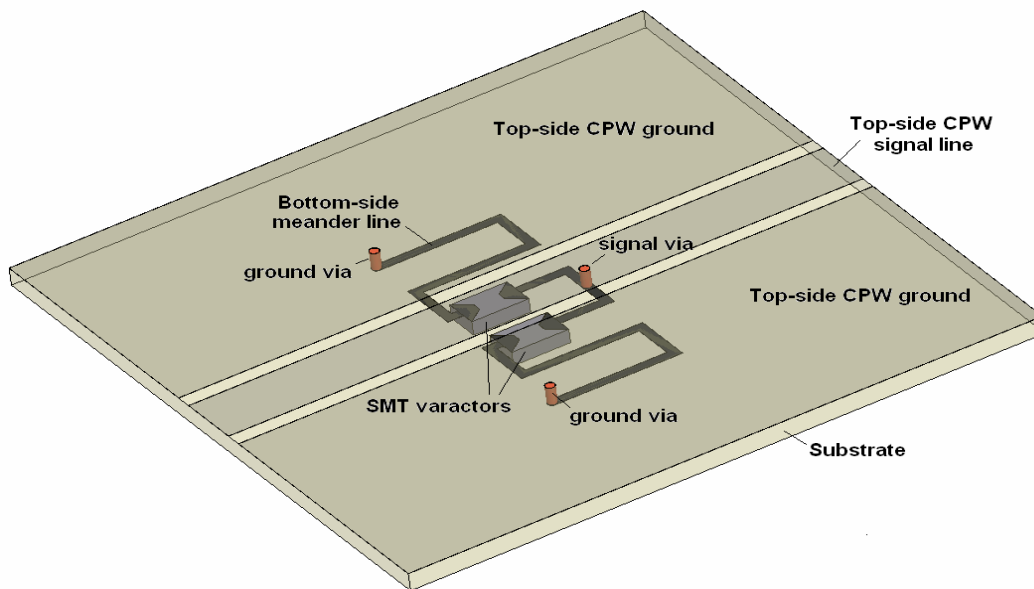


Fig.9 - Schematic of the coplanar waveguide bottom-side meander tunable bandstop resonator.

III. 2/ Performance:

By changing the value of the loaded SMT varactors, the electrical length of resonators can be varied, as well as the center frequency. The filter has been fabricated at Georgia Tech and measured. Fig. 10 shows the simulation results. They are in very good agreement with the measured results presented in Fig.11 . Center frequencies: 510 MHz - 1760MHz (tunability : 245%)

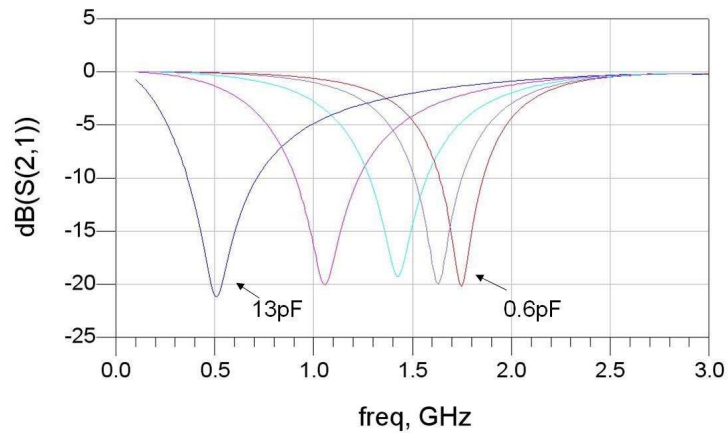


Fig.10 - Simulation results of the coplanar waveguide bottom-side meander tunable bandstop resonator.

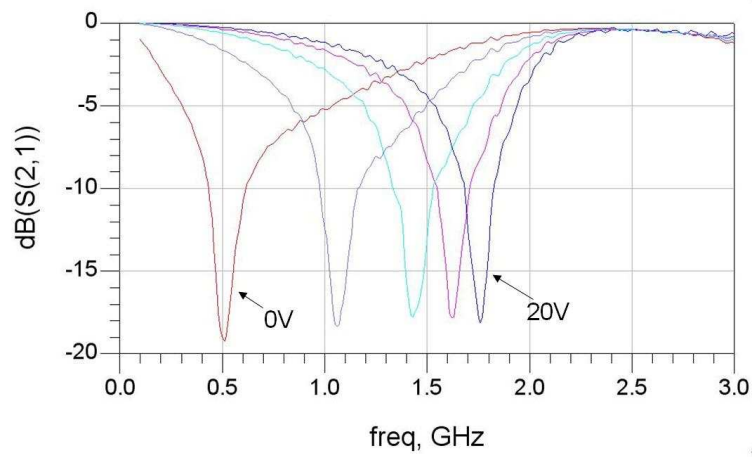


Fig.11 - Measured results of coplanar waveguide bottom-side meander tunable bandstop resonator.

IV. Double-layer filter

IV. 1/ Basic Structure:

This tunable filter is built through a multi-layer structure. Two Duroid substrates are piled up to offer a multi-layer structure. As indicated in Fig. 12, the combined multi-layer substrate consists of two Duroid boards. The metal on the top side of the second layer is previously removed. Then, *Layer1* is bonded on the top of *Layer2* to form the multi-layer structure.

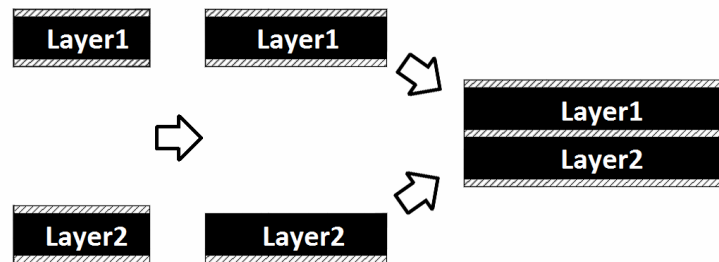
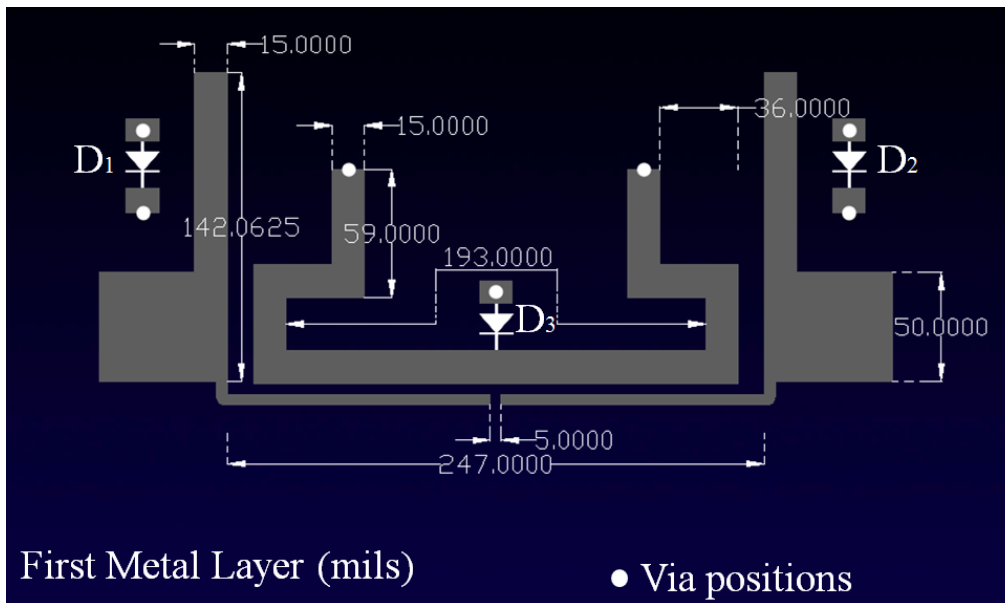


Fig. 12 – Layout of the double-layer filter.

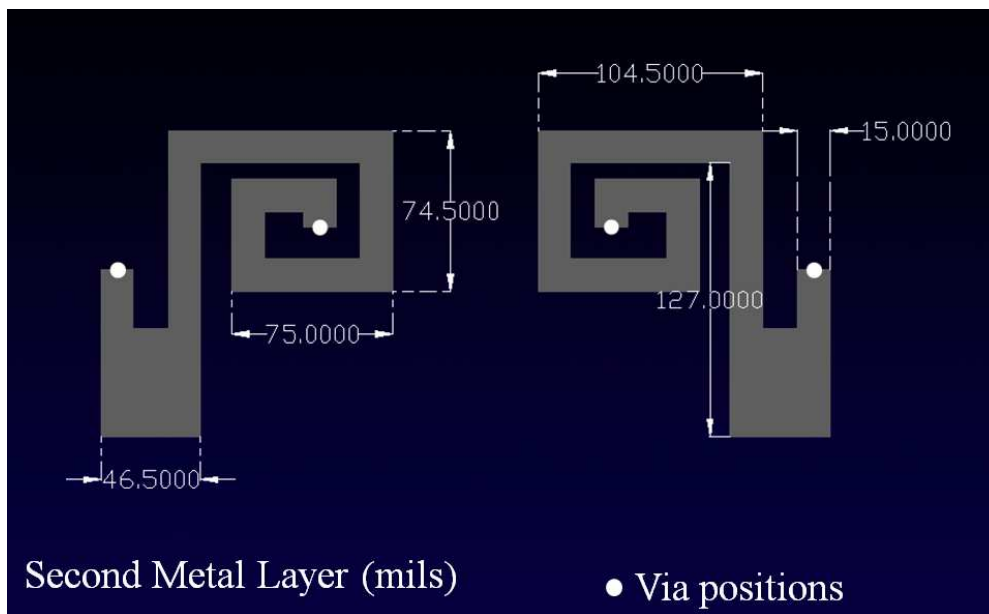
Within this structure, the copper on the bottom of *Layer2* is used as ground. The copper between *Layer1* and *Layer2* is assigned as the second conducting layer and the top side of *Layer1* is assigned as the first conducting layer.

IV. 2/ Designed Layout:

The microstrip patterns etched on the first and second metal layers are presented in the Fig. 13.



(a)



(b)

Fig. 13 – (a) First and (b) second metal layer patterns.

The resonator consists of one central microstrip line on the first metal layer and two microstrip inductors on the second metal layer.

The configuration of the proposed central resonator is presented in the Figure 14. With microstrip inductors unfolded, the whole resonator can be considered as a single long microstrip line. In analysis, it is assumed to be a lossless microstrip line with a characteristic admittance Y and a length L . Two varactors (D1 and D2) are attached at the open ends of the resonator and one varactor is attached at the center of the resonator. Since the structure is symmetrical, an odd and even mode analysis is applied. For the odd mode, the admittance Y_{odd} can be written:

$$Y_{odd} = j\omega C_V - jY \cot \theta$$

Where C_V is the capacitance of the varactors D1 and D2, and $\theta = \beta L/2$. From the resonance condition of $Im\{Y_{odd}\} = 0$, the odd-mode resonant frequencies can be determined by:

$$f_{odd} \times \tan\left(\frac{\pi f_{odd} L}{V_P}\right) = \frac{Y}{2\pi C_V}$$

Where V_p is the phase velocity. As for the even mode, it is controlled by the varactor D3. By changing the capacitance of D3, an extra transmission zero can be generated: therefore, the selectivity is improved.

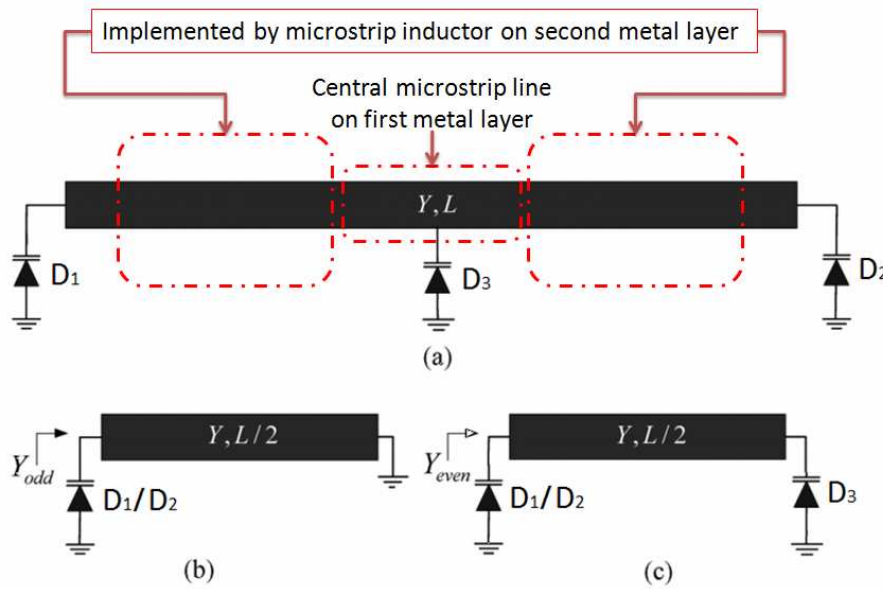


Fig. 14 – Layout of the central resonator.

IV. 3/ Simulated Results:

The 3-D structure is built in both ADS and HFSS with the layout presented in Fig. 15.

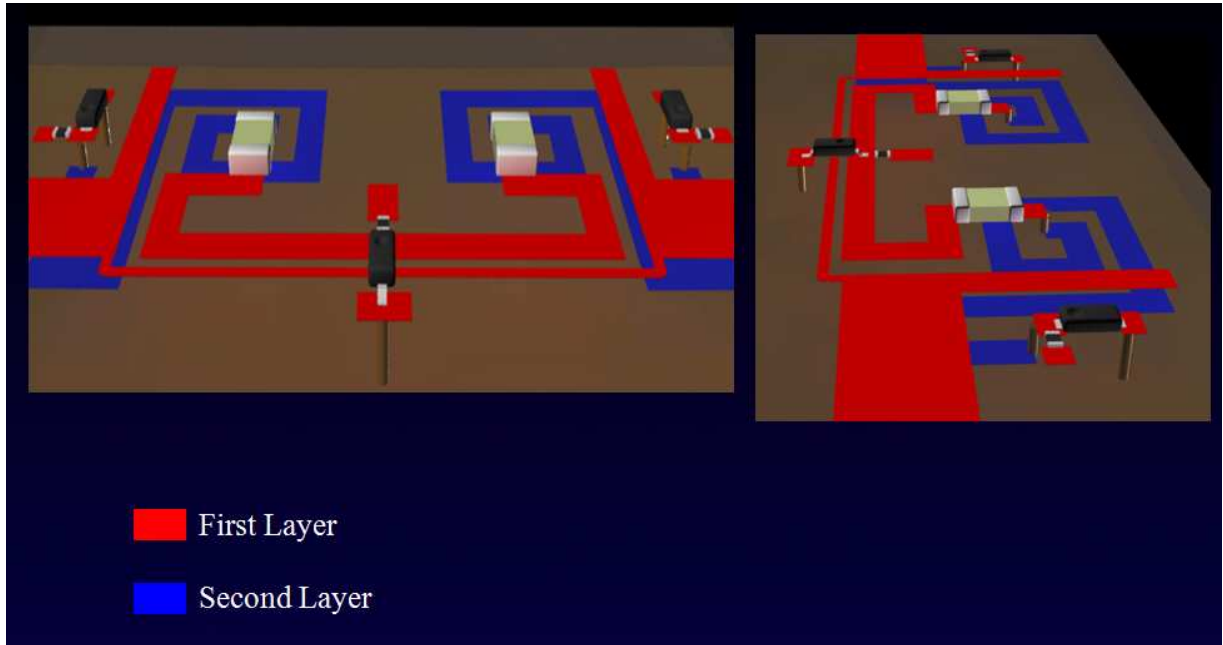


Fig. 15 – Layout of the double-layer filter with surface-mounted components.

The black components are the varactors and the yellow components are the capacitors that are used for DC blocking purposes. As the capacitance of the varactors is changing, the center frequency can be tuned. The simulated results are presented in Fig. 16.

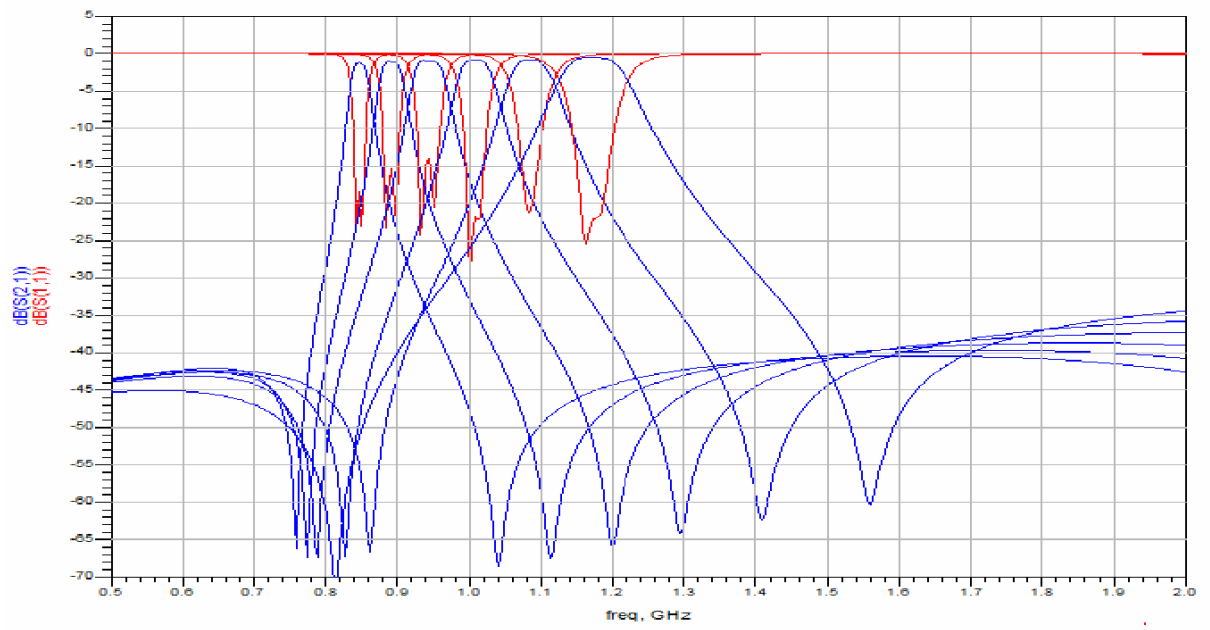


Fig. 16 – Simulated results of the designed tunable filter.

Conclusion:

This report has presented the design and simulations of tunable filters using BST varactors and SMT components (GaAs varactors and inductors).

The first filter, built on a sapphire substrate, operates at Ka-band. The designed CPW topology is loaded by four BST capacitors that allow a tuning of 11.2%. Insertion loss of 5.7 dB to 4.6 dB is achieved at 33 GHz and 36.9 GHz, respectively

Two similar filters operating at 550 MHz and 1000 MHz were then presented. BST varactors and SMT inductors allow a very large tuning of 45% for both filters. In the [457-663] MHz frequency range, insertion loss is 2.7 to 2.1 dB with return loss is better than 12.8 dB, while in the [870-1273] MHz range, insertion loss is 2.9 to 2.1 dB and return loss is better than 16 dB. Another filter that consists of an asymmetric CPW topology was also presented. Its center frequency tunes from 927 to 1441 MHz, resulting in a tuning of 55%. Insertion loss varies from 3.3 dB to 2.7 dB and return loss is better than 21 dB.

A tunable bandstop filter has also been designed and fabricated on a Duroid substrate. Its center frequency tunes from 510 MHz up to 1760 MHz. A very huge tuning of 245% has been demonstrated. Measurements are in very good agreement with simulations.

Finally, a compact size multi-layer tunable filter that operates at [850-1150] MHz has been designed. The compact size is achieved by folding the resonator on both top and bottom metal layers. This filter presents two transmission zeros.