

# Tunable Filter using Right/Left-Handed Transmission Lines

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## Abstract

*This paper describes the design and simulation results of an X-band tunable bandpass filter based on right/left-handed (RH/LH) transmission lines (TL) and varactor diodes. Due to the independent control of the cut-off frequency of each line, the filter exhibits tunable centre frequency and/or absolute bandwidth. The centre frequency can be tuned from 8.9 to 12.2 GHz.*

## Introduction

Tunable filters are important building blocks of multiband transceivers and wideband radar systems. Important attributes of such filters are low-loss, compactness and broad tuning range.

Different technologies have been utilised in the design of such filters. A common approach is the use of planar structures loaded with varactor diodes, for example in interdigital [1] or combline [2] configurations. A review of passive and active planar tunable filter is found in [3].

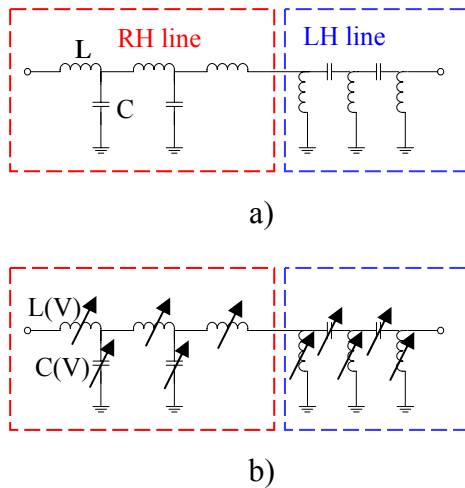
In this work, the design approach is based on cascading a left-handed (LH) and right-handed (RH) transmission line (TL) to provide the required passband [4]. LH TLs are synthetic lines designed with capacitors in series and inductors in shunt. An attribute of this TL is that the group and phase velocities point to opposite directions. In contrast to a conventional or RH TL (series inductors, shunt capacitors) which exhibit a lowpass characteristic, a LH TL acts as a highpass structures.

In order to achieve tunability the capacitors of the two lines have been replaced by

varactor diodes. Aside from the fact that the design of [4] has been scaled up to the X-band, the values of the inductors and capacitors have been chosen in such a way that they match a 6 dB Chebyshev lowpass and highpass prototype. This way the shape factor of the filter is improved as the skirts are made sharper. Additionally, as described further in the main text, using this approach the filter provides a degree of group delay tunability.

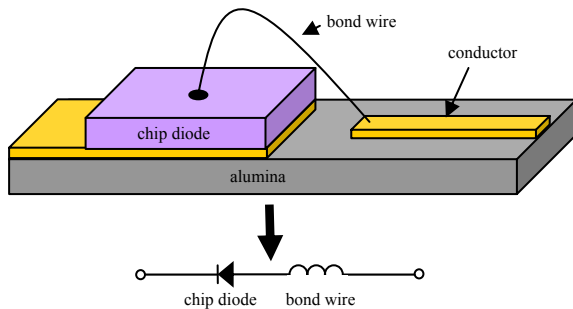
## Tunable Filter Topology

The X-band tunable bandpass filter is designed based on the concept of LH and RH TLs. Such lines exhibit highpass and lowpass behaviour and by cascading them, a bandpass filter can be formed. Figure 1a) shows the topology of a fixed LH/RH filter. In order to make the filter tunable, the lumped elements of the two sections will be replaced by tunable elements. The resulting filter is depicted in Figure 1b). Both lines 5<sup>th</sup> order.



**Figure 1:** a) Fixed LH/RH filter and b) tunable LH/RH filter topology

The tunable element of the design is shown in Figure 2. A chip varactor diode is connected in series with a bond wire, which has two purposes. Firstly, to provide access to the chip diode anode and secondly to act as a series inductor.



**Figure 2:** Tunable element

By properly designing the tunable structure of Figure 2, an effective inductor or capacitor can be realised. The use of both tunable inductors and capacitors will lead to higher tuning range and lower insertion loss compared to the case that only variable capacitors were employed.

The two equations for the effective inductor and capacitor are given below

$$L_{eq} = L_0 - \frac{1}{\omega^2 C(V)_{var}}$$

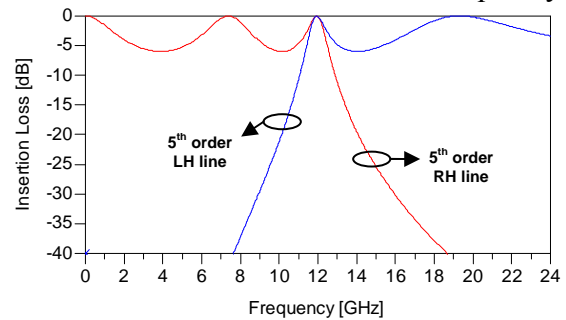
$$C(V)_{eq} = \frac{1}{\frac{1}{C(V)_{var}} - \omega^2 L_0}$$

where  $L_0$  is the bond wire inductance and  $C(V)_{var}$  the voltage dependent diode capacitance.

By increasing the bias voltage, both equivalent element values are reduced and thus the passband is transferred to a higher centre frequency.

### Design Based on the Chebyshev prototype

The first step in designing the tunable filter is to specify the values for the inductors and capacitors of the fixed filter in Figure 1a). For this purpose the values of the 6 dB Chebyshev prototype for both lines were chosen. Figure 3 shows the response of the two ideal lines at 12 GHz centre frequency.



**Figure 3:** Insertion loss of the ideal 6 dB Chebyshev prototype for the LH and RH case

The ripple was set at 6 dB, as the skirts were sharp without the value of the series inductance of the RH line being too high. Higher inductance means that the bond wire needs to be longer (more than 4 mm), leading to fabrication difficulties.

### Filter Implementation and Simulation Setup

The tunable filter was designed using microstrip technology on a 9.9 dielectric constant alumina substrate. The biasing for each varactor diode was provided by a  $\lambda/4$  line and an open radial stubs. Different bias networks were considered such as broadband conical inductors, but the loss was too high for this application. Four independent biasing voltages are needed to bias the diodes, two for each section. The varactors are GaAs hyperabrupt diodes by

Aeroflex/Metelics, models MGV075-08 and MGV07-09.

The circuit was designed and optimised in Agilent's Advanced Design System (ADS). Standard SPICE models were used for the varactors and all microstrip elements, such as 50 Ohm feeding lines and microstrip interconnects, were accounted for.

### Tuning Scenarios

As explained above, the filter has tunable centre frequency together with tunable bandwidth. This means that the following scenarios are available: a) keep the absolute bandwidth constant while tuning the centre frequency, b) keep the fractional bandwidth constant while tuning the centre frequency, c) tune the bandwidth at a fixed frequency and d) tune the group delay at a fixed frequency and bandwidth. While the three first points are a direct consequence of the nature of the filter, by replacing the fixed inductors and capacitors with tunable elements one is able to effectively tune the ripple of the Chebychev LH and RH lines. This means that the skirts can be more or less sharp providing a higher and lower group delay respectively, while the bandwidth and centre frequency remain constant.

#### Constant Absolute Bandwidth

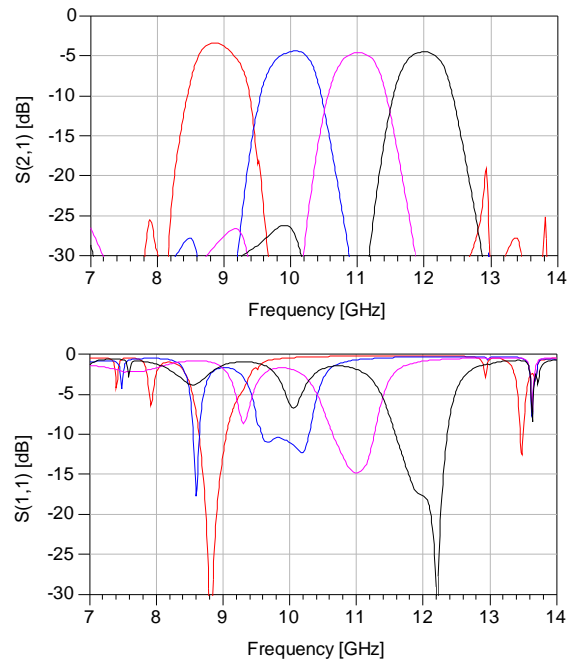
The bandwidth of the filter was kept at 710 MHz while the centre frequency was tuned. Figure 4 shows the insertion and return loss for this scenario. The insertion is kept less than 5 dB while the return loss is better than 10 dB.

#### Constant Fractional Bandwidth

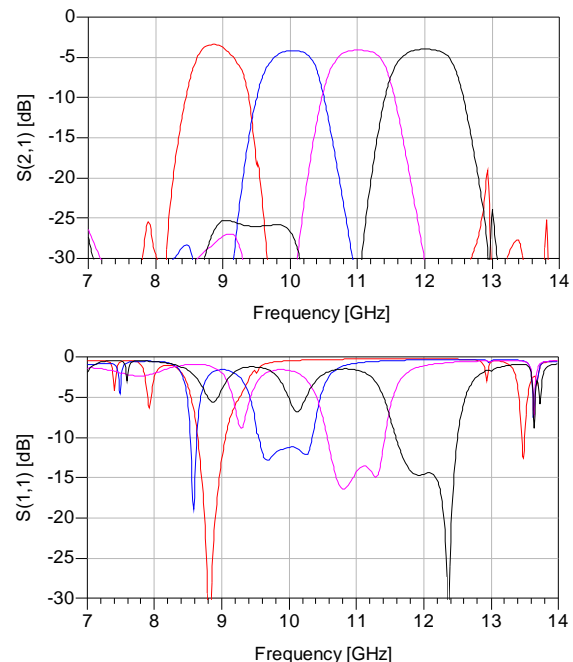
In this scenario, the fractional bandwidth is kept constant. The results presented in Figure 5 are for 8% fractional bandwidth.

#### Bandwidth Tuning at a Fixed Centre Frequency

The third scenario is a combination of the two previous cases. The bandwidth can be



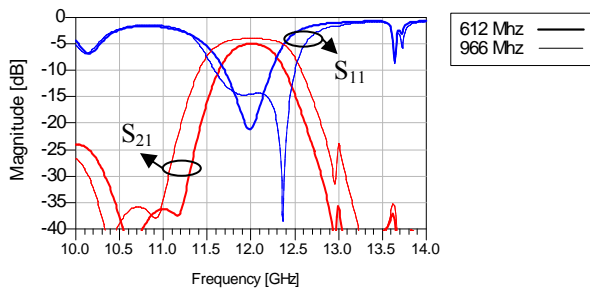
**Figure 4: Insertion and return loss simulation results for different centre frequencies with a constant absolute bandwidth of 710 MHz.**



**Figure 5: Insertion and return loss for different centre frequencies with an 8% constant fractional bandwidth.**

tuned at a fixed centre frequency. Figure 6 shows the results at 12 GHz as the bandwidth is tuned from 612 to 966 MHz

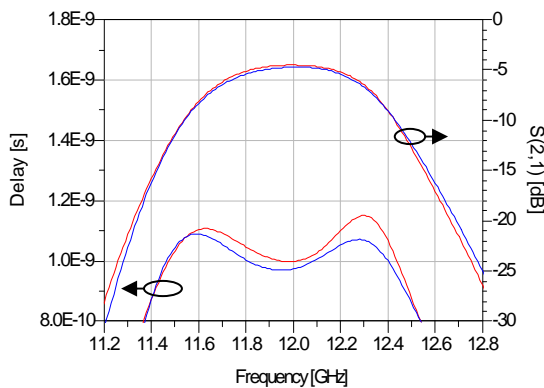
or 58%. As in the previous cases the insertion loss is kept better than 5 dB.



**Figure 6: Insertion and return loss for the minimum and maximum bandwidth at 12 GHz centre frequency**

### Group Delay Tuning

Apart from bandwidth and frequency tuning, group delay tuning is also possible. Figure 7 shows the results of two different tuning states with the same bandwidth and centre frequency but different group delay. Comparing the two states, the group delay was reduced by 27%.



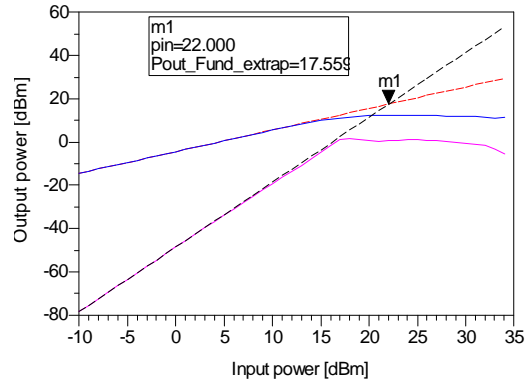
**Figure 7: Tuning the group delay while keeping the bandwidth and frequency constant.**

### Large Signal Simulation

The simulated output third-order intermodulation intercept point (IP3) is better than 16 dBm throughout the tuning range. Figure 8 shows the IP3 diagram at 10 GHz centre frequency.

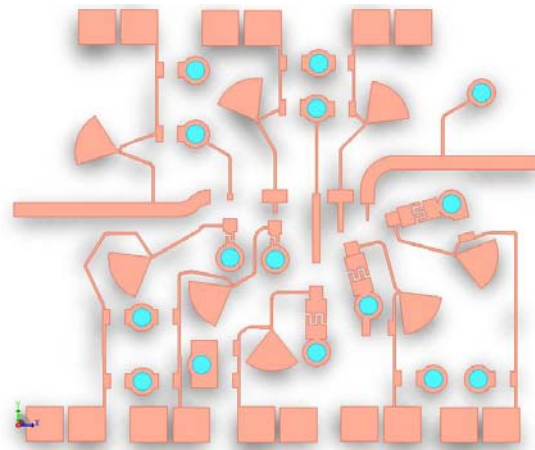
### Microstrip Layout

The microstrip layout was designed in ADS Momentum.



**Figure 8: IP3 diagram at 10 GHz**

Figure 9 contains the layout of the tunable filter including bias lines. Chip diodes and bond wires have been omitted. The dimensions are 23.3 x 18.8 mm<sup>2</sup>.



**Figure 9: Microstrip layout of X-band tunable filter**

### Future Work and Conclusion

The design of an X-band tunable bandpass filter based on LH/RH TLs has been presented. The filter is capable of frequency and/or bandwidth tuning. The centre frequency can be electronically tuned from 8.9 to 12.2 GHz while keeping the insertion loss less than 5 dB. The final step of this project is the fabrication and measurement of the filter. In the future, compactness can be achieved by designing the circuit using MMIC technology [5].

### Acknowledgements

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