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Characteristics of a Tunable Microstrip Bandpass Filter Under the Influence of Magnetic Field

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A magnetic-field tunable 2.4 GHz microwave bandpass filter having insertion loss < −5dB on an FR4 substrate with the flaky magnetic material was designed and characterized. The tunability in the designed bandpass filter was achieved by adhering soft magnetic materials on top of the device. This soft magnetic material can be composed of ferromagnetic substance or ferrimagnetic substance. The performance of the designed bandpass filter under its influence is investigated. The frequency offset ratio changes over 30 %. There is over 20 % change in the center frequency towards the lower frequency region due to this application. These magnetic material layers achieved the center frequency shift and bandwidth extension without actually changing the original structure of the device.

Keywords : band pass filter, magnetic field, microstrip

1. Introduction

Tunable filters are essential circuits used to detect and control radio frequency spectrums. Recently, the requirement of a low-cost tunable bandpass filter (BPF) has grown rapidly with the dramatic growth of wireless technologies [1-3]. The tunability in BPFs can be achieved in many ways, including magnetically tunable YIG (Yttrium Iron Garnet) based BPF [4-6], mechanically tunable BPF [7], magneto-electric (ME) coupling in ferrite/piezoelectric heterostructures [8], ferromagnetic thin film based tunability [9] or varactor-tuned BPFs [10, 11]. However, YIG based systems need a large external magnetic field to operate [4-6, 8] and ferromagnetic thin film based tunable filters work better for very high frequencies only. On the other hand, introduction of varactor diodes ensures the electronic tunability of a BPF but the variation in bandwidth or insertion loss within the tuning range can be significant and also the unloaded Q factor of the filter degrades.

In this work, a 2.4 GHz bandpass filter with single ended input and single ended output was designed on FR4 substrate, instead of using complicated YIG or piezoelectric process, to investigate the effect of flaky magnetic materials on a BPF. Four layers of magnetic materials were stacked on the top of the designed BPF. This magnetic field shifts the center frequency of the device towards the lower frequency region. That is, the center frequency of this BPF can be tuned by using a magnetic field generated by only magnetic layers on the top of the actual filter instead of changing its device structure. The main advantage of this structure is that the tunability can be achived very easily. And it also can be manufactured very easily and in a short time and finally in this structure there is no need to modify the original device.

2. Basic Principle and Circuit Design with Magnetic Materials

The microstrip bandpass filter was fabricated using a standard copper etching technique on a 60-mil thick FR4 substrate with a dielectric constant of 4.4 and the dielectric loss tangent of 0.02. These parameters were fed in the momentum function of the Agilent advanced design system (Agilent ADS) for simulations to compare between simulation and measurement results. The layout design and the fabricated filter are shown in Figure 1 (a) and 1 (b), respectively. The dimension of the bandpass filter is given in Table 1.

For this work, a few layers of flaky magnetic materials

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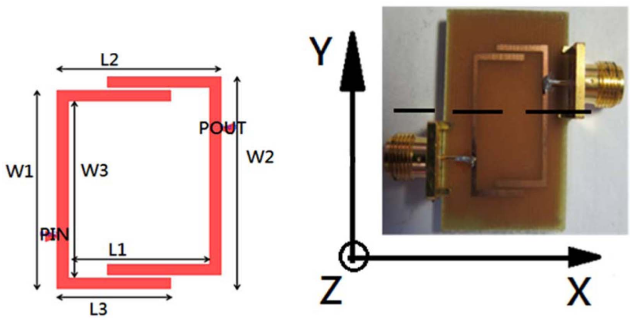


(a) (b)

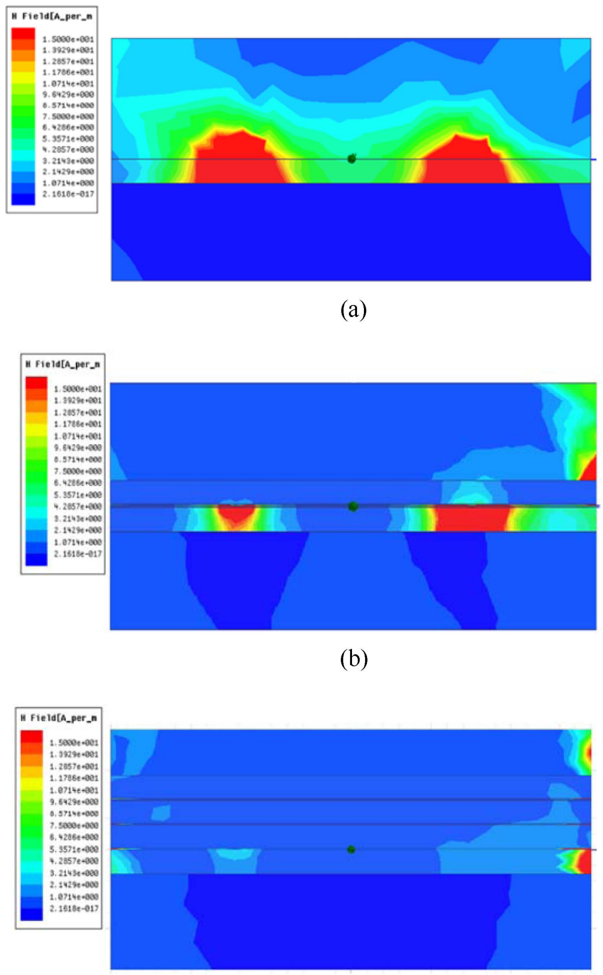
Fig. 1. (Color online) Microstrip bandpass filter (a) appearance designation (b) device layout.

Table 1. Microstrip bandpass filter size dimension.

L1	10 mm	W1	19 mm
L2	14.42 mm	W2	20.3 mm
L3	12.43 mm	W3	15.7 mm

were stacked on the top of the fabricated bandpass filter to investigate the effect of a magnetic field on the bandpass filter performance. For this work, a soft magnetic material was used. The soft magnetic material can be composed of ferromagnetic substance or ferrimagnetic substance. For example, a derivative of $MnZnFe_2O_4$ is this kind of material. This material is readily available in market as a sheet magnet. This kind of materials have light weight and small dimension, negligible eddy current loss and relatively low core losses. They also have good permeability and high electrical resistivity [12]. In this work, this material was used to investigate the change of overall circuit performance under its influence.

Figure 2 describes the conceptual diagram of effect of adding flaky magnetic materials on top of the band pass filter. From Fig. 2(a) it is evident that when there was no magnetic material on top of the microstrip line the magnetic field lines keep fading away as expected. When the first layer of magnetic material was added as in Fig. 2(b), the field lines get concentrated near the active region of the microstrip surface, which helps the modification of the performance parameters by changing the overall permeability [13]. By further adding more magnetic layers as shown in Fig. 2(c) the concentration of the field lines becomes more dense and as a result the change of permeability is more. This increase in magnetic permeability will increase the inductance of the microstrip line. However, as the magnetic layer height increases the distance

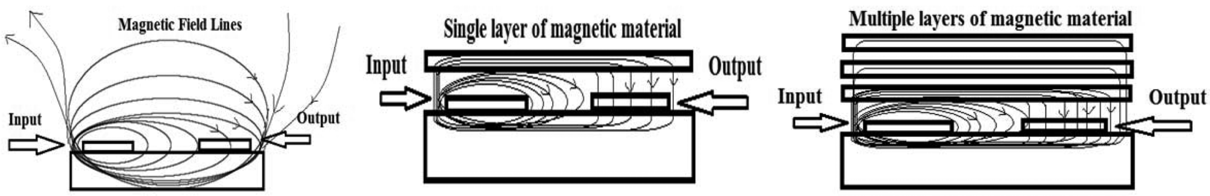


(a)

(b)

(c)

Fig. 3. (Color online) Simulation results of magnetic field analysis with (a) no magnetic layer (b) one layer of magnetic material and (c) multiple layers of magnetic material.



(a) (b) (c)

Fig. 2. Conceptual diagram of magnetic field lines without and with magnetic materials.

of the magnetic layer also increases from the microstip lines and as a result the effect saturates after a few layers.

Figure 3 shows the simulation results of the BPF without and with the magnetic material layer on top. The simulations were performed by ANSYS HFSS for magnetic field analysis in the same frequency range, along the dashed line in Figure 1(b).

Figure 3(a) shows when no magnetic material was applied the field lines concentrated near the microstrip line and kept fading away with distance. However, when the first layer of magnetic material was applied, as shown in Fig. 3(b), one significant effect happened. The magnetic field lines get more concentrated near the microstrip line especially near the output. Consequently, the overall inductance gets higher which finally shifts the center frequency to the lower frequency domain. At the end of the magnetic layer when the field lines come in contact with air the field pattern will be same as Fig. 3(a) as shown in the top right corner of Fig. 3(b). When multiple layers of magnetic material were added as shown in Fig. 3(c) it can be noticed that still the field lines were concentrated near the output microstrip line but its effect was saturated with frequency shift but in lower magnitude than that of Fig. 3(b). As with adding magnetic layers the permeability also changes, therefore the overall inductance also increases as explained in Fig. 2. The simulation results are supported by the measurements in the following sections.

According to the self-induction magnetic line distribution theory of high permeability materials, it is inferred that the equivalent inductance increases when the magnetic permeability of the substrate increases, so that the characteristic frequency shifts towards the low frequency. In engineering applications, the magnetization M is usually represented by the magnetic induction or magnetic flux density B (Wb/m^2). The relation between B and M is:

$$B = M + \mu_0\mu_r(t)H \tag{1}$$

From equation (1) and using the definition of inductance the modified inductance value due to the flaky magnetic layers can be modified as below

$$L = \frac{\mu_0\mu_r(t)AN^2}{l} + t.k \tag{2}$$

where $\mu_r(t)$ is the relative magnetic permeability of material which is considered a function of the thickness of magnetic layers, t is the thickness of magnetic layer, k is the assumed constant of proportionality and all other notations are of usual meanings. The value of "k" can be calculated from inductance versus stacked magnetic material width curve. The total equivalent capacitance was assumed constant due to self-resonance. Then k can be calculated using the relation between frequency and inductance for different center frequency values. Equations (1) and (2) show that the self-inductance can be altered by the magnetic permeability of magnetic materials. So keeping all other parameters fixed, the characteristic frequency of the designed filter can be varied just by the magnetic permeability variation i.e. in other words by adding magnetic materials on the top of the designed circuit. Due to the stacked magnetic materials above the circuit, a magnetic field generates around the mircostip line which overall increases the magnetic permeability around this area.

3. Simulation, Measurement Results and Discussions

Figures 4 and 5 show the simulated and measured center frequency deviation and bandwidth of the proposed bandpass filter, respectively. From Figure 4, simulated by Agilent ADS, it can be observed that the frequency (bandwidth) offset is 640 MHz and the frequency offset ratio is 32.1 % at the characteristic frequency point. The frequency offset ratio is defined as the ratio between the bandwidth and the center frequency.

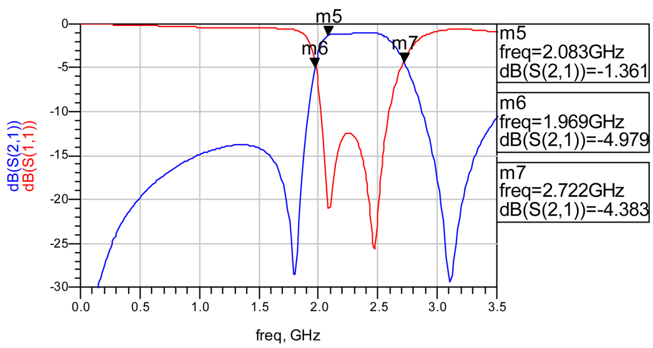


Fig. 4. (Color online) Simulated S21 and S11 of the filter without magnetic material.

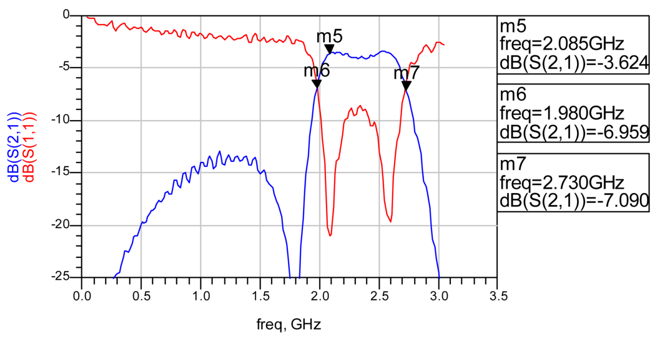


Fig. 5. (Color online) Measured S21 and S11 of the filter without magnetic material.

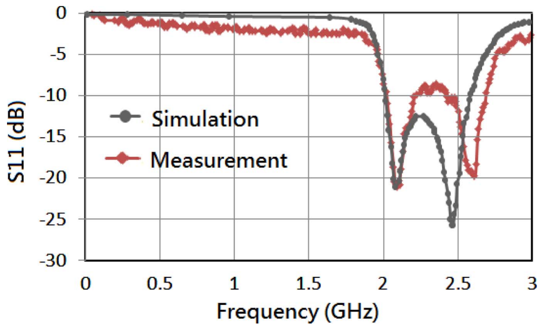


Fig. 6. (Color online) Simulated and measured S11.

On the other hand, from Figure 5, the measured frequency offset is 645 MHz and the frequency offset ratio is 31.18 % for the measured case.

The measured insertion loss of this filter was less than –5dB. The simulated and measured results of S11 were compared in Fig. 6. From the results it is evident that a close agreement between measurements and simulations was achieved.

After observing these agreements between simulated and measured results, the bandpass filter was again simulated with 4 layers of flaky magnetic materials in Fig. 7(a) and the complete structure is shown in Fig. 7(b). The thickness of each layer was 0.4 mm. At the time of simulations, a 0.1 mm air gap was considered between the circuit and the 1st layer of magnetic material and 0.05 mm air gap was considered between each magnetic layer to meet the real measurement situation.

Figure 7(a) represents the frequency offset deviation of the designed filter with 1.6 mm magnetic material and the relative permeability 20. It can be seen in Fig. 7(a) that the noise floor increases due to nonideal effects. The measurement results become somewhat noisy and it's hard to determine the standard bandwidth. Although, a rough calculation from the measurement values confirms that the bandwidth of this filter increases due to adding of the flaky magnetic material layers.

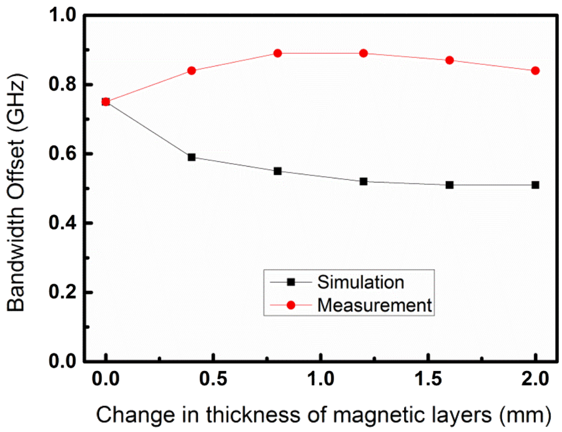
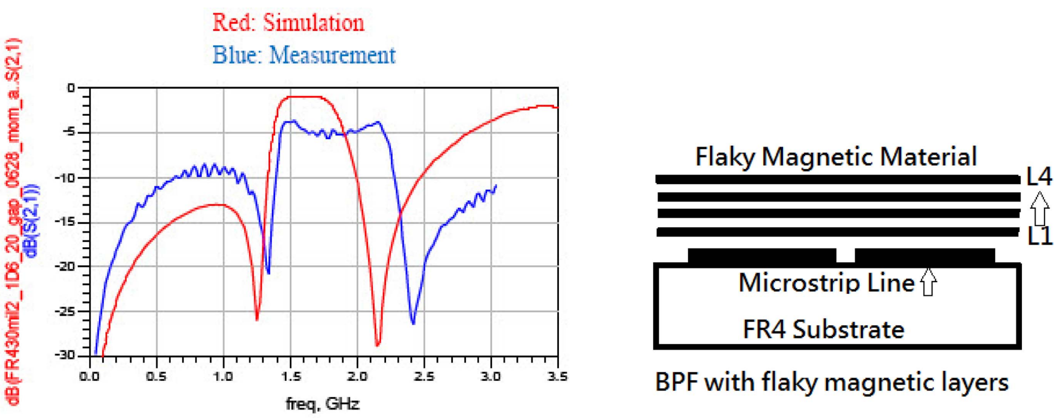


Fig. 8. (Color online) Measured and simulated bandwidths offset due to flaky magnetic layers.

From Fig. 8 it can be pointed out that after the 4th layer of flaky magnetic material the change in bandwidth saturates i.e. no further significant change can be observed as the magnetic layer increases. But the change is in different directions i.e. for simulations the bandwidth offset is decreasing while it is increasing in measurements. As explained earlier for Fig. 7(a), the bandwidth of the filter is also increased due to the magnetic layers so the bandwidth offset is also increased in the measurement results. The measurement results from Fig. 8 also support this observation.

Figure 9 depicts the change in the center frequency due to the application of magnetic layers for both measurements and simulations. From Fig. 9 it is also evident that the shift in the center frequency saturates after the application of maximum four layers of magnetic material. The



(a) (b)

Fig. 7. (Color online) (a) Simulated and measured frequency characteristics shift of filter with 1.6 mm soft, flaky magnetic material (b) Microstrip BPF with flaky magnetic layers.

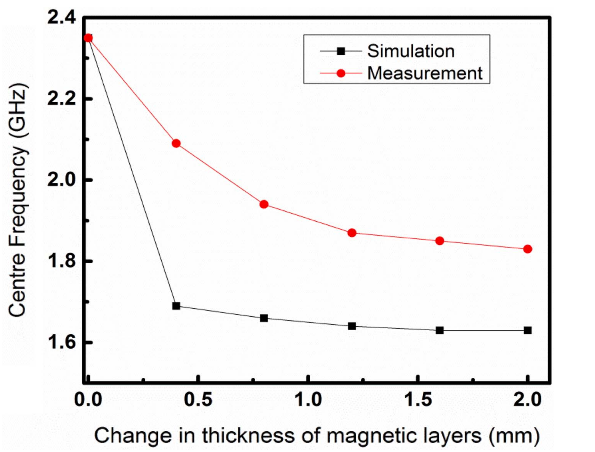


Fig. 9. (Color online) Measured and simulated center frequency shift due to flaky magnetic layers.

strength of the magnetic field due to the stacked magnetic material is stronger near the surface of the microstrip BPF surface and hence the change of the center frequency is higher for the first layer and changes very little as the height of magnetic material increases. The difference between simulation and measurement results comes due to the difference between the value from permeability in simulations and measurements and also due to the air gap between flaky magnetic layers. Figure 10 represents the change in the normalized effective inductance with the thickness of the magnetic material. From Fig. 10 it can be seen that the change in inductance is saturated after the third layer of magnetic material since the distance of the magnetic material layer is becoming higher with the device surface and hence no notable change can arise.

From Figs. 9 and 10, the value of the constant k has been calculated as mentioned in equation 2. To calculate the value of k, the capacitance in considered to be

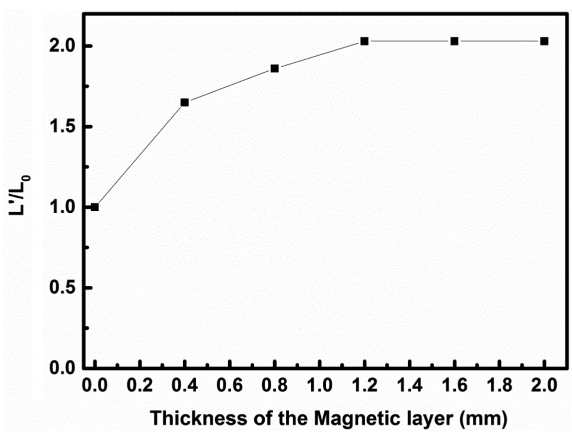


Fig. 10. (Color online) Change in normalized values of effective inductance with magnetic material thickness.

constant due to self resonance. For three different values of frequency, three different values of k were calculated and the average of these values is considered as the final value of 0.8 Henry/m. There is around 9 % change in both the calculated and measured values of inductance can be observed which might arise due to the averaging of k values.

This proposed device will be useful during the design of a bandpass filter with low center frequency and with smaller size because this post processing technique shifts the center frequency to the lower region without changing its actual size. This design technique can also be applied to the design of other circuits such as a voltage-controlled oscillator with adjustable frequency characteristics.

4. Conclusions

A 2.4 GHz bandpass filter with flaky magnetic materials, instead of complicated YIG or piezoelectric structure, has been designed and characterized. The proposed BPF design has been simulated for magnetic field analysis by using ANSYS HFSS without and with layers of magnetic materials on the top of the structure. The measurement results follow the simulated results in the trend of frequency change. A soft magnetic material was used to investigate the overall circuit performance under the influence of this material. The stacking of flaky magnetic materials increase the overall inductance by increasing the permeability, which changes the center frequency of the proposed BPF. The center frequency of the proposed BPF shifts towards the lower frequency region due to the application of these magnetic layers, without actually changing the device structure and the overall bandwidth tends to increase. Over 20 % shift in the center frequency is obtained towards the low frequency domain which will be useful to change the frequency of operation of the filter without actually changing its structure. The modified equation of the effective inductance due to the change in magnetic permeability by adding flaky magnetic layers is verified. This method of changing the center frequency is very simple to produce with low process cost. This design approach can be used in the design of other circuits for wireless applications.

Acknowledgements

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