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Review Article

On the review of magnetic metamaterials CRLH impedance transformers: Design and analysis

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Abstract
The trend of using metamaterials in designing microwave components and antennas has played a great role in the past two decades. One of these trends was the use of composite right/left-handed artificial transmission lines for these components. On the other hand, the development of tunable microwave components is one of the permanent demands in the electromagnetic designer community. Mixing the advantages of metamaterials with magnetic tunable components has opened a new window for the development of good components. This paper reviews different designs for tunable metamaterial-based microwave impedance transformers. The designs illustrate different functionalities based on the unique properties of the metamaterial composite/right-left-handed transmission lines. The designs are supported by detailed theory and mathematical modeling. The advantage of the presented devices is their combined properties of compactness and nonreciprocity. Furthermore, the devices require very low external DC magnetic bias due to their much lower demagnetization compared to the microstrip configuration.

I. INTRODUCTION

The great interest in using left-handed metamaterials in microwave circuit applications encourages the use of planar composite right/left-handed (CRLH) transmission lines (TLs) versions. CRLH TLs have been realized using transmission lines loaded with either SRR/wire pair[1], CSRR/capacitive gap pairs[2-4], or series capacitive load and shunt inductive load periodically,[5-7]. The versions making use of SRR are sometimes called resonant configurations while the others are called nonresonant configurations. The realization of planar non-resonant CRLH TLs is possible in either a 1-D TL structure in which the propagation is only along the structure principle's axis[5,6] or a 2-D TL structure which represents all directions of propagations in the 2-D structure[8-11]. Different configurations of non-resonant 1-D CRLH TLs in either microstrip[12,13] or CPW[14-18] configurations have been proposed using different types of loading capacitors and inductors. These studies have included the implementation of series capacitive load through the use of either lumped element capacitor, air gap capacitor, or interdigital capacitor. The shunt inductive load is implemented through the use of a shunt stub inductor or meandered line inductor. Based on these novel transmission lines, several microwave components have been reported in the literature such as power dividers[19-22], couplers[23,24], filters[25-31], and antennas[32-36].

Planar ferrite TL has a dispersive permeability whose value can be negative or positive. It demonstrates evanescent propagation within the frequency band of negative permeability. Also, such propagation can be nonreciprocal depending on the applied DC magnetic bias direction. Therefore, a tunable and nonreciprocal CRLH TL can be expected by using ferrite substrates.

However, the ferrite coplanar waveguide (CPW) transmission line has many advantages such as it compatible with MMIC circuits and it needs a small DC biasing magnetic field as a consequence of its small demagnetization factor. Examples of many non-reciprocal CPW couplers, isolators, and circulators are presented in[37,38].

Mixing the features of CRLH TLs and the ferrite substrates have encouraged researchers over years to contribute novel microwave components. Such features have been demonstrated by Tsutsumi[39,40] using microstrip TLs over mixed ferrite and dielectric substrate and by Abdalla[41,42] by using CPW ferrite substrates. Applying these TL configurations, many other reviewers have presented tunable microwave devices such as resonators[43,44], impedance transformers[45,46], phase shifters[47,48], diplexers[49], isolators[50], circulators[51], leaky wave antennas[52]-[56] and couplers[57]-[62] were suggested.

Quarter wavelength impedance transformers are widely used in many microwave applications. Left-handed quarter wavelength transformers on dielectric substrates have been reported as a novel application of the CRLH TL theory. The advantages of the CRLH TL Transformer are its multi-band functionality, arbitrary operating frequencies which are not essential to be the odd harmonics, and its compact size at lower frequencies, in addition to its enhanced bandwidth.

In this review paper, we introduce the detailed study of a quarter wavelength left-handed transformer implemented using a ferrite substrate in CPW configuration. Different types of ferrite CRLH CPW transformers are introduced. The main objective of studying these different transformers is to demonstrate a tunable operation and compact size. The first transformer type is a narrow band tunable CRLH transformer that operates in the left-handed passband. The whole operating frequency bandwidth can be tunable. Two different types for this transformer type are introduced to demonstrate both low and high-loading impedance matching possibilities. The third proposed type demonstrates a tunable wide operating frequency bandwidth. Finally, a left-handed transformer type with two perfect tunable operating points, multifunctional, has been introduced. For simplicity, the applied DC magnetic field was assumed to be uniform in all studied cases. All the results obtained, for all transformers, demonstrate tunable operation as a result of changing the applied DC magnetic bias. For all the transformers, the commercially Trans Tech YIG ferrite G-113* was employed as the hosting ferrite CPW TL substrate. The Trans Tech YIG ferrite material G-113* has a relative permittivity ε_f =15 and dielectric constant loss of less than 0.0002. Its magnetic properties are a saturation magnetization, 4πMs= 1780 Gauss, and a magnetic linewidth, ΔH_0 = 25 Oe. The ferrite substrate thickness is h=1mm. In these transformers, the internal DC magnetic field (H_0) is applied to the ferrite substrate horizontally causing the ferrite substrate to have saturation magnetization in the same direction. For simplicity, the applied DC magnetic field was assumed uniform in all studied cases. It has been demonstrated in this paper that all the proposed transformers have the advantages of tunable performance and compact size. Moreover, all the reported CPW transformers require a lower applied DC magnetic bias compared to microstrip configuration because of their horizontal DC magnetic bias.

II- THE ANALYSIS OF THE FERRITE CRLH TL

Similar to conventional CRLH TL, ferrite CRLH TL can be designed by periodically loading a hosting planar ferrite TL by a shunt inductive load (LL), resulting in negative effective permittivity, and series capacitive load (CL), resulting in negative effective permeability.

The analysis of the ferrite CRLH TL can be done similarly to the dielectric one using either the periodic circuit analysis or the CRLH analysis. In both analysis methods, the hosting ferrite TL will be expressed using its medium parameters for simplicity. The propagation constant along the hosting ferrite TL and its characteristic impedance can be expressed in terms of its medium permittivity and permeability as:

$$k = \omega\sqrt{\mu_o\,\mu_f\,\varepsilon_o\,\varepsilon_f} \tag{1-a}$$

$$Z_o = \sqrt{\mu_o\,\mu_f\,/\,\varepsilon_o\,\varepsilon_f} \tag{1-b}$$

Where μ_o and ε_o are the free space permeability and permittivity, respectively, while ε_f is the relative ferrite permittivity, and μ_f is the equivalent relative ferrite permeability of the hosting TL that changes according to the direction of the applied DC magnetic field. The negative permeability of the hosting ferrite TL is equivalent to negative series distributed impedance, instead of the ideal positive distributed impedance, This means that within the frequency band of negative permeability of a ferrite CPW TL, such ferrite TL contributes with a series capacitive parasitic distributed element, instead of the ideal parasitic inductive distributed element, which is a condition for realizing an ideal CRLH TL using TL approach. In other words, the negative permeability of the ferrite TL can play the role of a series capacitor load which is required for realizing LHM using the TL approach. Therefore, a CRLH TL can be theoretically designed using only a shunt inductive load.

A- The periodic analysis of the ferrite CRLH TL

The equivalent circuit approach of a lossless CRLH unit cell can be introduced as shown in Fig. 1. In the equivalent circuit model, the series inductor and the shunt capacitor are corresponding to the RH parameters of the hosting TL while the series capacitor and shunt inductor are corresponding to the loading CRLH elements.

Using periodic analysis, the dispersion equation:

$$\cos(\beta d) = 1 - \frac{\omega^2 d^2}{2}\left[\left(L'_R - \frac{1}{\omega^2 C'_L}\right)\left(C'_R - \frac{1}{\omega^2 L'_L}\right)\right] \tag{2-a}$$

The periodic analysis is applicable for the analysis of a ferrite CRLH TL, with the proper definition of the equivalent relative permeability of the hosting ferrite TL according to the direction of the DC magnetic bias. For simplicity, the periodic length of the unit cells (d) is assumed very small compared to the propagating wavelength such that it tends to be vanished mathematically (d=0). Hence, the dispersion equation can be proved as simplified in[41,42] as:

$$\cos(\beta\, d) = 1 - \frac{1}{2}\omega^2 d^2 \left(\mu_o \mu_f - \frac{1}{\omega^2 C_L\, d}\right)\left(\varepsilon_o \varepsilon_f - \frac{1}{\omega^2 L_L\, d}\right) \tag{2-b}$$

Where β denotes the complex propagation constant of the traveling wave along with the periodic structure. In case the lumped ferrite CRLH TL is designed using only a periodic shunt inductor, the ferrite CRLH TL line can be expressed using the same formula in () with using non-capacitive loading element condition; i.e. CL= ∞.

Also, using the CRLH TL theory, the dispersion equation can be simplified as:

$$\beta = \omega\sqrt{\left(L'_R - \frac{1}{\omega^2 C'_L}\right)\left(C'_R - \frac{1}{\omega^2 L'_L}\right)} \tag{3-a}$$

Also, the ferrite CRLH TL can be analyzed using the CRLH theory. The equivalent circuit of a lossless unit cell of length (d) of ferrite CRLH TL can be expressed using a standard lossless CRLH unit cell shown in Figure 2. 5. In the equivalent circuit, the parasitic inductance (LR) and capacitance (CR) of the hosting ferrite TL are calculated in terms of the ferrite medium permittivity and the equivalent relative ferrite permeability which depends on the DC magnetic bias direction. The series capacitive load (CL) is the contribution of the loading capacitive load and the equivalent capacitance produced by the ferrite TL when the ferrite TL has a negative permeability. Accordingly, the propagation dispersion equation can be defined as[45,46].

$$\beta = \omega \sqrt{\left(\mu_0\, \mu_f - \frac{1}{\omega^2\, C_L\, d}\right)\left(\varepsilon_0\, \varepsilon_f - \frac{1}{\omega^2\, L_L\, d}\right)} \quad \text{(3-b)}$$

III- CRLH Quarter Wavelength Transformer Theory

A conventional quarter wavelength (l = λ/4) TL transformer has an electrical length of Φ = -π/2 at the operating frequency (f1). The performance of the transformer will be repeated at the electrical length of Φ = -n(π/2) or frequencies of fn = n*f1, where n is an odd integer positive number; i.e. the odd harmonics of the first operating frequency.

A practical CRLH TL is a combination of both left-handedness due to the effect of the loading elements and right-handedness due to parasitic elements of the hosting TL medium, hence CRLH TL. As a result, a CRLH TL can achieve arbitrarily designed positive and negative electrical lengths according to the loaded CRLH elements and RH parasitic elements. Hence it can achieve π/2 phase shift or equivalent at arbitrary frequencies which are not a condition to be the odd harmonics of the first operating frequency.

In practice, a CRLH TL transformer is implemented by cascading a practical CRLH TL with a short RH TL section for feeding purposes. Its principle of operation is based on achieving the conventional transformer conditions at arbitrary frequencies that must fall within any passband, either in the CRLH or the RH passbands.

The phase shift of a CRLH TL can be extracted from the phase of the transmission coefficient S21[5] as:

$$\phi_{CRLH} = -\tan^{-1}\left(\frac{\left((\omega/\omega_{se})^2-1\right)(1-\chi/4)/(C_L\, Z_{CRLH}) + \left((\omega/\omega_{sh})^2-1\right) Z_{CRLH}/L_L}{\omega(2-\chi)}\right) \quad \text{(4-a)}$$

Where:

$$\chi = -\left(\frac{\omega}{\omega_R}\right)^2 + \left(\frac{\omega_L}{\omega}\right)^2 - \left(\frac{C_R}{C_L} + \frac{L_R}{L_L}\right) \quad \text{(4-b)}$$

The frequencies ωse and ωsh represent the resonant frequencies of the series and shunt branches of the CRLH TL respectively and are defined as:

$$\omega_{se} = \frac{1}{\sqrt{L'_R\, C'_L}} = \frac{1}{\sqrt{L_R\, C_L}} \quad \text{(4-c)}$$

$$\omega_{sh} = \frac{1}{\sqrt{L'_L\, C'_R}} = \frac{1}{\sqrt{L_L\, C_R}} \quad \text{(4-d)}$$

$$\omega_R = \frac{1}{\sqrt{L_R\, C_R}} \quad \text{(4-e)}$$

$$\omega_L = \frac{1}{\sqrt{L_L\, C_L}} \quad \text{(4-f)}$$

Z_{CRLH} is the characteristic impedance of the CRLH TL. It is defined as[5]:

$$Z_{CRLH} = Z_L \sqrt{\frac{(\omega/\omega_{se})^2-1}{(\omega/\omega_{sh})^2-1}} = Z_R \sqrt{\frac{(\omega_{se}/\omega)^2-1}{(\omega_{sh}/\omega)^2-1}} \quad \text{(5-a)}$$

Where ZR is the characteristic impedance of the hosting CPW TL while ZL is the characteristic impedance of the ideal CRLH TL, and given as:

$$Z_L = \sqrt{\frac{L_L}{C_L}} \quad \text{(5-b)}$$

It can be shown that at low frequencies, ZCRLH is reduced to the CRLH impedance (ZL).

The phase shift of a CRLH TL can be simplified for a balanced CRLH TL; i.e. ω_{se} and ω_{sh} are equal, and assuming that $\omega_L \prec\prec \omega \prec\prec \omega_R$ is close to either ω_{se} or ω_{sh} as[5]:

To match load impedance (Zload) to feeding line impedance (Zline), the input impedance of the proposed transformer TL (Zin) should satisfy the following condition[63]:

$$\phi_{CLRH} = -\beta l = \left(\frac{1}{\omega\sqrt{C_L L_L}} - \omega\sqrt{C_R L_R} \right) \qquad (6)$$

$$Z_{in} = Z_{CRLH} \frac{Z_{load} + j Z_{CRLH} \tan(\phi_{CRLH})}{Z_{CRLH} + j Z_{load} \tan(\phi_{CRLH})} = Z_{line} \qquad \text{(7-a)}$$

The design of a CRLH transformer is based on the first satisfying (π/2) phase shift at the desired frequency. Then, on satisfying the aforementioned phase shift and similar to a conventional quarter wavelength transformer, the designed CRLH TL characteristic impedance value can be obtained using the simple relation

Q1
$$Z_{CRLH} = \sqrt{Z_{line} Z_{load}} \qquad \text{(7-b)}$$

This impedance value must be always satisfied at the same (π/2) phase shift frequencies.

The progressive phase shift and the characteristic impedance of a CRLH TL unit cell, of length d, implemented on a ferrite substrate can be redefined approximately in terms of its medium parameters, the ferrite relative permittivity ε_f, and the relative permeability μ_f, as illustrated in[45,46] to be:

$$\phi_{CRLH} = \omega l \sqrt{\left(\mu_o \mu_f - \frac{1}{\omega^2 C'_L} \right)\left(\varepsilon_o \varepsilon_f - \frac{1}{\omega^2 L'_L} \right)} \qquad (8)$$

$$Z_{CLRH} = Z_L \sqrt{\frac{1 - \omega^2 \mu_o \mu_f C_L d}{1 - \omega^2 \varepsilon_o \varepsilon_f L_L d}} \qquad (9)$$

Where l is the length of the CRLH TL. Because of the dispersive nature of the ferrite medium, the hosting ferrite TL has a dispersive permeability such that the progressive phase shift and the CRLH characteristic impedance are dispersive.

Thus from (8) and (9), both electrical length and the characteristic impedance of the proposed CRLH transformer are dispersive quantities and vary with changing the applied DC magnetic bias.

The operation principles of the CRLH transformer implemented using ferrite substrate as a medium is to make use of these dispersive progressive phase shifts and characteristic impedance such that their combination always fulfills the impedance matching condition in (7-a). In other words, the operation mechanism of the proposed ferrite transformer is not exactly a typical quarter wavelength transformer, i.e., the electrical length *Φ*CRLH will no longer be 90° as the DC bias varies, and the characteristic impedance ZCRLH will also change. But, the overall effect of these changes is that the input impedance Zin will be almost constant for its desired value. As a result, a tunable transformer is expected.

IV- Low Impedance Tunable CRLH Transformer

In this section, we introduce a tunable ferrite CRLH CPW transformer. The objective of this transformer is to match a 25 Ω load to a 50 Ω line with tunable operating bandwidth whose center frequency can be tuned from 2.55 GHz to 3.2 GHz[46].

A- Low-impedance tunable CRLH transformer structure[46]

The layout of the ferrite CRLH CPW transformer is shown in Fig.1 (a). The transformer consists of a one-unit CRLH cell implemented using a series interdigital capacitor and a shunt planar segment line inductor. The detailed sketch for the loading interdigital capacitor is shown in Fig.1 (b). The loading elements' dimensions were chosen to satisfy the desired CRLH TL characteristic impedance in the CRLH passband.

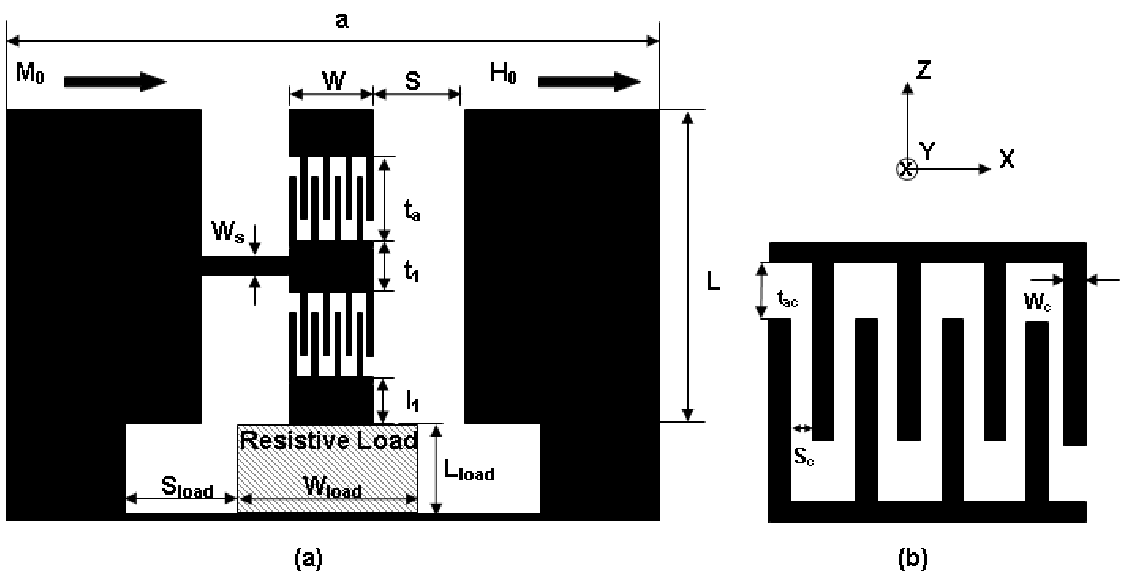

Fig. 1: (a) The layout of the ferrite CRLH CPW low impedance transformer, a = 21 mm, L = 2.25 mm, W = 5.5 mm, t_1 = 0.25 mm, t_a = 1 mm, l_1 = 1 mm ; (b) The detailed geometry of the interdigital capacitor W_c = 0.25mm, S_c = 0.5 mm, and t_{ac} = 0.25 mm[46].

The proposed transformer design was first done by assuming a very high DC magnetic bias applied to the ferrite substrate. At such a high bias, the dispersive properties of the ferrite substrate are very weak at the operating frequency band of interest, i.e., the ferrite substrate can be characterized by its isotropic properties. Accordingly, to meet the design objective of matching the load (25 Ω and the line impedance of 50 Ω at around 3.2 GHz approximately, the CRLH transformer requires a characteristic impedance of 35.35 Ω calculated from the simple relation in (7-b). Also, the progressive phase shift along TL terminals should satisfy the (π/2) phase condition at the desired frequency. These design requirements were fulfilled through the proper selection of both loading and parasitic elements of the proposed CRLH transformer.

The equivalent circuit model of the proposed CRLH transformer TL can be expressed as a conventional lossy CRLH as shown in Fig.2. L_R and C_R are the parasitic inductance and capacitance of the CRLH TL, whereas L_L and C_L are the shunt inductive and series capacitive loads, forming the pure CRLH TL. For the initial design, CL was calculated as suggested in[5] while LL was calculated as explained in[64], and the parasitic RH elements were calculated as explained in[65]. The final values of these elements were extracted through the circuit optimization and were found close to the calculated values as will be shown later.

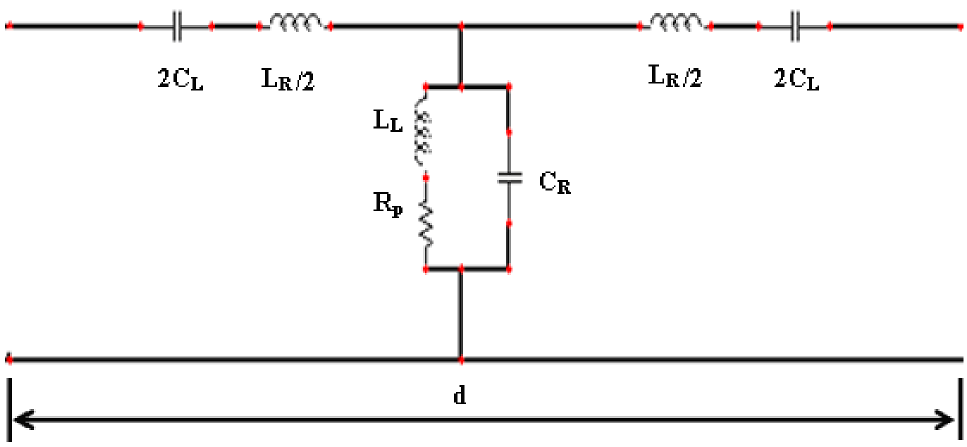

Fig. 2: The lossy CRLH equivalent circuit model of the CRLH transformer TL, C_L = 0.54 pF, L_L = 0.715 nH, L_R = 0.2645 nH, C_R = 2.028 pF, and R_p = 0.05 Ω.

By analytically studying the phase shift of the transmitted scattering parameter (S21) along the proposed CRLH TL calculated from (4-a), it was found that the proposed CRLH TL has a +90° phase shift around 3 GHz. Also, the characteristic impedance of the CRLH TL consisting of the proposed transformer can be calculated from the simple relation introduced in (5-b) to be equal to 35.14 Ω. Thus, as explained in (7-b), it is expected that the transformer can match a 50 Ω line to a 25 Ω load line approximately at 3 GHz at high DC bias, which is close to 3.2 GHz in the design requirement.

B- Low impedance tunable CRLH transformer numerical results

First, the calculated loading and parasitic elements of the transformer were verified through the optimization of the equivalent circuit model, shown in Fig.2, and comparing its response with HFSS simulation results assuming a very high applied DC magnetic bias. In both cases, terminal (1) is 50 Ω whereas terminal (2) is 25 Ω. These comparison results are shown in Fig.3, illustrating the scattering parameters obtained from the equivalent circuit model and HFSS simulations for H_0=50,000 Oe. At this bias, the onset frequency of the negative permeability is shifted up to be greater than 60 GHz which is much higher than the designed frequency band. Therefore, the ferrite substrate within the frequency band of interest can be characterized as an isotropic material. Thus, under this condition, it is accepted to model the ferrite CRLH transformer using its equivalent circuit model. It can be seen from that figure that there is a very good agreement between the circuit model and HFSS simulations.

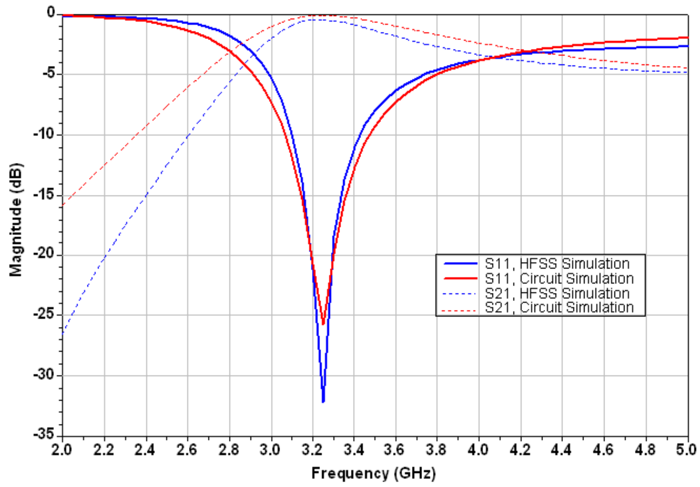

Fig. 3: The simulated scattering parameter magnitudes of the low impedance ferrite transformer, full wave simulation (HFSS) for H_0=50,000 Oe, and circuit model.

The phase shift of the ferrite CRLH TL transformer for H_0 = 50,000 Oe is shown in Fig.4. The figure shows that the TL has a +90° phase shift in the CRLH passband at 3.23 GHz approximately. The return loss and the transmission loss of the transformer terminated with a 25 Ω load is shown in the same figure. The transformer has a minimum return loss of better than 25 dB with an insertion loss of approximately 0.5 dB at 3.23 GHz. It has a 3 dB bandwidth from 2.95 GHz to 4.05 GHz (31%).

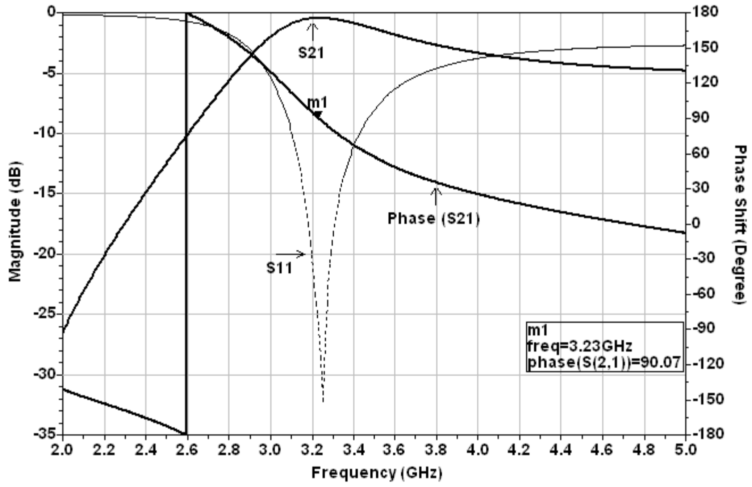

Fig. 4: The full wave simulated scattering parameter (magnitudes and phase) of the low impedance ferrite transformer, H_0= 50,000 Oe.

To illustrate the tuning capability of the ferrite CRLH transformer, two lower DC magnetic bias cases of 1000 Oe and 3000 Oe have been numerically studied as shown in Fig.5. The center frequency of the transformer can be tuned from 2.55 GHz to 2.9 GHz. The return loss is around 20 dB and the insertion loss better than 1 dB in both cases. Also, the operating bandwidth is tuned from 2.35 GHz to 2.95 GHz (23 %) in the first case, to from 2.65 GHz to 3.55 GHz in the second case (29%). However, the fractional bandwidth decreased at lower H_0 compared to the designed high DC magnetic bias, isotropic case.

More DC biases were studied numerically to further investigate the tunability of the transformer. The change of center frequency with the applied DC magnetic bias is shown in Fig.6. As shown, the center frequency of the transformer illustrates nonlinear variation with the applied DC magnetic bias. It increases from 2.55 GHz at H_0 = 1000 Oe to 2.75 GHz at H_0 = 1750 Oe and it decreases to 2.7 at H_0=2000 Oe before it continues increasing toward 3 GHz at H_0 = 4500 constantly up to 5000 Oe.

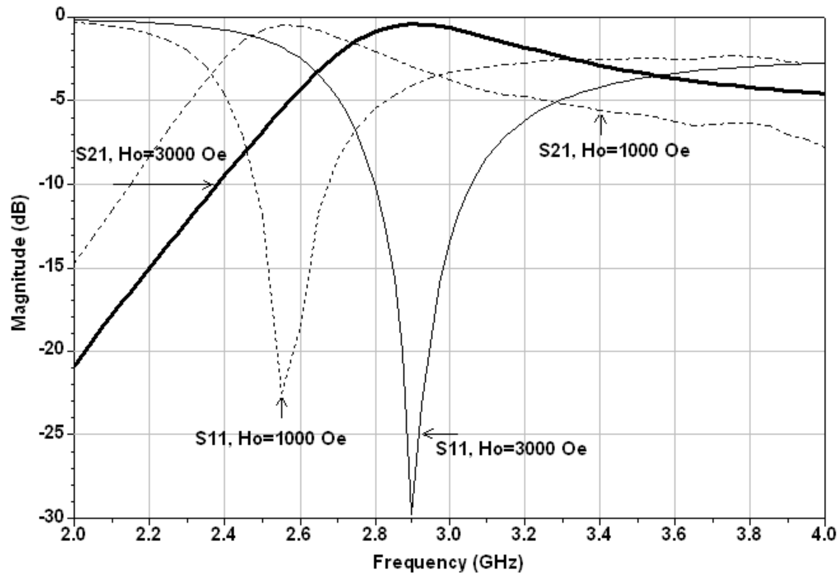

Fig. 5: The full wave simulated scattering parameter magnitudes of the low impedance ferrite transformer for H_0 = 1000 Oe (dotted lines) and H_0=3000 Oe (solid lines).

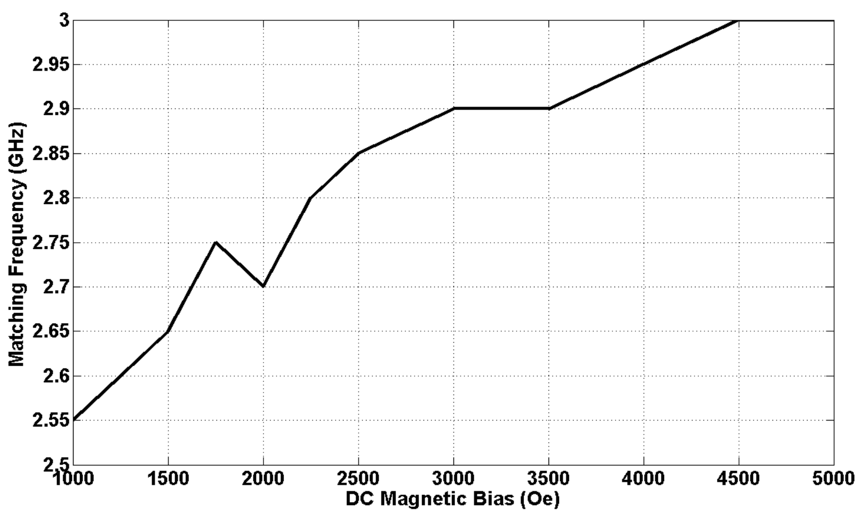

Fig. 6: Variation of the low impedance ferrite transformer center frequency against the applied DC magnetic bias.

Verification of the theoretical concept of the proposed transformer discussed before can be pointed out by studying the input impedance, the dispersion curves, and the characteristic impedance of the CRLH TL transformer for different H_0 values. Firstly, the input impedance of the proposed transformer for the two studied cases in Fig. 5 was calculated numerically and illustrated in Fig.7. The figure shows that the input impedance of the proposed transformer is Z_{in}= 43.943 + j 3.49 Ω at the frequency of 2.55 GHz for H_0= 1000 Oe. This changes to Z_{in}= 47.343 - j 1.732 Ω at the frequency of 2.9 GHz for H_0= 3000 Oe. The proposed transformer demonstrates almost 50 Ω input impedance at two different frequencies which are exactly the two matching points shown in Fig.5. It is worth it to iterate that both the electrical length and characteristic impedance of the transformer should have been altered from their original values (90° and 35.35 Ω, respectively) as the DC bias changes. However, the overall effect is that the input impedance is kept around 50 with various DC biases.

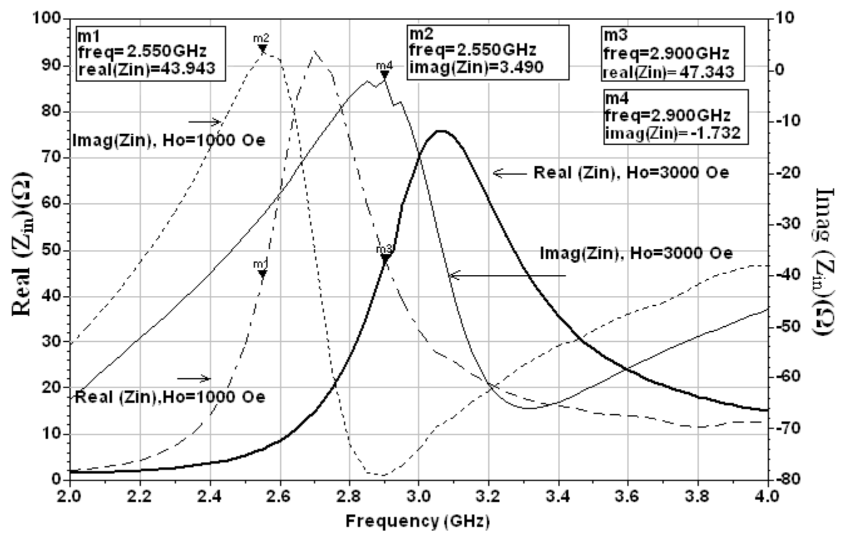

Fig.7: The full wave simulated input impedance of the low impedance ferrite transformer, for H_0 = 1000 Oe (dotted lines) and H_0=3000 Oe (solid lines).

Secondly, the dispersion curves for the proposed transformer were extracted numerically by studying the phase of the transmission coefficient (S21) for different H_0 as shown in Fig. 8. The curves illustrate that the transformer operates in the CRLH passband due to the positive progressive phase shift. Also, they demonstrate that the proposed transformer has different phase shift values at the matching frequencies illustrated for these DC magnetic bias cases which are shown in Fig.6.

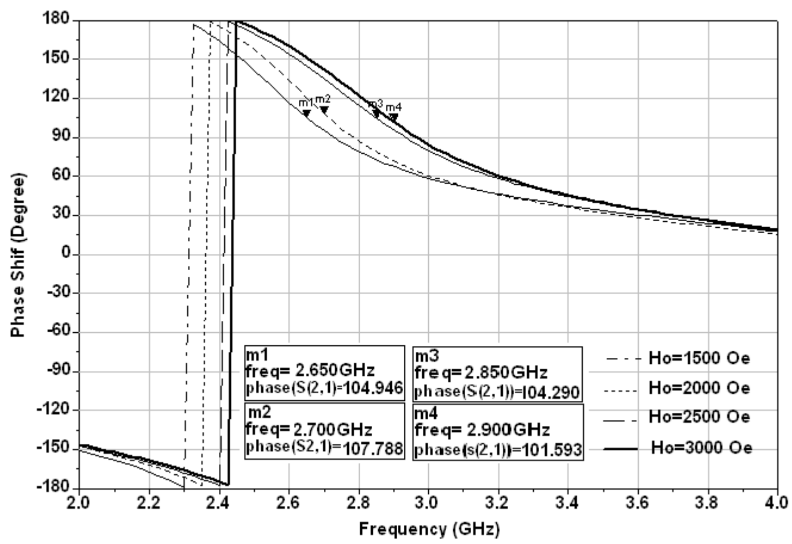

Fig. 8: The full wave simulated dispersion curves of the low impedance ferrite transformer for different DC magnetic biases.

Thirdly, as explained analytically above in (9), the value of the characteristic impedance of the proposed transformer depends on the ferrite permeability which changes by varying the DC magnetic bias. This characteristic impedance was calculated for different DC magnetic bias values of H_0=1500 Oe, 2000 Oe, 2500 Oe, and 3000 Oe and plotted in Fig. 9. The figure shows that the proposed transformer exhibits a varying real part impedance, corresponding to the propagation passband, and imaginary part, corresponding to the stopband, according to the applied DC magnetic bias. In all studied cases, the variation of the characteristic impedance depends on the dispersive relative permeability. However, the values of the characteristic impedance are approximated but it still demonstrates the main idea of its dependence on the applied DC magnetic bias.

Finally, it can be concluded that the tuning capability of the transformer can be explained due to the dispersive nature of the relative permeability of the hosting ferrite CPW TL. As a consequence of changing the applied DC magnetic bias, both the characteristic impedance of the ferrite CRLH CPW TL and the progressive phase shift are varied such that the transformer can satisfy the same designed input impedance at different frequencies.

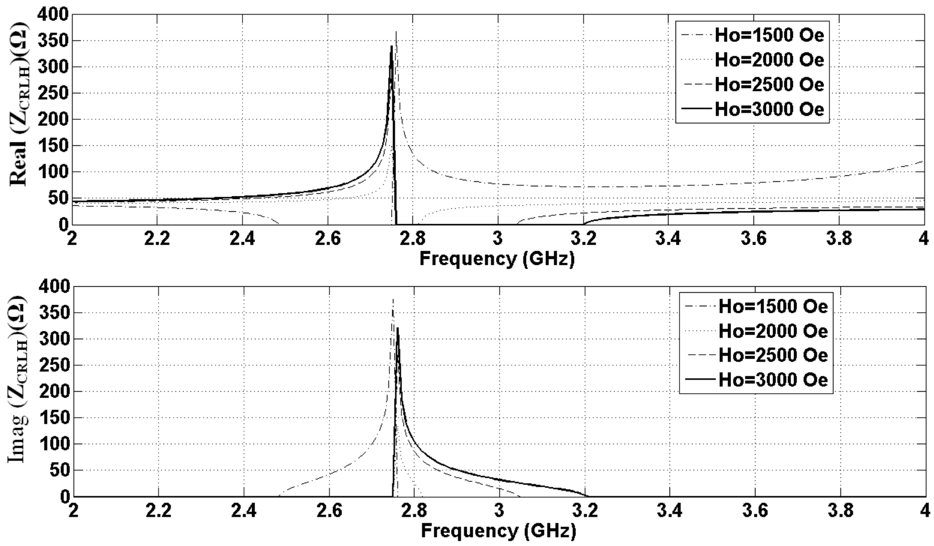

Fig. 9: The calculated characteristic impedance of the low-impedance ferrite transformer for different DC magnetic biases

In summary, a novel tunable ferrite CRLH CPW TL transformer has been proposed and verified numerically. The CRLH CPW TL is composed of CPW TL loaded with a unit cell of interdigital capacitor and shunt segment inductor loads on a ferrite substrate. The performance of the proposed transformer has been designed using its equivalent circuit model and verified using numerical simulations employing HFSS. The numerical results confirm that the transformer can match a 25 Ω load and a 50 Ω line with tunable nature for both the whole bandwidth and its center operating frequency by changing the applied DC magnetic bias. The transformer center frequency can be tuned from 2.55 GHz to 3.2 GHz. The return loss at the center operating frequency is smaller than 20 dB with insertion loss better than 1 dB. The proposed transformer has a compact size at its operating frequency, showing a 64 % size reduction in comparison with the RH transformer within the same operating frequency band.

V- High Impedance Tunable CRLH Transformer

In this section, a tunable CRLH transformer with higher impedance, compared to the previously reported one is studied[59]. The currently proposed transformer type is designed to match a load of 200 Ω to a 50 Ω line and its center frequency can be tuned from 2.8 GHz to 4 GHz.

A- High-impedance tunable CRLH transformer structure[66].

The employed CRLH TL layout in the design of the high-impedance ferrite CRLH CPW transformer is shown in Fig.10 (a). It consists of one unit cell CRLH implemented using a series air gap capacitor and a shunt meandered line inductor. The detailed sketch for the loading shunt meandered line inductor is shown in Fig.10 (b).

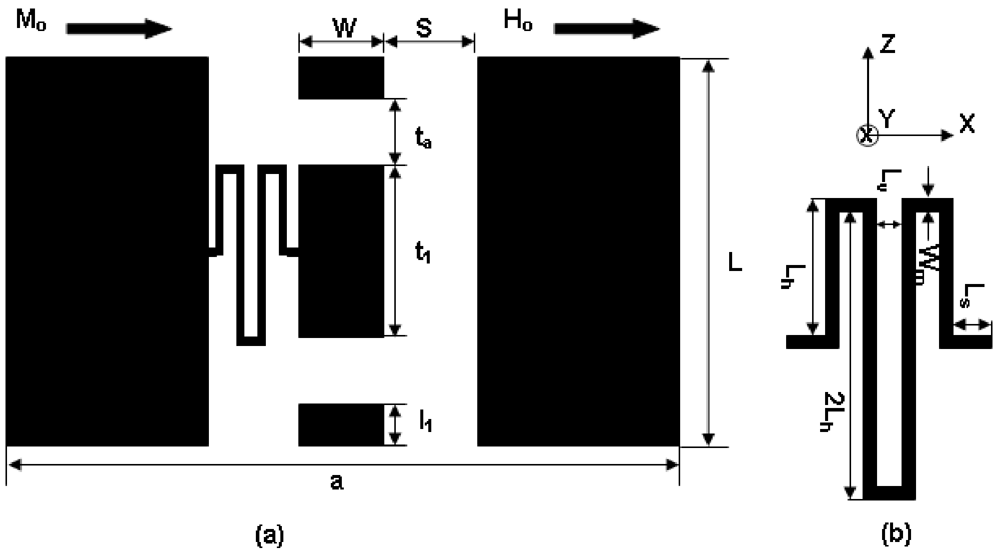

Fig. 10: (a) The layout geometry of the ferrite CRLH CPW high impedance ferrite transformer a=32.75 mm, L= 2.4 mm, W=1.8 mm, t_1 =0.4 mm, t_a =0.5 mm, l_1=0.5mm (b) The detailed geometry of the meandered line inductor W_m=0.05mm, L_s=0.357 mm, L_h=0.6 mm, and L_v=0.475 mm[66].

Similarly, to the design procedures explained in the previous type, the proposed CRLH transformer design was done assuming a very high DC magnetic bias applied to the ferrite substrate such that it is only characterized by its isotropic electric properties only within the operating frequency band of interest. Hence the desired CRLH TL characteristic impedance can be calculated as given in (7-b). Since the proposed ferrite CRLH transformer was designed to match a 200 Ω load to 50 Ω line at frequency 3.45 GHz, considering the high DC magnetic bias condition, therefore, it was designed to have a +90^o phase shift at its terminal output and its characteristic impedance is 100 Ω as calculated from (7-b) to meet these design requirements. Similar to the first introduced transformer, these design requirements were satisfied through the proper selection of both loading and parasitic elements of the proposed CRLH transformer.

The equivalent circuit of the proposed CRLH transformer can be expressed using the equivalent circuit introduced in Fig.2 with the loading and parasitic elements values of CL = 0.18 pF, L_L = 1.87 nH, L_R =1.7 nH, C_R =0.67 pF, and R_P = 0.35 Ω.

Based on these values, the phase shift of the transmitted scattering parameter (S21) along the proposed CRLH TL calculated from (4-a) has a +90^o phase shift of around 3.55 GHz. The characteristic impedance of the CRLH TL forming the proposed transformer was calculated from (5-a) to be equal to 101.65 Ω. Thus, as explained in (7-b), this transformer can match a 50 Ω line to a 200 Ω load very close to 3.45 GHz at high DC bias.

B- High impedance tunable CRLH transformer numerical results

First, the loading and parasitic elements of the transformer were verified similarly explained for the former low-impedance CRLH transformer. Hence, the comparison results between the equivalent circuit optimization and the transformer simulation using HFSS for H_0=50,000 Oe are shown in Fig.11. The figure illustrates a very good agreement between the scattering parameters obtained from both simulation results.

The phase shift of the ferrite CRLH TL transformer by applying a very high DC magnetic bias of H_0 = 50,000 Oe, as explained before, is shown in Fig.12. The figure shows that the TL has an almost 90^0 phase shift in the CRLH passband at 3.5 GHz. The return loss and the transmission loss of the transformer terminated with a 200 Ω load is shown in the same figure. The transformer has a minimum return loss of better than 25 dB with very closer to 0 dB insertion loss at 3.5 GHz. Also, it has a 3 dB bandwidth from 3.05 GHz to 4.4 GHz (36%).

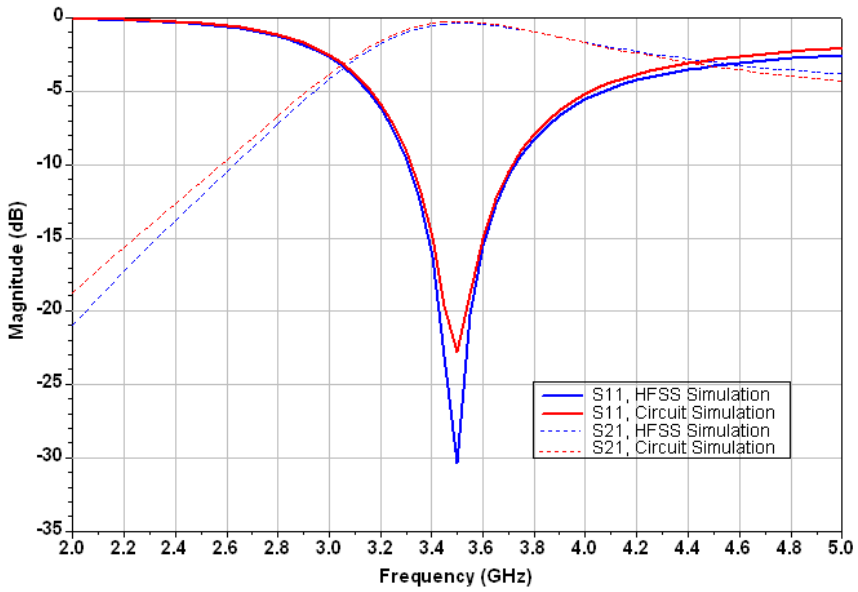

Fig. 11: The simulated scattering parameter magnitudes of the high impedance ferrite transformer, full wave simulation (HFSS) for H_0=50,000 Oe, and circuit model.

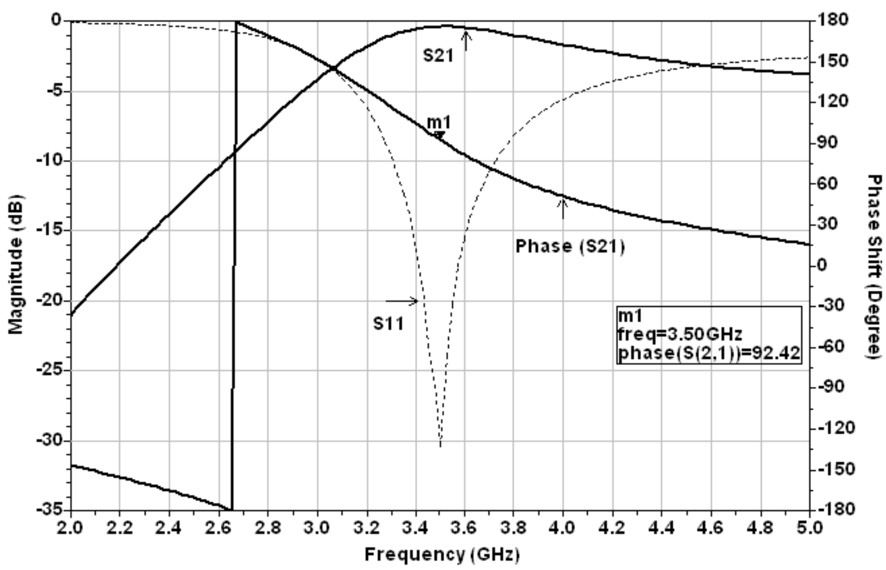

Fig. 12: The full wave simulated scattering parameter (magnitudes and phase) of the high impedance ferrite transformer, H_0= 50,000 Oe.

To illustrate the tuning capability of this proposed ferrite CRLH transformer, two lower DC magnetic bias cases of 1000 Oe and 3000 Oe have been numerically studied as shown in Fig.13. The operating frequency of the transformer can be tuned from 2.8 GHz in the first case to 3.35 GHz in the second case with a return loss of better than 15 dB and insertion loss of almost 0.5 dB in both cases. Also, the operating bandwidth is tuned from 2.55 GHz to 3.1 GHz (20 %) in the first case, to from 2.95 GHz to 4.2 GHz (35%) in the second case.

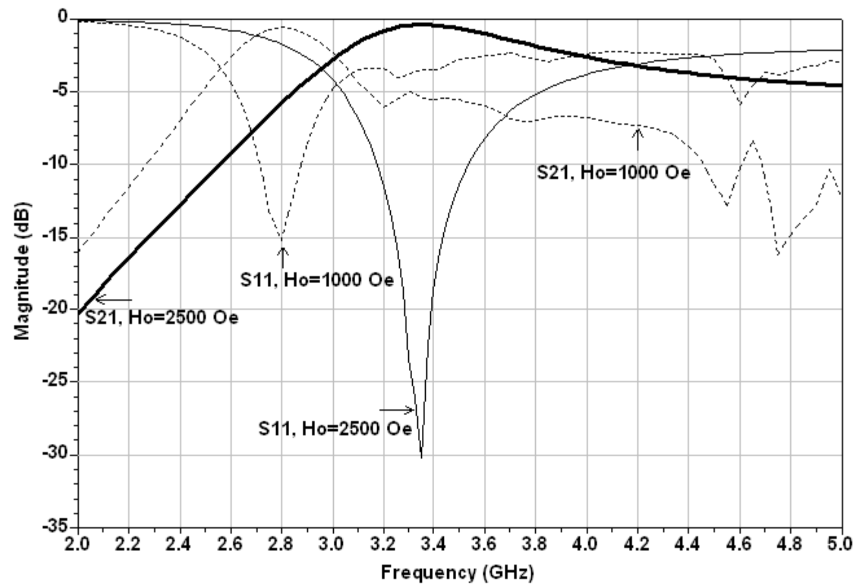

Fig. 13: The full wave simulated scattering parameters of the high impedance ferrite transformer for H_0 = 1000 Oe (dotted lines) and H_0=3000 Oe (solid lines).

For these two studied cases of H_0, the input impedance of the proposed transformer was calculated numerically and illustrated in Fig. 14. The figure shows that the input impedance of the proposed transformer is Z_{in}= 53.232 + j 15.218 Ω at the frequency of 2.8 GHz for H_0= 1000 Oe. This changes to Zin= 52.842 + j 1.392 Ω at the frequency of 3.55 GHz for H_0= 3000 Oe. The proposed transformer demonstrates almost 50 Ω input impedance at two different frequencies which are exactly the two matching points shown in Fig. 13.

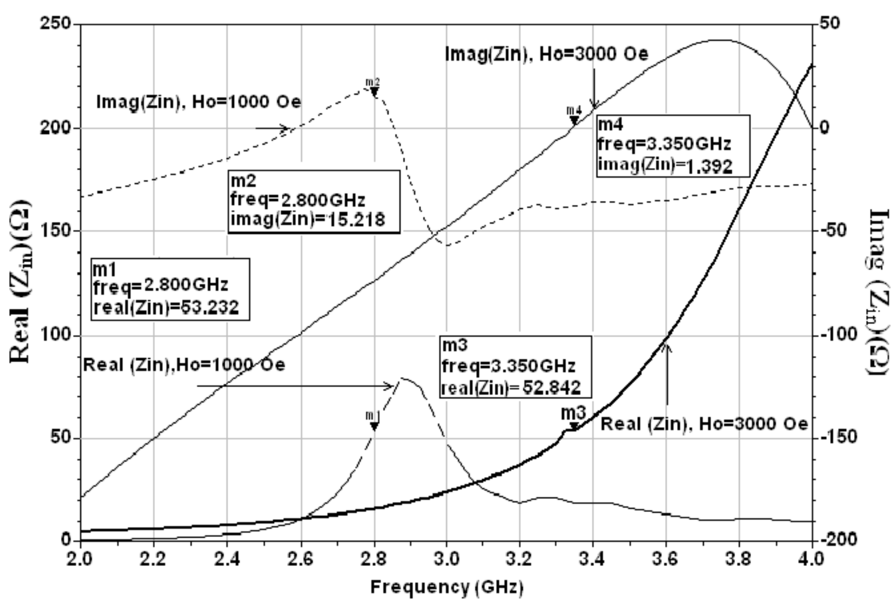

Fig. 14: The full wave simulated input impedance of the high impedance ferrite transformer for H_0 = 1000 Oe (dotted lines) and H_0=3000 Oe (solid lines).

Finally, by further increasing the DC applied bias, the tunability of the transformer becomes clearer. The change of center frequency of the transformer against the DC bias is shown in Fig.15. As shown in the figure, the transformer center frequency has a nonlinear variation with the applied DC magnetic bias. It increases from 2.8 GHz at H_0 = 1000 Oe to 4 GHz at H_0 = 1500 Oe and decreases to 3.05 GHz at 2000 Oe. Then, this increase/decrease process repeats two times with small frequency variations steps. Finally, the matching frequency reaches 3.4 GHz at 4500 Oe and continues constantly up to 5000 Oe.

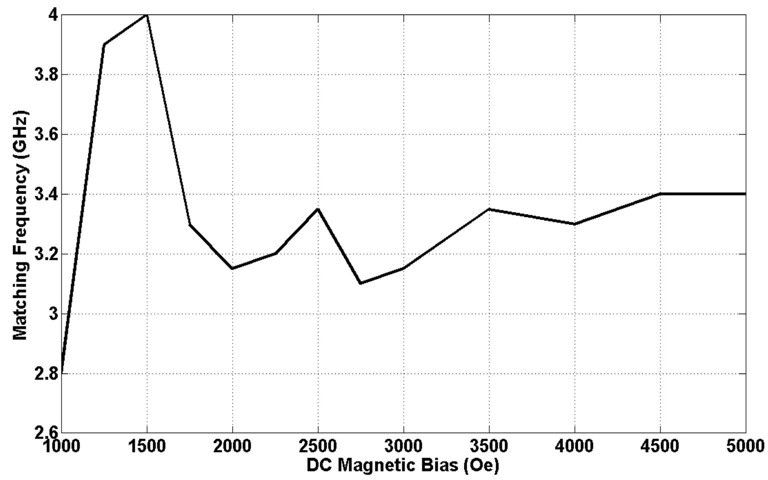

Fig. 15: Variation of the high impedance ferrite transformer center frequency against the DC magnetic bias.

In summary, a high impedance and compact ferrite tunable CRLH CPW TL transformer has been introduced. The CRLH CPW TL transformer has been designed using simple series air gap capacitors and a shunt meandered line inductor. The proposed transformer has been studied analytically and numerically. The numerical results confirm that the transformer can match a 200 Ω load and a 50 Ω line whose whole bandwidth can be tuned and whose center frequency changes from 2.8 GHz to 3.4 GHz by changing the applied DC magnetic bias. The proposed transformer size is only 2.4 mm which is approximately a 78% reduction in conventional RH transformer length operating within the same frequency band.

VI- Wide Band Tunable CRLH transformer

In this section, we introduce a compact wideband tunable ferrite CRLH CPW transformer. The transformer is designed to match a load of 25 Ω to a 50 Ω line with tunable wide operating bandwidth (more than 64%) [60]. The tuning of the proposed transformer is obtained by tuning its lower cut-off frequency and hence, its center operating frequency.

A- Wideband tunable CRLH transformer structure[67]

The CRLH TL layout used in the wideband ferrite CRLH CPW transformer design is shown in Fig. 16 (a). It consists of a CRLH unit cell formed by a series of air gap capacitors and a shunt meandered line inductor whose detailed sketch is shown in Fig.16 (b).

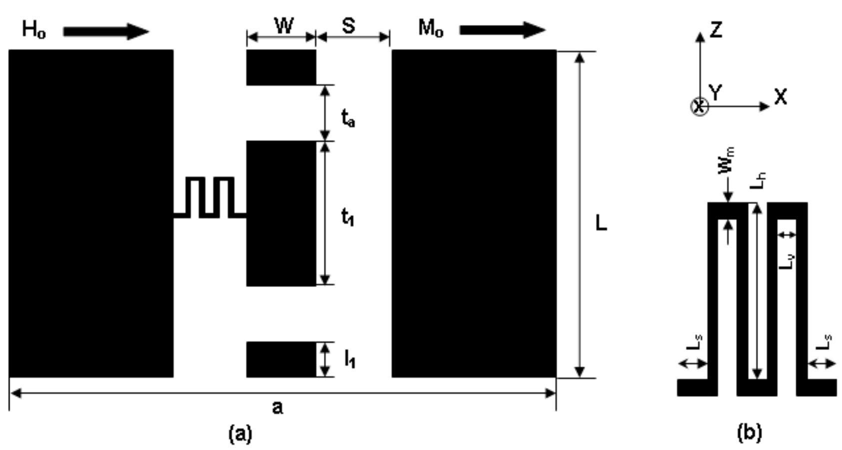

Fig. 16: (a) The layout geometry of the ferrite CRLH CPW transformer a=30 mm, L=1.7mm, W=1.8 mm, l_1=0.5 mm, t_a =0.1 mm, t_1 =0.5 mm (b) The detailed geometry of the meandered line inductor W_m=0.05 mm, L_s=0.35 mm, L_h=0.35 mm, and L_v=0.4 mm[67].

The design of the current transformer was done similarly to the two former transformers' design procedures. The extra design objective in this transformer is to introduce wider operating bandwidth which has been realized by circuit parameter optimizations. The proposed ferrite CRLH transformer is required to match a 25 Ω load to 50 Ω line at center frequency 4.25 GHz, considering the high DC magnetic bias condition, therefore, it was designed to have +90° phase shift at its terminal output and its characteristic impedance is 35.35 Ω as calculated from (7-b), at the center frequency, to meet these design requirements. The proposed wideband CRLH transformer can be modeled using the lossy CRLH equivalent circuit as shown previously in Fig.2. Instead, the current loading and parasitic elements values are as follow, C_L = 0.45 pF, L_L = 0.59 NH, L_R =1.15 NH, C_R =1.2 pF, and R_P = 0.01Ω. Using these values, the forming CRLH transformer TL demonstrates a +90° phase shift of the transmitted scattering parameter (S21) around 4.1 GHz calculated from (4-a). Also, its characteristic impedance is 36.2 Ω calculated from (5-b). Thus, as explained in (7-b), this transformer TL can match a 50 Ω line to a 25 Ω load approximately around 4.1 GHz at high DC bias.

B- Wideband tunable CRLH transformer numerical results

The simulated scattering parameters obtained from HFSS for H_0=50,000 Oe and the optimization result of the transformer equivalent circuit model are shown in Fig.17. It can be seen that there is a good agreement between the two simulations which confirms the previously calculated analytical design.

However, there is a 2 dB to 4 dB variation difference between the two simulations for (S11) level at frequencies higher than 5 GHz. But this does not violate the passband propagation confirmed from the agreement for (S21) which is almost -0.5 dB within this band.

The phase shift of the scattering parameter (S21) of the proposed ferrite CRLH TL for H_0 = 50,000 Oe is shown in Fig.18, using the right vertical axis. The figure shows that the TL has a +90° at 4.25 GHz. Then transmission scattering parameters of that TL for the same DC magnetic bias and connecting a 50 Ω line and terminating with a 25Ω load is shown in the same figure on the left vertical axis. The proposed transformer has a minimum return loss at 4.25 GHz and the CRLH TL transformer has a +90° phase shift at its output terminals. Also, the figure shows that the proposed transformer has a wide operating frequency whose 3 dB transmission coefficient bandwidth extends from 3.6 GHz to 15.8 GHz (79.5 %). Within this operating bandwidth, the reflection coefficient is better than -10 dB.

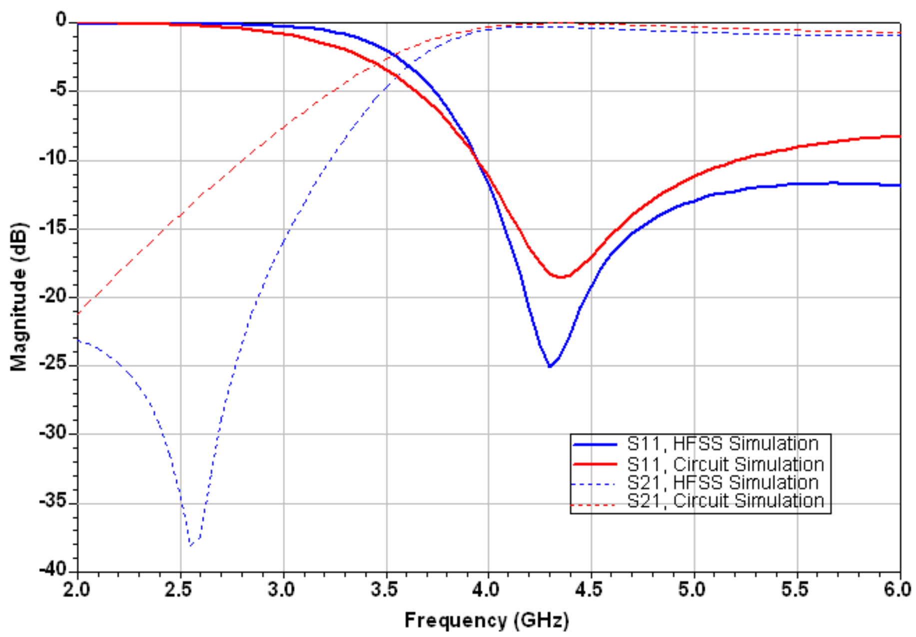

Fig. 17: The simulated scattering parameter magnitudes of the wideband ferrite transformer, full wave simulation (HFSS) for H_0=50,000 Oe, and circuit model.

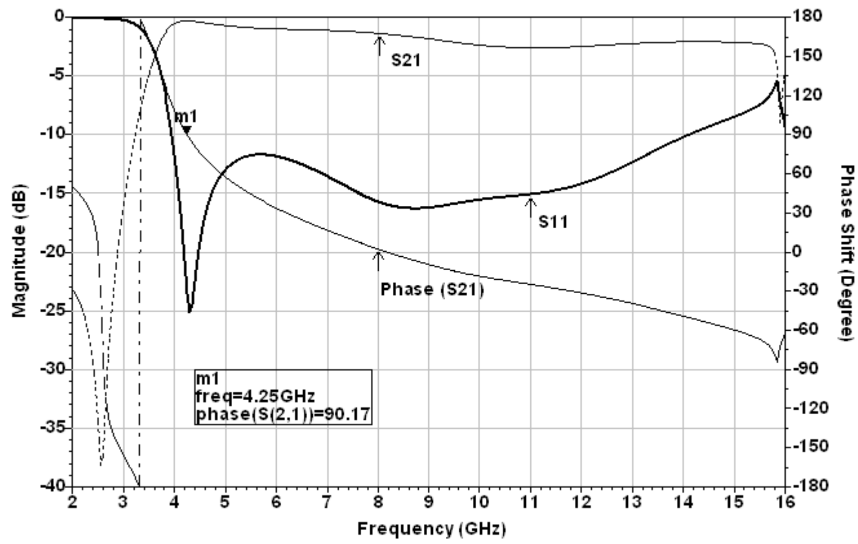

Fig. 18: The full wave simulated scattering parameter (magnitudes and phase) of the wideband ferrite transformer for H_0= 50,000 Oe.

From the previous two transformers, changing the applied DC magnetic bias results in tuning their cut-off frequencies. This concept can be used to design a wideband ferrite transformer. The upper cut-off frequency of the current transformer type was set by the selection of the minimum applied DC magnetic bias value. Therefore, the upper cut-off frequency of the current transformer is the onset of the lossy propagation within the negative ferrite permeability frequency band. Accordingly, to set up the upper cut-off frequency to 7 GHz, the applied DC magnetic bias values are greater than 2000 Oe. The simulated scattering parameters of the proposed CRLH transformer are for H_0= 2000 Oe, 2250 Oe, and 2500 Oe as shown in Fig.19. Both the lower cut-off and operating center frequencies of the transformer are increasing by increasing H_0. On the other hand, the upper cut-off frequency is kept constant at 7 GHz. Within the operating bandwidth, the insertion loss is close to 0 dB at its perfect matching, center, and frequency while it increases to no more than 1.5 dB over the rest bandwidth. On the other hand, return loss is close to 20 dB at the perfect matching frequencies while its worst-case value, over the whole operating bandwidth, is 8 dB, at which the insertion loss is 1.2 dB which still satisfies a reasonable transformer operation condition.

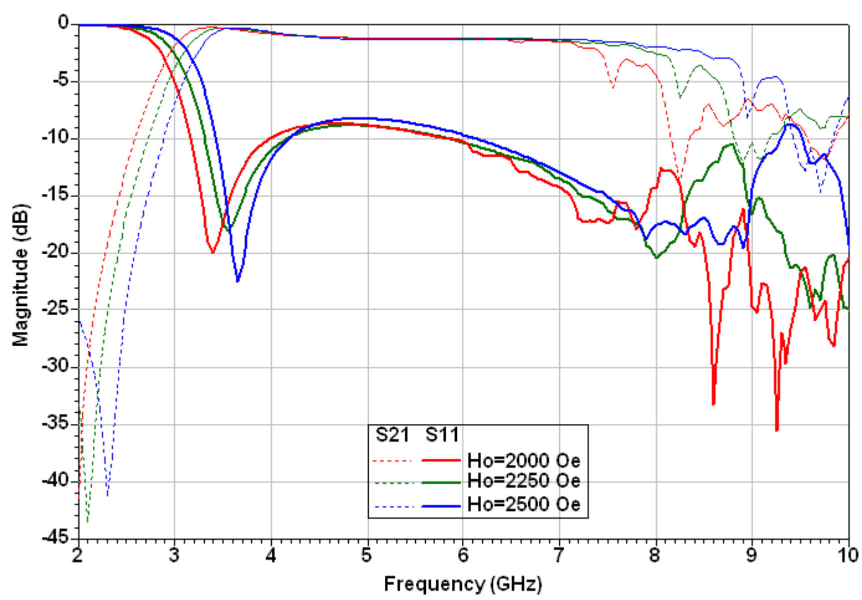

Fig. 19: The full wave scattering parameters magnitudes of the wideband ferrite transformer for different H_0 values

The variation of the center operating frequency and lower cut-off frequency against the applied DC magnetic bias value are shown in Fig. 20. As shown in the figure, these quantities demonstrate almost linear variation with the applied DC magnetic bias. The center matching frequency increases with increasing the DC magnetic bias from 3.4 GHz at H_0=2000 Oe to 3.65 GHz at H_0=2500 Oe and keeps constant for higher DC magnetic bias up to 3500 Oe. It decreases a little to 3.6 GHz at 4000 Oe and then it re-increases to 3.9 GHz at 5000 Oe. The lower cut-off frequency has a similar change against the DC magnetic bias. Its starts with 2.95 GHz at H_0=2000 Oe (81% fractional bandwidth) and ends at 3.35 GHz for H_0=5000 Oe (70 % fractional bandwidth).

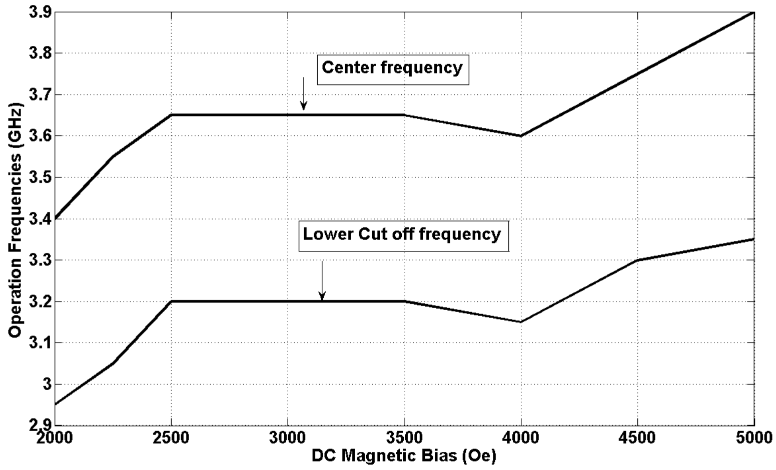

Fig. 20: Variation of the wide band ferrite transformer operational frequencies against the DC magnetic bias.

In a summary, a novel tunable ferrite CPW CRLH wideband transformer has been proposed and verified numerically. The CRLH transformer has been designed using simple series air gap capacitors and a shunt meandered line inductor. The performance of the proposed transformer has been explained numerically using HFSS. The numerical results confirm that the transformer can match a 25 Ω load and a 50 Ω line with tunable nature over a wide bandwidth (more than 64%) by changing the applied DC magnetic bias.

VII- Dual Band Tunable CRLH transformer[52]

In this section, we introduce a dual-band tunable CRLH CPW transformer designed on a ferrite substrate[52]. The objective of this transformer is to match a load of 150 Ω to 50 Ω lines with tunable and dual-band multifunctional operation centered in the frequency range of 2.35 GHz to 3.85 GHz.

A- Dual-band tunable CRLH transformer structure

The layout of the proposed CRLH CPW transformer on a ferrite substrate is shown in Fig. 21 (a) which shows that the transformer consists of two unit CRLH cells implemented using a series air gap capacitor and a shunt meandered line inductor. The detailed sketch for the loading shunt meandered line inductor is shown in Fig. 21 (b). The dimensions of the loading elements were chosen to satisfy the desired impedance in the CRLH passband as explained later.

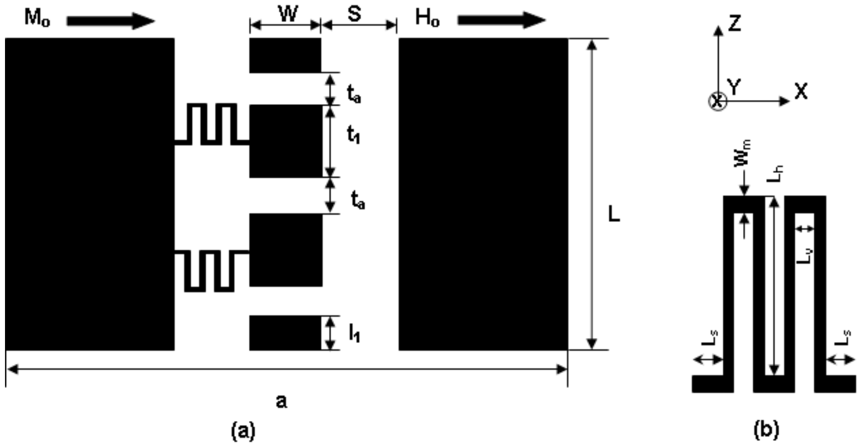

Fig. 21: (a) The layout geometry of the ferrite CRLH CPW dual band transformer a=35 mm, L=6.52mm, W=1.8mm, t_1 =2 mm, t_a =0.5 mm, l_1=0.5mm (b) The detailed geometry of the meandered line inductor W_m=0.05mm, L_s=0.45mm, L_h=0.95mm, and L_v=0.5mm [52].

At the design conditions, the proposed transformer was designed to match perfectly a 150 Ω load to 50 Ω TL at two arbitrary center frequencies selected to be 2.7 GHz and 3.8 GHz. Therefore, considering the high DC magnetic bias condition, the proposed transformer was designed to have a characteristic impedance is 86 Ω as calculated from (7-b) and illustrates 90^o, or equivalent, phase shift at its terminal output at the two desired centers frequencies. The two operating frequencies of this transformer were designed within the CRLH passband.

B- Dual-band tunable CRLH transformer numerical results

The phase shift of the transmission scattering parameter (S21) of the proposed ferrite CRLH TL for H_0 = 50,000 Oe is shown in Fig. 22 using the right vertical axis. As shown in the figure, the TL has a 2700 unwrapped phase shift, equivalent to a -90^0 phase shift, between 2.65 GHz and 2.7 GHz and it has a +90^0 phase shift between 3.8 GHz and 3.85 GHz. Hence the two operating frequencies are within the CRLH passband.

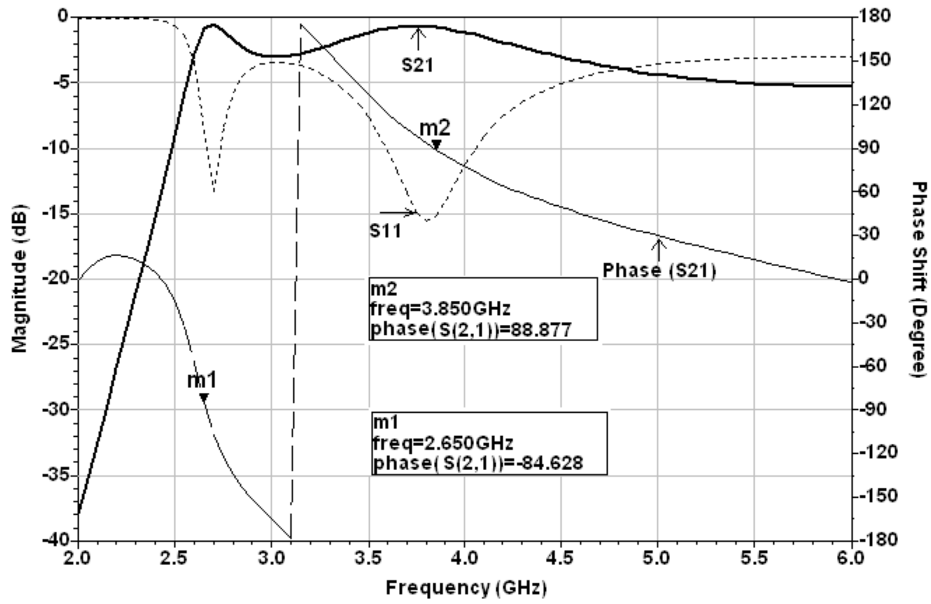

Fig. 22: The full wave scattering parameter (magnitudes and phase) of the dual-band ferrite transformer for H_0= 50,000 Oe.

Then transmission scattering parameters of the proposed CRLH transformer connecting a 50 Ω line to a terminating load of 150 Ω for the same DC magnetic bias are shown in the same figure using the left vertical axis. The proposed transformer matches the load to the line with a minimum return loss of better than 16 dB at 3.8 GHz, the primary operating frequency, and better than 10 dB close to 2.7 GHz, the second operating frequency. These two frequencies are identical to those frequencies around which the used CRLH TL illustrates 90^o phase shift at its output terminals. In both cases, the transmission coefficient is close to 0 dB. The proposed transformer illustrates dual operating bands around its primary and secondary center operating frequencies. The primary band has reasonable bandwidth that extends approximately from 3.25 GHz to 4.75 GHz. On the other hand, the secondary band has a narrow bandwidth due to the fast variation of the phase of (S21) in the right-hand axis around the second operating frequency. A narrow overlap between the two separated bands results in a narrow imperfect matching bandwidth between 3 GHz and 3.25 GHz.

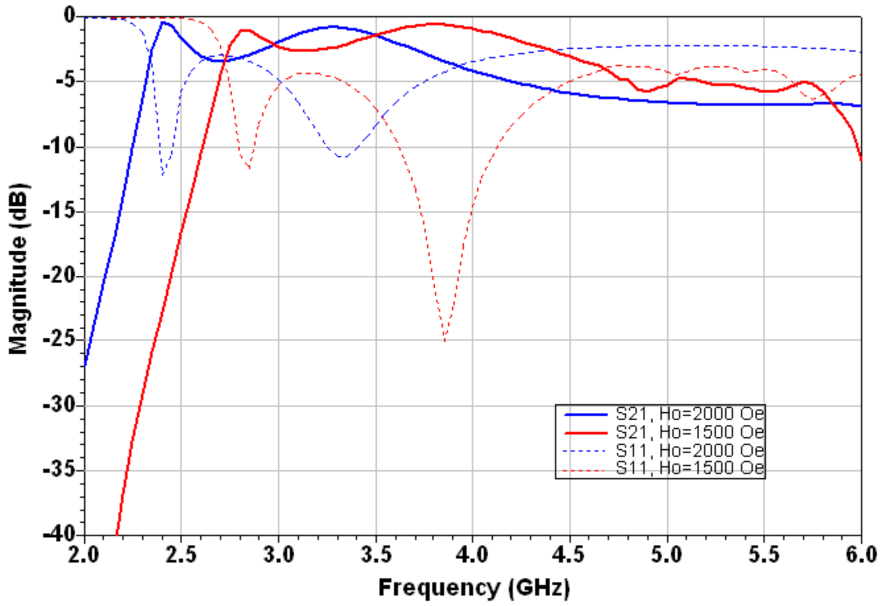

Fig. 23: The full wave scattering parameter magnitudes of the dual-band ferrite transformer for H_0=1500 Oe and H_0=2000 Oe

The tuning capability of the proposed left-handed transformer can be illustrated numerically for different lower DC magnetic bias values of 1500 Oe and 2000 Oe as shown in Fig.23. It can be seen that the proposed transformer still has dual-band operation. The secondary frequency is tuned from 2.4 GHz to 2.85 GHz while the primary operating frequency is tuned from 3.3 GHz to 3.85 GHz for H_0= 2000 Oe and 1500 Oe respectively.

To further study the effects of DC bias H_0 from 1000 Oe to 5000 Oe was applied to the transformer. It is found that the two matching frequencies illustrate a nonlinear variation with the applied DC magnetic bias as shown in Fig. 24. It can be seen that both of them increase by increasing H_0 from 1000 Oe until 1500 Oe then they are almost constant by increasing H_0 to 1750 Oe before they decrease by more increasing of H_0 till 2000 Oe. By further increasing H_0, both frequencies start to increase slightly to approach the designed values assuming high DC magnetic bias is applied shown in Fig. 22.

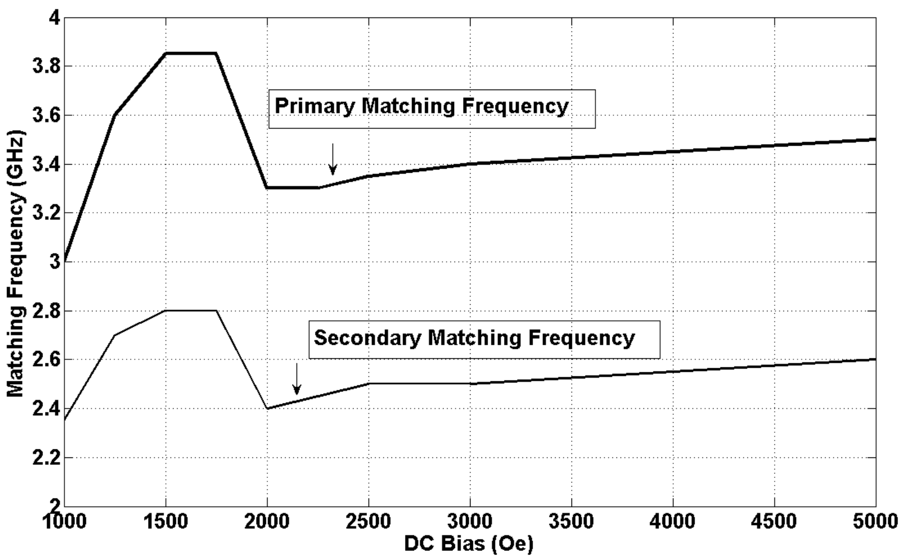

Fig. 24: The change of the primary and secondary matching frequencies against the applied DC magnetic bias.

In summary, a tunable dual-band compact CPW CRLH transformer has been presented and verified numerically. It has been confirmed that the proposed transformer has tunable performance with two operating bands over the frequency bandwidth from 2.35 GHz to 3.85 GHz and with a return loss of better than 10 dB in all cases.

VIII- CONCLUSION

Different compact sizes and tunable ferrite CRLH CPW quarter wavelength impedance transformer types are introduced. A conventional tunable CPW quarter wavelength impedance transformer will require at least 7 mm – 10 mm length to satisfy the predesigned characteristic impedances of former transformer TLs at 4 GHz. Compared to our proposed ferrite CRLH CPW transformers, the length of each one does not exceed 2.5 mm which demonstrates the reduction of size. Also, the proposed dual-band tunable transformer is a unique transformer, with only a 6.5 mm length, which can not be achieved using any conventional ferrite or dielectric CRLH transformer. All the proposed ferrite transformers types were designed using horizontally magnetized ferrite substrates to have the advantage of their small demagnetization factors. The tunable nature of these impedance transformers was achieved by varying the applied DC magnetic bias. The theoretical concepts of tunable ferrite CRLH quarter wavelength transformer are explained and verified using full-wave simulations. It has been pointed out, and verified numerically, that each proposed ferrite transformer type can maintain the designed input impedance at the different operating frequencies to be constant with changing the DC magnetic bias. This functionality is due to the contribution of the two varying quantities, the ferrite CRLH TL characteristics impedance and the progressive phase shift along the ferrite CRLH TL at the operating center frequency.

The detailed operation of each proposed transformer has been explained using its equivalent circuit model and ferrite principles. All transformers can introduce the good impedance-matching performance. In most studied cases, the return loss is better than 20 dB and the insertion loss is approximately 1 dB at the center operating frequencies. Also, all transformers can show a very huge size reduction in comparison with RH transformers within the same operating frequency band, up to 78 % in some cases.

The first tunable ferrite transformer formed using only one CRLH unit cell is designed to match low load impedance, 25 Ω, to a 50 Ω line. The whole operating bandwidth of this transformer can be tuned. The center frequency can be tuned from 2.55 GHz to 3.2 GHz. The second tunable ferrite transformer, formed using only one CRLH unit cell, is designed to match high load impedance, 200 Ω , to a 50 Ω line. Also, the whole operating bandwidth of this transformer can be tuned. The center frequency can be tuned from 2.8 GHz to 3.4 GHz. The third proposed tunable transformer has a wider bandwidth, also formed using only one CRLH unit cell. The results show that the transformer can match a 25 Ω load to a 50 Ω line over a wide bandwidth (more than 64%). Finally, a tunable dual-band compact CPW CRLH transformer has been presented. This transformer was designed using two CRLH unit cells. The numerical results confirm that the two operating bands of the proposed transformer can be tuned. The proposed transformers can have practical applications in a variety of microwave subsystems.

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