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Effect of Negative refractive index of Metamaterials on filter performance

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Abstract

This paper is devoted to study the effect of the negative refractive index of the Metamaterials (MTM) on the filters' performance. Two filters are used, third and fifth order low pass filter using stepped impedance technique with MTM unit cell replacing the low impedance line to enhance the roll off factor of the filters. The filters are implemented and fabricated on FR4 with operating bands till 1.9 GHz. The roll off factor of the third and fifth order filters is 89.375 dB/GHz and 48.125 dB/GHz respectively. The study of the negative refractive index conducts a good agreement between the transmission bands of the filters with the band of mutual negative permittivity and permeability of the MTM unit cell.

Keywords—*low pass filters; negative; permeability; permittivity; plasma frequency; refractive index; resonant frequency; SRR.*

I. Introduction

Metamaterials (MTMs) are materials that gain their properties from the structures they are made of rather than the matter that composes them. They have unusual properties due to the negative refractive index property [1,2].

Metamaterials have both negative permittivity (ε) and permeability (μ) resulting in the negative value of the refractive index so the electric field, the magnetic field and the propagation direction of the wave follow the left handed rule. Possessing negative permittivity or permeability leads to the presence of an evanescent mode and so no transmission occurs, however, when both properties are mutually negative, the so called Double Negative material (DNG) is now a backward material and propagation of the mode is possible [3-7].

This article presents the effect of negative refractive index on the response of third and fifth orders low pass filter. The filter is implemented using stepped impedance method incorporating MTM unit cell of rectangular Split Ring Resonator.

The MTM unit cell replaces the low impedance line of the conventional stepped impedance filter to enhance the roll off factor of the filter as presented in [9].

II. Basic formulas:

Using Lorentz model, the formulas for the permittivity and the permeability can be derived according to Eqs. (1, 3) respectively with the real permittivity given in Eq. (2) [8].

$$\epsilon_r = 1 + \frac{{\omega_p}^2}{{\omega_0}^2 - \omega^2 - j\omega\Gamma} \qquad (1)$$

$$\epsilon'_r = 1 + {\omega_p}^2 \frac{{\omega_0}^2 - \omega^2}{({\omega_0}^2 - \omega^2)^2 + \omega^2\Gamma^2} \qquad (2)$$

$$\mu_r = 1 + \frac{{\omega_{mp}}^2}{{\omega_{m0}}^2 - \omega^2 - j\omega\Gamma_m} \qquad (3)$$

where ω_p stand for the plasma frequency, ω_0 stands for the resonant frequency and Γ stands for the damping factor.

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From equation 2, it is concluded that if the frequency is greater than the resonance frequency, the real permittivity is negative and so there is reflection rather than transmission. However, if the frequency is greater than the plasma frequency, the real permittivity is positive again and so transmission is possible.

The same behavior happens with the permeability and so the permittivity and the permeability are mutually negative in the band between the resonant and the plasma frequencies as shown in Fig. 1 resulting in the negative refractive index property within this band.

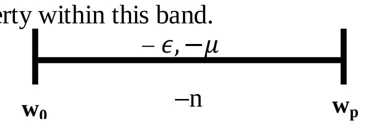
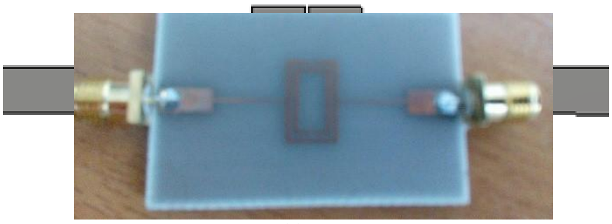


Fig. 1. Band of negative refractive index

III. Implementation

Two low pass filters of third and fifth orders are implemented using stepped impedance method with the replacement of the low impedance lines of the filters with the SRR unit cell in [9] as shown in Fig.2 and Fig.3. It is fabricated on FR4 with $\epsilon_r = 4.3$ *and* $tan\delta = 0.025$ and lengths modified to tune the cut off frequency at 1.9 GHz.



(a)

(b)

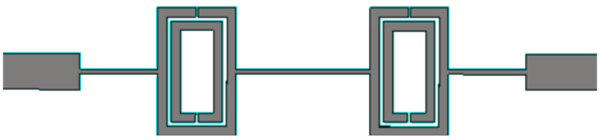
Fig.2 3rd order MTM filter (a) design, (b) fabricated

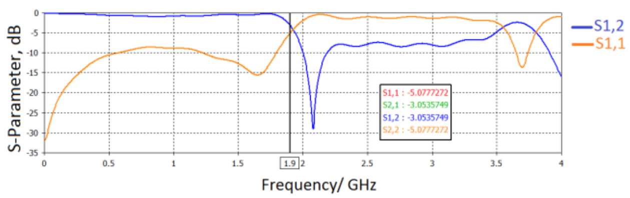
(a)

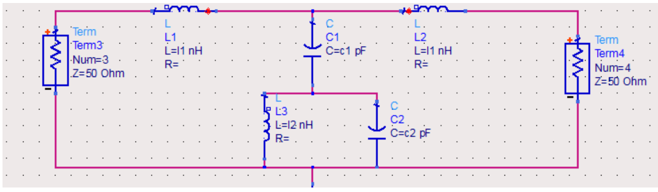
(b)

Fig.3 5th order MTM filter (a) design, (b) fabricated

The equivalent circuits of the proposed designs of the filters are derived and tuned to best match the simulated scattering parameters of the two filters in [9] and presented in Fig.3 and Fig.4.







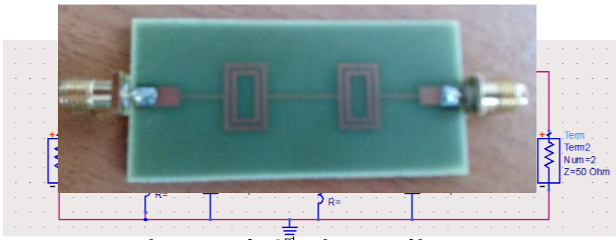


Fig. 4. Equivalent circuit for 3rd order MTM filter

Fig. 5. Equivalent circuit for 5th order MTM filter

IV. Results

The simulated scattering parameters for the third order MTM filter are shown in Fig.6. The filter operates till 1.9 GHz with roll off factor 89.375 dB/GHz. The measured scattering parameters for this filter are presented in Fig. 7 and the tuned scattering parameters obtained from the equivalent circuit model are depicted in Fig. 8.

Fig.6. 3rd order simulated scattering parameters

Fig.7. 3rd order measured scattering parameters

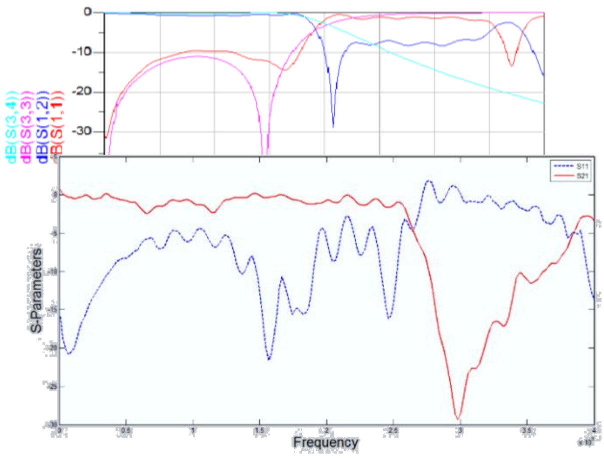


Fig.8. 3rd order MTM filter's equivalent scattering parameters

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These scattering parameters are used to get the values of the permittivity and permeability corresponding to the filter structure shown in Fig.9 and Fig.10 respectively followed by the refractive index depicted in Fig.11. These values are derived with different transformation between the CST and Matlab. These figures confirm that the design unit cell of SRR is exhibiting the MTM properties. Additionally, it is found that the effect of the negative values of permittivity and permeability properties along with the negative refractive index property is related to the transmission bands of the filters.

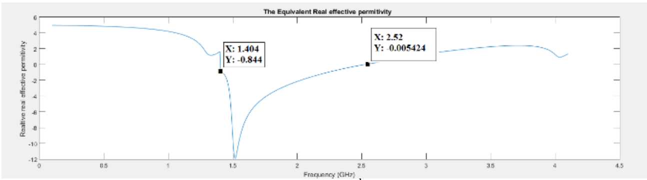


Fig.9. Effective real permittivity for 3rd order MTM filter

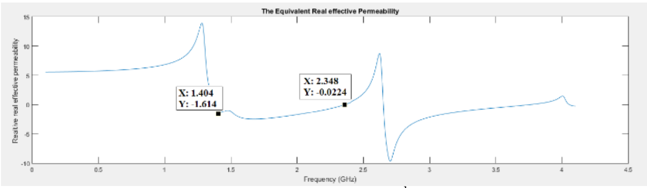


Fig.10. Effective real permeability of 3rd order MTM filter

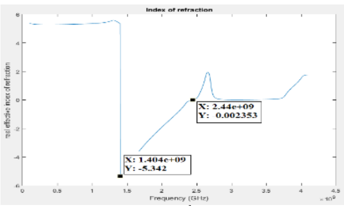


Fig.11. Refractive index of 3rd order MTM filter

One notices from Fig. 9 that the electric resonant 2.502 GHz. In addition, from Fig. 8, the magnetic resonant frequency is 1.404 GHz and the magnetic plasma frequency is 2.348 GHz. Hence, the band where both properties are negative, where backward propagation takes place, lies between 1.404 GHz and 2.348 GHz and so transmission occurs which is verified from the simulated scattering parameters of the filter.

The fifth order low pass MTM filter depicted in Fig.12 operates till 1.9 GHz with roll off factor equal to 48.125 dB/GHz. The measured scattering parameters for the filter is presented in Fig.13 and the equivalent circuit's tuned scattering parameters are shown in Fig. 14 with matching results.

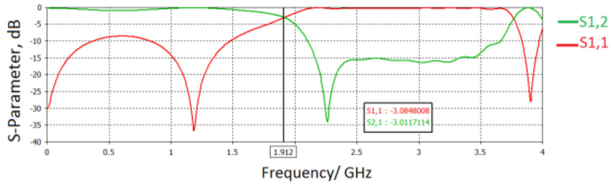
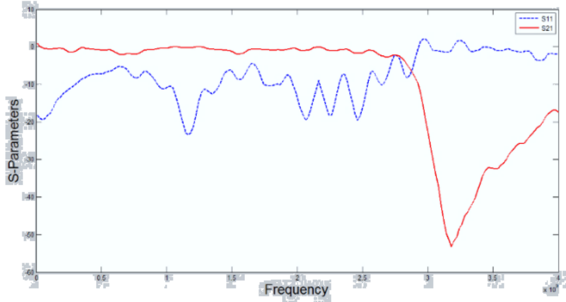
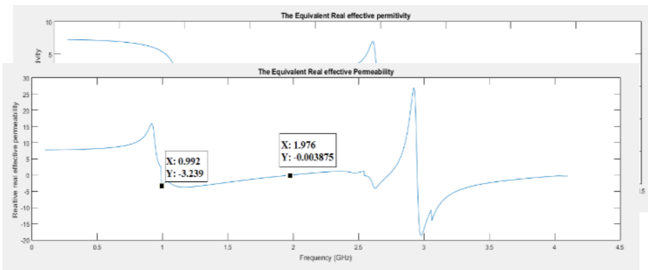


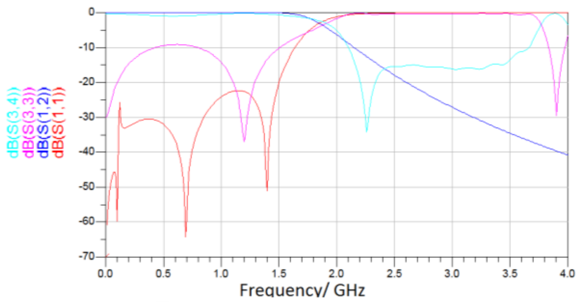
Fig.12. 5th order simulated scattering parameters for the MTM filter
Fig.13. 5th order MTM filter measured scattering parameters
Fig.14. 5th order MTM filter equivalent circuit's scattering parameters

Same technique is applied to get the values of the effective real permittivity and permeability for



the 5th order MTM filter with results shown in Fig. 15-17.
Fig. 15. Equivalent effective real permittivity for 5th order MTM filter
Fig. 16. Equivalent effective real permeability for 5th order MTM filter





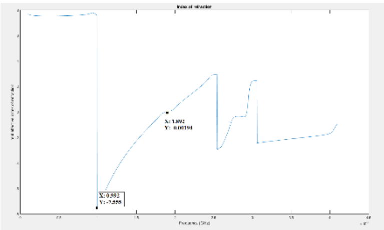


Fig. 17. Refractive index for 5th order MTM filter

Fig. 15 shows that the electric resonant frequency is 0.992 GHz and electric plasma frequency is 1.816 GHz. From Fig. 16 it is depicted that the magnetic resonant frequency is 0.992 GHz and the magnetic plasma frequency is 1.976 GHz.

Hence the band with mutual negative permittivity and permeability and consequently negative refractive index lies between frequencies 0.992 GHz and 1.816 GHz with transmission possible in such a band as verified from the simulated scattering parameters of the filter.

V. Conclusion

Two low pass filters of third and fifth orders are implemented and fabricated using the stepped impedance technique with the replacement of the low impedance line with the MTM unit cell in form of a rectangular SRR. The equivalent circuits for both filters are derived and tuned to match the scattering parameters of the simulated filters. The data is used to get the corresponding values of the permittivity, permeability and refractive index for the structures. The rectangular SRR exhibits the properties of MTM which is proved from the matching of the transmission bands with the bands of mutual negative permittivity and permeability and hence negative refractive index. These bands lie between the resonant and the plasma frequencies which are 1.404 GHz and 2.348 GHz for the third order filter and 0.992 GHz and 1.976 GHz for the fifth order filter.

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