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Design of UWB Notch Filter Using CRLH Metamaterials

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Abstract

In this paper, we propose a stop-band notch filter, which rejects the narrow frequency band of the Wi-MAX 802.16d (3.4 GHz to 3.6 GHz) and keeps the remaining UWB spectrum (3.1-3.4 and 3.6-3.9 GHz) unchanged. The proposed filter has been realized using the metamaterial technology based on the CRLH metamaterial structures. The selected center operating frequency is 3.5 GHz, which is the mid-band frequency for the Wi-MAX. The obtained results have shown that the 3-dB notch bandwidth is about 200 MHz frequency band which extends from 3.4 to 3.6 GHz. The filter has been designed, simulated, optimized and fabricated using conventional MICs technologies. The simulation and the measurement results have been compared. The insertion loss shows –29 dB at the frequency of interest. The comparison reveals good agreement between the simulated and the measured results.

Key words: CRLH, metamaterial, IDC, notch filter, UWB.

Resumen

(Diseño de un filtro de corte UWB empleando metamateriales CRLH)

En este trabajo se propone un filtro de corte que rechaza la estrecha banda de frecuencia del Wi-MAX 802.16 d (3.4 a 3.6 GHz) manteniendo intacto el restante espectro UWB (3.1-3.4 y 3.6-3.9 GHz). El filtro propuesto se ha elaborado mediante tecnología apoyada en las estructuras de metamateriales CRLH. El centro de frecuencia seleccionado opera a 3.5 GHz, que es la frecuencia de banda media para el Wi-MAX. Los resultados obtenidos muestran que el ancho de banda de corte de 3-dB está alrededor de 200 MHz extendiéndose de 3.4 a 3.6 GHz. El filtro se ha diseñado, simulado, optimizado y fabricado utilizando tecnologías MIC convencionales. Se han comparado los resultados experimentales con la simulación, encontrándose un buen acuerdo entre ellos. La pérdida de inserción muestra –29 dB a la frecuencia de interés.

Palabras clave: CRLH, metamaterial, IDC, filtro de corte, espectro UWB.

1. Introduction

Since the Federal Communications Commission (FCC)'s decision to permit the ultra-wideband (UWB) operation from 3.1 to 10.6 GHz [1], the UWB radio technology has generated a popular research topic in the practical wireless applications. The existed radio signals (e.g. the 3.5 GHz-band Wi-MAX signals) may interfere with the UWB operation within the range defined by the FCC. Thus, the UWB notch filters are required to suppress the Wi-MAX interferences [2][3].

In recent years, Metamaterials (MTMs) have been widely used for microwave circuits and antenna designs due to their unique electromagnetic properties, such as anti-parallel phase and group velocities and zero propagation constant at a certain frequency [4][5][6][7]. One of the novel applications is the notch filter, which is based on composite right/left-handed (CRLH) transmission lines (TLs) periodic structures. It has a potential for broadband wireless access networks, radar systems and UWB applications. One of the challenging problems in the UWB communications is the interference due to the Wi-MAX applications that necessitate the application of notch filters in conjunction with the UWB antennas to mitigate these interferences. The Wi-MAX 802.16d standard assigns the frequency range from 3.4 to 3.6 GHz (200 MHz bandwidth) which lies inside the UWB frequency band. This frequency band should be suppressed for proper operation of the UWB communication system.

In this paper a notch filter is realized using CRLH TL MTMs by inserting an interdigital capacitor in series with a stub inductor between the feed line and ground. This configuration is fabricated using the conventional microstrip fabrication technique. In Section 2, the design principle of a CRLH unit cell is investigated. In Section 3, the principle theory of the CRLH notch filter is explained. In Section 4, the simulation and optimization procedures are done. Section 5, includes the comparison between the simulation and experimental results. Finally, the paper is concluded followed the relevant references.

2. Schematic and operation

The notch filter principle theory depends on passing all frequencies except a certain band should be rejected *i.e*. the circuit must behave at those frequencies (notches) as a short circuit. This can be verified by a conventional transmission line that connect the output port to the input port and a resonant circuit is inserted between the transmission line and ground as shown in Fig.1. This resonant circuit resonates at the frequency of interest and we can control the bandwidth by optimizing the circuit components and the dimensions parameters.

The convention CRLH-TL is a periodic structure with multi cells shown below in Fig.2 [5].

The *i-th* cell consists of (C_{Li}, L_{Li}) for the left-handedness and (C_{Ri}, L_{Ri}) for the right-handedness property.

The lumped elements of the unit cell CRLH-TL are obtained to have the centre frequency f_0 at 3.5 GHz and the reject-band edges f_L and f_R at 3.4 GHz and 4.6 GHz, respectively.

Considering the balanced condition [5], f_0 is let equal to the Zeroth Order Resonance (ZOR) point of the CRLH metamaterial line where the following formulas are used to determine the circuit lumped elements:

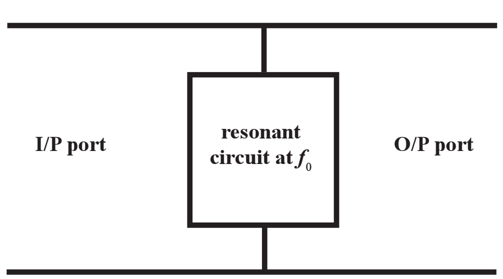

Fig. 1. Notch filter basic diagram.

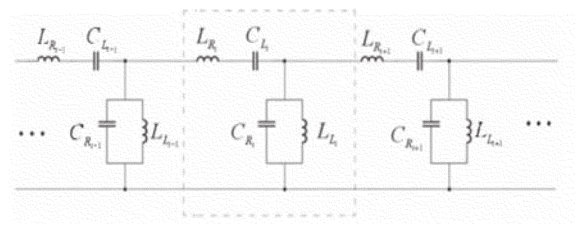

Fig. 2. Circuit model of the periodic CRLH-TL.

$$f_R = \frac{1}{2\pi\sqrt{L_R C_R}} \quad (1)$$

$$f_L = \frac{1}{2\pi\sqrt{L_L C_L}} \quad (2)$$

$$f_{se} = \frac{1}{2\pi\sqrt{L_R C_L}} \quad (3)$$

$$f_{sh} = \frac{1}{2\pi\sqrt{L_L C_R}} \quad (4)$$

$$f_0 = \frac{1}{2\pi\sqrt[4]{L_R C_L L_L C_R}} = \sqrt{f_{se} f_{sh}} \quad (5)$$

Where f_R represents the upper-limit for right hand frequency range, f_L represents the upper-limit for left hand frequency range, f_{se} represents the series resonance frequency for the series branch which constituted with L_R, C_L. f_{sh} represents the shunt resonance frequency for the series branch which constituted with L_L, C_R and f_0 represents the transition frequency from left-hand region to the right-hand region as shown in Fig.3. For balanced condition, so $f_0 = f_{se} = f_{sh}$ which has a distinct characteristic *i.e*. phase will be zero. The propagation constant varies nonlinearly with frequency in the left-hand ($\beta < 0$), linearly in the right-hand region ($\beta > 0$) and equal to zero at the resonant frequency f_0.

3. Principle theory of the notch filter

This section describes the operation principle and implementation of the notch filter.

A. Operation principle

The design of the proposed notch filter is based on a balanced short-ended CRLH transmission line. As shown in Fig. 4(a), the short-ended CRLH transmission line, with

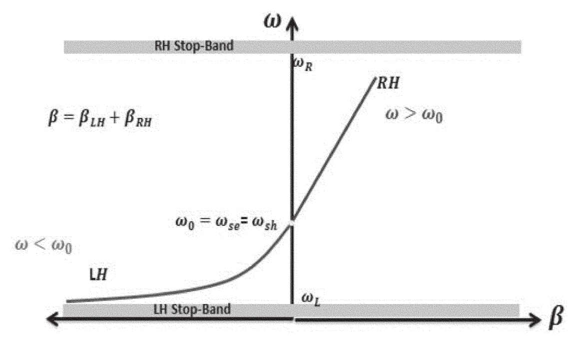

Fig. 3. Dispersion diagram for a balanced case of a MTM (propagation constant *versus* frequency).

characteristic impedance Z_{in} and the propagation constant β, acts as a shunt branch between the input port and output port. For the short-ended CRLH lossless TL, the input impedance Z_{in} seen from one end of the shunt branch toward the shorted end is given by:

$$Z_{in} = jZ_{CRLH}\tan(n\beta p) \qquad (6)$$

where n is the number of the unit cells in the balanced CRLH transmission line. Different from the symmetric T network in Fig. 5, an asymmetrical circuit model in Fig. 4(b) is used, which consists of series impedance Z constituted by an inductor L_R in series with a capacitor C_L and shunt admittance Y constituted by a capacitor C_R in parallel with an inductor L_L.

The propagation constant of the asymmetric CRLH transmission line is given by:

$$\cos(\beta p) = 1 + \frac{ZY}{2} = 1 + \frac{1 - (\omega L_R - \frac{1}{\omega C_L})(\omega C_R - \frac{1}{\omega L_L})}{2} \qquad (7)$$

For the case of a balanced CRLH transmission line (*i.e.* $L_L C_R = L_R C_L$), the propagation constant β vanishes at the critical frequency ω_0 and the characteristic impedance in this case is given by:

$$Z_{CRLH} = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{Z_L}{C_L}} = \sqrt{\frac{L_R}{C_R}} \qquad (8)$$

When the propagation constant β vanishes at the frequency f_0, Z_{in} is also vanished and the shunt CRLH stub becomes

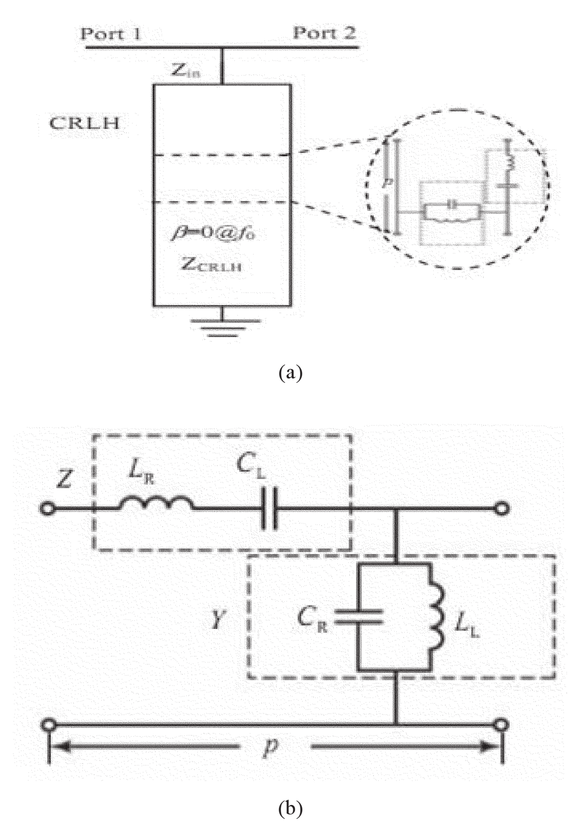

Fig. 4. (a) Structure of the proposed notch filter; (b) The lumped LC unit cell for the CRLH TL.

shorted at f_0. Thus, the transmission from port 1 to port 2 vanishes also, which can behave as a notch filter at f_0. The design of our model has been based on this principle.

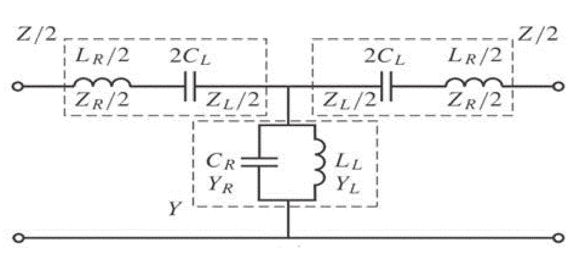

Fig. 5. Symmetric unit cell of CRLH TL.

B. Microstrip implementation

Figure 6 depicts the layout of the UWB notch filter with a wide notch of 200 MHz, which is proposed on the FR4 substrate with permittivity of 4.5 and thickness of 1.5 mm. As shown in Fig.4, the microstrip structure with interdigital capacitor (IDC) and short-circuited stub on the top side is employed.

The IDC is composed of five pairs of fingers; each has length l_c, and width w_s, coupled together with a gap which has spacing width S. The IDC is connected with a short-circuited stub which has a length l_c and width w_s and shorted at its end through a via with radius 0.25 mm.

Both components together constitute the unit cell for the CRLH TL metamaterial. The dimensions are selected such that the operation of the unit cell is in its balanced state so there will be a smooth transition from left-hand side to the right-hand side. In this case, the matching condition can be extends over a wide frequency range as the characteristic impedance in this case is frequency independent.

4. The simulation and optimization procedures

The following steps for the filter design have been carried out:

(1) Based on the design equations from 1-5 stated above, the lumped elements are evaluated where the filter performance is far away from the requirements.
(2) The lumped elements are transformed to a distributed elements and feeded to the (ADS software package) in the optimization mode to change the element values for the optimum performance.
(3) The values of the elements from the ADS package are taken as initial values for the HFSS full-wave simulator in the optimization mode. The dimensions of the designed in its final stage are shown in table 1.

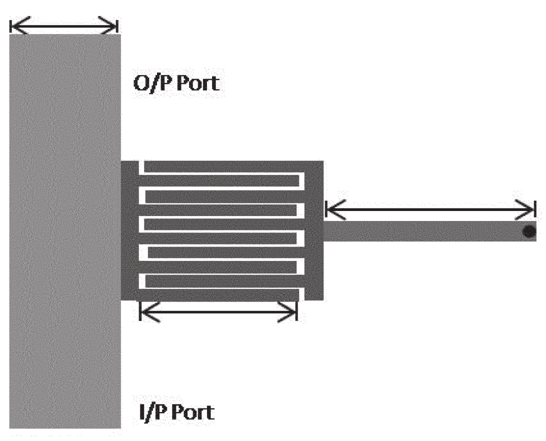

Fig. 6. Layout of the proposed UWB notch filter.

Table 1. Parameters of the notch filter.

Dimension	Length (mm)	Description
l_s	7.9000	Stub length
w_s	0.6040	Stub width
l_m	5.0000	MIM length
w_m	0.3887	MIM width
S	0.2800	Finger spacing
w_t	3.0000	TL width
Via radius	0.2500	

After that, a parametric study is done to show the effect of various parameters on the notch filter response characteristics.

Figure 7 shows the variation of insertion loss (S21 dB) with respect to the length of stub inductor . As the inductor length increases the resonance frequency decreases and magnitude of S21 stay approximately unchanged.

Figure 8 illustrates the effect of finger spacing variations on the resonance frequency. As seen from the figure, with

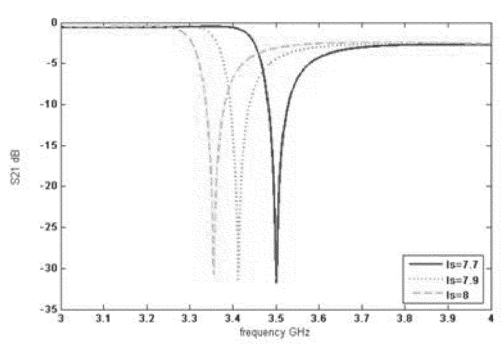

Fig. 7. S21 *versus* stub length.

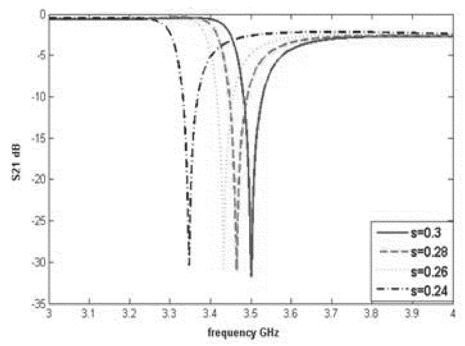

Fig. 8. S21 *versus* finger spacing *S*.

reducing finger spacing *S*, the resonant frequency f_0 is also reduced.

5. Fabrication and experimental results

The CRLH notch filter consists of one unit cell as previously shown in Fig. 6, it is fabricated on FR4 substrate of permittivity 4.5 and thickness 1.5 mm. The dimensions of the overall notch filter are ($14*6.4\ mm^2$). The filter is mounted using a fixed structure and two SMA connectors. The fabricated structure is shown in Fig. 9.

The fabricated UWB notch filter is tested using the vector network analyzer (HP-8510C).

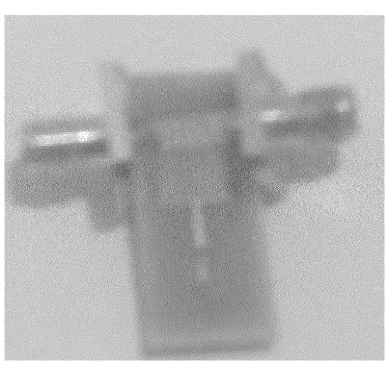

Fig. 9. The fabricated prototype.

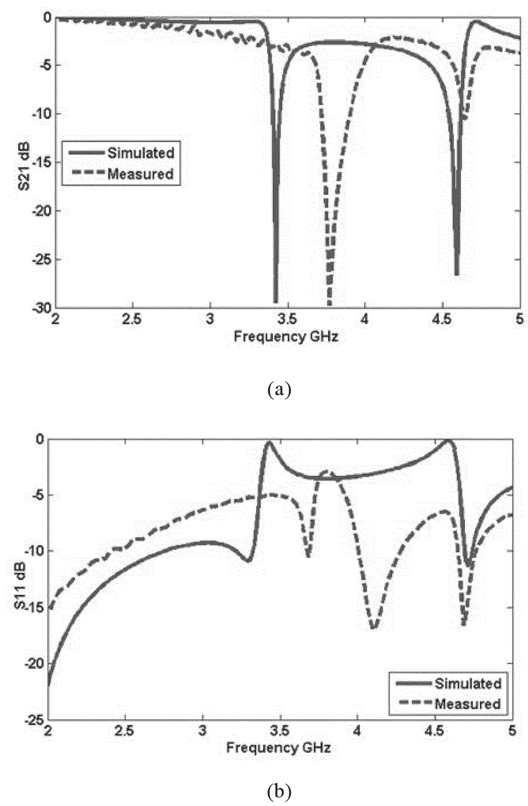

Fig. 10. Comparison between simulated and measured results: (a) S21 response (b) S11 response.

A comparison is made between the simulated results and the measured response is depicted in Fig. 10.

From the comparison of the results, it is clear that:

(1) The measured frequency response almost agrees with the simulated results.
(2) As shown in Fig. 10(a), the insertion loss |S21| has a magnitude of about –30 dB which is verified with the simulated results but the frequency of the notch is slightly shifted towards the high frequency side. This difference between the two notches (the simulated and the measured) is due to the imperfections resulted from the fabrication and SMA connectors.
(3) As shown from Fig. 10(b), the return loss |S11| is 1.0 dB at the frequency 3.5GHz for the simulated response.
(4) The undesired notch appeared at frequency above 4.5 GHz is mainly due to the spurious resonance coming from the intercoupling between the fingers of IDC.

6. Conclusions

A compact UWB notched filter has been presented. Initially, an UWB notch filter has been achieved by a CRLH metamaterial unit cell. The desired notch (rejection) band is introduced by a short-circuited resonant circuit connected to the ground. The design parameters were optimized to meet the optimum desired performance.

The notched band can be controlled by properly selection of the length of the stub, width of the stub, and length of the IDC fingers. A filter with a WLAN notch band is designed, simulated and fabricated. The measured results show close agreement with the simulated results which validates the proposed fillter design theory.

The proposed UWB notch filter is promising for the application in new UWB wireless technologies due to its simple structure, low insertion loss, broad pass band width, high stop band suppression, compact size, and easy integration with antennas and other devices. This filter can be integrated with UWB radio systems and efficiently enhance the interference immunity.

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References

[1] "Revision of Part 15 of the Commission's Rules Regarding Ultra-wideband Ttransmission System," FCC, Washington, DC, ET-Docket 98-153, First Note and Order, Feb. 14, 2002.

[2] W. Tong, and Z. Hu, "Left-handed Miniaturized Microstrip Dual Mode Bandstop Filter," in Proc. 3rd EMRS DTC Technical Conference - Edinburgh 2006.

[3] H. Kumar, and MD. Upadhayay, "Design of UWB Filter with WLAN Notch," Hindawi Publishing Corporation, *International Journal of Antennas and Propagation*, vol. 2012, Article ID 971097.

[4] G. V. Eleftheriades, A. K. Iyer, and P. C. Kremer, "Planar Negative Refractive Index Media Using Periodically LC Loaded Transmission Lines," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 12, pp. 2702-2712, Dec. 2002.

[5] C. Caloz, and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. Hoboken, NJ: Wiley, 2006.

[6] G. V. Eleftheriades, and K. G. Balmain. *Negative-Refraction metamaterials: Fundamental Principles and Applications*. Hoboken, NJ:Wiley, 2005.

[7] A. Lai, T. Itoh, and C. Caloz, "Composite Right/left-handed Transmission Line Metamaterials," *IEEE Microw. Mag.*, vol. 5, no. 3, pp. 34-50, Sep. 2004.