Ultra Wide Band Filter with Notch at WiMax using Epsilon Near Zero (ENZ) Methodology

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Abstract **- In this article an ultra wide band filter with a notch at WiMax band using Epsilon Near Zero (ENZ) approach is presented. It is shown that great miniaturization is achieved as the ENZ tunnel length is independent of frequency. This filter is investigated numerically and experimentally. Measured results show a good agreement with the simulated analysis.**

Index terms **– Epsilon Near Zero (ENZ), Metamaterials, Microwave filters, Plasmonic structures.**

I. INTRODUCTION

The development race for commercializing the UWB technology has increased enormously after FCC (Federal Communication Commission) authorization for civil purposes [1]. Miniaturization of devices plays a crucial role for UWB applications. Several UWB band pass filters (BPFs) with embedded notch band using compact structures have been proposed [2-4]. Dong et.al., [5] designed Substrate integrated waveguide notch cavities to decouple power at particular bands for UWB filters. However, the size of such SIW cavities is relatively large as their length depends on the propagation wavelength [6]. To overcome this problem Plasmonic or ENZ method is a new technology which has a potential advantage in miniaturization as energy can be tunneled through a narrow waveguide at a particular frequency independently of its total length [7, 8, 9]. Based on this method, we developed an Substrate Integrated filter from 3.1 – 7 GHz (which covers the three channels in the UWB MultiBand OFDM Alliance (MBOA) [10]) with a miniaturized plasmonic notch tunnel at 5.6GHz to suppress the unwanted WiMax frequency.

The paper is organized as follows: In section I we present the introduction of the UWB filters and ENZ materials. Section II describes the ENZ approach at 5.6 GHz and further explains the design procedure of UWB filter (3.1 GHz – 7 GHz) with a notch at a frequency of 5.6 GHz using Plasmonic tunnels. Section III presents the simulation and measurement results of the UWB filter.

II. UWB FILTER (ENZ APPROACH)

An UWB filter (3.1 – 7 GHz) with a notch at 5.6 GHz has been designed using the ENZ approach. To achieve ENZ behavior, waveguide technology is adopted. The effective permittivity (ε_{eff}) and effective permeability (μ_{eff}) of the rectangular waveguide filled with dielectric material (ε_r) operating at dominant mode is given below [11].

$$\frac{\varepsilon_{eff}}{\varepsilon_0} = n^2 - \frac{c^2}{4\varepsilon_r f^2 w_t^2} \; ; \quad \mu_{eff} = \mu_0 \tag{1}$$

where n is the refractive index of the material, c is the velocity of light in vacuum, ε_r is the dielectric permittivity of the material, W_t is the waveguide H-plane width, and f is the desired frequency. This equation shows that at cutoff frequency, the effective permittivity (ε_{eff}) is approximately zero and therefore the propagation constant is zero (β=0) [12]. The width of the ENZ tunneling waveguide operating at TE_{10} mode is given by

$$W_t = \frac{c}{2 f_0 \sqrt{\varepsilon_r}} \tag{2}$$

where f_o is the tunneling frequency, c is the speed of light and ε_r is the relative permittivity. For the selected substrate RT Duroid 5880 (ε_r =2.2 and height h_m= 1.575mm) and a frequency of operation (f_o) of 5.6 GHz the tunnel width is W_t= 18mm. In order to tunnel a single frequency, a very abrupt discontinuity between the waveguide and the tunnel must exist as shown in figure 1(a), hence the waveguide height should be much larger than the tunnel height (h_m>>h_t). The E-field pattern of tunneling of single frequency is shown in figure 1(b). In our case the tunnel height is fixed to h_t=0.4mm. The length of the tunnel is 4.5mm, equivalent to only about λ/8 of the propagation wavelength.

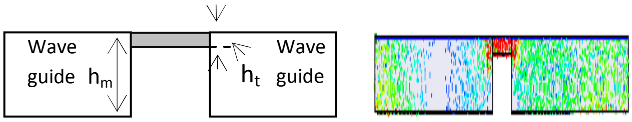


Figure: 1 a) Schematic of the ENZ approach using waveguide technology b) E- Field pattern of the tunnel structure.

This tunnel was simulated and the S parameter results are shown in figure.2. It is clearly seen that a single frequency is tunneled through and the rest of the frequencies are reflected back.

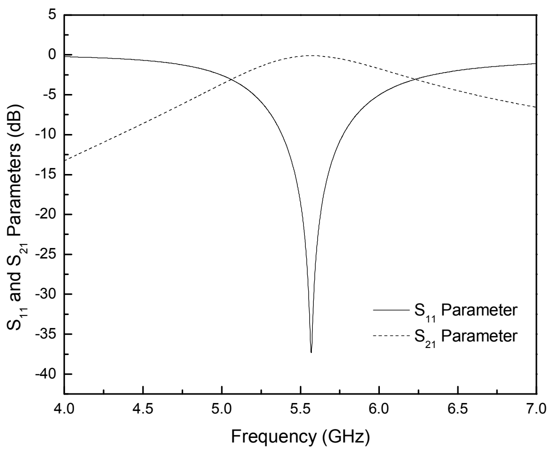


Figure: 2 Reflection and transmission parameters (simulated) of the tunnel structure.

The effective permittivity (ε_{eff}) of the tunnel structure shown in figure 1 was extracted from the S_{11} and S_{21} simulated parameters using equations (3), (4) and (5) [13]. The reflection/transmission and scattering parameters are related as given below

$$S_{11} = \frac{\Gamma\left(1-T^2\right)}{1-\Gamma^2 T^2}; \quad S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2} \tag{3}$$

The above equation can be rearranged and written in the following form

$$\Gamma = K \pm \sqrt{K^2 - 1}; \quad T = \left(\frac{S_{11} + S_{21} - \Gamma}{1-(S_{11}+S_{21})\Gamma}\right) \tag{4}$$

Where $\Gamma = \left(\frac{Z_{eff} - Z_0}{Z_{eff} + Z_0}\right)$ is the reflection coefficient and $T = \mathrm{e}^{(-\gamma d)}$ is the transmission coefficient. $\gamma = \left[\ln\left(1/T\right)\right]/d$; $K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}$;

γ_0 is the free space propagation constant; λ_0 is the free space wavelength. Z_{eff} is the effective impedance of the tunnel structure and Z_0 is the free space impedance. From the above equation the effective dielectric permittivity can be derived as

$$\varepsilon_{eff} = \frac{\gamma\left(1-\Gamma\right)}{\gamma_0(1+\Gamma)} \tag{5}$$

Furthermore by using equation (6) the phase constant is extracted [14].

$$\beta = \arccos\left(\frac{1 - S_{11}S_{22} + S_{21}S_{12}}{2S_{21}}\right) \tag{6}$$

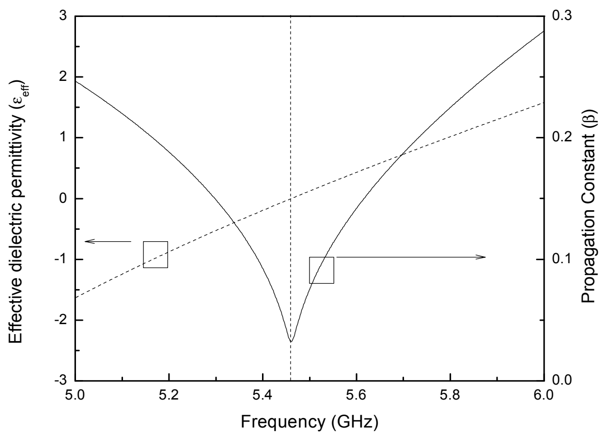
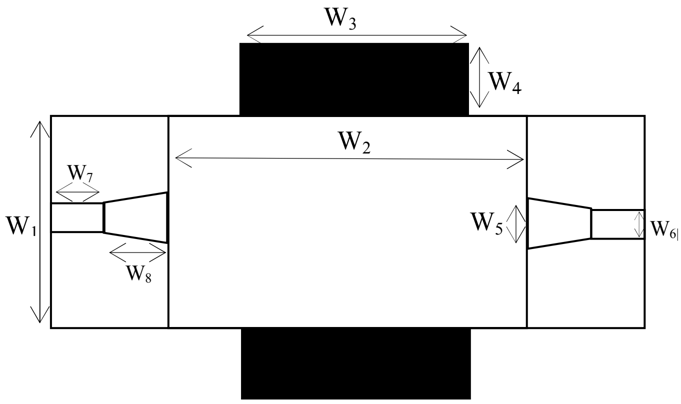


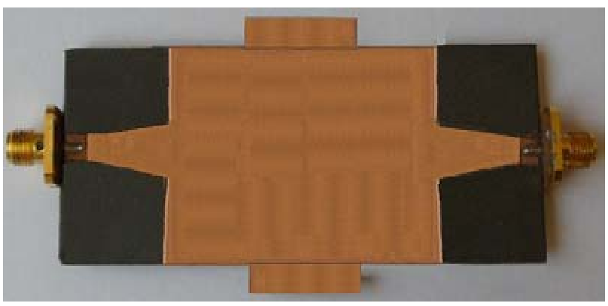
Figure: 3 Extracted dielectric permittivity and propagation constant parameters.

The effective dielectric constant and the propagation constant parameters of the structure shown in figure 1 are extracted from the procedure discussed above. The variation of these parameters with frequency is shown in figure 3. It is clear that the effective dielectric constant having zero values near the tunneling frequency (5.6 GHz) and also the propagation constant has near zero which satisfy the ENZ behavior.

The tunnel described in this method is connected in a decoupled mode to suppress the frequency of 5.6 GHz. In order to achieve the decoupling mode, the above design is modified with one edge of the tunnel coupled to the waveguide and the other edge left with an air interface as shown in figure 5. The dimensions of the designed filter shown in figure 4(a) are: W_1= 36 mm, W_2= 51.4 mm, W_3= 20 mm, W_4=4.5 mm, W_5=7 mm, W_6= 4.5 mm, W_7= 5mm, W_8= 15mm.



(a)



(b)

Figure: 4 a) Schematic of the Ultra wide band filter with notch b) Photograph of the proposed filter.

III. RESULTS AND DISCUSSION

To validate the proposed filter, it was simulated in a full wave simulator [15] and fabricated using conventional PCB milling machine. The substrate is Duriod-5880 substrate with dielectric constant ε_r = 2.2, δ= 0.001, thickness h=1.575 mm. The plasmonic tunnel was machined down to the proper height and all the layers were properly metalized. Figure 4(b) shows a photograph of the fabricated filter.

Measurements are performed using Agilent PNA Series microwave Vector Network Analyzer (E8361A). The measured results of the proposed filter using waveguide method have shown a good agreement with the theoretical results as shown in figure 5. The experiment results demonstrate that the fabricated filter has a notch at 5.58 GHz and there is a shift of cutoff frequency of about 180 MHz. The insertion loss is -2dB and -1.38 dB at the passband when measured and simulated. Simulated and measured reflection losses are found to be -10 dB. Discrepancies in the simulated and measured results are due to the fabrication errors.

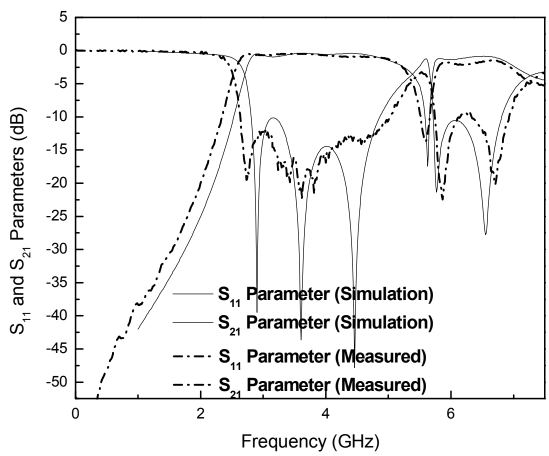


Figure: 5 Simulated and Measured results of the proposed filter.

IV. CONCLUSIONS

A substrate integrated UWB filter (3.1- 7 GHz) with a highly miniaturized notch tunnel at 5.6 GHz (WiMax) using ENZ approach was designed and fabricated. It was proven that the effective permittivity and phase constant of the plasmonic tunnel become near zero at the tunneling frequency. Simulation and experimental results of the UWB filter with notch are in good agreement.

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