Tri-band Patch Antenna Using Double Negative Metamaterials

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***Abstract*— In this paper, we investigate the potential of using double negative metamaterials to achieve a tri-band operation of microstrip antenna. We have shown that the three resonant frequencies of the microstrip antenna are not limited to integer multiples of the fundamental mode that operate at different harmonics. By choosing double negative metamaterials with different dispersion properties, the desired resonant frequencies can be achieved. Our proposed structure can produce two different radiation patterns at same time.**

I. Introduction

With the increasing desire of capability of mobile systems in the past decades, the operations that are able to work at different frequency bands using one specific multi-band device are desirables. Additionally, many innovative wireless communications also call for developing more frequency bands for licences free use [1], that demand bandwidth of the antenna to cover the required frequencies. All the desires make multi-band technology a hot topic and multi-band applications such as GSM/DCS/PCS tri-band antenna [2], GPS/K-PCS Bluetooth [3] draw great attention. The multi-band function of antennas can generally be achieved in several ways, for example, using two feed lines to excite two harmonic modes [4-5], adding additional resonator [6] and using parasitic element coupling antenna [7]. However, these methods have such and such limitation, e.g. can only operating at harmonic frequencies and produce one simple radiation pattern.

Due to their unusual electromagnetic properties, many applications of double negative metamaterials have been explored. The structures that composed of double negative metamaterials and conventional materials have been proposed and testified to be very useful in minimizing the geometry size of resonators attributing to the phase compensation effect in two different materials [8-12]. Meanwhile, the unique dispersion property of metamaterials is another highlight. The double negative metamaterial which possess Drude-model like dispersive characteristic exhibits dual-band responds. At frequencies below ω_p, where ω_p denotes plasma frequency, the "left-handed" (phase-lead) behaviour dominates while at frequencies above ω_p, the "right-handed" behaviour (phase-lag) dominates. At the point of ω_p, there is no phase shift. The properties open doors for multi-band applications.

In this paper, we present the potential of achieving tri-band resonances of patch antenna by using single layer of double negative metamaterial substrate. The proposed structure is designed to work at three different frequencies that are not harmonics to each other. This paper is organized as follows:

II. Tri-band Patch Antenna

A. Double Negative Metamaterials

At present, the practical realization of double negative metamaterials was carried out generally in two approaches, either a lattice of split-ring resonators and thin wires or a negative-refractive-index transmission-line implementation. Drude model is chosen in this paper to describe the frequency response of double negative metamaterials. It yields negative refractive index and zero refractive index at low frequency. To simplify the relation of refractive index, the magnetic model is selected to be identical with electric model. We use time-harmonic convention $e^{j\omega t}$ for monochromatic time variation. The real part and imagine part of the relative permittivity and permeability are described as

$$\varepsilon' = \mu' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+(\omega t_0)^2} \tag{1}$$

$$\varepsilon'' = \mu'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega t_0}{1+(\omega t_0)^2} + \frac{\sigma}{\omega \varepsilon_0} \tag{2}$$

where ε_∞ is the infinite frequency relative permittivity; ε_s is the static relative permittivity; σ is the electric conductivity; and t_0 is the relaxation time.

For the Drude dispersive material, there are assignments that $\varepsilon_\infty = \mu_\infty = 1$, $\sigma = -\frac{\varepsilon_0(\varepsilon_s - \varepsilon_\infty)}{t_0}$ (see equation of 8.30, 8.32 and 8.33 in [13]).

In low loss cases (loss can be restrained by setting $\frac{1}{t_0} \ll \omega_p$ where $\omega_p^2 = \frac{\varepsilon_\infty - \varepsilon_s}{t_0^2} = \frac{1-\varepsilon_s}{t_0^2}$), equation (1) can be simplified as

$$\varepsilon' = \mu' \approx \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(\omega t_0)^2} = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \quad (3)$$

Dispersion of the double negative metamaterials only depends on ω_p .

B. Tri-band resonance

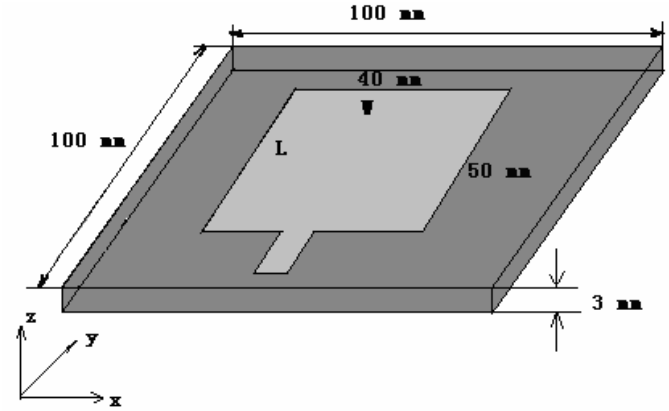

Fig. 1 Patch antenna loaded with double negative metamaterials

The microstrip antenna depicted in Fig. 1 consists of a metallic patch with dimensions L × W. The underneath substrate is filled with homogeneous isotropic double negative metamaterials. L is the length that attribute to the resonant frequency.

The resonant condition of the microstrip antenna is determined by $\beta l = N\pi$. In the case that microstrip antenna is loaded with double negative metamaterials, N can be a negative integer, positive integer, or zero.

In our example, there is:

$$\beta = \omega\sqrt{\varepsilon'\mu'\varepsilon_0\mu_0} = \omega\varepsilon'\sqrt{\varepsilon_0\mu_0} \quad (4)$$

The length of the patch L is chosen to be 50 mm. The loaded double negative metamaterials is with ω_p =30×10^9 rad/s, additional with relation of equation (3) , the dispersion along the L direction is plotted in Fig.2.

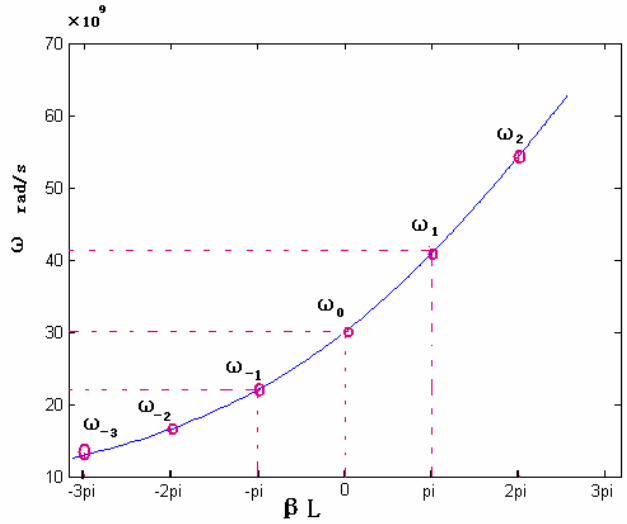

Fig. 2 Dispersion diagram along the length direction of the patch

The resonant frequencies points are plotted on the curve. The back-ward wave is supported at the frequencies below ω_0 which attribute to the N =-1 resonant mode. The forward wave is supported at the frequency above ω_0 which attribute to the N =1 resonant mode. At these two frequencies, the general half-wavelength field distribution is supported. At ω_0 , the zero phase-shift point, the wavelength is approaching infinite. All of the four edges of the patch contribute to the resonance. The equivalent magnetic current along the edges form a loop. The resonance frequencies of theses three modes are not harmonics each other. Using double negative metamaterials with different ω_p , the wanted resonant frequencies can be obtained.

As indicated in Fig.2, the tri-band antenna will operate at f_{-1}=3.5047 GHz, f_0=4.775 GHz and f_1=6.5047 GHz.

III. SIMULATION RESULT

In Fig.1, a rectangular patch with dimension 50mm × 40mm, is properly printed on a substrate filled with the double negative metamaterials. The double negative metamaterial is simulated by setting ε_∞ =1, ε_s =-9×10^6, σ =796.877, t_0 =1 ×10^{-7} s.

The patch antenna is fed from the edge side by a microstrip of 7 mm in width. The substrate and ground plane are both 100×100 mm^2. The thickness of the substrata is 1.5 mm. The structure was simulated with commercial software XFDTD.

The full-wave simulation result in Fig. 3 has shown multiple resonance of the structure as predicted. A Tri-band resonance is obtained at f_{-1}=3.5856 GHz, f_0=4.781 GHz,

f_1=6.723 GHz, respectively, showing good agreement with the calculation.

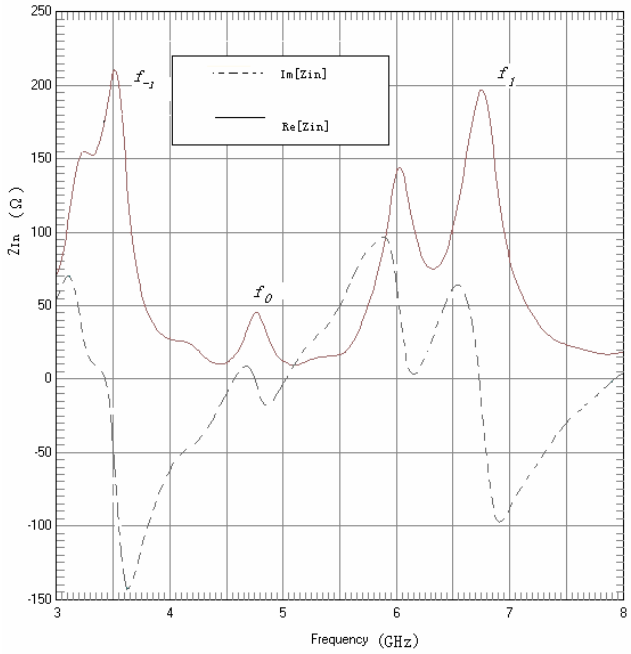

Fig. 3 Full wave simulation result of input impedance of the rectangular patch antenna feed by a microstrip

The normalized radiation pattern for the proposed tri-band patch antenna resonant at 3.5856 GHz and 6.723 GH are plotted in Fig .4 and Fig.5 respectively. At these two frequencies, the electric field distribution exhibit half wavelength distribution like the dominant mode of a conventional patch antenna. The radiance pattern in Fig. 4 and Fig. 5 confirmed these patch-like resonances. The maximum gain of -0.64dBi and -1.67dBi were achieved at f_{-1} and f_1 respectively. At f_0, because all the four edges contribute to resonance, the radiation pattern was similar to a monopolar. The radiation pattern is depicted in Fig. 6. The maximum gain of 8.729dBi is achieved.

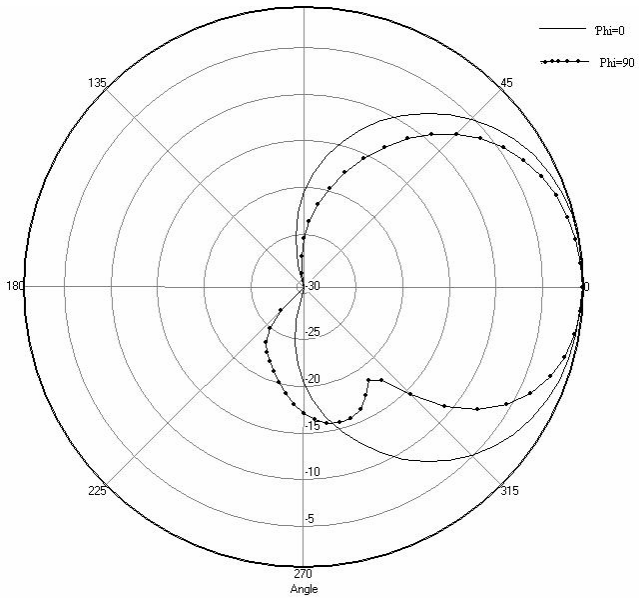

Fig. 4 Full wave simulation of radiation pattern at f_{-1} (Gain)

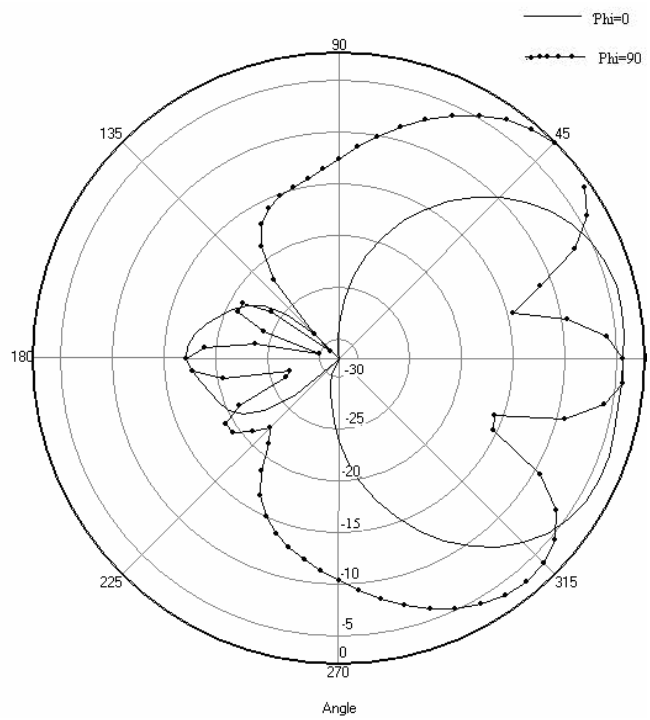

Fig. 5 Full wave simulation of radiation pattern at f_1 (Gain)

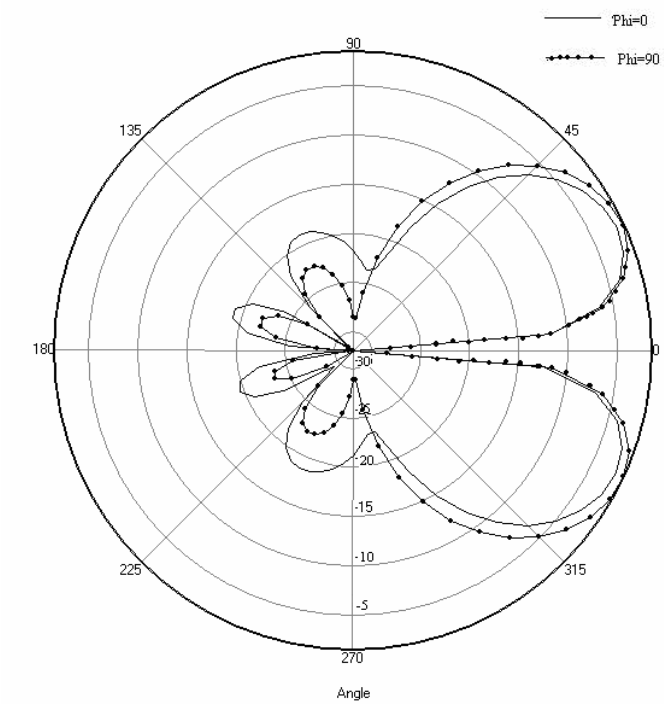

Fig. 6 Full wave simulation of radiation pattern at f_0

IV. CONCLUSIONS

In this paper, we have proposed a tri-band microstrip antenna structure using single layer of double negative metamaterials which works at both "left-hand" band and "right–hand" band. Three useful resonant modes can be achieved by using the structure. The resonant frequencies are not restrained to harmonics of each other. By changing the substrate metamaterials with different dispersion properties, the wanted operating frequencies can be obtained. The antenna is able to produce patch-like radiation pattern at two frequencies and monopolar radiation pattern at the third one.

The resonant frequencies of the patch antenna can be adjusted to GPS (dual-band application of e.g., 1.575 GHz and 1.227 GHz) by using metamaterials with smaller plasma frequency. The structure can also be used for multi-band applications of WiMax antennas that work over very wide band from 2.3 GHz to 5.9 GHz.

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