Analytical Approach of Permittivity and Permeability of Spiral-Resonator Shaped Planar Structure Implemented as Antenna Radiator

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***Abstract*—This paper presents analytical approach of permittivity and permeability of planar structure which takes a shape of spiral-resonator (SR) implemented as an antenna radiator. The use of planar structure for instance as an antenna radiator is recently required in order to have communication devices with compact and light in weight. The approach is carried out by calculating the effective impedance of SR shaped planar structure through its equivalent circuit which consists of resistance, inductance, and capacitance. Afterwards, the effective permittivity and permeability are obtained. To verify the proposed analytical approach, the SR shaped planar structure is also characterized using 3D simulation software to gain the effective permittivity and permeability. It shows that the effective permittivity and permeability which are yielded from simulation and analytical approach have good agreement each other for positive permittivity ($\epsilon > 0$) and negative permeability ($\mu < 0$) at the frequency range above 0.8 GHz.**

***Keywords*—Antenna radiator; permeability; permittivity; planar structure; spiral-resonator.**

I. INTRODUCTION

In the last 2 decades, the researches in electromagnetics material with exceptional properties have attracted academicians explore intensively their properties as well as their applications [1]–[2]. The materials with such kind properties are well-known as artificial material or metamaterial. In 1948, Kock has suggested to make dielectric lenses antenna by using the array of conducting wire [3]. This was probably one of forerunners of artificial materials which is known as artificial dielectric. Based on this concept, some applications of artificial dielectric have been recently implemented for filter and antenna [4]–[6]. Meanwhile, in 1968 Veselago has theoretically investigated plane wave propagation in a material with permittivity and permeability assumed to be simultaneously negative which is preferred as metamaterial [7]. Then this investigation was experimentally demonstrated to show the presence of anomalous refraction [8]–[9].

Discussion related electromagnetics material including artificial material and metamaterial, in general it is always specified by the electric property called as permittivity (ϵ) and the magnetic property known as permeability (μ). Therefore, based on its properties, the metamaterial is divided into four types [2], i.e. double positive (DPS) material with $\epsilon > 0$ and $\mu > 0$, double negative (DNG) material with $\epsilon < 0$ and $\mu < 0$, epsilon negative (ENG) material with $\epsilon < 0$ and $\mu > 0$, miu negative (MNG) material with $\epsilon > 0$ and $\mu < 0$. The ENG and MNG metamaterials are not transmitting the surface wave into the substrate material [10]. Hence, both materials are appropriate to be applied for the design of antennas. In addition, the MNG metamaterial has better property for planar antenna application compared to the ENG metamaterial due to the magnetic property.

Many researches of planar antennas design with the negative permeability and positive permittivity have been conducted emphasizing to reduce the dimension. For example in [11]–[12], the use of split ring resonator (SRR) and spiral-resonator (SR) have been discussed to observe the resonant frequency as an effect of number of SRR ring or spiral turn. It seems that the SR structure has greater reduction factor compared to the SRR structure. Moreover, the SRR and SR structures are also applied to observe behaviour of the complex permeability to the frequency. Meanwhile, the SR shaped planar structure characterized by the negative permeability at certain frequency was implemented as an antenna radiator [13]. However, it is necessary to characterize the structure the positive permittivity since the MNG material was insufficient characterized by only the negative permeability.

Therefore, in this paper, the permittivity and permeability of SR shaped planar structure is proposed for analytical approach with the implementation as an antenna radiator. The analytical approach is carried out by calculating the effective impedance of SR shaped planar structure through its equivalent circuit. Then, by using the relation equation of impedance towards permittivity and permeability, the effective permittivity and permeability are obtained. In addition, the effective permeability of SR shaped planar structure is also analyzed from the equivalent circuit as the varied number of spiral loops, strip width, and gap width of SR shaped planar structure. Whilst as comparison, the SR shaped planar structure is also characterized using 3D simulation software to verify the results of analytical approach.

II. SR SHAPED PLANAR STRUCTURE

Figure 1 shows the SR shaped planar structure implemented as an antenna radiator and its equivalent circuit used for analytical approach. The structure which is made of metallic conductor on a dielectric substrate has a side length of l, a number of spiral loops of N, a strip width of w, and a gap

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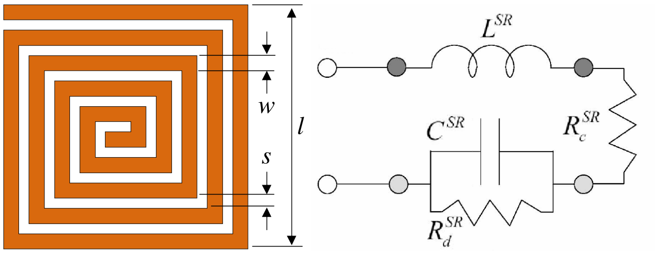

Fig. 1. SR shaped planar structure and its equivalent circuit [12].

width of s. By using the equivalent circuit which consists of loss resistance in metallic conductor (R_c^{SR}), shunt resistance due to the dissipation in lossy dielectric substrate (R_d^{SR}), inductance in metallic conductor (L^{SR}), and capacitance of gap between metallic conductors (C^{SR}), the effective impedance of structure (Z_{eff}) can be obtained as expressed in (1) [12].

$$Z_{eff} = R_c^{SR} + \frac{R_d^{SR}}{1+(\omega C^{SR} R_d^{SR})^2} + j\omega\left[L^{SR} - C^{SR}\frac{(R_d^{SR})^2}{1+(\omega C^{SR} R_d^{SR})^2}\right] \tag{1}$$

The values of R_c^{SR}, R_d^{SR}, L^{SR}, and C^{SR} are determined by the geometrical structure and its electric and magnetic properties which are given in (2)–(5) [12].

$$R_c^{SR} = \frac{\rho}{\omega t}\frac{L^{SR}}{\mu_0} \tag{2}$$

$$R_d^{SR} = \frac{1}{\sigma_d}\frac{s}{4h[l-(2w-s)]}\frac{l_{avg}^{SR}}{4l} \tag{3}$$

$$L^{SR} = \frac{\mu_0}{2\pi} l_{avg}^{SR}\left[\ln\left(\frac{l_{avg}^{SR}}{2w}\right)+\frac{1}{2}\right] \tag{4}$$

$$C^{SR} = C_0\frac{1}{4(w+s)}\frac{N^2}{N^2+1}\sum_{n=1}^{N-1}\left[l-\left(n+\frac{l}{2}\right)(w+s)\right] \tag{5}$$

where l_{avg}^{SR}, C_0, ϵ_r^{sub}, and k are defined in (6)–(9).

$$l_{avg}^{SR} = 4l - 2(s+w)\left(N+1-\frac{3}{N}\right) \tag{6}$$

$$C_0 = \epsilon_0\epsilon_r^{sub}\frac{K(\sqrt{1-k^2})}{K(k)} \tag{7}$$

$$\epsilon_r^{sub} = 1+\frac{2}{\pi}\tan^{-1}\left[\frac{h}{2\pi(w+s)}\right](\epsilon_r-1) \tag{8}$$

$$k = \frac{s}{(s+2w)} \tag{9}$$

with l_{avg}^{SR} is the average length of spiral loops, C_0 is the per-unit-length capacitance between two parallel strips having width of w and separation of s in the presence of a dielectric substrate with the relative permittivity of ϵ_r and the thickness of h, ϵ_r^{sub} is the effective relative permittivity related to the dielectric filling the substrate, h is the substrate thickness, and k is a modulus of the first kind complete elliptic integral. The value is affected by the strip width and the gap width of spiral as expressed in (9).

By using the relation of the impedance towards the permeability and the permittivity, the effective permeability and permittivity of SR shaped planar structure are obtained by varying the number of spiral loops, strip width, and gap width based on a first-order approximation of the permeability function which is derived using ClausiusMosotti in [11]– [14] as expressed in (10) and (11).

$$\mu_{eff} = \mu_0\left[1-\frac{(jn\omega\mu_0 l^2)/Z_{eff}}{1+(jn\omega\mu_0 l^2)/3Z_{eff}}\right] \tag{10}$$

$$\epsilon_{eff} = \frac{\mu_{eff}}{Z_{eff}^2} \tag{11}$$

The values of effective permeability and effective permittivity are required to observe the MNG property of SR shaped planar structure implemented as an antenna radiator. The structure has a MNG property if it has simultaneously negative value of effective permeability and positive value of effective permittivity at a certain frequency.

III. RESULT AND DISCUSSION

For analyzing the permeability and permittivity of SR shaped planar structure implemented as an antenna radiator, the first geometrical structure takes a number of spiral loops N of 3 with the strip width w of 3.1 mm and the gap width s of 0.5 mm. While the second one has a number of spiral loops N of 3 with the strip width w of 2.5 mm and the gap width s of 1.5 mm. By substituting the geometrical structure into equations explained in the previous section, the effective permeability and permittivity of the structure are then calculated using (10) and (11), respectively. Meanwhile, the effective permeability and permittivity of the structure are also obtained from 3D simulation results through the value of reflection coefficient (S_{11}) and transmission coefficient (S_{21}). The comparison between the analytical approach and simulation results for the effective permeability and permittivity are plotted in Figs. 2 and 3 for the first geometrical structure, respectively, and in Figs. 4 and 5 for the second geometrical structure, respectively.

From Fig. 2, it can be observed that the SR shaped planar structure implemented as an antenna radiator has a negative effective permeability at the real part for all frequency ranges through the analytical approach and above 0.8 GHz through the simulation. Whereas the imaginary part of effective permeability is negative above 0.7 GHz through the analytical approach and above 0.55 GHz through the simulation. From Fig. 3, it can also be observed that the real part of effective permittivity is a positive at all frequency ranges through the analytical approach and at the frequency range of 0–2.5 GHz, 0.45–0.7 GHz, and above 0.75 GHz through the simulation.

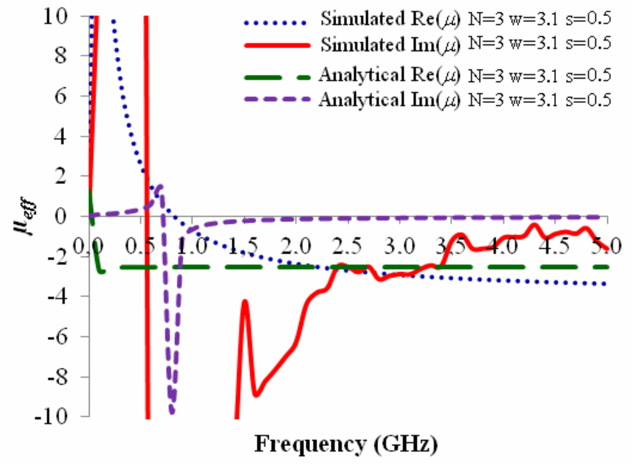

Fig. 2. Analytical approach and simulation results for effective permeability of first geometrical structure (N = 3, w = 3.1 mm, s = 0.5 mm).

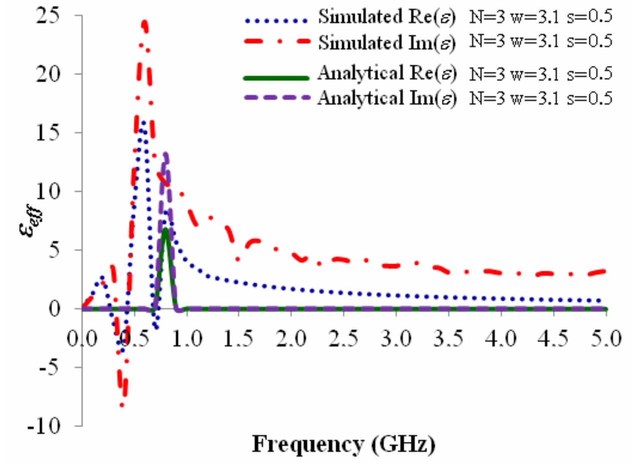

Fig. 3. Analytical approach and simulation results for effective permittivity of first geometrical structure (N = 3, w = 3.1 mm, s = 0.5 mm).

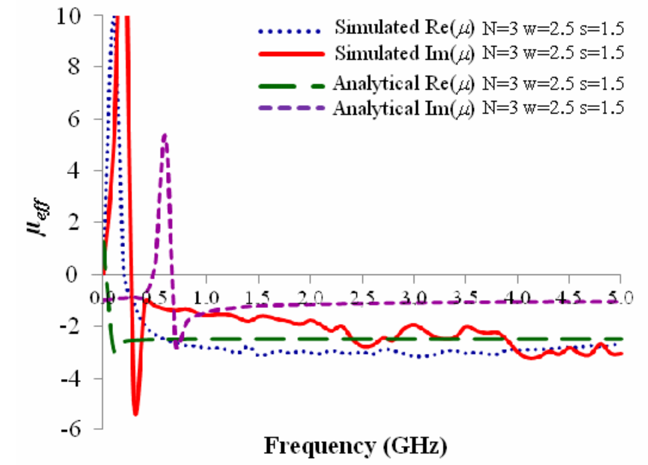

Fig. 4. Analytical approach and simulation results for effective permeability of second geometrical structure (N = 3, w = 2.5 mm, s = 1.5 mm).

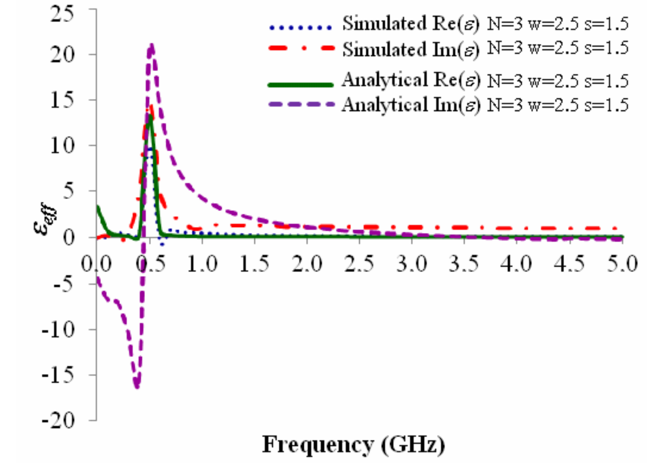

Fig. 5. Analytical approach and simulation results for effective permittivity of second geometrical structure (N = 3, w = 2.5 mm, s = 1.5 mm).

Whilst the imaginary part of effective permittivity is a positive at all frequency ranges through the analytical approach and through the simulation is a positive at the frequency range of 0–3.5 GHz and above 0.45 GHz.

Figures 2–5 show the similar pattern for the effective permeability and permittivity at the frequency above 0.8 GHz. However, there are obvious discrepancies between the analysis and simulation. This phenomenon can be explained by hypothesis that the dielectric substrate has low conductivity at the low frequency and contrarily high conductivity at the high frequency. The dielectric substrate with low conductivity affects the material characteristic to be susceptible by noise. Therefore, the effective permeability and permittivity in 2–5 show the erratic pattern at the frequency below 0.8 GHz.

From the above description, it can be found out that the negative permeability absolutely occurred at the frequency range above 0.8 GHz and the positive permittivity absolutely occurred at the frequency above 0.75 GHz. Therefore, the positive permittivity ($\epsilon > 0$) and negative permeability ($\mu < 0$) called as μ negative or MNG was achieved absolutely at the frequency range above 0.8 GHz. In the frequency range above 0.8 GHz, the antenna can be applied for cellular communications, wireless local area network (WLAN) communications, etc. However, the antenna is designed to operate at the frequency range of 2.3 GHz to 2.4 GHz for WLAN application. In addition, it is noted that the analytical approach and simulation results of complex permittivity and permeability for the SR shaped planar structure implemented as an antenna radiator show good agreement each other as demonstrated in the both results.

IV. CONCLUSION

The analytical approach of permittivity and permeability of SR shaped planar structure implemented as an antenna radiator has been presented. The equivalent circuit has been used to calculate the effective impedance of SR shaped planar structure yielding the effective permittivity and permeability. The SR shaped planar structure has also been characterized using 3D simulation software to compare with the analytical approach. The analytical approach of effective permittivity and permeability of SR shaped planar structure has had similar graph with the simulation. However, it was slightly differ at the frequency below 0.5 GHz. Nevertheless, the simulation and analytical approach could be inferred to have good agreement at the frequency above 0.8 GHz.

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