Analysis of bandwidths for various types of metamaterial zeroth-order resonant antennas

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Abstract

This paper presents design methods of metamaterial zeroth-order resonant (ZOR) antennas and analysis of their bandwidth. Besides, the Q-factors for metamaterial resonant antennas have been derived and analyzed. Two ZOR antenna structures have been designed and fabricated using the provided design formulas, to result in good agreement among theory, circuit/EM simulation, and measurement.

Keywords : Antennas Metamaterial Zeroth-order Bandwidth Q-factor

1. Introduction

Recently, there has been intense research on metamaterial-based transmission lines (or RLH-TL). The composite RLH-TL can be constructed and many applications in the microwave (and other) band have followed [1-4]. Especially, the resonant RLH-TL's have been applied to zeroth-order resonant (ZOR) antennas [5,6] with a good deal of their promising features such as resonance with a very small size. The return loss bandwidths of ZOR antennas reported in these papers and others are narrow (typically less than 10%). The bandwidth has been reported to be the key limiting factor of ZOR antennas. In this paper, the works in [3] are more refined through modeling of radiation effects using simple circuit parameters and very convenient design formulas are provided based on them with two design examples. Two ZOR antenna structures have been designed and fabricated using the provided design formulas. Their performances are compared among circuit/EM simulations and measurements.

2. Extraction of Circuit Parameter

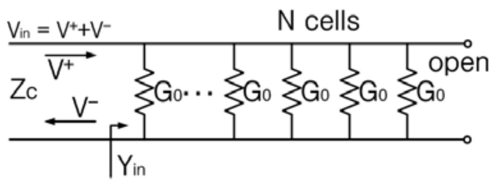


Figure 1: Equivalent circuit of open-terminated resonant RLH-TL.

Fig. 1 shows the equivalent circuit for open-terminated Double Negative (DNG) ZOR RLH-TL. V^+ and V^- are the incident and reflected voltages at the input and G_0 is the shunt conductance to explain the loss in realizing L_0 [3]. The input admittance Y_{in} up to the N-cell is given by

$$Y_{in} = NG_0 \tag{1}$$

at the transition frequency f_0 where β=0. The reflection coefficients S_{11} at the input is given by

$$S_{11} = \frac{Y_c - Y_{in}}{Y_c + Y_{in}} = \frac{1 - NG_0/Y_c}{1 + NG_0/Y_c} \tag{2}$$

where Y_c is characteristic admittance of the line. The total input voltage V_{in} can be expressed as

$$V_{in} = V^{+}\left(1+S_{11}\right) = V^{+}\frac{2}{1+NG_0/Y_c}. \tag{3}$$

The total radiation rate (P_{rad} / P_{in}) up to the Nth cell ($\eta_{T,N}$) can be shown to be given by

$$\eta_{T,N} = \frac{P_{rad}}{P_{in}} = \frac{4\cdot NG_0/Y_c}{\left(1+NG_0/Y_c\right)^2} \tag{4}$$

which must be equated with 1-$|S_{11}|^2$ obtained based on EM simulations.

From this relation, the radiation parameter G_0 for a unit cell can be obtained as

$$G_0 = \frac{Y_c}{N}\left[\left(\frac{2}{\eta_{T,N}}-1\right) - \sqrt{\left(\frac{2}{\eta_{T,N}}-1\right)^2 - 1}\,\right]. \tag{5}$$

The radiation rate η per unit cell is given by $\eta = \eta_{T,N}$ / N.

Fig. 2 shows the equivalent circuit of the open-terminated metamaterial-based DNG ZOR antenna having N unit cells with a coupling capacitor with C_1. In general, the coupling capacitor is necessary for the matching of the ZOR antenna to the input transmission line with a characteristic impedance Z_c. We can find a new resonant radian frequency ω_1, which is somewhat lower than the resonant radian frequency ω_0 of the ZOR antenna itself, and the coupling capacitance value C_1 [6]. In case of a short termination, the new resonant radian frequency and the coupling inductance can be found easily using duality.

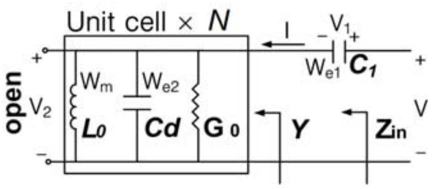


Figure 2: Equivalent circuit of open-terminated DNG ZOR antenna.

The voltages V_1 and V_2 are given by

$$V_1 = V\cdot\frac{N\left[G_0 + j2(Cd)(\omega_1-\omega_0)\right]}{N\left[G_0 + j2(Cd)(\omega_1-\omega_0)\right]+j\omega_1 C_1},\quad V_2 = V\cdot\frac{j\omega_1 C_1}{N\left[G_0 + j2(Cd)(\omega_1-\omega_0)\right]+j\omega_1 C_1}. \tag{6}$$

The radiated power is given by

$$P_{rad} = N\cdot\frac{1}{2}\mathrm{Re}\left[V_2 I^*\right] = \frac{|V_2|^2}{2}NG_0. \tag{7}$$

The quality factor for an open-terminated zeroth-order resonator (Q_{open}) at ω_1 can be shown to be given by

$$Q_{open} = \omega_1\cdot\frac{W_{e1}+\left(W_m+W_{e2}\right)}{P_{rad}} = \frac{1}{2G_0}\left[\omega_1(Cd) + \frac{1}{\omega_1 L_0} + \frac{N|Y|^2}{\omega_1 LC_1}\right] \tag{8}$$

where W_m and W_e are the time-averaged stored magnetic and electric energy.

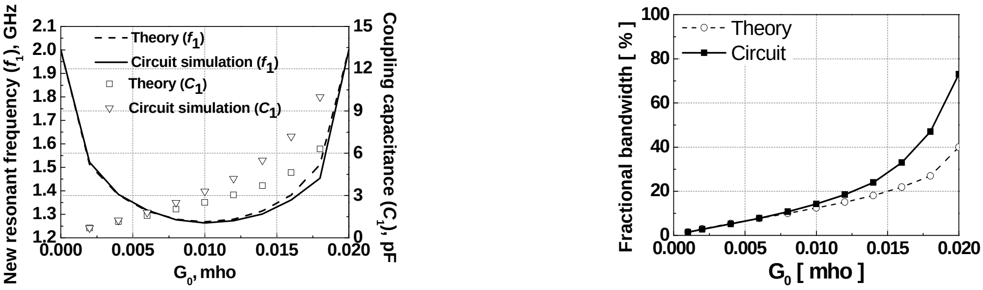
The fractional bandwidth can also be shown to be given by

$$BW = \frac{2|S_{11}|}{\sqrt{1-|S_{11}|^2}} \cdot \frac{1}{Q} \tag{9}$$

where $|S_{11}|$ is a reference reflection level for the bandwidth.

3. Simulation Results

Fig. 3 (a) shows the new resonant frequency (f_1) obtained using [6] and circuit simulation as a function of G_0. The circuit values L_0, C_0, and electrical length kd are 7.42 nH, 2.97 pF, and $\pi/6$, respectively, and the design frequency is 2 GHz (N=1). Please note in connection with [6] that when G_0 is small, ω_1 is close to ω_0, when $G_0=Y_c/2=0.01$mho, ω_1 becomes the lowest, and when $G_0=Y_c$, ω_1 again becomes ω_0. In Fig. 3 (a), the circuit simulation results agree well with the calculated results using [6]. Fig. 3 (b) presents the fractional bandwidth (based on -20dB) with different radiation parameters (R_0, G_0). The coupling capacitance for matching is obtained by using [6]. The bandwidth in case of open termination has been obtained based on (9). The estimated bandwidth using (9) is seen to be accurate when $G_0 \le Y_c/2$, but shows discrepancies when $G_0 \ge Y_c/2$. It is judged to come from the linear approximation of the resonator admittance Y_{in}.



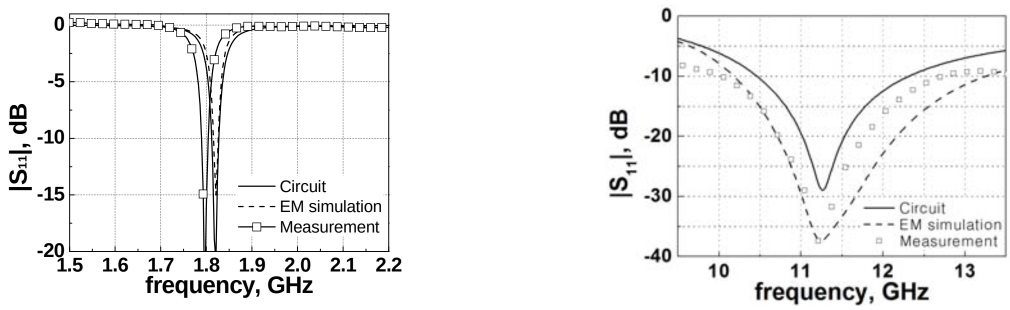
(a) New resonant frequency (f_1) (b) Fractional bandwidth

Figure 3: Extraction of parameters with increasing loss parameters (open terminated circuit)

We have designed two zeroth-order resonant antenna structures. One is a low radiation structure (G_0 = 0.00014 S) designed at 2 GHz, another one is a high radiation structure (G_0 = 0.0079 S) designed at 14GHz. Fig. 4 shows the fabricated open-terminated ZOR antennas. Both structures are realized on a Teflon substrate with a relative permittivity of 2.2 and a height of 2.37 mm. Using the design formulas in [3], we obtain the values of C_0 and L_0. Fig. 4 (a) shows the Double Negative (DNG) ZOR antenna designed at 2GHz. The former is realized using a chip capacitor in a transverse cut with its gap and the latter is realized employing a shunt shorted stub. Fig. 4 (b) shows the Epsilon Negative (ENG) ZOR antenna designed at 14GHz. It employs a mushroom structure with two parallel vias.

(a) DNG ZOR antenna at 2 GHz (b) ENG ZOR antenna at 14 GHz

Figure 4: Fabricated open terminated ZOR antenna.



(a) DNG ZOR antenna
(low radiation)

(b) ENG ZOR antenna
(high radiation)

Figure 5: Reflection coefficients of ZOR antenna.

Fig. 5 (a) shows the reflection coefficient of the DNG ZOR antenna. The 10 dB circuit/EM-simulated and measured bandwidths are 15 MHz (0.83%), 11 MHz (0.61%), and 14 MHz (0.78%), respectively, at the new resonant frequency of about 1.8 GHz, In Fig 5. (b), we show the reflection coefficient of the ENG ZOR antenna. The 10dB return loss bandwidths are 1.84 GHz (16.37%), 3.07 GHz (27.31%) and 2.70 GHz (24.02%), respectively, at the new resonant frequency of about 11.24 GHz.

4. Conclusion

We have analyzed the bandwidth of the ZOR antennas based on the Q-factor considering effects of coupling elements and provided very convenient design formulas. These design formulas are provided for the case of open terminations, and dual expressions may be used for the case of short terminations. The two zeroth-order antenna structures have been designed using the provided design formulas, fabricated and measured, to result in reasonable agreement among theory (calculated result), circuit/EM simulation, and measurement.

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Acknowledgments

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