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A NOTE ON RADIATION LOSS OF ZEROTH ORDER RESONATORS

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Abstract—A composite right/left-handed transmission line resonator with 3 unit cells is fabricated and its radiation loss is investigated. At the zeroth order resonance state, the resonator shows radiation loss, which is dominant over other conductor and dielectric losses. This paper investigates the radiation loss of zeroth order resonators from a quality-factor point of view. With the use of a metal shield, the quality factor is considerably increased through a reduction of the radiation loss. The increase in the quality factor is explained by means of the extracted parameters of the equivalent circuit model.

1. INTRODUCTION

A composite right/left-handed (CRLH) transmission line (TL) approach is a useful format for realizing planar type left-handed metamaterials [1]. Unlike the conventional TLs, the CRLH TLs exhibit infinite wavelength at nonzero frequencies, which brings about zeroth order resonators (ZORs) [2]. Therefore, zeroth order resonant frequencies do not rely on the physical length of the structure, but on the reactive loadings. This unique property makes it possible to design a novel device such as an N-port series divider [3].

The zeroth order resonances occur in the radiation region of the CRLH dispersion diagram. If the resonant structure is open to air, it inevitably radiates a substantial amount of power into the free space under the zeroth order resonances. This radiation loss leads to undesirable effects, such as possible crosstalk with other circuits.

The effects of radiation losses on the quality factor Q were reported for open-ended microstrip resonators [4, 5]. Meanwhile, there has been relatively little reported research on the radiation loss problem of the CLRH TL resonators.

This paper elucidates the radiation loss of the fabricated ZOR based on an evaluation of the Q factor under the use of a metal shield. In addition, the parameters of an equivalent circuit model are extracted.

2. CRLH TL RESONATOR

A complete circuit pattern of a 3-cell CRLH TL resonator with microstrip technology is shown in Fig. 1. It is noted that typical CRLH TL resonators have been implemented by enforcing an open or short boundary condition at two ends of the CRLH TLs instead of matched boundaries. The resonator is coupled with $50\,\Omega$ microstrip lines by a capacitive coupling gap.

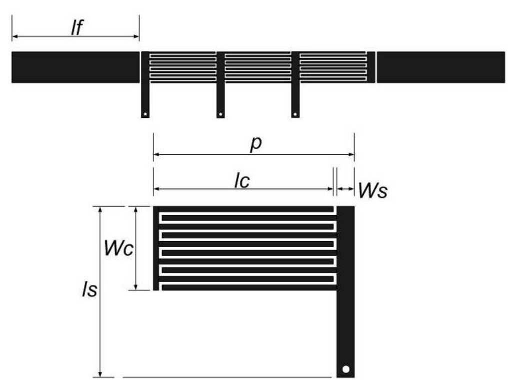

Figure 1. Pattern of a microstrip CRLH TL resonator and its unit cell comprising of an interdigital capacitor and a shorted stub inductor.

Figure 2 illustrates the equivalent circuit model of the unit cell. The parameters L_R, C_R, L_L, and C_L can be extracted by using the Parameter Extraction Method and full-wave simulation results [6]. It should be noted that the unit cell is assumed to be lossless ($R = G = 0$) for the extraction of the parameters, and the losses will be taken into consideration later. According to the simple circuit theory, CRLH TL resonators can have two zeroth order resonances in accordance with

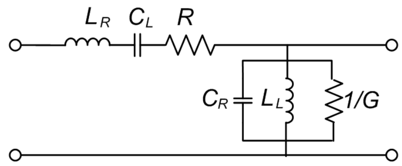

Figure 2. Equivalent circuit model of the unit cell.

an open or short boundary condition. The series and shunt resonant frequencies are respectively

$$\omega_{res}^{short} = \omega_{se} = \frac{1}{\sqrt{L_R C_L}}, \tag{1}$$

$$\omega_{res}^{open} = \omega_{sh} = \frac{1}{\sqrt{L_L C_R}}. \tag{2}$$

When the series and shunt resonant frequencies are equal, the structure is said to be balanced. For simplicity, the parameters are chosen to meet the balance condition.

The resonant frequencies of the 3-cell CRLH TL resonator are plotted together with the dispersion curve of a balanced CRLH TL in Fig. 3. The propagation constant β is related with the resonant frequencies, as given below

$$\beta = \frac{1}{p}\cos^{-1}\left(1 + \frac{ZY}{2}\right) = \frac{n\pi}{Np} \tag{3}$$

where p is the period of the unit cell, N is the number of unit cells, $Z = j\omega L_R + 1/j\omega C_L$, and $Y = j\omega C_R + 1/j\omega L_L$. According to (3), the predicted resonant frequencies are 1.1 ($n = -2$), 1.5 ($n = -1$), 2.4 ($n = 0$), 3.9 ($n = 1$), and 5.3 GHz ($n = 2$). For $n = 0$ mode, the structure has a zero propagation constant at nonzero frequency.

In Fig. 3, the radiation region is 1.9 GHz through 3.8 GHz in which the wave is faster than the velocity of light. As seen in this figure, the zeroth order resonance mode ($n = 0$) is always in the radiation region. This implies that the resonator radiates power that will be losses of the resonator. This radiation is investigated in detail in the next section.

3. FULL-WAVE SIMULATION AND MEASUREMENT RESULTS

In order to extract parameters of the equivalent circuit model for the unit cell shown in Fig. 1, the interdigital capacitor and the shorted stub inductor are simulated separately. The resonator is designed so that the transition frequency is 2.4 GHz. The dimension of the unit cell is $p = 11.6$ mm, $l_c = 10.4$ mm, $W_c = 4.8$ mm, $l_s = 9.9$ mm, $W_s = 1.0$ mm, and 5 pairs of digits with width of 0.3 mm and 0.2 mm spacing between two adjacent digits. The length of feed lines l_f is 26.3 mm. The simulation is performed using the method of moment simulation (Ansoft ENSEMBLE). The extracted parameters are $L_R = 3.29$ nH, $C_L = 1.37$ pF, $L_L = 3.35$ nH, and $C_R = 1.22$ pF at the transition frequency. These values are slightly different from those in the caption of Fig. 3.

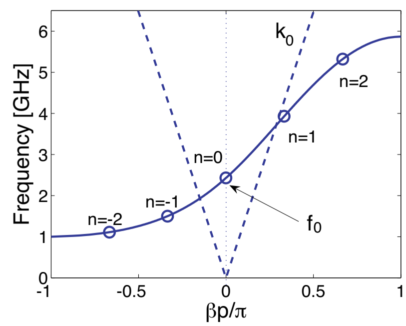

Figure 3. Resonance frequencies (denoted by the circles) along the dispersion diagram of a balanced CRLH TL. The parameters used are $L_R = L_L = 3.3$ nH, $C_L = C_R = 1.3$ pF, and $R = G = 0$. k_0 is the free space wavenumber and f_0 is called the transition frequency for balanced structures.

A fabricated 3-cell microstrip CRLH TL resonator with a metal shield is shown in Fig. 4. Fig. 5 shows the measured resonant characteristics with the HFSS simulation results and the circuit simulation results. The comparison between the measured results and the HFSS simulation results reveals excellent agreement. The zeroth order resonant frequency in the circuit simulation is 2.4 GHz, whereas it is 2.3 GHz in the HFSS simulation and measured result. The discrepancies are attributed to the difference in the capacitive coupling level and possible numerical error in the extraction of parameters.

To verify how much power the 3-cell CRLH TL resonator radiates, the relative radiation loss ratio (r) is computed. The value of r is defined as

$$r = \frac{P_{rad}}{P_{rad} + P_{diss}}, \tag{4}$$

where P_{rad} represents the radiated power into free space and P_{diss} is the dissipated power, which accounts for conductor and dielectric losses. These conductor and dielectric losses of materials are included in the HFSS simulation.

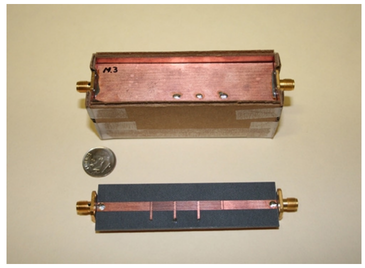

Figure 4. Photo of the 3-cell microstrip CRLH TL resonator and a metal shield box (bottom view). The prototype is implemented on Rogers RT/Duroid 5880 with dielectric constant of 2.2, thickness of 1.57 mm, and loss tangent of 0.0009. The substrate size is $88.8 \times 24\,\text{mm}^2$ and the dimension of the metal shield is $88.8 \times 24 \times 28\,\text{mm}^3$ (length $\times$ width $\times$ height).

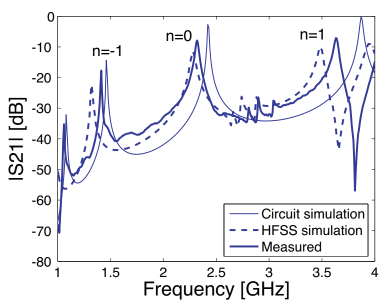

Figure 5. Measured resonant characteristics compared with HFSS result and circuit simulation result.

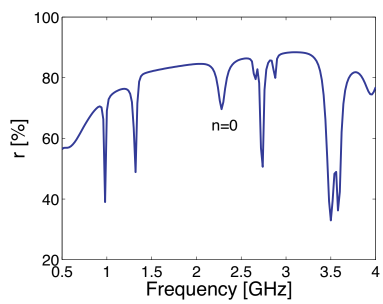

Figure 6. Simulated relative radiation loss ratio of the 3-cell CRLH TL resonator.

As seen in Fig. 6, the relative radiation loss ratio is larger than 70% at $n = 0$ resonance mode, which implies that the radiation loss accounts for at least 70% of the overall losses. In addition, the radiation loss at $n = 0$ resonance mode is, as expected, greater than that of other non-zero resonant modes ($n = \pm 1$, ± 2) within the guided region.

We also demonstrate the radiation loss of the ZOR by experiment. Examining this phenomenon from a quality-factor point of view, it is expected that radiation loss reduction will result in a Q factor increase of the ZOR. We present experimental results for a 3-cell CRLH TL resonator with a metal shield.

The metal shield is made of copper and soldered to the ground (See Fig. 4) so that excitation of spurious parallel-plate modes is eliminated. First, in order to determine the optimal side wall spacing of the metal shield box, the HFSS simulation is performed. From the simulation, the side wall spacing is determined to be $5W_c$, and thus the side walls do not significantly perturb the field distribution in the vicinity of microstrip lines on the substrate. In addition, the height is set to be greater than a critical shield height ratio introduced in [7, 8]. When the height is less than this critical value, the metal shield considerably influences the electromagnetic field distribution and causes a significant shift of the resonant frequency.

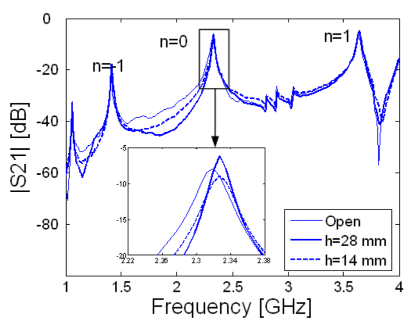

Figure 7. Measured scattering parameters of the shielded ZOR for the different heights of the metal shield.

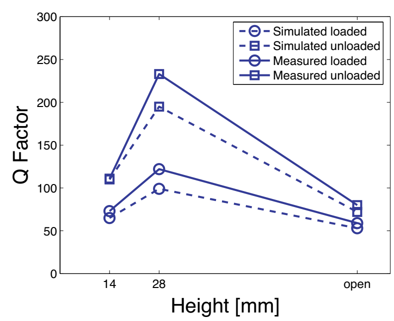

Figure 8. Measured loaded and unloaded Q factors for the 3-cell microstrip ZOR versus the heights of the metal shield.

The measured scattering parameters are shown in Fig. 7 for different metal shield heights. Considering that the fractional bandwidth for the shielded ZOR becomes narrower compared to an open case, it appears that the metal shield prevents most of the radiation loss. In order to confirm this reduction of radiation loss, the Q factors are calculated. The unloaded Q factors are estimated using the measured insertion loss and the loaded Q factor [9]

$$Q_0 = \frac{Q_L}{1 - |S_{21}|}. \tag{5}$$

The measured Q factors are shown in Fig. 8. Although the size of the metal shield is not optimized, the Q factor is remarkably increased at a height of 28 mm. The measured unloaded Q factors are 230 for the height of 28 mm and 80 for the open case. The increase in the Q factor is verified by simulation and experiment using the metal shield, thus demonstrating that ZORs have remarkable radiation loss at the zeroth order resonant frequency.

Table 1. Newly extracted parameters for the shielded ZOR with different heights of the metal shield.

Height	Open	28 mm	14 mm
L_L (nH)	3.35	3.08	3.01
C_R (pF)	1.22	1.30	1.31

Table 1 summarizes the newly extracted values of C_R and L_L for the shielded ZOR with different metal shield heights. Based on the new parameters and (2), the resonant frequencies of the shielded ZOR are shifted slightly to the higher frequency, as shown in Fig. 7. The shielding effect leads to additional shunt capacitance and shunt inductance between microstrip lines and the ground plane. This means that the effective C_R increases and the effective L_L decreases.

The unloaded Q of the shunt resonant circuit can be rewritten as

$$Q_0 = \frac{1}{\omega_{sh} L_L G} = \frac{\omega_{sh} C_R}{G}. \tag{6}$$

The increase in the unloaded Q of the ZOR with the metal shield is attributed to the effect of increasing C_R and decreasing L_L and G, as given in (6), where G stands for the total effective losses. Therefore, it is possible to increase the Q factor considerably by using the metal shield within a height limit that does not change the resonant frequency significantly. However, the shielding effects are more complicated when the height of the metal shield is reduced to a level comparable to the thickness of the substrate. In this case, the influence of the metal shield has to be considered in the initial design stage for novel ZORs. At the same time, it is important to devise methods for minimizing the radiation losses for applications of CRLH TL resonators.

4. CONCLUSION

In this paper, an example of a microstrip CRLH TL resonator with a metal shield was presented. It has been demonstrated by simulations and measurements that the CRLH TL resonator suffers from significant radiation loss at the zeroth order resonance mode. Radiation loss reduction with the metal shield resulted in a more than twofold increase of Q factors without affecting the zeroth order resonant frequency. The influence of the metal shield on the Q factor is explained with the extracted parameters. Radiation losses degrade the resonator quality factor and one has to take them into account especially at the transition frequency.

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