Modeling of Radiation Effects for 1-D RLH-TL Using Extraction of Circuit Parameters

회로 파라미터 추출을 통한 1-D RLH-TL의 방사 효과 분석

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Abstract

The equivalent circuit for the RLH-TL is proposed considering radiation effects due to the inclusion of a series capacitor and shunt inductor in a unit cell for the right/left-handed transmission line(RLH-TL). The design equations to realize a specific phase shift at a given frequency is also provided. The S-parameters for unit cells with N=1, 3, 5, and 10 are analyzed in various aspects based on the EM and circuit simulations especially for the purpose of controlling radiation along RLH-TL's. A modification formula for the radiation rate per unit cell is also proposed for good agreement between the EM and circuit simulation results.

요 약

일반적으로 손실이 없는 우형 전송선 모델에 직렬 커패시터와 병렬 인덕터를 삽입하여 만든 우좌형 전송 선로에 손실을 고려한 등가 회로를 제안한다. 제안된 식을 이용하면 원하는 주파수에서의 위상 조절이 가능하며, 단위 셀을 점차 늘려갈수록 발생하는 방사율에 대한 조정 역시 용이하게 된다. 단위 셀의 구조의 증가는 안테나의 배열과 같으며, 이러한 배열 구조에서는 균등한 방사가 요구된다. 따라서 방사율의 조정을 위한 식은 일반적인 마이크로스트립 기판에 제작된 평면 안테나에 비해 소형화된 안테나를 구성하는데 적용될 수 있다. 그리고 회로 시뮬레이션과 EM 시뮬레이션 사이에서 발생하는 방사율에 대한 편차는 수정된 식을 적용하면 부합된 결과를 얻을 수 있으므로 간단한 방사 구조의 설계시 간편하게 이용할 수 있을 것으로 기대된다.

Key words : Metamaterials, Left-Handed Materials, Negative Refractive Index, Radiation Effect, Transmission Line

Ⅰ. Introduction

There has been intense research on metamaterial-based transmission lines. The conventional transmission lines, which usually support TEM waves and follow the right hand rule(right-handedness), have been characterized by the distributed series inductance L(given in unit of H/m) and shunt capacitance C(given in unit of F/m). By adding a lumped-type series capacitance C_0 and shunt inductance L_0 periodically with a unit cell size of d much smaller than the wavelength, the composite right- and left-handed transmission line can be constructed and many applications in the microwave band have followed[1]~[6]. The lumped series capacitance C_0 has been commonly realized by a transverse cut or interdigital cut on the signal line, while the lumped

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shunt inductance L_0 has been commonly realized by a shunt shorted stub. In realizing C_0 periodically on the line, some power is leaked out of the cuts. In realizing L_0, some power is also leaked out of the shorted stub due to a discontinuity problem. These radiation losses are inevitable. For most applications such as phase shifters, directional couplers, power dividers, and etc, this radiation effect behaves adversely to their desired performances since the transmitted power levels are usually somewhat less than the required ones. For these applications, design must be carried out to minimize the radiation losses. The minimization of the radiation losses is possible although it is limited. For antenna applications such as leaky wave antennas, these radiation effects need to be controlled. Some beneficial features of leaky wave antennas have been widely reported, while some refining study still needs to be performed further. In this paper, radiation effects are investigated based on the proposed equivalent unit cell. The radiation rate formula for the series gap capacitor and shunt stub inductor is derived using transmission line theory. The equivalent circuit is examined in terms of the Bloch impedance of complex propagation constant[7]. Some design equations for the control of radiated power are also presented. The S-parameters for unit cells with N=1, 3, 5, and 10 are analyzed in various aspects based on the EM and circuit simulations especially in terms of radiation rates. A modification formula for the radiation rate per unit cell is proposed and its validity is investigated.

Ⅱ. Analysis of Equivalent Circuit for RLH-TL Considering Radiation Effects Based Transmission Line Theory

In Fig. 1, we propose the equivalent circuit of a unit cell considering radiation effects. The right-handed transmission line(RH-TL) with its electrical length kd is usually characterized by the distributed series inductance $L(H/m)$, series resistance $R(\Omega/m)$, shunt capacitance $C(F/m)$, and shunt conductance $G(\mho/m)$. The

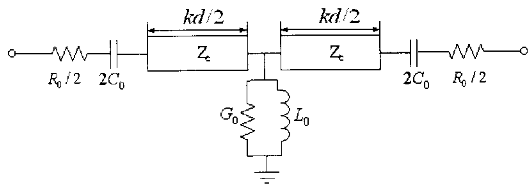


Fig. 1. Equivalent circuit of a unit cell considering radiation effects.

left-handedness comes from C_0 and L_0 but they are inevitably accompanied by R_0 and G_0. For most practical applications, $R \ll \frac{R_0}{d}$ and $G \ll \frac{G_0}{d}$, and thus we will assume that $R=G=0$ throughout our analysis.

For an ideal lossless RLH-TL with loading of C_0 and L_0, the important analysis equations are given by

$$LC = \mu\varepsilon = \mu_0\varepsilon_0\varepsilon_e, \tag{1}$$

where μ_0, ε_0, and ε_e are the permittivity, permeability, and relative effective dielectric constant, respectively,

$$Z_c = \sqrt{\frac{L}{C}} = \sqrt{\frac{L_0}{C_0}} \text{ (matching condition)}, \tag{2}$$

and $$(-\beta d) \approx -\left(\omega\sqrt{LC}d - \frac{1}{\omega\sqrt{L_0C_0}}\right) = \phi_\omega (rad) \tag{3}$$

The symbol ϕ_ω denotes the phase shift per unit cell at a specific radian frequency of ω.

For a specific phase shift ϕ_ω per unit cell at a radian frequency of ω, the design equations for the C_0 and L_0 loadings can be expressed as

$$C_0 = \frac{1}{Z_c}\frac{1}{\omega^2\sqrt{LC}d + \omega\phi_w} = \frac{1}{Z_c}\frac{1}{\omega(kd + \phi_w)} \tag{4}$$

and $$L_0 = Z_c^2 C_0. \tag{5}$$

The solutions (4) and (5) are valid in the limiting case where kd is very small.

More exact solutions can be determined from the dispersion equation given by

$$\cosh(\alpha d + j\beta d) =$$

$$\cos\theta - \frac{1}{2\omega^2 L_0 C_0}\cos^2\frac{\theta}{2} \quad (\theta = kd).$$
$$+\frac{1}{2\omega}\left(\frac{1}{C_0 Z_c}+\frac{1}{L_0 Y_c}\right)\sin\theta \qquad (6)$$

Most design employing metamaterial-based transmission lines is now based on the lossless equivalent circuit, although some optimization trial follows to deal with losses through EM simulation and actual measurement.

The lumped series capacitance C_0 can be realized by a transverse cut or interdigital cut on the signal line, while the lumped shunt inductance L_0 can be realized by a shunt shorted stub. In realizing C_0 and L_0, some power is leaked out of the transverse cut and shunt shorted stub. In a trial to consider this radiation effects, a lumped resistance R_0 and conductance G_0 have been included as shown in Fig. 1. The radiation rate η_1 per unit cell due to the series loading of C_0 can be shown to be given by

$$\eta_1 = \frac{R_0}{Z_c} \qquad (7)$$

if $\frac{1}{\omega C_0} \ll Z_c$, which is indeed true for most practical cases. The derivation for the radiation rate η_2 due to inclusion of a shunt stub inductor L_0 similarly goes with the one for η_1 due to inclusion of a series capacitor C_0. The radiation rate due to a stub inductor can be shown to be given by

$$\eta_2 = \frac{G_0}{Y_c}. \qquad (8)$$

The distributed series impedance per unit length(Z) may now be written by

$$Z = j\omega L + \frac{1}{j\omega C_0}/d + R_0/d$$
$$= j\omega\left(L - \frac{1}{\omega^2 C_0 d}\right) + (\eta_1 Z_c)/d$$
$$= j\omega L_{eff} + (\eta_1 Z_c)/d\ (\Omega/m)\ . \qquad (9)$$

The effective distributed series inductance L_{eff} may be positive, zero, and negative depending on the degree of the added left-handedness due to periodic L_0 loading in a unit cell size d. The distributed shunt admittance per unit length(Y) may now be written as

$$Y = j\omega C + \frac{1}{j\omega L_0}/d + G_0/d$$
$$= j\omega\left(C - \frac{1}{\omega^2 L_0 d}\right) + (\eta_2 Y_c)/d$$
$$= j\omega C_{eff} + (\eta_2 Y_c)/d(\mho/m)\ . \qquad (10)$$

The effective distributed shunt capacitance C_{eff} may be positive, zero, and negative depending on the degree of added left-handedness due to periodic L_0 loading in a unit cell size d. The effective distributed series inductance L_{eff} and shunt capacitance C_{eff}(Circuit parameters) are related with the effective relative permeability μ_{eff} and permittivity ε_{eff} as

$$L_{eff} = \mu_0 \mu_{eff}\, g(H/m) \qquad (11)$$

and $$C_{eff} = \varepsilon_0 \varepsilon_{eff}\frac{W}{h} = \varepsilon_0\varepsilon_{eff}/g(F/m) \qquad (12)$$

where the geometrical factor g can be found from the ratio of the substrate-filled Z_c and air-filled $Z_{c,air}$ as $Z_c / Z_{c,air}$.

L_{eff} is seen to be proportional to μ_{eff} with the proportionality constant $\mu_0 g$ and C_{eff} is seen to be proportional to ε_{eff} with the proportionality constant ε_0/g. The pair of L_{eff}(or μ_{eff}), C_{eff}(or ε_{eff}) may be both positive (Double Positive(DPS): RH region), both negative(Double Negative(DNG): LH region), only μ_{eff}(or L_{eff}) negative(Mu Negative(MNG)), or only ε_{eff}(or C_{eff}) negative(Epsilon Negative(ENG)) depending on the degree of added left-handedness(LH) to the host RH-TL.

The total radiation rate η due to a gap capacitor and stub inductor is the sum of each and given by

$$\eta = \eta_1 + \eta_2 = \frac{R_0}{Z_c} + \frac{G_0}{Y_c}. \qquad (13)$$

The radiation rate η may also be understood as a perturbation factor inflicted on a lossless RLH-TL unit cell. The Bloch impedance Z_B, which differs from the characteristic impedance due to loading effects of C_0 and L_0, is related with the ratio of Z(9) and Y(10) as given by

$$Z_B = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{j\omega\left(L - \frac{1}{\omega^2 C_0 d}\right) + (\eta_1 Z_c)/d}{j\omega\left(C - \frac{1}{\omega^2 L_0 d}\right) + (\eta_2 Y_c)/d}} \tag{14}$$

For the case of no radiation($\eta_1 = \eta_2 = 0$), it is well known that the Bloch impedance Z_B reduces to the characteristic impedance Z_c. By observing equation (14), we can see that when the radiation rates η_1 and η_2 are the same, Z_B also reduces to the characteristic impedance Z_c. This means that if the degrees of radiation due to the transverse cut(for C_0) and the shorted stub(for L_0) characterized by η_1 and η_2 are the same, there is a perfect match at the input connecting the RH transmission line and RLH loaded transmission line. Usually, the typical radiation rates are approximately in the range 0.01~0.1(1~10 %) depending on loading structures. The control of the radiation rate η_1 is usually easier than the control of η_2. Thus, the realization of L_0 is recommended in advance of C_0. If L_0 is realized on any TEM transmission line with a specific radiation rate η_2, then we need to make an effort to obtain the same radiation η_1 as η_2 by adjusting the transverse cut for C_0.

The complex propagation constant γ is related with the product of Z and Y and given by

$$\gamma = \alpha + j\beta = \sqrt{ZY}\,. \tag{15}$$

The attenuation constant α in (15) can be shown to agree with

$$\alpha = \frac{1}{2d}\left(\frac{R_0}{Z_c} + \frac{G_0}{Y_c}\right) = \frac{1}{2d}(\eta_1 + \eta_2) = \frac{\eta}{2d} \tag{16}$$

The propagation constant is almost the same when radiation effects are small.

The control of radiation rate η_1 is possible by adjusting the width w and gap g shown in Fig. 2.

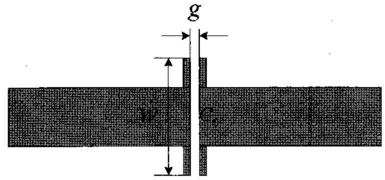


Fig. 2. Geometry of gap capacitor.

The gap capacitance C_0 in Fig. 2 is roughly proportional to the ratio of w/g and radiation from the gap increases as w increases. Thus, the control of radiation rate η_1 is possible by a proper choice of w and g.

For antenna applications(leaky wave antenna for an example), we need to design a RLH unit cell such that $\eta_1 = \eta_2$ as much as possible. If this is the case, $Z_B \rightarrow Z_c$ and the periodically loaded RLH-TL is completely matched to the unloaded input RH-TL. In a periodic RLH-TL with identical unit cells, power leaking out of the each unit cell decreases exponentially. The total radiated power up to the Nth cell($\eta_{T,N}$) is given by

$$\eta_{T,N} = 1 - e^{-\eta N} \tag{17}$$

where η is the radiation rate for a unit cell.

If a specific $\eta_{T,N}$ is desired, the total required number N of the unit cells is obtained by

$$N = -\frac{\ln(1 - \eta_{T,N})}{\eta}\,. \tag{18}$$

The uniformly radiating array may be more frequently needed than the exponentially radiating array. This may be possible with non-uniform radiation rates along the transmission line given by

$$\eta_n = \frac{\eta_0}{1 - n\eta_0} \quad (n=0,\ 1,\ 2,\ \cdots) \tag{19}$$

using the first approximation, where η_0 is the radiation rate referred to the input power reaching the first unit cell and the total required number N of the unit cells for a specific $\eta_{T,N}$ is given by

$$N = \frac{\eta_{T,N}}{\eta_0} \tag{20}$$

Ⅲ. Comparison of S-parameters in Terms of Radiation Rates Based on EM and Circuit Simulations

When the size of the RLH-TL unit cell is very small compared with the wavelength, the effective medium concept can be applied and the relative effective permeability($\mu_{eff}=\mu_{eff}' - j\mu_{eff}''$) and permittivity ($\varepsilon_{eff}=\varepsilon_{eff}' - j\varepsilon_{eff}''$) can be obtained [8] from the simulated or measured S_{11} and S_{21} referred to both ends of the unit cell. Using the obtained μ_{eff} and ε_{eff}, we have

$$Z = R_0/d + j\omega\left(L - \frac{1}{\omega^2 C_0 d}\right) = j\omega L_{eff} = j\omega\cdot\mu_0\mu_{eff}\, g\,(\Omega/m) \tag{21}$$

and

$$Y = G_0/d + j\omega\left(C - \frac{1}{\omega^2 L_0 d}\right) = j\omega C_{eff} = j\omega\cdot\varepsilon_0\varepsilon_{eff}/g\,(\mho/m). \tag{22}$$

With the additional matching condition

$$\omega_0 = \frac{1}{\sqrt{(Ld)C_0}} = \frac{1}{\sqrt{(Cd)L_0}}, \tag{23}$$

the six circuit parameters can be extracted as

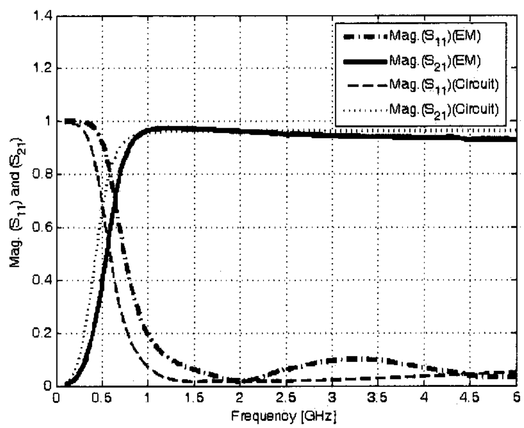
$$R_0 = \omega\mu_0\mu_{eff}'' dg\,(\Omega),\quad G_0 = \omega\varepsilon_0\varepsilon_{eff}'' d/g\,(\mho),$$

$$L = \frac{1}{\omega_0^2 C_0}/d\,(H/m),\quad C_0 = \frac{\frac{1}{g}\left(\frac{1}{\omega_0^2} - \frac{1}{\omega^2}\right)}{\mu_0\mu_{eff}' d}(F),$$

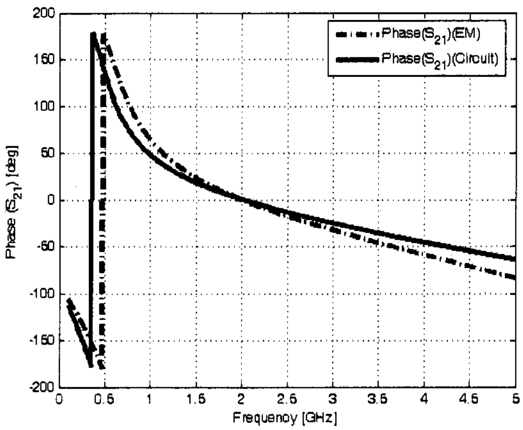
$$C = \frac{1}{\omega_0^2 L_0}/d\,(F/m),\ \text{and}\quad L_0 = \frac{g\left(\frac{1}{\omega_0^2} - \frac{1}{\omega^2}\right)}{\varepsilon_0\varepsilon_{eff}' d}(H). \tag{20}$$

To validate the formulation given in section II based on transmission line theory, we construct a unit cell on a Rogers RT Duroid 5880 substrate. The relative permittivity ε_r is 2.2. The height h of the substrate is 1.6 mm. The width of the RH 50 Ω transmission line is 4.9 mm. The length of the unit cell is 9.09 mm, which is $\lambda/12$ at the transition frequency of 2 GHz where β =0. Using equation (6), the loading capacitance and inductance are found to be C_0=3.03 pF and L_0=7.28 nH, respectively, which are tried to be realized using a chip capacitor in a transverse cut with its gap 1 mm, a shunt shorted stub with width 1.254 mm(characteristic impedance Z_1 of 92.64 Ω), and length 13.44 mm.

Fig. 3 shows the magnitude (a) and phase (b) of S_{11} and S_{21} obtained from EM and circuit simulations. We can observe a wide passband at around the transition frequency of 2 GHz. The magnitude of S_{21} at 2 GHz is shown to be somewhat less than 1 due to losses mainly due to radiation. For the circuit simulation, we have used C_0=3.03 pF and L_0=7.28 nH. Besides, we have



(a) Magnitude



(b) Phase

Fig. 3. EM- and circuit-simulated S_{11} and S_{21} for unit cell.

included the radiation effects using R_0=2.654 Ω and G_0=0.0005 ℧ (to be determined later).

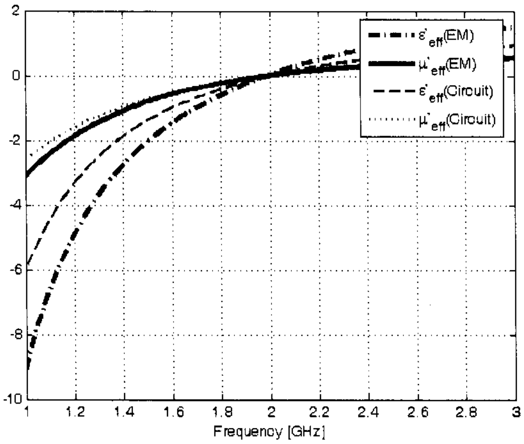
The phase of S_{21} at 2 GHz is shown to be almost 0. For frequencies below 2 GHz, the phase shift φ_ω in (3) is positive($\beta<0$: LH region), and for frequencies above 2 GHz, φ_ω is negative($\beta>0$: RH region). The S-parameters based on EM and circuit simulations are shown to be in good agreement.

In Fig. 4, we compare the real parts of the effective relative permittivity(ε_{eff}) and permeability(μ_{eff}) extracted from S_{11} and S_{21} referred to both ends of the unit cell based on EM and circuit simulation. The real parts of ε_{eff} and permeability μ_{eff} are shown to in reasonable agreement, while the imaginary parts of them show some disagreement except near the transition frequency of 2 GHz.

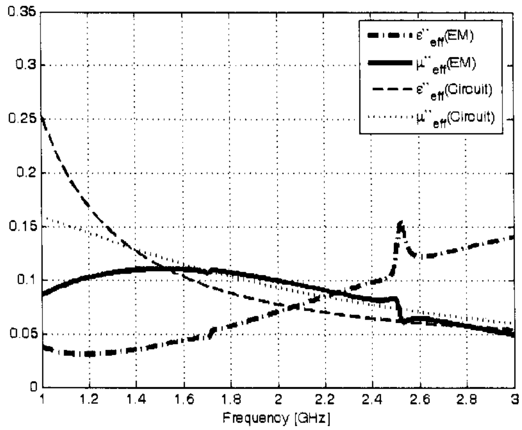
Based on the effective relative permittivity(ε_{eff}) and permeability(μ_{eff})(Fig. 4), the extracted circuit parameters using the solutions in (24) at 2 GHz are R_0=2.654 Ω, G_0=0.0005 ℧, C_0=2.8 pF and L_0=5.0 nH.

More details are summarized in Table 1. In Table 1, the radiation rates per unit cell obtained using $1-|S_{11}|^2-|S_{21}|^2$(EM data) and equation (13) are shown to be exactly the same(0.078 or 7.8 %).

We show in Fig. 5 the magnitude (a) and phase (b) of S_{11} and S_{21} obtained from EM and circuit simulations for RLH-TL composed of 3 unit cells. A wide passband

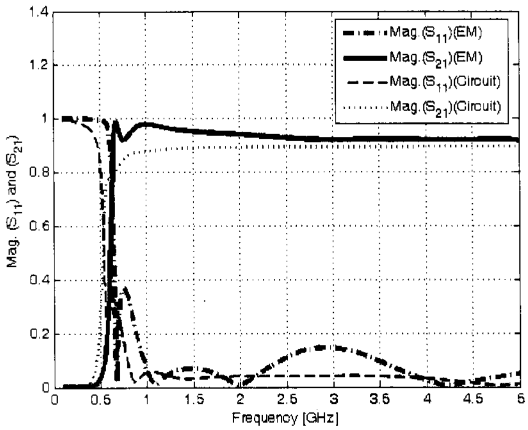


(a) Real part

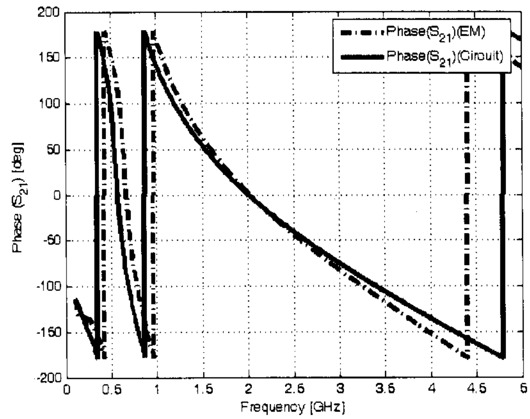


(b) Imaginary part

Fig. 4. Effective relative permittivity(ε_{eff}) and permeability(μ_{eff}) extracted from S_{11} and S_{21}.



(a) Magnitude



(b) Phase

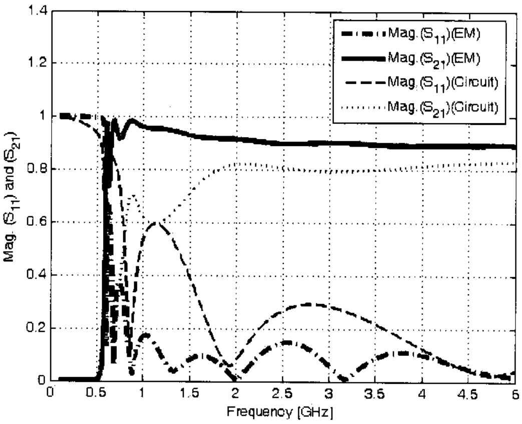
Fig. 5. EM- and circuit-simulated S_{11} and S_{21} for RLH-TL with 3 unit cells.

is observed at around the transition frequency of 2 GHz. For EM simulation, we have used a lumped capacitance of 2.60 pF in a gap of 1 mm, W=1.254 mm, and l= 14.539 mm to compensate for some coupling between cells. For circuit simulation, we continue to use the same unit cell employed for Fig. 3. The magnitude of S_{21} at 2GHz is shown to be somewhat less than 1 due to losses mainly caused by radiation.

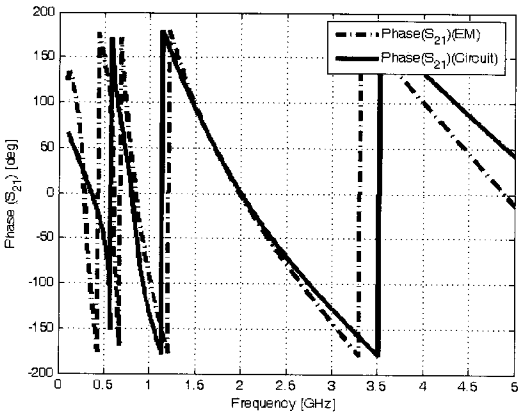
Fig. 6 shows the magnitude (a) and phase (b) of S_{11} and S_{21} obtained from EM and circuit simulations for RLH-TL with 5 unit cells. For EM simulation, we have used the same unit cell employed for Fig. 5.

The magnitudes of S_{21} based on EM and circuit simulations are shown to have a significant difference. The phases of S_{21} based on EM and circuit simulations are shown to agree well with each other. The radiation rate for 5 unit cells obtained using $1-|S_{11}|^2-|S_{21}|^2$(EM data) and equation (17) with N=5 are 13.36 % and 32 %, respectively, showing a large discrepancy.

Fig. 7 shows the magnitude (a) and phase (b) of S_{11} and S_{21} obtained from EM and circuit simulations for RLH-TL with 10 unit cells. For EM simulation, we have used a lumped capacitance of 2.75 pF in a gap of 1mm, W=1.254 mm, and l=14.249 mm to compensate for some coupling between unit cells. Here too, the magnitudes of S_{21} based on EM and circuit simulations are shown to have a significant difference. The phases of S_{21} between EM and circuit simulations are shown to

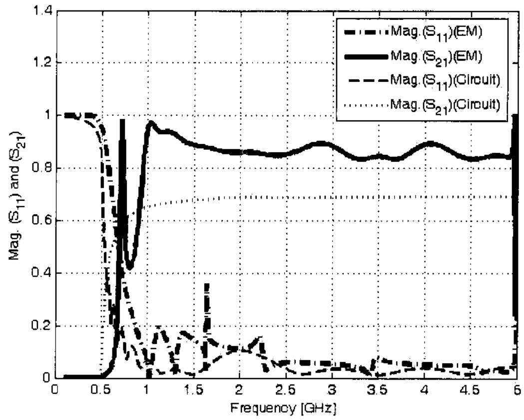


(a) Magnitude

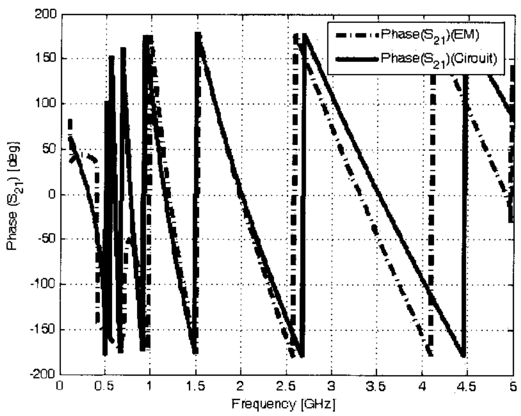


(b) Phase

Fig. 6. EM- and circuit-simulated S_{11} and S_{21} for RLH-TL consisting of 5 unit cells.



(a) Magnitude



(b) Phase

Fig. 7. EM- and circuit-simulated S_{11} and S_{21} for RLH-TL with 10 unit cells.

Table 1. Summary of parameters for RLH-TL unit cell.

Description	C_0(pF)	L_0(nH)	$R_0(\Omega)$	$G_0(\mho)$	η_1	η_2	η
Design	3.0294	7.2765					
EM data	2.2275 (gap=1 mm)	W=1.254 mm l=13.44 mm Z_l=92.64					0.078
Extracted circuit parameters	2.8	5	2.654	0.0005	0.053	0.025	0.078

agree well with each other. The radiation rate for 10 unit cells obtained using $1-|S_{11}|^2-|S_{21}|^2$(EM data) and equation (17) with N=10 are 24.83 % and 52 %, respectively, showing a large discrepancy.

Ⅳ. Modification of Radiation Rate η for RLH-TL with a Large Number of Unit Cells

The large difference of $|S_{21}|$ between the EM and circuit simulations in case of a large number of unit cells seems to come from following reasons.

1. The edge problem is alleviated in the EM simulations while it is not done in the circuit simulations since the same unit cells are just repeated.
2. The number of the transverse cuts does not increase in proportion to the number of unit cells used for EM simulations while it does in the circuit simulations.
3. There are some coupling effects between unit cells in the EM simulations while there are not in the circuit simulations.

To address these discrepancies for the case of a large number of unit cells, we modify the radiation rate per unit cell(η) based on EM simulation as

$$\eta = -\frac{\ln\left[1-\eta_{T,N}(EM)\right]}{N} \tag{25}$$

where N is the used number of unit cells and $\eta_{T,N}(EM)$ is the EM-simulated total radiation rate determined from $1-|S_{11}|^2-|S_{21}|^2$ for N unit cells.

When N=10, $\eta_{T,N}(EM)$ has been obtained as 0.2483,

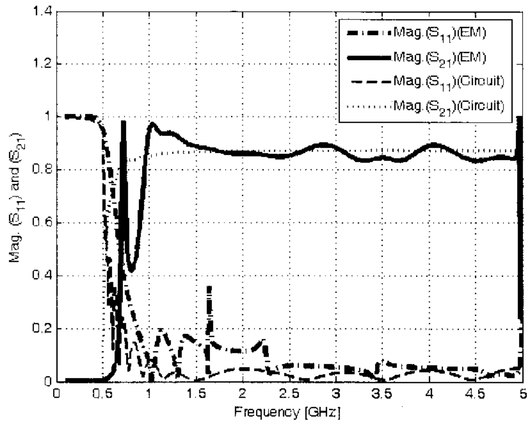


Fig. 8. EM- and circuit-simulated $|S_{11}|$ and $|S_{21}|$ for RLH-TL with 10 unit cells with modified η.

and the radiation rate per unit cell(η) is modified to be 0.0285(or 2.85 %). In Fig. 8, we compare the EM- and circuit-simulated $|S_{11}|$ and $|S_{21}|$ for RLH-TL consisting of 10 unit cells with the modified η. They are shown to be in good agreement.

Ⅴ. Conclusions

We have analyzed the equivalent circuits for 1-D RLH-TL considering radiation effects. The radiation rate formula has been derived considering the inclusion effects of a series capacitor and shunt inductor in a unit cell for the right/left-handed transmission line(RLH-TL). The method of realizing uniform excitation along the RLH-TL has also been proposed for antenna applications. The S-parameters for unit cells with N=1, 3, 5, and 10 have been examined based on the EM and circuit simulations especially in terms of radiation rates.

A modification formula for the radiation rate per unit cell has been proposed for good agreement between the EM and circuit simulation results.

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