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Wider frequency domain for negative refraction index in a quantized composite right–left handed transmission line*

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The refraction index of the quantized lossy composite right-left handed transmission line (CRLH-TL) is deduced in the thermal coherence state. The results show that the negative refraction index (herein the left-handedness) can be implemented by the electric circuit dissipative factors(i.e., the resistances R and conductances G) in a higher frequency band (1.446 GHz$\leq \omega \leq$ 15 GHz), and flexibly adjusted by the left-handed circuit components ($C_{\rm l}$, $L_{\rm l}$) and the right-handed circuit components ($C_{\rm r}$, $L_{\rm r}$) at a lower frequency ($\omega = 0.995$ GHz). The flexible adjustment for left-handedness in a wider bandwidth will be significant for the microscale circuit design of the CRLH-TL and may make the theoretical preparation for its compact applications.

Keywords: quantized composite right–left handed transmission line, negative refraction index, frequency domain

PACS: 81.05.Xj, 78.67.Pt, 78.20.Ci, 42.50.Gy **DOI:** 10.1088/1674-1056/27/6/068102

1. Introduction

A well-established route to constructing negative refractive index materials (NRMs)[1,2] is based on Veselago's theory of left-handed materials (LHM), simultaneous negative permittivity (ϵ) and magnetic permeability (μ) with different types of metamaterials.[3–9] Although very exciting from a physics point of view, the negative ϵ and μ produced by electromagnetic resonance may bring about a very highloss[10,11] and narrow bandwidth consequently. Due to the weaknesses of resonant-type structures, three groups almost simultaneously introduced a transmission line (TL) approach for NRM,[12–15] i.e., the composite right–left handed transmission line (CRLH-TL), which refers to the right-handedness accompanying the positive refraction index at high frequencies and to the left-handedness with the negative refraction index (NRI) at lower frequencies.[16] The CRLH-TL, initially the non-resonant-type one, is perhaps one of the most representative and potential candidates due to its low loss, broad operating frequency band, and planar configuration,[16,17] which is often related to the easy fabrication for NRI applications in a suite of novel guided-wave,[18] radiated-wave,[19] and refracted-wave devices and structures.[20,21] Nowadays, the CRLH-TLs show a tendency to the compact applications influenced by the nanotechnology and microelectronics.[22–24] Recently, a new class of miniaturized nonreciprocal leaky-wave antenna is proposed for miniaturization, nonreciprocal properties and wide-angle scanning at the same time.[25] With four unit cells of CRLH-TL a wide-band loop antenna is proposed in a compact size.[26]

However, when the compact size of the CRLH-TL approaches to the Fermi wavelength, the quantum effects[22–24,27] on the CRLH-TL must be taken into account. In our former work, we firstly deduced the quantum features of NRI of the lossless mesoscopic left-handed transmission line (LH-TL).[28,29] Then we quantized the lossy LH-TL and discussed the quantum influence of dissipation on the NRI[30] in a displaced squeezed Fock state. Some novel quantum effects were revealed and the significance for the miniaturization application of LH-TL was pointed out.

In this paper, the flexible adjustment of negative refraction index is achieved from a wider frequency bandwidth than in the former work[16,28–30] in the quantized lossy CRLH-TL in the thermal coherence state. The rest of this paper is organized as follows. In Section 2, we quantize the travelling current field in the unit-cell circuit of the CRLH-TL, and deduce its refraction index in the thermal coherence state. Then we evaluate the refraction index via the numerical approach in Section 3. Section 4 is devoted to our summary and conclusions.

2. Quantized refraction index in thermal coherence state

The equivalent unit-cell circuit model of the proposed lossy CRLH-TL is shown in Fig. 1. Compared with the loss-

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less CRLH-TL,[28,29] the imported resistance R and conductance G represent the loss except the series capacitor $C_{\rm l}$ and inductance $L_{\rm r}$, shunt inductance $L_{\rm l}$ and capacitor $C_{\rm r}$[31] in each unit cell circuit. The dimension Δz of the equivalent unit-cell circuit is much less than the wavelength at operating frequency. Hence, we now consider Kirchhoff's voltage and current laws for this unit-cell circuit in Fig. 1, which respectively read

$$u(z) = j(z)\left[R + \frac{1}{\mathrm{i}\omega C_{\rm l}} + \mathrm{i}\omega L_{\rm R}\right]\Delta z + u(z+\Delta z), \quad (1)$$

$$j(z) = u(z)\left[G + \frac{1}{\mathrm{i}\omega L_{\rm l}} + \mathrm{i}\omega C_{\rm R}\right]\Delta z + j(z+\Delta z), \quad (2)$$

where $u(z)$ is the voltage, $j(z)$ is the current, and ω is the angle frequency. When $\Delta z \to 0$, the above equations lead to the following system:

$$\frac{\partial^2 j(z)}{\partial z^2} = \left[G + \frac{1}{\mathrm{i}\omega L_{\rm l}} + \mathrm{i}\omega C_{\rm R}\right] \times \left[R + \frac{1}{\mathrm{i}\omega C_{\rm l}} + \mathrm{i}\omega L_{\rm R}\right] j(z).$$

The above electric current equation leads to the forward plane-wave solution:

$$j(z) = \exp(-\sigma z)[A\,\mathrm{e}^{(\mathrm{i}\beta z)} + A^*\,\mathrm{e}^{(-\mathrm{i}\beta z)}], \quad (3)$$

in which

$$\sigma + \mathrm{i}\beta = \sqrt{\left[G + \frac{1}{\mathrm{i}\omega L_{\rm l}} + \mathrm{i}\omega C_{\rm R}\right] \times \left[R + \frac{1}{\mathrm{i}\omega C_{\rm l}} + \mathrm{i}\omega L_{\rm R}\right]}. \quad (4)$$

In Eq. (3), A^* is the complex conjugate of A for normalization purposes. We adopt the quantization method similar to Louisell's[32] to achieve the current operator. In Fig. 1, the given unit-length, i.e., $z_0 = m\lambda$ where λ is the wavelength labelled typically by wavenumber k and frequency ω, its Hamiltonian can be written as follows:

$$H = \frac{1}{2}\int_0^{z_0}\left(Rj^2 + L_{\rm r}j^2 + C_{\rm l}u_{C_{\rm l}}^2 + \frac{1}{G}j_G^2 + L_{\rm l}j_{L_{\rm l}}^2 + C_{\rm r}u^2\right)\mathrm{d}z,$$
$$= FA^*Az_0$$

where

$$F = \frac{1 + R\omega C_{\rm l} + \omega^2 L_{\rm r}C_{\rm l}}{\omega C_{\rm l}} + \frac{L_{\rm l}^2\omega^2(G+1)}{(1+\omega L_{\rm l}G + \omega^2 L_{\rm l}C_{\rm r})^2}$$
$$+ \omega C_{\rm r}\left(\frac{1 + R\omega C_{\rm l} + \omega^2 L_{\rm r}C_{\rm l}}{\omega C_{\rm l}} + \frac{\omega L_{\rm l}}{1 + \omega L_{\rm l}G + \omega^2 L_{\rm l}C_{\rm r}}\right)^2.$$

Then, with the definitions $A = a\sqrt{\hbar\omega/Fz_0}$, and $A^* = a^*\sqrt{\hbar\omega/Fz_0}$, we achieve the Hamiltonian of the unit-cell circuit:

$$H = \hbar\omega a^* a. \quad (5)$$

According to the canonical quantization principle, we can quantize the system by operators $\hat{q}$ and $\hat{p}$, which satisfy the commutation relation $[\hat{q}, \hat{p}] = \mathrm{i}\hbar$. The annihilation and creation operators $\hat{a}$ and $\hat{a}^\dagger$ are defined by the relations

$$\hat{a} = \frac{1}{\sqrt{2\hbar\omega}}(\omega\hat{q} + \mathrm{i}\hat{p}), \quad \hat{a}^\dagger = \frac{1}{\sqrt{2\hbar\omega}}(\omega\hat{q} - \mathrm{i}\hat{p}).$$

Thus the quantum Hamiltonian of Fig. 1 can be rewritten as $\hat{H} = \hbar\omega\hat{a}^\dagger\hat{a} = \frac{1}{2}(\omega^2\hat{q}^2 + \hat{p}^2)$. Thus the current in the lossy unit cell equivalent circuit for CRLH-TL can be quantized as

$$j(z) = \sqrt{\frac{\hbar\omega}{Fz_0}}\exp(-\sigma z)[\hat{a}\,\mathrm{e}^{\mathrm{i}\beta z} + \hat{a}^\dagger\,\mathrm{e}^{-\mathrm{i}\beta z}]. \quad (6)$$

The thermal coherent state we adopted here is $|\alpha\rangle = D(\alpha)|0\tilde{0}\rangle_T = D(\alpha)T(\theta)|0\tilde{0}\rangle$.[33–35] Here, $D(\alpha) = \exp(\alpha a^\dagger - \alpha^* a)$ and $T(\theta) = \exp[-\theta(a\tilde{a} - a^\dagger\tilde{a}^\dagger)]$ with $\sinh^2(\theta) = [\exp(\hbar\omega/k_{\rm B}T) - 1]^{-1}$, in which $k_{\rm B}$ is the Boltzmann constant. In thermo-field dynamic (TFD) theory, the tilde space is accompanied with the Hilbert space, and the tilde operators commute with the non-tilde operators.[36] Thus the creation and annihilation operators $\hat{a}^\dagger$ and $\hat{a}$ are associated with their tilde operators $\tilde{\hat{a}}^\dagger$ and $\tilde{\hat{a}}$ are according to the rules:[36] $[\tilde{\hat{a}}, \tilde{\hat{a}}^\dagger] = 1$, $[\tilde{\hat{a}}, \hat{a}] = [\tilde{\hat{a}}, \hat{a}^\dagger] = [\hat{a}, \tilde{\hat{a}}^\dagger] = 0$. We can prove the following equalities easily,

$$\begin{aligned} &T^\dagger(\theta)aT(\theta) = ua + v\tilde{a}^\dagger, && T^\dagger(\theta)a^\dagger T(\theta) = ua^\dagger + v\tilde{a}, \\ &D^\dagger(\alpha)aD(\alpha) = a + \alpha, && D^\dagger(\alpha)a^\dagger D(\alpha) = a^\dagger + \alpha^*, \\ &\tilde{D}^\dagger(\tilde{\alpha})\tilde{a}\tilde{D}(\tilde{\alpha}) = \tilde{a} + \tilde{\alpha}, && \tilde{D}^\dagger(\alpha)\tilde{a}^\dagger\tilde{D}(\alpha) = \tilde{a}^\dagger + \tilde{\alpha}^*, \end{aligned} \quad (7)$$

with $u = \cosh(\theta)$ and $v = \sinh(\theta)$. Then with Eqs. (6) and (7), the quantum fluctuation of the current in the thermal coherent state is

$$\langle(\Delta\hat{j})^2\rangle = 2u^2\frac{\hbar\omega}{Fz_0}\exp(-2\sigma z). \quad (8)$$

It notes that σz is infinitesimal when z is dimensionless, and we can transform Eq. (8) by using the first order approximation of Taylor expansion as follows:

$$\frac{\langle(\Delta\hat{j})^2\rangle Fz_0}{2u^2\hbar\omega} = 1 - 2\sigma z. \quad (9)$$

With the relation $2\sigma\beta = \eta$ deduced from Eq. (4), and the relation ($n = c_0\beta/\omega$,[37] c_0 is the light speed in a vacuum) between propagation constant and refraction index in the CRLH-TL, the refraction index can be deduced from Eq. (9),

$$n = \frac{2\hbar c_0 u^2\eta z}{2u^2\hbar\omega - \langle(\Delta\hat{j})^2\rangle Fz_0}. \quad (10)$$

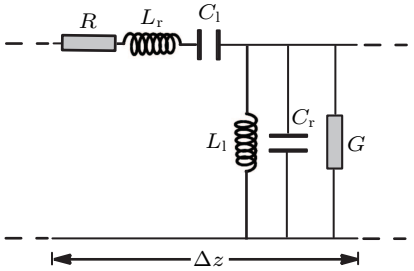


Fig. 1. Schematic diagram of an equivalent unit-cell circuit of the mesoscopic lossy CRLH-TL.

3. Numerical simulations and discussions

In a previous work,[16] the negative refraction index happened in the lower frequency bandwidth of the microwave wave. In order to investigate the minus refraction index, we should work with the refraction index from Eq. (10). However, the analytical equation (10) of the refraction index is rather cumbersome to obtain, so, we follow the numerical approach to analyze the refraction index of the CRLH-TL. Several parameters should be selected prior to the analysis. The length of the unit CRLH-TL circuit is $z = 4z_0 = 4$ nm, and the quantum fluctuation of the current $\langle(\Delta j)^2\rangle = 10^{-9}$. Other parameters used in our simulation are listed in Table 1 whose order of magnitudes are cited from Ref. [38].

Table 1. Parameters of the circuit components in the quantized lossy CRLH-TL.

	C_l/pF	L_l/pH	C_r/nF	L_r/nH	ω/GHz	R/μΩ	G/μS
Fig. 2(a)	3.667	416.7	9.80	129.8	–	–	99.8
Fig. 2(b)	3.667	416.7	9.80	129.8	–	0.95	–
Fig. 3(a)	–	416.7	–	129.8	0.995	0.35	99.8
Fig. 3(b)	1.000	416.7	–	–	0.995	0.35	99.8
Fig. 4(a)	–	416.7	98.0	–	0.995	0.35	99.8
Fig. 4(b)	285	–	98.0	–	0.995	0.35	99.8

The frequency bandwidth for negative refraction index (i.e., the left-handedness) is of interest to the mesoscopic CRLH-TL. Besides the role of the imported resistance R and conductance G representing the loss is also important here. Figure 2 shows the refraction index-dependent input resistance R and conductance G in the frequency domain. The relation between the refraction index and the resistance R is shown in Fig. 2(a). It is noted that in the lower frequency band [0, 1.446 GHz] the refraction indices are positive, and that its values are negative in the higher frequency band [1.446 GHz, 15 GHz], which surpasses the frequency band for left-handedness mentioned by Ref. [16]. We notice that the resistance R plays a passive role in both left-handedness and right-handedness frequency bands, i.e., the resistance R restrains the growth of the refraction index n in the two frequency bands. Figure 2(b) shows a similar behavior of the conductance G to that of the refraction index. The positive refraction index in the lower frequency band [0, 1.428 GHz] and the negative refraction index in the higher frequency band [1.428 GHz, 15 GHz] can be observed from the curves in Fig. 2(b). While increasing conductance G increased by 0.2 μS can enhance the refraction index from the dotted curve to the solid curve in both frequency bands, i.e., [0, 1.428 GHz] and [1.428 GHz, 15 GHz]. We note that the frequency band for negative refraction index (i.e., the left-handedness) in Fig. 2 surpasses what was mentioned in Ref. [16]. Generally speaking, neither of the resistance R and the conductance G is a desired role in electricity produced from the Joule heat via the Ohm law. In this quantized CRLH-TL, the resistance R and the conductance G can adjust the refraction index except the classic Ohm law. Throughout Fig. 2, this quantized CRLH-TL demonstrates the positive refraction index (i.e., the right-handedness) in the lower frequency band and the negative refraction index (i.e., the left-handedness) in the higher frequency band.

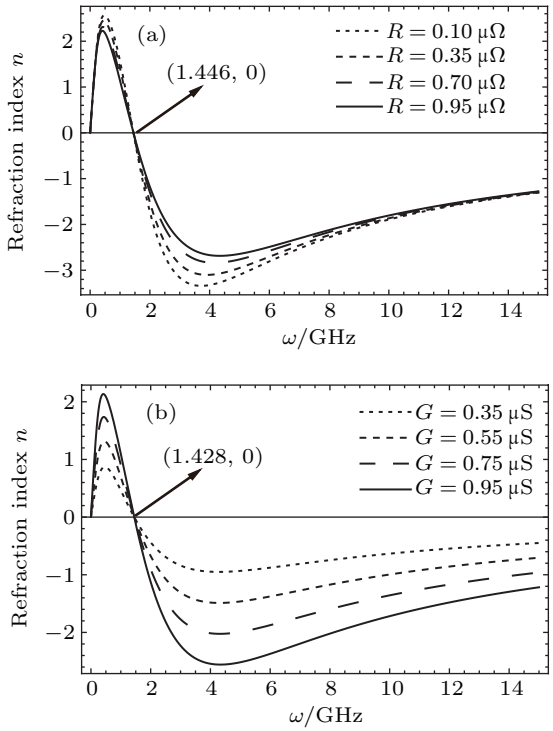


Fig. 2. Variations of refraction index n with frequency ω tuned by different values of (a) resistance R and (b) conductance G, respectively.

A notable question is whether it is possible to realize negative refraction index (i.e., the left-handedness) in the lower frequency bands. Figures 3 and 4 provide the refraction index dependent parameters of the circuit components at a lower frequency $\omega = 0.995$ GHz.

The refraction index dependent shunt capacitor C_r is provided in Fig. 3 at frequency $\omega = 0.995$ GHz. The curves each show that the refraction index is positive when the values of series capacitor C_l are assigned to 7.0 pF and 7.5 pF in Fig. 3(a), respectively. However, the refraction index is negative and reaches its maximum in a range [10 nF, 15 nF] of the

shunt capacitor C_r when the series capacitor C_l is set to be the larger values, i.e., $C_l = 8.5$ pF and 9.0 pF, respectively. The curves from dotted to solid in Fig. 3(b) show a similar feature when the refraction index is tuned by the different series inductances L_r's. However, we also note that a larger negative refraction index can be implemented by a smaller shunt capacitor $C_r \approx 1$ nF but a larger series inductance $L_r = 1150$ nH. Figure 3 demonstrates that the refraction index can be negative at a lower frequency $\omega = 0.995$ GHz with the appropriate parameters of series capacitor C_l and inductance L_r within the range [0, 20 nF] of the shunt capacitor C_r.

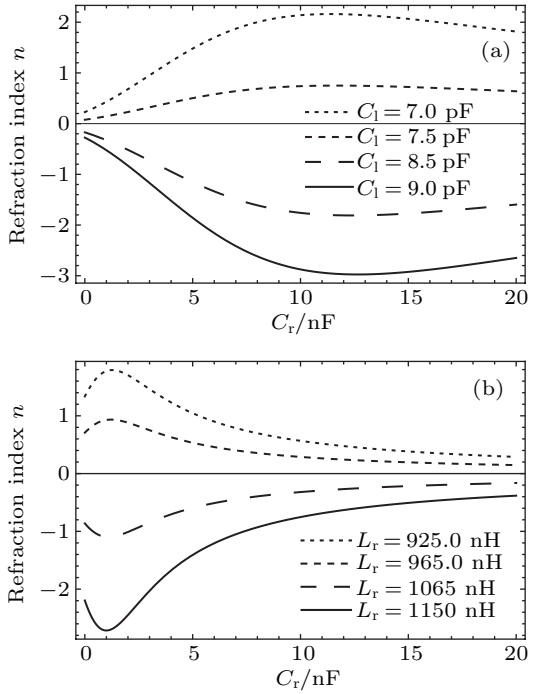


Fig. 3. Curves of refraction index n versus the shunt capacitor C_r tuned by different values of (a) series capacitor C_l and (b) inductance L_r, respectively.

At the lower frequency $\omega = 0.995$ GHz, figure 4 shows the refraction index dependent series inductance L_r for different values of series capacitor C_l in Fig. 4(a) and shunt inductance L_l's in Fig. 4(b), respectively. The increasing series capacitor C_l expands the range of the series inductance L_r's for negative refraction index and gradually increases the values of negative refraction indices in Fig. 4(a). The curves in Fig. 4(b) display the similar growth trends for negative refraction indices, but the increase of the negative refraction index in Fig. 4(a) is larger than that in Fig. 4(b). These results demonstrate that the left-handed circuit components (C_l, L_l) can enhance the negative refraction index in the mesoscopic lossy CRLH-TL.

Before concluding this paper, we should point out that how to broaden the frequency band for a negative refraction index is an active field for metamaterials, and the metamaterials within a wider band are always a research object. However, the frequency bands for negative refraction index only exist in the microwave band introduced by the first researchers[10–13] in the CRLH-TL. In our current study, we implement the negative refraction index within a wider frequency band in the quantized CRLH-TL and conclude that the negative refraction index in the higher frequency band (1.446 GHz$\leq \omega \leq$ 15 GHz) tuned by resistance R and conductance G and at a lower frequency ($\omega = 0.995$ GHz) tuned by the parameters of the circuit components. These achievements show the new characteristic for the quantized CRLH-TL, which should receive enough attention in the near future.

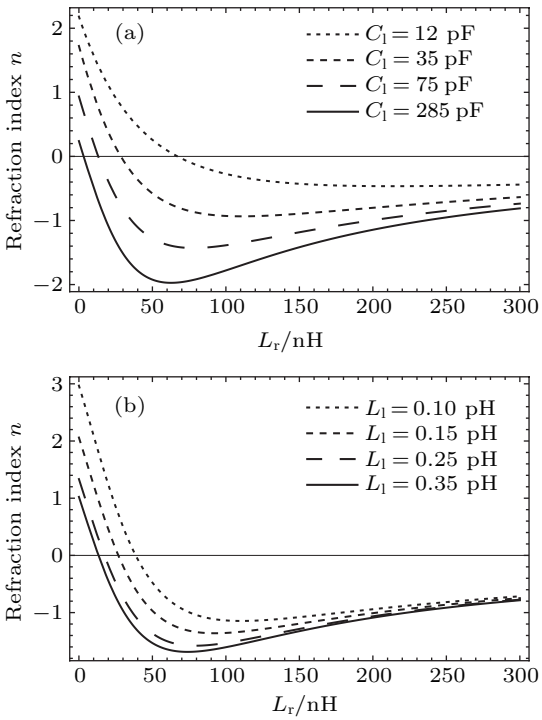


Fig. 4. Refraction index n versus series inductance L_r tuned by different series capacitors C_l (a) and shunt inductances L_l (b), respectively.

4. Conclusions

In the present paper, the negative refraction index has been obtained in a wider frequency band for the quantized CRLH-TL. The frequency domain for a negative refraction index is 1.446 GHz$\leq \omega \leq$ 15 GHz with the values of negative refraction index being opposite through tuning the resistance R and conductance G, respectively. At a much lower frequency ($\omega = 0.995$ GHz), the negative refraction indices can also be flexibly obtained by the left-handed circuit components (C_l, L_l), and the right-handed circuit components (C_r, L_r), respectively. The adjusting of negative refraction index within a wider bandwidth in this quantized CRLH-TL is significant for the microscale circuit design and compact applications for the CRLH-TL.

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