Introduction

The negative refraction index (NRI) is a consequence of negative permittivity and negative permeability. A media having negative refraction index is so called metamaterial or left-handed (LH) material. Properties of such materials were analyzed theoretically by Veselago [1] over 30 years ago, but only recently were them experimentally verified [2]. One of the intriguing properties of metamaterials is negative refraction. Through negative refraction, electromagnetic wave on one side of a NRI lens will refocus on the other side to achieve super-resolution. It is well known as a superlens which overcomes the diffraction limit of the conventional parallel sided lens made by positive refraction index (PRI) material. However, the losses are always inevitable for the superlens. There are three types of losses, one is the material dielectric loss, another is the metallic loss and the other is associated with the impedance mismatch on the interface between PRI/NRI materials. They would degrade the energy strength of the refocused wave. Therefore, a method is presented in this paper to reduce these losses by embedding amplifiers in the transmission path of NRI material as an active lens. The losses of material dielectric, metal and impedance mismatch can then be compensated.

Analysis and Simulation of Unit Cell

Fig. 1(a) shows the unit cell design parameters of the periodic structure. The implementation of unit cell is based on the mixed microstrip line/CPW structures. The top layer is the microstrip line structure, and the bottom one is CPW structure. The slot in the bottom layer is to increase the parallel inductor value and decrease the operation frequency of NRI material. Fig. 1(b) is the equivalent circuit model of unit cell. The series element 2C_L considers the coupling gap between cells. The series element L_R/2 considers the high-impedance microstrip line. The parallel elements L_L and C_R are for the effect of CPW structure on the ground plane. In addition, the slot on the ground plane provides a large effective inductance and capacitance to the microstrip line.

Fig. 2(a) shows the dispersion diagram of unit cell computed by using HFSS under periodic boundary condition. The solid line is the low frequency range of negative refraction index called left-handed (LH) mode. The dotted line is then the high frequency range of positive refraction index called right-handed (RH) mode. Due to the effect of surface wave, the LH mode will couple with the TM air mode. To acquire the element values of circuit model, discrete elements are extracted individually. The results of parameter extraction are C_L=0.223pF, L_L=0.615pF, C_R=7.63pF, L_R=12nH. Substituting these element values and βp into

\[
f = \sqrt{\frac{(2 - 2 \cos \beta p) - \sqrt{(2 - 2 \cos \beta p)^2 - \frac{4}{L_L C_L L_R C_R}}}{2}},
\]

the corresponding frequency can be found. The box line shown in Fig. 2(a) is the dispersion diagram computed using the equivalent circuit model. It agrees well with the HFSS simulation. The refraction index can then be computed from the dispersion diagram and is shown in Fig. 2(b) with a good agreement from the calculation using (2) and (3) given by
Active Lens Design

Fig. 3(a) is the unit cell of PRI material consisting of four microstrip lines with W=0.9mm and L=5.9mm. The effective refraction index of PRI material at 2.251GHz is 2.514. For the NRI material, the design parameters are given in Fig. 1(a). The effective refraction index of NRI material at 2.251GHz is -2.198. Fig. 3(b) shows the active lens design with an NRI material sandwiched by two PRI materials. The 1st interface between the left side PRI material and the right side NRI material is located at 10th column. The 2nd interface between NRI material and PRI material is located at 18th column. It is totally composed of 13 rows by 27 columns with 27 cells per row and 13 cells per column. Each PRI material is composed of an array of 13x9 cells. The NRI material is composed of an array of 13x7 cells. The source excitation is at the 7th row and 5th column. The active lens is designed to have amplifiers in the transmission path of NRI material to boost up the signals for easily visualizing the focusing and refocusing phenomena. Six amplifiers are located at the 13th and 15th columns.

Measurements Results

The measurement is performed by using an Agilent E8364B PNA in two-port measurement mode. The PNA port 1 is connected to the source point in the region of left PRI material. The port 2 is connected to an Agilent 85024A active probe which scans over the surface of the active lens to record the S21 value at each cell. Two samples are prepared. One is an active lens, whereas the other is a passive lens for comparison. The passive lens is configured with the same PRI and NRI materials as the active lens but having no amplifiers. Fig. 4(a) shows the measured S21 magnitude of the passive lens. The focus and refocus phenomena can be observed in the NRI material and right side PRI material. Due to the losses of material dielectric, metal and the impedance mismatch, the power distribution shows to decrease gradually in the focus region and refocus region. In addition, because of the difference of refraction indices of PRI and NRI materials, the focus region degenerates into a diffuse region. Fig. 4(b) shows the phase distribution of S21 of the passive lens from which the wavefront in the source region can be clearly observed. Although the wavefront becomes unclear in the NRI material due to the difference of refraction indices, the reversal of wavefront can be observed in the region of NRI material and the right side PRI material. It demonstrates the existing of negative refraction index of NRI material. Fig. 4(c) shows the S21 measured magnitude of the active lens. The dark color region in NRI material reveals the cells with amplification after passing through amplifiers. Due to the embedding amplifiers in the transmission path of NRI region, the power distribution in the refocus region of the right side PRI material is enhanced and clearly observed.

Conclusion

In this paper, a distributed active lens with PRI/NRI materials is designed and measured. The unit cell of NRI material is analyzed using HFSS under periodic boundary condition to give the dispersion diagram of unit cell. The corresponding refraction index and LH mode frequency computed by circuit model and HFSS are also shown in a good agreement. A scanning arrangement is developed using an Agilent E8364B PNA and an Agilent 85024A.
active probe to record the $S_{21}$ values for both the active and passive lenses. The focus and refocus phenomena are observed in the NRI material and the right side PRI material to demonstrate the negative refraction phenomenon. Moreover, the active lens with amplifiers embedded in the transmission path of the NRI material can compensate the imperfect match including dielectric loss, metal loss and impedance mismatch to clearly show the refocusing phenomenon in the right side PRI material.

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**References**


**Figures**

![Figure 1](image1.png)

Figure 1. (a) Unit cell of NRI material. The design parameters are $W_1=6.35\text{mm}$, $L_1=1.4\text{mm}$, $W_2=0.9\text{mm}$, $L_2=3.5\text{mm}$, $W_3=1.8\text{mm}$, $G=0.2\text{mm}$, slot width=0.4mm, slot spacing=0.4mm. The size of unit cell is $11.8\text{mm} \times 11.8\text{mm}$. The via diameter is 1mm. The dielectric substrate is FR4 with $\varepsilon_r = 4.4$, $H = 1\text{ mm}$ and $\tan\delta = 0.02$. (b) Equivalent circuit model of unit cell.

![Figure 2](image2.png)

Figure 2. Results of (a) dispersion diagram and (b) refraction index of NRI material.
Figure 3. (a) Unit cell of PRI material and (b) active lens with embedding amplifiers in the region of NRI material.

Figure 4. Measured results of (a) $S_{21}$ magnitude, (b) $S_{21}$ phase of passive lens, and (c) $S_{21}$ magnitude of active lens.