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FREQUENCY-SCANNED LEAKY-WAVE ANTENNA FROM NEGATIVE REFRACTIVE INDEX TRANSMISSION LINES

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Abstract

A microstrip frequency-scanned leaky-wave metamaterial-based antenna is presented in this paper. It is built from two negative refraction index transmission lines fed with opposite phase using an integrated balun. The microstrip leaky-wave antenna is a two-layer structure without any vias. The antenna works well at C band from approximately 3.5 GHz to 5.5 GHz, in which the main beam scans from -40° (backfire) to 40° (endfire). As it does not include any interdigital capacitors or vias, it can be easily extended to millimeter-wave frequency bands.

1 Introduction

The microstrip leaky-wave antenna has been discovered nearly thirty years ago [1]. It exhibits a simple structure, is easy to fabricate, and is very attractive in modern microstrip antenna design as well. The original microstrip leaky-wave frequency-scanned antenna uses the first higher-order mode, and the main beam can scan only towards the endfire direction. Special structures, e.g. baluns, are usually applied to feed such leaky-wave antennas in the first higher-order mode. Some efforts have been done on leaky-wave antennas to achieve beam scanning at a fixed frequency, such as with tunable ferroelectric materials [2], [3] or with the integration of varactors [4].

Metamaterials, left-handed (LH) materials, or negative refractive index (NRI) materials at microwave frequency show unique properties, such as both negative permittivity and negative permeability in a certain frequency range. These materials are first proposed by Veselago in 1960s and attract interests of many researchers. There are some potential dramatic applications, such as a perfect lens to focus microwave or an invisible "cloak" in the microwave/optical region. Besides those, with many remarkable characteristics of metamaterials [5], [6], there are many applications towards new microwave devices.

LH microstrip transmission line (TL) structures were already employed to realize antennas which scan from backfire to endfire [7], [8]. The combination of leaky-wave antennas and NRI TLs results in a novel antenna design. In this paper, we present a frequency-scanned leaky-wave antenna built from two combined NRI TLs where the main beam can scan from backfire (-40°) to endfire (40°). The NRI TLs are based on a microstrip multilayer techniques. No vias and tolerance-critical interdigital capacitors are used in this leaky-wave antenna. The antenna gain is about 10 dB from 3.5 GHz to 5.5 GHz. The structure can easily be extended to work up to millimeter-wave frequency bands.

2 Negative refractive index transmission line

2.1 NRI TL structure

The kernel of the microstrip leaky-wave antenna presented in this paper are two coupled NRI TL in a two-layer structure, fed with equal amplitude and opposite phase. The top and middle metallization layers include patch-like circuit elements with a ground metallization at the bottom. A number of identical microstrip resonators are uniformly and alternatively distribute in the top and the middle metallization layers. The principle structure of the arrangement is shown in Fig. 1. The elements in blue (dashed contour), e.g. with number 2 and 4, are located in the middle metallization layer, and those in red (solid contour), e.g. with number 1, 3, and 5, are on the top layer. Each unit element in the coupled NRI TLs, as shown in Fig. 1, is one resonator in either the top or the middle metallization plane. Each resonator consists of two patch-like structures connected by a narrow line. The series capacitance in the NRI TL is formed by the overlapping between two resonators on the top and in the middle metallization layer. Some series inductance results from the unavoidable parasitic effects. With balanced feeding, the NRI TL works in the odd mode. The symmetry plane thus becomes a virtual ground, and the shunt inductance and capacitance of the NRI TL are provided by the narrow lines crossing the virtual ground. The overlap between two resonators is 2.2 mm, and the distance between them (from one center to the other) is 3.8 mm. It therefore satisfies the requirement for the NRI TL approximation - the distance between two adjacent elements is much less than the guided wavelength at the operating frequency. If we analyze the equivalent circuit of the NRI TL, it may also be regard as the composite right/left handed (CRLH) TL.

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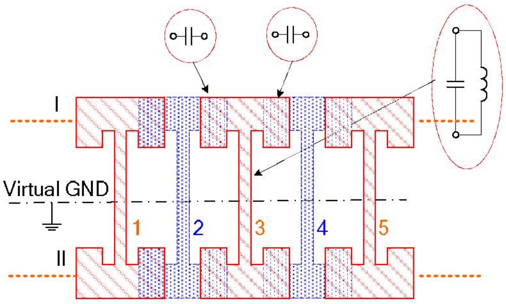

Fig. 1 Structure of the coupled NRI TLs with equivalent circuits. Unit elements 1, 3 and 5 (in red, solid lines) are on the top layer, and unit elements 2 and 4 (in blue, dashed lines) are in the middle metallization layer.

2.2 NRI TL characteristics

Based on the NRI TL analysis, it is dominantly LH, dominantly RH, and with infinite wavelength, while $f < f_0$, $f_0 < f$, and $f = f_0$, respectively [6]. Here f_0 is the transition frequency between the LH and the RH region. At the transition frequency, the wavelength becomes infinite. If a NRI TL resonator is built, the resonant mode at the transition frequency is called the zeroth-order resonance (ZOR), which is independent on the length of the NRI TL.

Let us take a look at the NRI TL in the matched case, in which the source and load are set to the characteristic impedance of the NRI TL. From the EM simulation, it can be seen that all unit elements exhibit the same phase due to the infinite wavelength at the transition frequency. A NRI TL of 17 unit elements according to the structure as shown in Fig. 1 has been simulated for the matched case. At $f_0 = 4.08\,\text{GHz}$, the phase shift between any unit elements is zero, as shown in Fig. 2. It is also worth noticing that: a) the phase shift between any two unit elements becomes greater when frequency is further away from f_0; b) the phase shift reverses (from advanced to delayed or vice versa) when frequency is varied from $f < f_0$ to $f < f_0$ or vice versa.

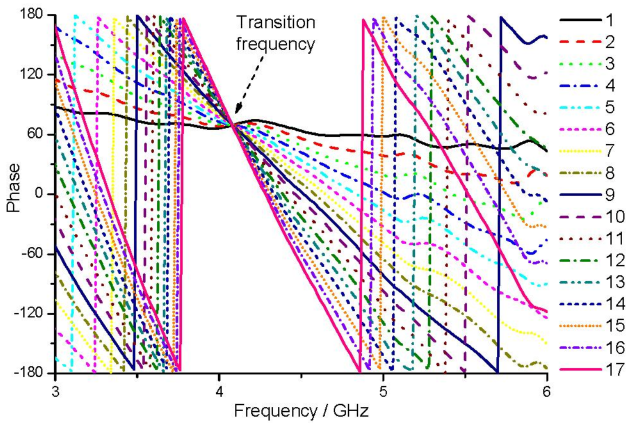

Fig. 2 Phase distribution between elements of the NRI TL with 17 unit elements which are numerated from 1 to 17

The dispersion of the NRI TL with 17 unit elements is obtained also from the simulated phase shift from the source to the load. It shows that in the dominant LH region $f < f_0$, wavelength increases with increasing frequency; at the transition frequency $f = f_0$, wavelength is infinite, and in the dominant RH region $f > f_0$, wavelength decreases with the increase of frequency.

3 Leaky-wave antenna

The leaky-wave antenna presented in this contribution is composed of two identical NRI TLs, which are separated by a virtual ground between them. To form the virtual ground, the two NRI TLs must be fed in the balanced mode with opposite phases. Therefore, a balun is also required to convert the unbalanced input signal from a coaxial cable to the balanced mode. In our design, the balun is directly integrated into the NRI TLs including two attached microstrip stubs, leading to a very compact antenna feeding system. The design and the performance of the integrated balun will not be discussed here in detail.

The resonators of each unit element may produce radiation like a dipole antenna, and the NRI TLs will work in the same way as leaky-wave antennas do. When the NRI TLs are dominantly RH, it is similar to a normal leaky-wave antenna (but in dominant mode), and the radiation direction turns to the load. When the NRI TL is dominantly LH, the phase velocity is reversed, and the radiation direction turns towards the source. Thus, the main beam of the NRI TL leaky-wave antenna scans from back-fire in the LH mode $f < f_0$ to end-fire in the RH mode $f > f_0$.

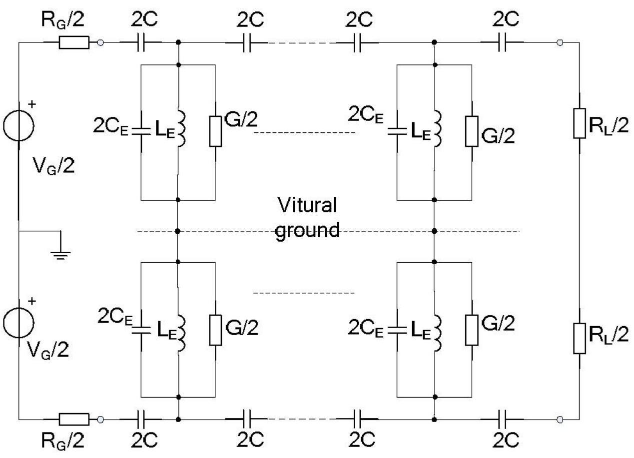

Fig. 3 Equivalent circuit of two lossy NRI TLs connected via the virtual ground

The effective radiation resistance of each unit element is included in the equivalent circuit of the NRI TL as shown in Fig. 3. Therefore, the NRI TLs applied in the leaky-wave antenna are, in fact, two lossy transmission lines. The analysis of the lossy transmission lines is performed by the image

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impedance method. The characteristic impedance (the image impedance) is

$$Z_C = \frac{1}{2}\sqrt{\frac{\frac{\omega^2}{\omega_E^2} + 8\omega^2 L_E C - 1 - j\frac{2\omega L_E}{R}}{\omega^2 C^2\left(1 - \frac{\omega^2}{\omega_E^2} + j\frac{2\omega L_E}{R}\right)}} \qquad (1)$$

where $\omega_E = \frac{1}{\sqrt{2L_E C_E}}$, $G = \frac{1}{R}$, and R is the equivalent antenna radiation resistance shunt-connected in each unit element. As required by the principle of leaky-wave antennas, the radiation from each unit element should not be strong, which implies $R >> \omega L_E$ in this design. Then, the passband of the NRI TL is determined from (1) as

$$\left(\omega_E^{-2} + 8L_E C\right)^{-\frac{1}{2}} < \omega < \omega_E \qquad (2)$$

The final frequency-scanned leaky-wave antenna contains a balun, two NRI TLs, and a matched load. It is built as a microstrip multilayer structure using two RT/Duroid 5880 substrates with a relative dielectric constant ε_r=2.2 and of thicknesses 0.254 mm and 1.58 mm, respectively. The advantage of this constellation is that it does not require any vias as used in most NRI TL designs to build the shunt inductors. Furthermore, the series capacitances do not require tolerance-sensitive interdigital or lumped capacitors. It has a broader bandwidth, and its design can be easily extended to the millimeter-wave frequency range.

The finally fabricated NRI TL leaky-wave antenna comprises 41 unit elements plus two unit elements combined into the balun. Each unit element extends 16.8 mm (resonator length) laterally and 7.4 mm in the longitudinal direction of the NRI TL. The total size (with the integrated microstrip balun and the feed line) is about 300 mm by 20 mm. The characteristic impedance of each NRI TL is designed to be 75 Ω. Since there are two NRI TLs operating in the balanced mode, the load should be 150 Ω which is realized by a normal chip resistor (size code 0805) in our design. A view on the two metal layers of the NRI TL leaky-wave antenna is shown in Fig. 5.

The antenna was simulated with the Sonnet software [10]. The reflection of the antenna was measured with a HP 8510C vector network analyzer. Measured and simulated $|S_{11}|$ are plotted and compared in Fig. 4. It shows a very good agreement except for the high frequency RH region. The leaky-wave antenna works at C-band from about 3.5 GHz to 5.5 GHz with a return loss lower than 10 dB. The central frequency (also the transition frequency) is at 4.15 GHz, where the reflection is slightly higher. As shown in Fig. 2, the reflections introduced by each unit element have zero phase shift at the center frequency and add up coherently at the feeding port, leading to an increased $|S_{11}|$ at the central frequency. On the other hand, the ripple of the reflection is obvious. It is caused by the periodical nature of the NRI TL leaky-wave antenna.

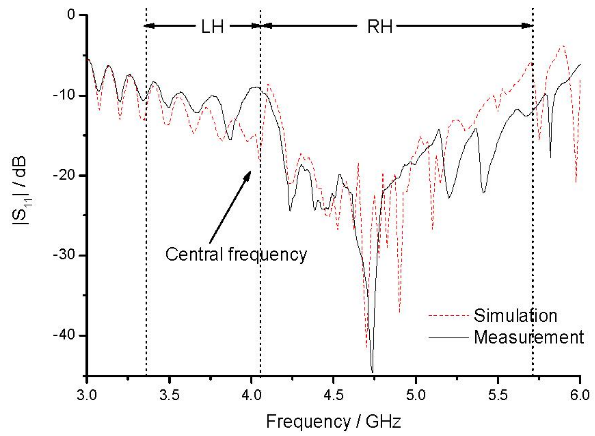
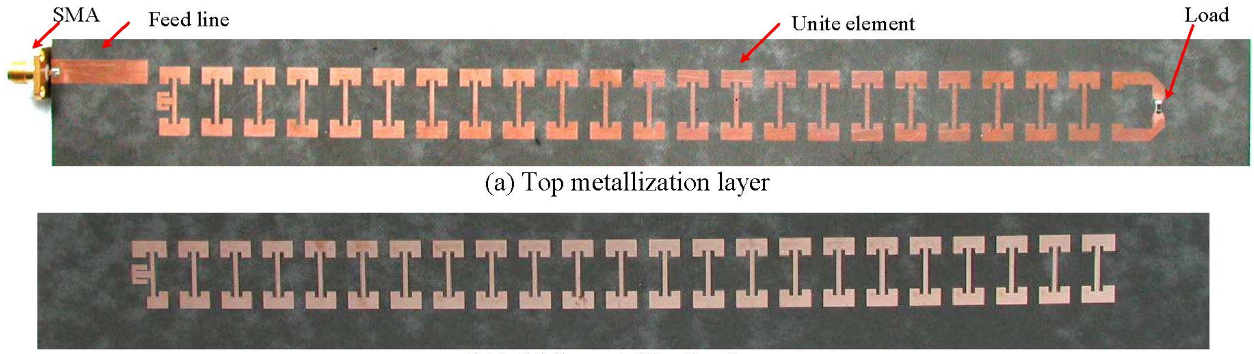


Fig. 4 Measured and simulated voltage reflection coefficients of the leaky-wave antenna. The operating band is from about 3.3 GHz to 5.7 GHz. The central frequency is 4.15 GHz, at which the reflection is slightly higher.



(a) Top metallization layer

(b) Middle metallization layer

Fig. 5 Leaky-wave metamaterial antenna with 21 and 22 unit elements on the top and in the middle metallization layer, respectively. The bottom layer is the ground. The feeding port is a 50 Ω microstrip line connected to a SMA connector.

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Finally the leaky-wave antenna radiation pattern was measured as well. The experimental results are shown in Fig. 6. In the operating frequency range, the main beam scans from backfire to endfire with the angle range from -40° to 40°. All sidelobe levels are more than 10 dB lower than the main beam. The antenna gain is about 10 dB in this frequency range compared to a standard gain horn. Due to the fixed aperture size, the antenna gain at the higher frequencies is higher than that of low frequencies, which is seen from the variation of the beamwidths versus frequency. In addition, the sidelobe levels around the central frequencies are much lower than those near either end of the passband.

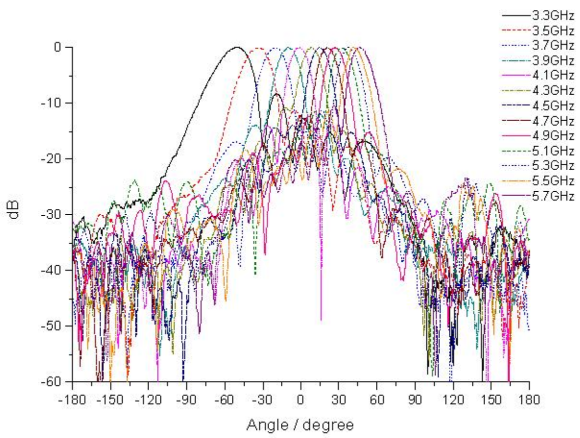

Fig. 6 Measured antenna radiation patterns on the H-plane from 3.3 GHz to 5.7 GHz, in which the main beam scans from about -40° to 40°. All side lobes are lower than -10 dB. The beamwidths at low frequencies are wider than those at high frequencies.

4 Conclusion

In this paper, design, simulation, and implementation of a novel microstrip metamaterial leaky-wave antenna is presented. The antenna is composed of two NRI TLs, a balun and a load. With a two-layer structure, no vias are necessary for the metamaterial leaky-wave antenna. Its main beam scans from -40° to 40° with the antenna gain about 10 dB. It exhibits a good performance at C band from 3.3 GHz to 5.7 GHz.

In future, we will redesign the antenna and apply it to 24 GHz. With the same aperture size, a much higher antenna gain is expected. Additionally, with the implementation of an antenna array, the antenna gain can be further improved.

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