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A Double-Beam Radiation Leaky Wave Antenna Based on Left-Handed Material Slab with Metallic Strips Periodically Loaded

Yongmei Pan · Shanjia Xu

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Abstract A new leaky-wave antenna structure is carefully investigated in the paper, which is based on a grounded Left-Handed material (LHM) slab periodically loaded with metal strips. A rigorous formulation similar to the spectral domain method for planar circuits is deduced to analyze the radiation characteristics of the antenna. Theoretical analysis results reveal that at specific frequency region or with proper geometrical parameters chosen, the present structure supports simultaneously two leaky modes corresponding to the forward and backward radiations. The principle of the antenna is due to the peculiar propagation properties of the unperturbed LHM grounded slab waveguide, which is totally different from the phenomenon of double or even more space harmonic mode radiations in normal periodic structures. Extensive numerical results of the leakage characteristics are given to establish useful guidelines for the design of the new type leaky wave antenna.

Keywords Leaky-wave antenna · Left-handed material · Radiation characteristics · Two leaky modes · Peculiar propagation properties

1 Introduction

LHM, i.e., materials with both negative permittivity and permeability, have been a topic of high interest in the scientific and engineering communities in recent years. These materials exhibit unusual scattering and propagation properties within a specific frequency range, which opens up a unique possibility to design novel types of devices. Various fundamental issues and many ideas or suggestions for potential applications of this media have been addressed [1–5].

Because of low cost, small size, and ease of manufacture using integrated circuit technology, the dielectric periodic structure is very attractive for applications in electromagnetic engineering

Y. Pan (✉) · S. Xu
Department of Electronics Engineering and Information Science,
University of Science & Technology of China, Hefei, P.R. China 230027
e-mail: ympan@ustc.edu

S. Xu
e-mail: xusj@ustc.edu.cn

and has been applied to many devices in integrated optics, such as filters, directional couplers, frequency selective surfaces, and feedback amplifiers *etc.* Also the dielectric grating structure has shown substantial promise as leaky-wave antenna [6–8]. In this paper, we propose a new dielectric grating antenna structure composed of a planar grounded LHM slab waveguide with periodic metallic strips, shown in Fig. 1. The antenna is excited by a surface wave propagating along the dielectric slab, which is assumed to be lossless, homogeneous, and isotropic. The radiation characteristics of the antenna structure are investigated through a rigorous formulation that is essentially the same as the spectral domain approach [9], which is a powerful tool for the analysis of striplines. Our analyses reveal that at specific frequency region or with proper geometrical parameters chosen, the present structure supports simultaneously two leaky modes corresponding to the forward and the backward radiations. The principle of this antenna is based on the peculiar propagation properties of the unperturbed grounded LHM slab waveguide. The antenna is of narrow beams and it is possible to scan the beam by varying frequency.

2 Analysis

Figure 1 shows the geometry of planar LHM dielectric waveguide (ε_r<0, μ_r<0) with periodic metallic strips and the coordinate system for present analysis. The metallic strips are placed on top of the dielectric substrate slab with periodic intervals d. Here, we assume that the metal and dielectric materials are lossless, and the structure is of infinite width and no variation in the y direction. Since both TM and TE modes can be analyzed in a similar manner, without loss of generality, we will focus our discussion on the TM modes.

The TM modes have three nonvanishing field components H_y, E_x and E_z. E_x and E_z components can be expressed in terms of H_y component as:

$$E_x = \frac{j}{\omega\varepsilon_r\varepsilon_0}\frac{\partial H_y}{\partial z} \tag{1}$$

$$E_z = \frac{-j}{\omega\varepsilon_r\varepsilon_0}\frac{\partial H_y}{\partial x} \tag{2}$$

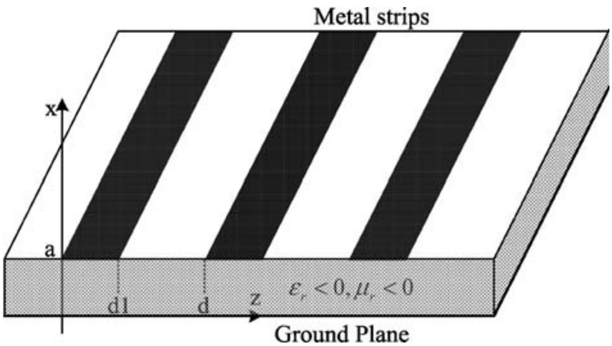


Fig. 1 Geometry of the planar dielectric waveguide with periodic metallic strips.

According to the Floquet theorem, electromagnetic fields in the periodic structure can be represented in terms of space harmonics whose phase constants in the z direction are:

$$k_{zn} = k_{z0} + \frac{2n\pi}{d} \qquad n = 0, \pm 1, \pm 2, \ldots \tag{3}$$

Where k_{z0} is the phase constant of the dominant space harmonic. The H_y component in the air and substrate regions is given by:

$$H_y(x,z) = \begin{cases} A_n e^{-w_n(x-a)} e^{-jk_{zn}z} & a \le x \\ B_n \cos u_n x e^{-jk_{zn}z} & 0 \le x \le a \end{cases} \tag{4}$$

Here A_n, B_n are unknown expansion coefficients and w_n, u_n are transverse propagation constants of the nth space harmonic in the air and substrate, respectively. These parameters are related through the wave equation as:

$$\begin{aligned} w_n^2 &= k_{zn}^2 - k_0^2 \\ u_n^2 &= \varepsilon_r \mu_r k_0^2 - k_{zn}^2 \end{aligned} \tag{5}$$

Where k_0 is the free space wavenumber, ε_r, μ_r are relative permittivity and permeability in substrate.

The unknown phase constant k_{z0} and expansion coefficients A_n, B_n are determined by matching the tangential electric and magnetic fields at $x=a$. The boundary conditions at the interfaces are given by:

$$H_{y1}(a,z) - H_{y2}(a,z) = \begin{cases} J_z(z) & \text{on metallic strips} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$\begin{matrix} E_{z1}(a,z) = E_{z2}(a,z) \\ E_{z1}(a,z) = E_{z2}(a,z) \end{matrix} = \begin{cases} 0 & \text{on metallic strips} \\ E_z(z) & \text{otherwise} \end{cases} \tag{7}$$

The substrates 1 and 2 correspond to the substrate and air region. $E_z(z)$, $J_z(z)$ are, respectively, the unknown electric fields on the slots and the unknown surface current density on the metallic strips. From the Floquet theorem, we can expand them as follows:

$$J_z(z) = \sum_{n=-\infty}^{\infty} J_{zn} \exp(-jk_{zn}z) \tag{8}$$

$$E_z(z) = \sum_{n=-\infty}^{\infty} E_{zn} \exp(-jk_{zn}z) \tag{9}$$

Substituting (2), (4), (9) into (7), expansion coefficients A_n, B_n are represented in terms of space harmonics of the electric fields E_z (z) as

$$\begin{aligned} A_n &= -j\omega\varepsilon_0 \frac{E_{zn}}{w_n} \\ B_n &= -j\omega\varepsilon_0\varepsilon_r \frac{E_{zn}}{u_n \sin(u_n a)} \end{aligned} \tag{10}$$

Then substituting (4), (8), (10) into (6), we get

$$J_{zn} = -j\omega\varepsilon_0 \left(\frac{\varepsilon_r \cos(u_n a)}{u_n \sin(u_n a)} - \frac{1}{w_n} \right) E_{zn} \tag{11}$$

That is

$$J_{zn} = -j\omega\varepsilon_0 T_n E_{zn} \tag{12}$$

Where

$$T_n = \frac{\varepsilon_r \cos(u_n a)}{u_n \sin(u_n a)} - \frac{1}{w_n} \tag{13}$$

On the other hand, we can expand the unknown electric field $E_z(z)$ in terms of known basis functions $\xi_i(z)$, which must satisfy the Floquet theorem, i.e.,

$$E_z(z) = \sum_{n=-\infty}^{\infty} \sum_{i=1}^{\infty} c_i \xi_{in} \exp(-jk_{zn} z) \tag{14}$$

Where

$$\xi_{in} = \frac{1}{d} \int_0^d \xi_i(z) \exp(jk_{zn} z) dz$$

Comparing (9) with (14), we get

$$E_{zn} = \sum_{i=1}^{\infty} c_i \xi_{in} \tag{15}$$

Inserting (15) into (12), we obtain

$$-j\omega\varepsilon_0 T_n \sum_{i=1}^{\infty} c_i \xi_{in} = J_{zn} \tag{16}$$

Multiplying (16) by ξ_{pn}^* and summing over all n from -∞ to +∞, the following matrix equation is yielded:

$$-j\omega\varepsilon_0 \sum_{i=1}^{\infty} \sum_{n=-\infty}^{\infty} \xi_{in} \xi_{pn}^* T_n c_i = \sum_{n=-\infty}^{\infty} J_{zn} \xi_{pn}^* = 0 \tag{17}$$

Since E_z (a, z) is zero on the metallic strip, furthermore J_z (a, z) is zero otherwise, as a result the above summation becomes zero. That is

$$\boldsymbol{R}c = 0 \tag{18}$$

Where

$$R_{pi} = \sum_{n=-\infty}^{\infty} \xi_{pn}^* \xi_{in} T_n \tag{19}$$

A nontrivial solution for (18) exists only if the following determining equation holds

$$\det \boldsymbol{R} = 0 \tag{20}$$

The determinants (20) define the dispersion relation for TM mode, from which the complex propagation constant $k_{z0} = \beta - j\alpha$ can be obtained; and then, the radiation characteristics of the leaky-wave antenna can be completely determined. For instance, the main beam radiation angle θ_n for the nth space harmonic is determined mainly by the phase constant of the guided wave as follows:

$$\theta_n = \sin^{-1}(\beta_n/k_0) = \sin^{-1}\left(\beta/k_0 + \frac{n\lambda}{d}\right) \tag{21}$$

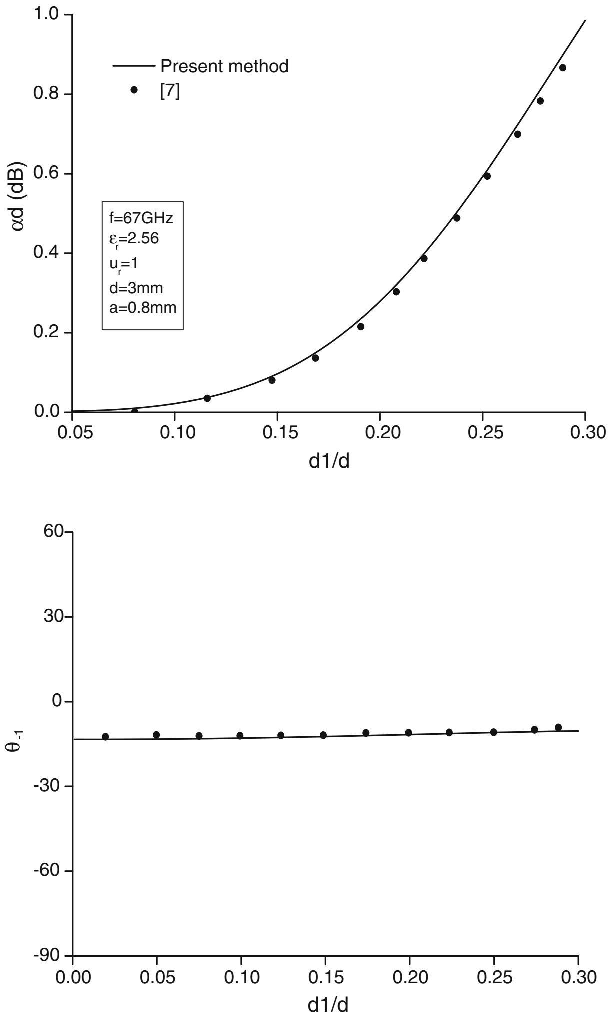
3 Numerical results

The solution accuracy of the present analysis is strongly influenced by the choice of basis functions. If the accurate electric field distribution on the slot is given, the solution becomes exact. In the present paper, the following basis function has been chosen.

$$\xi_i(z) = \begin{cases} 0 & \text{on metallic strips} \\ \cos\left[(i-1)\pi(z-d_1)/(d-d_1)\right] & \textit{otherwise} \end{cases} \tag{22}$$

The dispersion relation (20) is exact in principle, but they involve matrices of infinite order which must be truncated to obtain numerical results. The accuracy depends on the order of

Fig. 2 Comparison of the numerical results obtained with different analysis methods.



the truncated matrix or the term number of the basis function and the number of the Floquet modes retained in the analysis. In the present calculations, 5 basis functions and 31 Floquet modes are employed, and the solution convergence is guaranteed by checking the numerical results carefully.

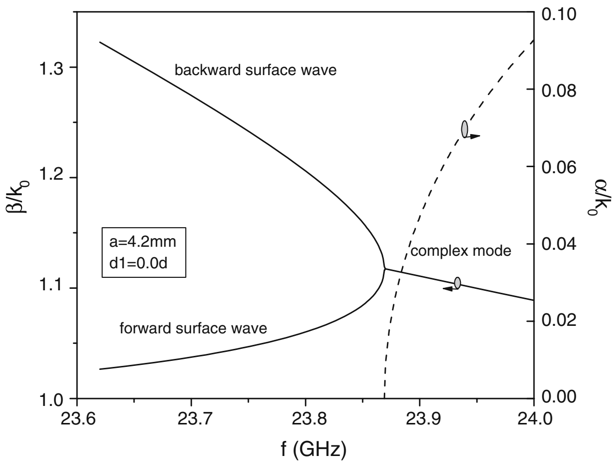
A comparison between the present analysis and the mode-matching results of leakage constant α and radiation angle θ_{-1} for the similar periodic metal strip structure is given in Fig. 2, but with the Right-Handed material (RHM) slab grounded instead. Here the solid lines represent the results achieved by present analysis, while the dots are values obtained with the mode matching method [7]; very good agreement has been found, the effectiveness and reliability of the present approach are thus verified.

It is well known that left-handed material is always dispersive. In the present calculation, the relative permittivity and permeability of LHM slab are given by the Drude Model (23) with F=0.56, $\omega_0/2\pi$=19.3 GHz, $\omega_{ep}/2\pi$=51.2 GHz:

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{ep}^2}{\omega^2} \qquad \mu_r(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2} \tag{23}$$

It is known that before the metal strips are introduced, the uniform dielectric slab guide, to be named as unperturbed structure, supports a bound surface wave that is a slow wave and therefore does not radiate. The periodic strips excite an infinite number of space harmonics along the guiding structure, if the ratio of wavelength to the strip period is appropriate, one of these space harmonics could be above cutoff, it then becomes a leaky wave forming the main radiation beam of the antenna radiating transversely in air region. This radiation occurs only in certain preferred directions, which is essentially determined by the phase constant of the unperturbed structure and the period of the perturbation. Above description indicates that to get the knowledge of the radiation characteristics of present antenna, the dispersion properties of the unperturbed structure (d=0) must be carefully analyzed first. Figure 3 shows the results of calculation with parameters depicted in the inset. It is clearly illustrated that there are two real modes and one complex mode existing in the calculated frequency region. As frequency increasing, the two real proper solutions representing respectively the forward and backward surface waves merge at a critical frequency point 23.87 GHz, which rises to a complex solution. It is noted that due to the lossless nature of the structure, the complex modes always exist in pairs, with complex conjugate propagation constants of opposite sign. The pair will

Fig. 3 Dispersion characteristics of the unperturbed planar slab structure.



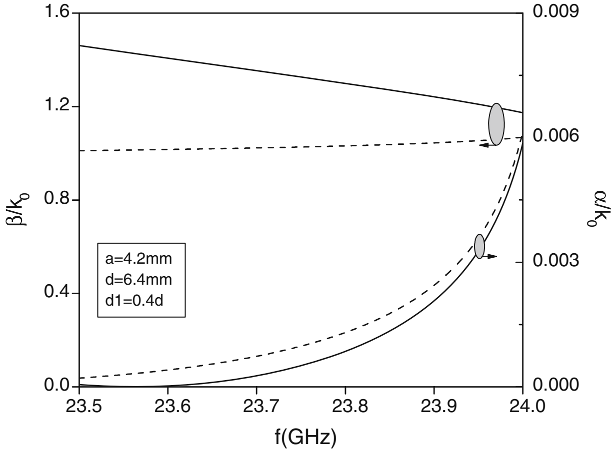


Fig. 4 Radiation characteristics of the present antenna structure versus frequency.

only carry reactive power, without net real average power [10]. In fact, this peculiar dispersion phenomenon of LHM slab has been revealed elsewhere in [4] and [5]. The net total power flow of the guided forward mode is parallel with the direction of the phase flow, while the net total power flow of the guided backward mode is antiparallel with the direction of the phase flow. It is reasonable to assume that the sign of the power flow along the structure is positive, then, the phase flow of forward mode is also positive, whereas the phase flow of the backward mode is negative.

Based on the knowledge given above, it is reasonable to speculate that when metallic strip perturbation is introduced the proper space harmonic of the unperturbed real modes of both

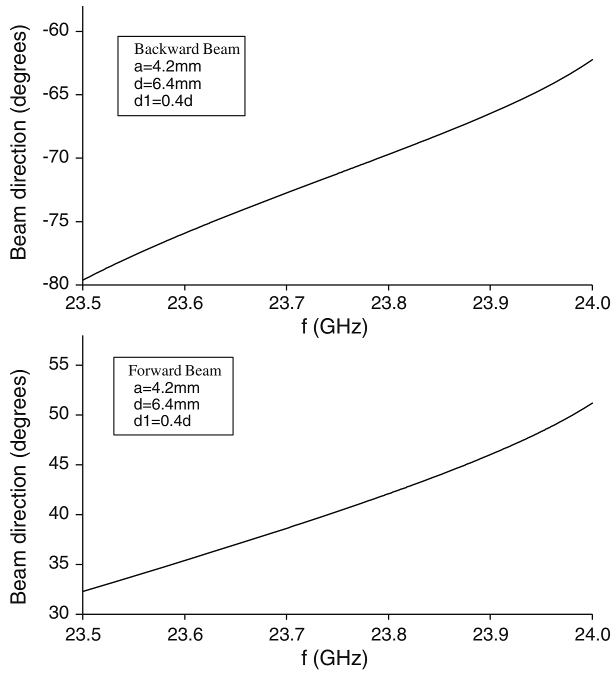


Fig. 5 Variation of radiation angle with frequency.

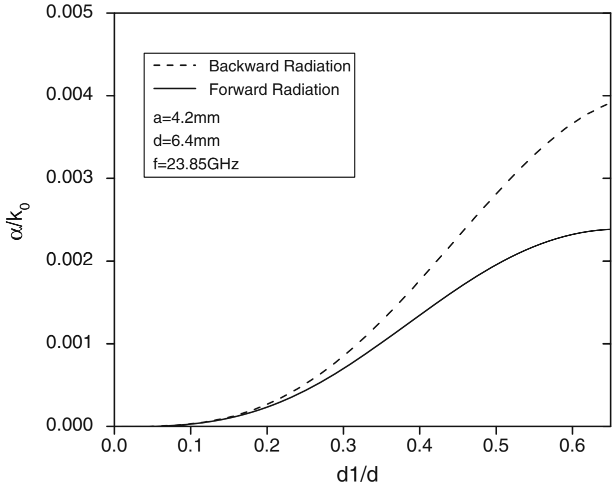


Fig. 6 Variation of the normalized leakage constant on relative metallic strip width.

forward and backward waves will become leaky, a double beam leaky wave antenna is thus produced, which will radiate into forward and backward directions simultaneously. For a practical design, the behavior of the antenna versus frequency is important, because this structure can be used as a frequency scanable antenna. Figure 4 shows the radiation characteristics of the present leaky wave antenna in a frequency range from 23.5 GHz to 24.0 GHz. Referring to formula (21), it is easy to deduce that with proper geometrical parameters chosen, the n=-1 space harmonic of the forward surface wave with positive phase flow will radiate into backward direction, while the n=1 space harmonic of the backward surface wave with negative phase flow will radiate into forward direction. In other words, the co-existent forward/ backward surface waves in the structure bring on backward /forward space harmonic leaky waves simultaneously. In the figure, the solid lines represent the propagation constants for the backward dominant wave (forward radiation) while the dash lines for forward dominant wave (backward radiation) respectively. It is seen from Fig. 4 that the leakage becomes stronger for both type waves as the frequency increases.

It is known that the scanning angle of the radiation pattern is mainly determined by β. Figure 5 shows the variations of beam direction of the antenna. As frequency increases from 23.5 GHz to 24.0 GHz, the forward beam scans from 32.3° to 51.2° which covers a

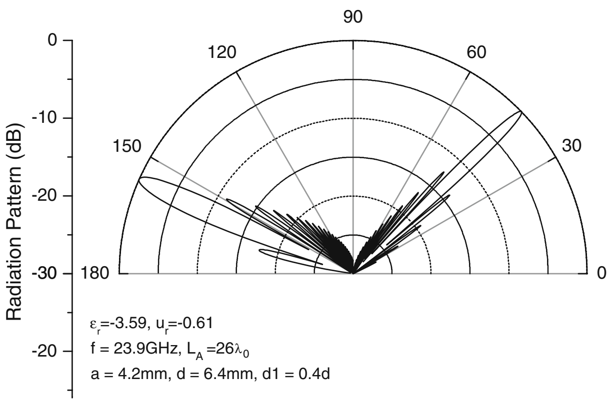


Fig. 7 Radiation pattern of the antenna at 23.9 GHz.

sector of almost 19°; the backward beam, in contrast, scans from back fire direction -79.6° to broadside -62.2°, covering a sector of 17.4°.

Since the radiation is caused by the periodic metallic perturbation, it is necessary to investigate the effect of the aspect ratio d1/d on the radiation characteristics. Figure 6 shows the dependence of the normalized leakage constant on the relative metal strip dimension. As seen, when d1 increases, the perturbation of the metallic strips to the guide wave becomes stronger, as a result, the radiation or the leakage constant increases gradually.

The radiation pattern formulation of a traveling wave antenna has been derived in [11] by using the Kirchhoff-Huygens integration method. Following the same procedure, the normalized radiation pattern of the present antenna is obtained and shown in Fig. 7, with the physical parameters depicted in the inset. There ε_r=-3.59, μ_r=-0.61 are determined by Eq. (23) at frequency of 23.9 GHz, for the DNG materials are all dispersive. It is noted that here θ is measured from the end fire direction. The two beams are clearly demonstrated, with one related to the backward type mode (θ_m=156.1°) and the other one related to the forward type mode (θ_m=44.0°). These results agree very well with that given in Fig. 5.

4 Conclusion

A new leaky wave antenna based on LHM dielectric waveguide with periodic metallic strips has been investigated theoretically. It is found that due to the peculiar propagation characteristics of the unperturbed LHM grounded slab waveguide, the present periodic structure support two leaky modes, which radiate into backward and forward directions simultaneously at specific frequency region. This unique feature may provide potential applications in the electromagnetic engineering.

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