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Beam-scanning Performance of Leaky-wave Slot Array Antenna on Variable Stub-loaded Left-handed Waveguide

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1. Introduction

Recently, metamaterials are being developed in many organizations [1]- [3]. Left-handed transmission line (LHTL) supports waves with anti-parallel phase and group velocities. Miniaturization of antennas and wide design flexibility of radiation pattern could be expected because effective wavelength can be designed to be negative value by changing the dimensions of periodic structure in the transmission line.

Dielectric material is filled in the waveguide in order to shorten a guided wavelength. When the metamaterial is used, the same property can be provided as filling dielectric material in the waveguide. Metamaterials composed of waveguide circuits, such as iris and stub, have advantages in the point that dielectric material is not necessary to be filled in the waveguide. There is no dielectric loss and inhomogeneous problems do not exist in manufacturing. The desired material constant can be designed over a wide range, that is huge permittivity to zero and negative permittivity with a left-handed medium by metamaterial. The design flexibility of radiation pattern is improved by using left-handed medium. We developed a left-handed waveguide transmission line. A leaky wave slot array antenna is designed to confirm the left-handed phenomenon of backward radiation. Moreover, beam-scanning performance is demonstrated by changing the stub length in the waveguide.

2. Left-handed Waveguide Leaky Wave Slot Array Antenna

A left-handed waveguide (LHWG) leaky wave slot array antenna is designed at X-band. An overall configuration is shown in Fig. 1. Dimensions of the rectangular waveguide are 16 mm × 8 mm. The guided wavelength of the design frequency (10 GHz) is $\lambda_g = 86.2$ mm. Wideband E-bends are connected at the input and output ports, therefore, the antenna is fed from back of the antenna.

Series capacitance and shunt inductance can give phase advance in the transmission line. When positive phase perturbation is larger than phase delay due to path length [2], phase advance for LHTL is observed, consequently. Ten sets of short stub, inductive iris and series slot shown in Fig. 2 are periodically arranged in this waveguide. These structures are called perturbation elements. The structure of short stub and its equivalent circuit is shown in Fig. 3(a). It is connected with main waveguide to cut the current flowing on the broad-wall toward the longitudinal direction of the waveguide. Its equivalent circuit is a series of parallel-connected inductance L and capacitance C. Its input impedance can be controlled from inductive to capacitive impedances by variation of stub length. When the stub length L_s is around $\lambda_g/4$, phase perturbation changes rapidly from negative to positive values. When the stub length is a little longer than $\lambda_g/4$, it works as large capacitance. Positive phase perturbation can be obtained. The structure of inductive iris and its equivalent circuit is shown in Fig. 3(b). The inductive iris is composed of two symmetrically-extended walls from both narrow-walls into the waveguide. Its equivalent circuit consists of shunt inductance L and series capacitance C [4]. Since dominant parameter of inductive iris is a shunt inductance L, it works for phase advance in the waveguide. The series slot is cut on the broad-wall toward perpendicular direction of the waveguide axis, as shown in Fig. 3(c). The equivalent circuit mainly consists of parallel circuit of LC and R_r that means radiation resistance.

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A leaky wave antenna is designed to confirm the propagation characteristic of the LHTL. The general leaky wave antenna forms a beam whose direction is determined by the ratio between the phase constant β_g in the feeding transmission line and the phase constant β_0 in a free space. The excitation phase difference between the adjacent elements is $-\beta_g d$ when the radiating element of the array is arranged with spacing d. When the phase perturbation $\angle S_{21}$ due to the perturbation elements in the waveguide is taken into account, beam direction θ_t of leaky wave antenna is calculated as;

$$\theta_t = \sin^{-1}\left(\frac{\beta_g}{\beta_0}\right) = \sin^{-1}\left(\frac{k_g d - \angle S_{21}}{\beta_0 d}\right) \tag{1}$$

where $k_g(= 2\pi/\lambda_g)$ is wavenumber in the waveguide. The beam direction can be designed by controling phase perturbation $\angle S_{21}$ based on Eq. (1). Therefore, it is necessary to satisfy $\angle S_{21} > k_g d$ for LHTL phenomenon and backward radiation.

3. Design of One Period of Perturbation Element

The phase perturbation $\angle S_{21}$ of each element is calculated by subtracting the transmission phase of the waveguide without the perturbation element from the transmission phase when one set of perturbation elements is located in the waveguide. A commercial electromagnetic simulator of finite element method is used in the calculation.

The LHWG leaky wave antenna is an array of the periods. Each one consists of a short stub, an inductive iris and a series slot. Required phase perturbation for left-handed phenomenon is closely related with the physical length of one period. Therefore, the physical length of one period should be short compared with a guided wavelength, where required phase perturbation of a period is smaller. When the broad-wall width is small, that is, a guided wavelength is long, phase change $-k_g d$ per physical length is small. As the result, required phase perturbation $\angle S_{21}$ can be reduced. On the other hand, mutual coupling grows large when the period is too short. Concerning about these facts, the length d of the period is designed to be 6 mm. The phase change for 6 mm waveguide is 25.3 degrees at 10 GHz. Thus, in order to realize backward radiation that is a feature of LHWG, the phase perturbation $\angle S_{21}$ larger than +25.3 degrees is needed for one period.

The dimensions of stub waveguide are 16 mm × 2 mm. The guided wavelength in the stub is the same length of the main waveguide 86.2 mm. The extended length w of the inductive iris is 2 mm, thickness t is 1 mm. The slot length r is 10 mm, width s is 1 mm. Figure 4 shows phase perturbation variation of the structure when stub length L_s is changed from 22 to 26 mm. This waveguide works as LHWG and beam scanning can be expected when stub length L_s is changed in this range.

4. Experiments

An antenna is fabricated to confirm the feature of LHWG and beam-scanning performance. A photograph of the antenna is shown in Fig. 5. The antenna consists of one waveguide with 10 periods. The slotted plate is screwed out on the waveguide together. No dielectric is filled in the waveguide. The measured S-parameters are shown in Fig. 6 for stub length $L_s = 23$ mm. Measured results almost agree with simulation though frequency of measured results shifts to lower frequency slightly compared with the simulation. Transmission band in which reflection coefficient $|S_{11}|$ is lower than −1 dB appears around the design frequency 10 GHz.

Beam scans due to the change of effective wavelength in the waveguide when stub length L_s is changed. Figure 7 shows measured and simulated beam direction when stub length is changed. We can confirm left-handed phenomenon of backward radiation. As a result of the measurement, when stub length L_s is changed from 22 to 26 mm, the beam direction changes −59 to −3 degrees. On the other hand, the beam direction changes −75 to −3 degrees as a result of electromagnetic simulation. The perturbation decreases in comparison with the calculation because the transmission band shifts to the lower frequency compared with the result of the simulation. Therefore, the beam direction has changed into lower angle. Figure 8 is measured radiation patterns when stub lengths L_s are 22, 23, 24, 25 mm.

Beam scanning is achieved by changing the stub length. Figure 9 is measured absolute gain and antenna efficiency. Gain is around 6 dBi and is stable even when stub length L_s is changed.

5. Conclusions

We fabricate a left-handed waveguide leaky wave antenna. As a result of the measurement, the characteristic of a left-handed transmission line and the beam-scanning performance by changing the structure of perturbation element are confirmed.

Acknowledgments

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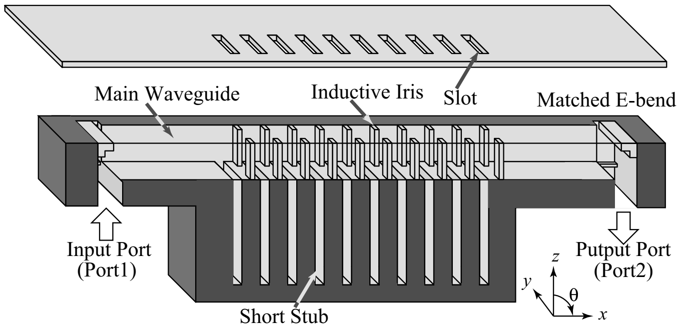


Figure 1: Left-handed Waveguide Slot Array Antenna

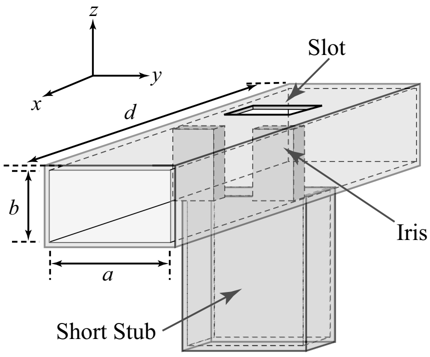
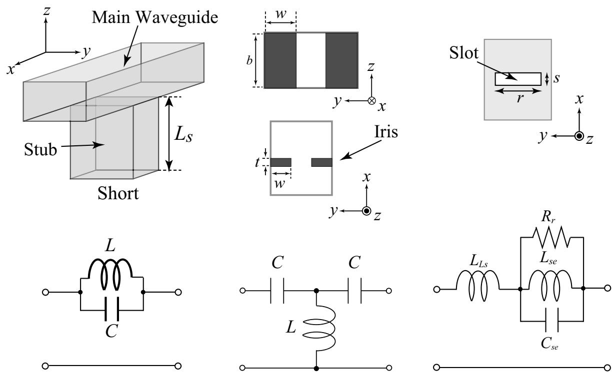


Figure 2: Configuration of One Period



(a) Short Stub (b) Inductive Iris (c) Series Slot

Figure 3: Structures and Equivalent Circuits

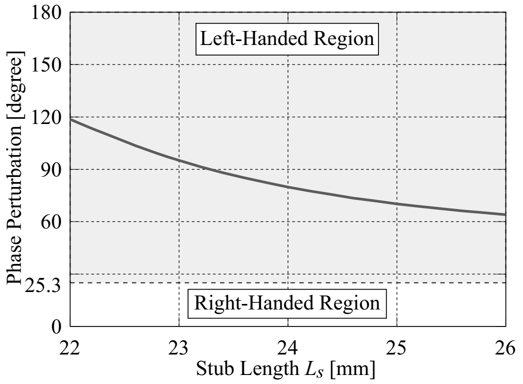


Figure 4: Simulated Phase Perturbation of One Period

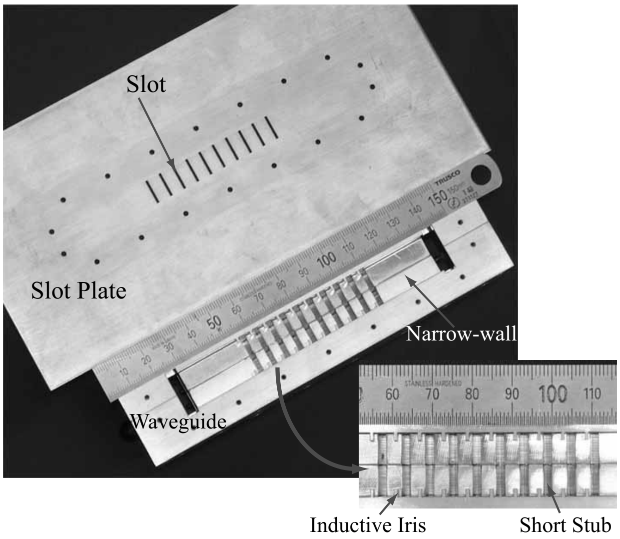


Figure 5: Photograph of Fabricated Antenna

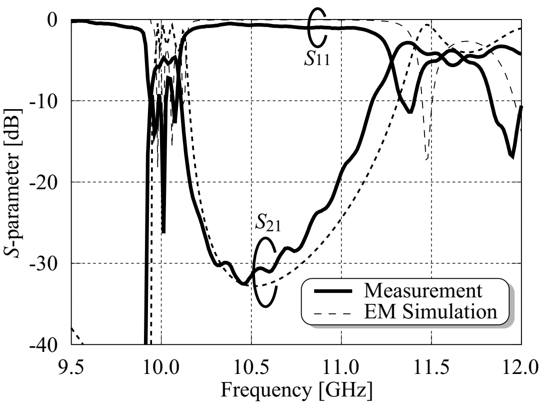


Figure 6: S-parameters (L_s = 23 mm)

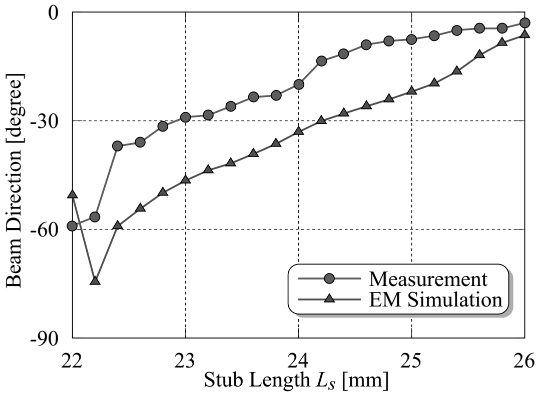


Figure 7: Stub Length Dependency of Beam Direction

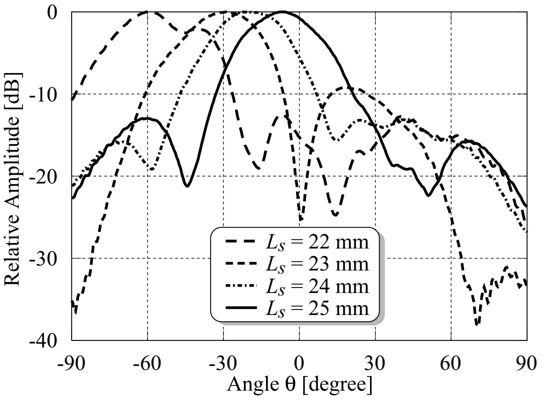


Figure 8: Stub Length Dependency of Radiation Patterns

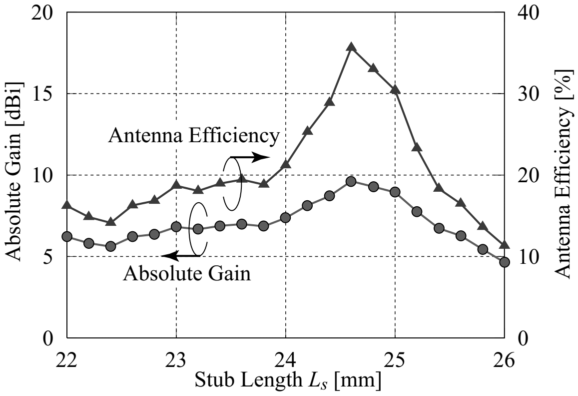


Figure 9: Stub Length Dependency of Gain and Antenna Efficiency