Design of Left-Handed Waveguide by Controlling Phase Constant of Transmission Line Using Periodic Structures

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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 phase constant can be designed to be any values form negative to positive values by changing the dimensions of periodic structures in the transmission line.

We have already developed a left-handed waveguide leaky-wave antenna [4]. The purpose of this research is to develop metamarerial waveguide transmission line whose phase constant changes continuously from negative to positive values. In order to confirm superiority in the waveguide application of metamarerial, transmission loss due to periodic structure is estimated by experiments. Moreover, a leaky wave array antenna was fabricated to evaluate radiation patterns. Continuous beam scanning from right-handed to left-handed was confirmed by the experiment.

2. Left-handed waveguide

Left-handed waveguide transmission line is designed at X-band. Figure 1(a) shows one periodic structure. Dimensions of the rectangular waveguide is 18 mm × 9 mm and one period is composed of the short stub and inductive iris. Because the length of one period is much smaller than that of the guided wavelength in the waveguide, left-handed operation will appear by the periodic structure. Twenty one sets of short stub and inductive iris are periodically arranged. Since series capacitance and shunt inductance can give phase advance, when the perturbation is larger than phase delay of waveguide, it can cancel the phase delay due to path length and create a left-handed waveguide (LHWG) with phase advance in transmission [5].

The structure of short stub and its equivalent circuit is shown in Fig.2. 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 \( C \). When the stub length is a little longer than \( \frac{\lambda}{4} \), it works as large capacitance and positive phase perturbation can be obtained. The dimensions of the stub waveguide is 18 mm × 2 mm. The guided wavelength in the stub is the same with that of the main waveguide 62.9 mm at the design frequency (9.6GHz). Length \( \ell \) of the stub is 18 mm (0.29 \( \lambda \)). The structure of inductive iris and its equivalent circuit is shown in Fig.3. The inductive iris is composed of two symmetrically extended walls from both narrow-walls into the waveguide. Its equivalent circuit is shunt inductance \( L \) in series with small capacitance \( C \). The width \( w \) of the inductive iris is 1.5 mm and thickness \( t \) is 2 mm.

3. Leaky wave slot array antenna

In order to confirm the propagation characteristic of the LHTL, slots (11 mm × 1 mm) are cut on the broad wall toward perpendicular direction of the waveguide axis to compose a leaky
wave antenna. Series slot is arranged every three periodic structure in the waveguide as shown in Fig.1(b). Since slot spacing is still 0.38 wavelength, grating lobe does not appear. In order to prevent the mutual coupling effect from slot to the feature of LHWG, coupling power to the air from slot are designed to be small. Leaky wave antenna is an antenna with a beam whose direction is determined by the ratio between the phase constant $\beta_g$ in the feeding line and the phase constant $\beta_0$ in free space. The phase change of the feeding line is $-\beta_g d$ when the radiating element of the array is arranged with spacing $d$. When the phase perturbation $\angle S_{21}$ caused by the periodic structure is taken into account, beam direction $\theta_t$ of leaky wave antenna is calculated as:

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

(1)

where $k_g = 2\pi / \lambda_g$ is wave number of the waveguide without periodic structure. When phase perturbation $\angle S_{21}$ is larger than $k_g d$, $\theta_t$ is negative angle and the transmission line is left-handed. The length $d$ of period is designed to be 4 mm. It consists of 2 mm of the stub in length $b'$ and 2 mm of the inductive iris in thickness $t$. The phase change in the waveguide with 4 mm is $k_g d = 22.9$ degrees at 9.6GHz. Thus, in order to realize backward radiation that is a feature of LHWG, the phase perturbation larger than $+22.9$ degrees is needed for one period. As a result of the simulation, phase perturbation due to one period is $+38.7$ degrees.

3. Experiments

Left-handed waveguide and a leaky wave antenna are fabricated to confirm the feature of LHWG. The photograph of the waveguide is shown in Fig.4. The insertion loss due to the perturbation element in the waveguide with periodic structure is estimated. Measured S-parameters and the insertion loss are shown in Fig.5 and Fig.6. The insertion loss due to the perturbation element is 1.2dB at the design frequency (9.6GHz) for left-handed operation.

Measured S-parameters of the antenna are shown in Fig.7. Measured results almost agree well with simulation. The radiation patterns and gain are measured to confirm left-handed phenomenon. Figure 8 shows the measured radiation patterns at 9.6GHz, 9.8GHz, 10GHz and 11GHz. Backward (negative direction) radiation of LHTL is observed at 9.6GHz and broadside (0 degrees direction) radiation is at 9.8GHz and forward (positive direction) radiation of right-handed transmission line (RHTL) is at 10GHz and 11GHz. Figure 9 shows frequency dependency of beam direction. A continuous beam scanning due to frequency change is confirmed. Measured beam scanning performance almost agrees well with simulation. The boundary frequency between right-handed and left-handed is confirmed as 9.8GHz.

4. Conclusions

We fabricate a left-handed waveguide and an leaky wave antenna to confirm the feature of LHWG. The characteristics of a left-handed transmission line is confirmed.

References

Fig. 1. Left-handed waveguide slot array antenna

(a) Configuration of one period

(b) Left-handed waveguide slot array antenna

Fig. 2. Short stub

(a) Structure

(b) Equivalent circuit

Fig. 3. Inductive iris

(a) Structure

(b) Equivalent circuit

Fig. 4. Fabricated antenna
Fig. 5. $S$-parameters (no slot)

Fig. 6. Insertion loss of periodic structure

Fig. 7. $S$-parameters

Fig. 8. Radiation patterns

Fig. 9. Beam direction