Left-Handed Waveguide with Variable Phase Constant Composed of Planar Resonator Patterns

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Abstract

A left-handed waveguide whose phase constant can be changed electrically is proposed. It is compact and non-radiated transmission line composed of planar circuit-type resonators in a cutoff waveguide, and can be fabricated easily. The existence of a left-handed mode is ensured by a dispersion relation, and the frequency shift of effective permeability of the resonator is shown in evaluation as a negative-permeability particle. A fabricated left-handed waveguide composed of two cells has a phase constant varying by 2π/3 per unit cell.

1. INTRODUCTION

Artificial materials in microwave and millimeter-wave areas bring about new electromagnetic effect that can not be realized by conventional materials[1]-[7]. The study of left-handed material has attracted interests since microwave propagation in the artificial material was demonstrated[1]. In the material the wave has the wave vector with the direction opposite to the Poynting vector and some unique phenomena are exhibited.

A leaky wave antenna composed of left-handed material has radiated wave in the backward direction[2], and the material has been used to a lead or lag phase shifting line[3]. These devices use the negative phase velocity of the left-handed material. The principal characteristic depends on the phase constant of the transmission line. Thus, electrical changeability of the phase constant leads to a flexible and multi-functional device.

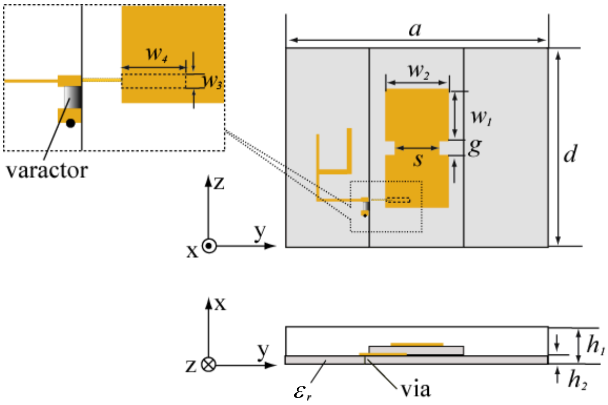
Some structures of artificial material for realizing negative permittivity and negative permeability have been investigated. A class of left-handed material is constituted of periodic arrays of thin wires and split ring resonators[1]. Instead of thin wires a rectangular waveguide in the cutoff region of TE mode has been used as a structure for negative permittivity[4], and the idea has been applied to a miniaturized waveguide[5]. A feature of the waveguide-type transmission line is not to radiate wave. To tell in another meaning, it is suitable for a radiation device because the radiation characteristic can be controlled by selecting shape of apertures on the waveguide wall.

In this manuscript a simple structure of left-handed transmission line with phase constant variable electrically is investigated. It is composed of planar circuit-type resonators in a waveguide in the cutoff region, so that the structure is simple and compact. It can be fabricated easily using PCBs. The effective permeability of the resonator particle is evaluated to show that the negative value changes for varactor capacitance. The dispersion relations are calculated for making sure of the existence and the band-tunability of a left-handed mode. It is confirmed experimentally that left-handed transmission characteristic is shifted and the phase constant can be changed by a varactor diode.

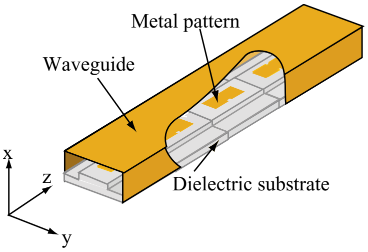
2. STRUCTURE

Figure 1 shows the structure of the proposed left-handed waveguide. Two dielectric substrates with a metal pattern are put in a waveguide in a cutoff region as shown Fig. 1(a). A dumbbell pattern on the upper substrate works as a resonator. A small pattern on the lower substrate is connected to the bottom wall of the waveguide through a varactor diode. A bias line is formed on the lower substrate, too. The unit cell is located at equal interval d in the waveguide axis direction as shown in Fig. 1(b). The interval d is small compared with the wavelength. Figure 1(c) shows capacitance among the dumbbell pattern, the small pattern, and the bottom schematically. The capacitance C_v of varactor diode has an influence on the resonant frequency. Such a simple structure is fabricated easily using a planar circuit technology.

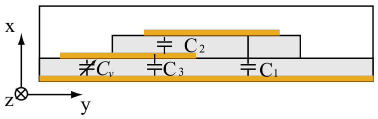
The dumbbell pattern with the waveguide bottom wall constitutes a λ/2 microstrip resonator. When an external magnetic flux is impressed in the normal direction to the resonator, current comprised of conduction current and displacement current between conductors flows circularly in the x-z plane as shown in Fig. 2. The resonator represented as an L-C series circuit becomes inductive above the resonant frequency. The phase of the current is opposite to that of the external magnetic flux. The current creates magnetic field with phase opposite to the external magnetic field. The resonator works as a



(a)



(b)



(c)

Fig. 1 (a) Structure of left-handed waveguide (b) Structure of unit cell (c)Schematic representation of capacitance among the dumbbell pattern, the small pattern, and the waveguide bottom

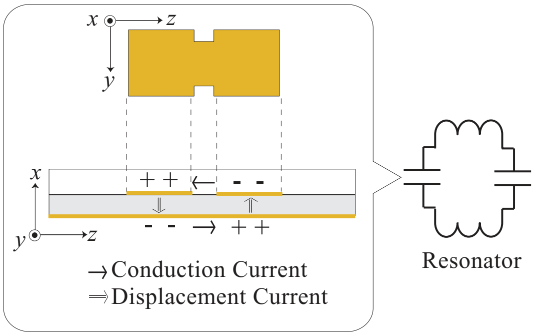


Fig. 2 Operation of a dumbbell pattern as a ring resonator

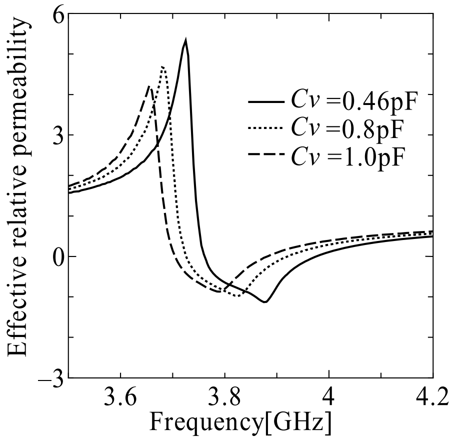


Fig. 3 Effective relative permeability for a=25mm, d=19mm, w_1=5mm, w_2=7mm, w_3=0.4mm, w_4=4mm, h_1=3.56mm, h_2=0.78mm, g=1.5mm, s=4.25mm, ε_r=10.2, $\tan\delta$=0.004, conductivity of waveguide $\sigma_w=1.5*10^7$, conductivity of metal pattern $\sigma_m=5.8*10^7$

particle with negative permeability like a split ring resonator does.

The effective permeability of the resonator is plotted for different values of C_v in Fig. 3. The values can be calculated from S_{11} and S_{21} using the evaluation equation[8]. The scattering parameters are calculated for the simulation model where a plane wave is incident to the same structure as one cell in Fig. 1(a), but the side walls are replaced by magnetic walls to enable the plane wave to propagate. Above the resonant frequency the effective permeability becomes negative similar to the split ring resonator[1]. Owing to the change of C_v the resonant frequency and the negative-permeability region move.

3. Left-Handed Mode

Figure 4 shows the calculated dispersion relations of the proposed structure where β denotes phase constant of each mode. The eigen modes are analyzed by the electromagnetic simulator based on the finite element method. The dispersion curve of the lowest mode has a negative slope though the phase constant is positive. The sign of phase velocity is positive, while the sign of group velocity is negative. The backward wave propagating in the opposite direction to the energy flow is proper to a left-handed transmission line. For some capacitance values of C_v the region of the left-handed mode shifts up and down. The phase constant of the mode at a frequency can be changed by the varactor. Though the curve is plotted from βd=0 to π, it should be noted that only for small βd range the discrete structure can be considered as material discussed in this manuscript. The second mode is a conventional guided mode with TE_{01}-type field.

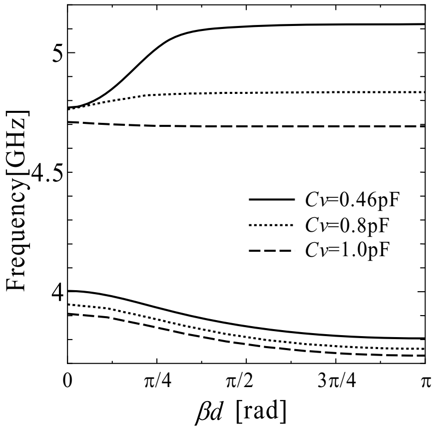


Fig. 4 Dispersion relation for a=25mm, d=19mm, w_1=5mm, w_2=7mm, w_3=0.4mm, w_4=4mm, h_1=3.56mm, h_2=0.78mm, g=1.5mm, s=4.25mm, ε_r=10.2, $tan\delta$=0.004, σ_w=1.5*10^7, σ_m=5.8*10^7

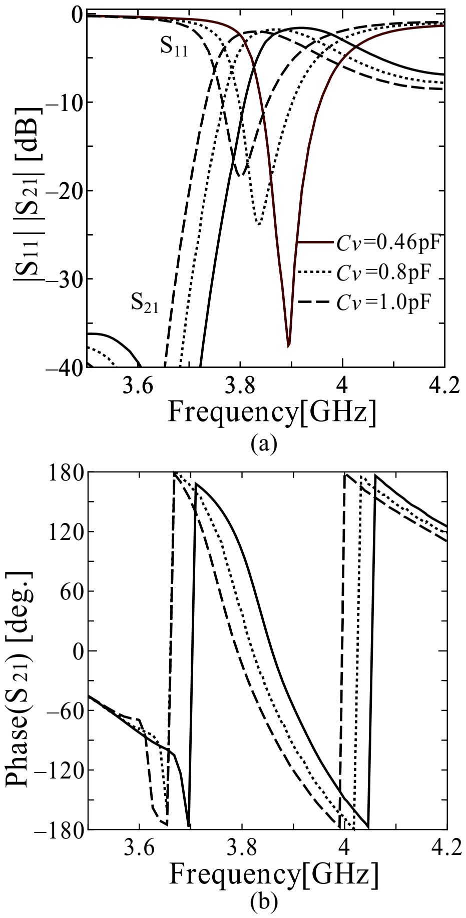


Fig. 5 Transmission characteristics (a) Magnitude (b) Phase for a=25mm, d=19mm, w_1=5mm, w_2=7mm, w_3=0.4mm, w_4=4mm, h_1=3.56mm, h_2=0.78mm, g=1.5mm, s=4.25mm, ε_r=10.2, $tan\delta$=0.004, σ_w=1.5*10^7, σ_m=5.8*10^7

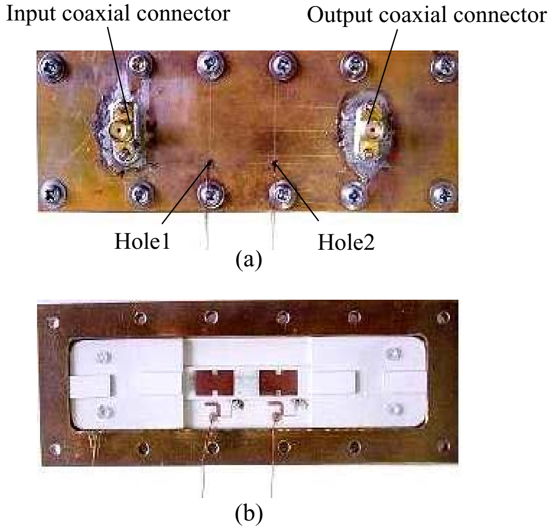


Fig. 6 A fabricated left-handed waveguide
(a) The top view (b) The inner view

Figure 5(a) shows the calculated transmission characteristic of the left-handed waveguide composed of two cells. At the both ends the waveguide is connected to a conventional waveguide. It is filled with dielectric for guiding wave at the cutoff frequency. The input and the output waveguides are excited by using a coaxial probe. Below 4.7GHz the conventional mode can not be guided. The passband below the cutoff frequency is due to the left-handed mode. As C_v changes, the passband moves. The phase constant of the mode changes, so that the phase of transmission coefficient increases and decreases as shown Fig. 5(b).

4. EXPERIMENT

We fabricated a left-handed waveguide composed of two cells as shown in Fig. 6. On the top wall there are two holes for letting bias lines go through. Thin wires extending vertically in the picture are the bias lines. Fig. 7 shows the experimental transmission characteristic. On the whole the experimental result is in agreement with the simulation result. For small C_v the passband frequency is high compared with the simulation value, so that the phase difference of S_{21} between C_v=0.46 pF and 1.0 is also large. When the varactors are removed, the experimental result agrees with the simulation result. The difference can be caused by overestimation of the varactor capacitance.

The phase in Fig. 7(b) denotes the phase difference between the input coaxial connector and the output one, which includes the conventional waveguide, the connectors, and two left-hand cells. Figure 8 shows the phase difference between two cells. After measuring the near-field at the holes above cells by a coaxial probe, the phase difference βd is obtained by subtracting the phase at the cell near the input from that near the output. The phase in the waveguide increases as the

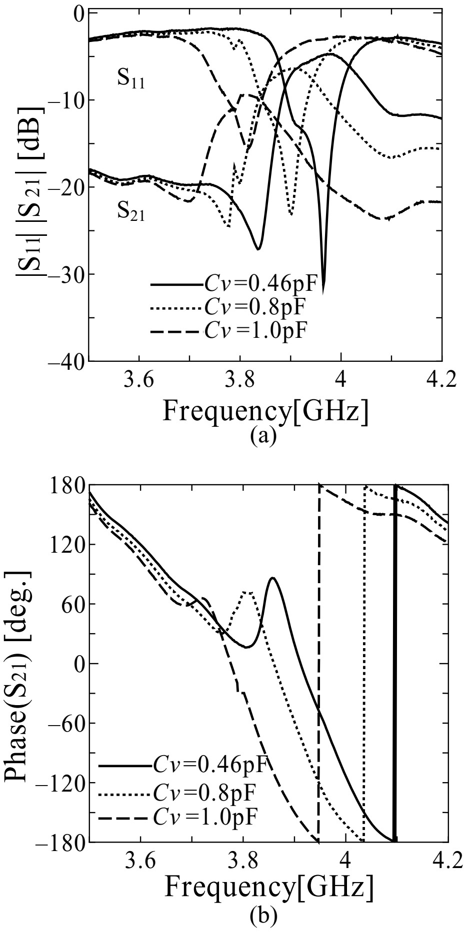


Fig. 7 Measured transmission characteristic (a) Amplitude (b) Phase for a=25mm, d=19mm, w_1=5mm, w_2=7mm, w_3=0.4mm, w_4=4mm, h_1=3.56mm, h_2=0.78mm, g=1.5mm, s=4.25mm, ε_r=10.2, $tan\delta$=0.004, σ_w=1.5*10^7, σ_m=5.8*10^7

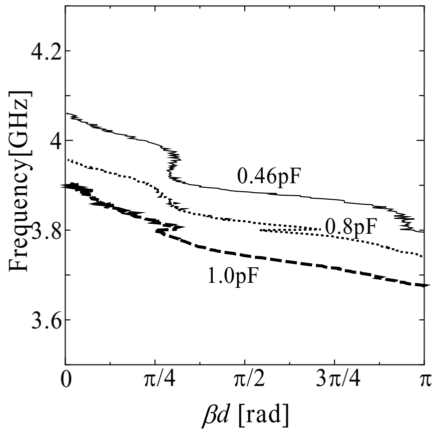


Fig. 8 Measured dispersion relation for a=25mm, d=19mm, w_1=5mm, w_2=7mm, w_3=0.4mm, w_4=4mm, h_1=3.56mm, h_2=0.78mm, g=1.5mm, s=4.25mm, ε_r=10.2, $tan\delta$=0.004, σ_w=1.5*10^7, σ_m=5.8*10^7

observation point goes away from the input, so that the phase difference becomes positive. The measurement curve has the almost same tendency as the calculated one as shown in Fig. 4 though it is noisy. It can be said that they are proper to a left-handed transmission line and the phase constant changes according to the varactor capacitance. Near 3.8GHz the phase difference per one cell changes by 3π/4.

5. Conclusion

A left-handed waveguide with variable phase constant has been proposed. It is compact, non-radiative, and easy fabricated left-handed material composed of planar circuit-type resonators in a cutoff waveguide. The dispersion curve with a negative slope has been moved by a varactor connected to the resonator. The phase between cells has changed by 3π/4.

Acknowledgement

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