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A Variable Phase Shifter Using a Movable Waffle Iron Metal Plate and Its Applications to Phased Array Antennas

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SUMMARY A variable phase shifter using a movable waffle iron metal plate comprised of iron rods a quarter-wavelength in length is proposed. A study of the waffle iron structure was carried out and the design method for creating a structure that would achieve large phase changes, small loss, and good isolation between adjacent phase shifters is discussed. Experiments on 1-port and 2-port phase shifters operating in the 5 GHz band show that they not only have low loss characteristics but also wide phase changes. Furthermore, the application to phased array antennas using the proposed phase shifter and its principle are demonstrated.
key words: *waffle iron, PMC (Perfect Magnetic Conductor), phase shifter, phased array antenna, vehicle radar*

1. Introduction

Beam steering array antennas are mainly employed for mobile satellite systems [1] and defense equipment with DBF (Digital Beam Forming) technology. In the DBF phased array antenna, all of the antenna elements are equipped with up-converters and down-converters. In TX mode, IF signals generated in a digital signal processor with independent phase and amplitude are converted to RF signals by an up-converter [2], and in RX mode, IF signals converted from RF signals by a down-converter are sent to a digital signal processor [3], so that the shape of the beams radiated in the air can be optionally controlled. High sensitivity and high operating speed are remarkable features of this type of antenna.

Recently there has been considerable interest in beam steering antennas for applications to vehicle radar and video transmission systems in the millimeter wave band. For such systems, the requirements for sensitivity and/or operating speed are not so great as in other applications such as satellite and defense systems. However, the capability for achieving low cost and the suitability for mass production is highly desirable. For vehicle radar systems, for example, the operating speed is less than 20 cycles per second with beam steering capability in the horizontal plane only. For a video transmission system, it is sufficient to follow the walking speed of a human operator in a room. The particular requirements for realizing beam steering antennas for consumer applications lie not only in the small number of electrical and mechanical parts and the assembly steps in fabrication for attaining low cost, but also in eliminating adjustment of the matching conditions and circuit gain for semiconductor devices installed in the antenna module.

To solve these requirements, several types of phase shifter with simple structures employing liquid crystal material [4], movable dielectric bricks [5], and ferroelectric material [6] have been proposed. The phase shifters employing liquid crystal and ferroelectric materials utilize the property of changing the permittivity by altering the bias voltage. The phase shifter employing movable dielectric bricks utilizes the variation induced in the electrical length of a transmission line by retracting the bricks from the transmission line. These phase shifters have a simple structure, and thus possess the ability to control the RF signals directly, which allows the number of up/down-converters to be reduced, leading to a low cost phased array antenna.

On the other hand, liquid crystal and ferroelectric materials have relatively large dielectric losses for practical use at high frequencies such as in the millimeter wave band. Furthermore, the transmission line covered by dielectric bricks has the disadvantage of unavoidable radiation losses because its structure is such that half of its area is exposed to the ambient air.

In this paper, we propose a new type of phase shifter adopting a movable waffle iron metal structure [7] (denoted as 'WI' hereinafter) which has the characteristics of favorable low loss and large phase changes. The WI structure has mainly been used for waveguide filters utilizing the high impedance section due to the spaces between the rods, as an equivalent L connected in series, and a low impedance section due to the rods themselves, as an equivalent C connected as a shunt [8], [9]. In conventional WI filters, the length of the rods is limited to less than a quarter-wavelength in order to prevent a slot mode from being excited in the guide. This limitation has to be imposed so that the TE mode corresponding to the slot mode is not allowed to propagate through the longitudinal slots in the filter at frequencies where the sum of the height of the WI rods created on the upper and lower walls is greater than a half-wavelength.

The unique feature of our work is that we have attempted to utilize the WI structure in two ways for providing the basic elements of the phase shifter. The first one is that the WI structure is used as a reflection boundary, which has a PMC (Perfect Magnetic Conductor) -like surface extended on the top of the quarter-wavelength high rods. The second way is that the WI structure is used as a section that has

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the ability to prevent electromagnetic waves from propagating in the guide by using the band elimination characteristics, which results in good isolation between adjacent phase shifters. Besides the electrical aspects mentioned above, the proposed phase shifter has a unique mechanical function. In order to realize a variable phase capability, we have employed the WI structure in such a manner that the upper and lower metal plates can be moved relative to each other in the plane parallel to each. To confirm the validity of this concept, the phase shifter has been fabricated and experiments in the 5GHz band have been carried out. Furthermore, the characteristics of an antenna with beam steering capability have been evaluated using the data measured with the phase shifter.

This paper is organized as follows: Sect. 2 presents the principle of the phase shifter. In Sect. 3, some discussion is devoted to the study and design method of the WI structure. The results of experiments on 1-port and 2-port phase shifters in the 5 GHz band are provided in Sect. 4, which verify the concept of the new type of phase shifter. Section 5 demonstrates the applications to phased array antennas. Finally, the conclusion is given in Sect. 6.

2. Principle of the Phase Shifter

Up to the present, WI or corrugated waveguides with periodic structures have been used for filters [8], [9]. Periodic structures are also used for the EBG (Electromagnetic Band Gap) devices in the applications of Meta material technologies [10], [11]. There are some reports in the literature [10], [11] that EBG surfaces have PMC-like characteristics and a corrugated slab surface of a quarter-wavelength in height has the same characteristics. In the literature [9], a WI structure has been analyzed as a kind of corrugated structure containing longitudinal slots cut through the slabs.

A new type of phase shifter is proposed based on the above background information and the following characteristics:

(1) The surface at the top of quarter-wavelength high WI rods shows PMC-like characteristics.

(2) A parallel plate waveguide employing PMC and PEC (Perfect Electric Conductor) with a distance of less than a quarter-wavelength has the same band elimination characteristics as a corrugated structure.

(3) Increasing the cross sectional area of the rods, changes the surface gradually from PMC-like to PEC.

(4) The surface reflection coefficients of PMC-like and PEC differ by around 180 degrees.

Figure 1 shows examples of movable WI metal plate structures. Figure 1(a) shows a movable WI metal plate with WI rods created on both the upper and lower plates, and Fig. 1(b) shows WI rods created on one plate only. We have used the structure shown in Fig. 1(b) for the basic element of our new type of variable phase shifter.

Figure 2 shows a cross sectional view of the basic element. As shown in Fig. 2, the basic element is a parallel plate waveguide comprised of a WI (PMC-like) metal structure with rods a quarter-wavelength in height, and a metal ground plane (PEC), with the distance between the ground plane and the WI structure less than a quarter-wavelength. A radiation element is mounted on the ground plane. The ground plane is shared between the parallel plate waveguide and the feed circuit layer formed in the tri-plate stripline. In Fig. 2, there are two kinds of WI rods. One is the WI structure with a cross-sectional area smaller than the radiation element in order to allow its surface to have a PMC-like nature (denote this WI rod as WI-S hereinafter), and the other is the WI structure with a cross-sectional area larger than the radiation element in order to allow its surface to change to PEC (denote this WI rod as WI-L hereinafter).

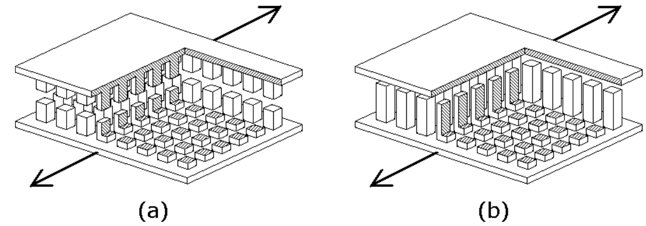

Fig. 1 Examples of a movable WI metal structure.

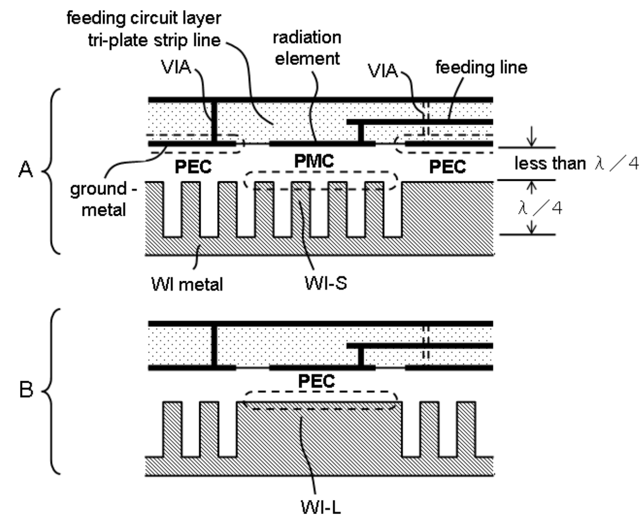

Fig. 2 Cross sectional view of the basic element.

The principle of the phase shifter is explained as follows; in Fig. 2, state *A* shows WI-S situated in front of the radiation element, whereas state *B* shows WI-L situated in front of the radiation element. In state *A*, the RF energy radiated into the parallel plate waveguide from the radiation element spreads toward the surrounding area. However, the parallel plate waveguide with the WI structure with quarter-wavelength rods has band elimination characteristics so that the RF energy is pushed back to the radiation element with low loss. In a similar manner, in state *B*, the RF energy radiated into the parallel plate waveguide is pushed back to the radiation element with low loss because the PEC boundary is located in proximity to the radiation element. In these two states, it should be noted that the surface reflection phase be-

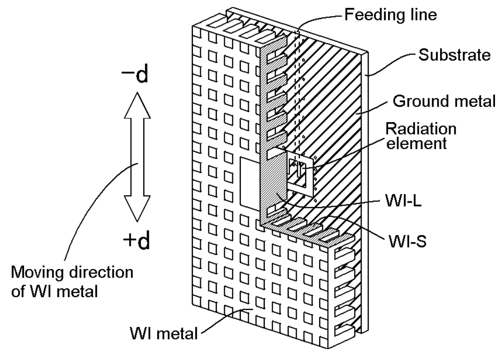

Fig. 3 Cut-away view of the 1-port phase shifter.

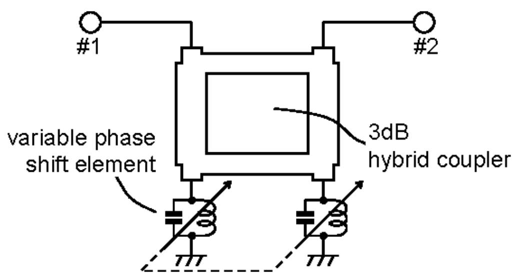

Fig. 4 Schematic of the 2-port phase shifter.

tween WI-S (PMC-like) and WI-L (PEC) differ by around 180 degrees. Furthermore, in the intermediate state between states *A* and *B*, where the radiation element stretches over both WI-S and WI-L, the phase of the surface reflection coefficient has an intermediate value. Consequently, if the WI metal plate is moved continuously between the two states, continuous phase shift characteristics with low loss and large phase changes can be obtained.

Figure 3 shows a cut-away view of the 1-port phase shifter, which includes the single basic element explained above. Figure 4 shows a schematic of a 2-port phase shifter using a 3 dB hybrid coupler and a pair of phase shift elements [12], and Fig. 5 shows a cut-away view of the 2-port phase shifter, which includes the two basic elements described above. In Fig. 3 and Fig. 5, the E-shaped patch is used as the radiation element for wide band operation [13]. The direction in which the WI plate moves is shown by a bold arrow in the figures. As shown in Fig. 5, the 2-port phase shifter is comprised of a 3 dB hybrid coupler fabricated on a feed circuit layer and a pair of basic elements, which move in unison. For the 2-port phase shifter, there is the WI-S section between the two WI-L sections, and thus the electromagnetic coupling between the two basic elements is very small because of the band elimination characteristics of the WI section. With the condition that a pair of WI-L sections is moved by the same amount, the reflection coefficients of the two basic elements also change simultaneously. Consequently, the 2-port phase shifter has the attribute of large phase changes while maintaining good impedance matching of the ports.

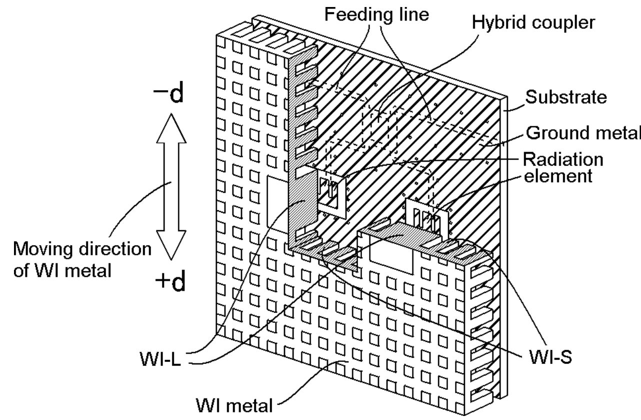

Fig. 5 Cut-away view of the 2-port phase shifter.

3. Study of the Waffle Iron Structure

3.1 Evaluation of the Size of the Waffle Iron Rods

To realize a variable phase shifter using a moving WI metal plate, the surface of WI-S should have PMC-like reflection characteristics in order to give large phase changes. Thus, we have studied the size of the WI rods needed to satisfy this requirement. Materials with PMC do not occur naturally. The boundary conditions of a PMC surface are expressed by the following.

$$H_t = 0 \quad \text{and} \quad E_n = 0 \tag{1}$$

where the subscripts *t* and *n* refer to the transverse and normal directions to the surface, respectively, whereas a PEC can be considered to be a lossless conductor, and the boundary conditions for its surface are expressed as follows.

$$E_t = 0 \quad \text{and} \quad H_n = 0 \tag{2}$$

In general, the cross sectional plane, located at a quarter-wavelength from the shorted terminal of a lossless transmission line, on which the TEM mode propagates, is equivalent to a PMC surface because the electrical current on the transmission line is zero so that $H_t = 0$. In the first step of our investigation, we have to obtain a qualitative knowledge of the size of the WI rods required in order to create a good PMC surface. Supposing that the gap between two WI rods is regarded as a transmission line, in which the two rods form the upper and lower conductors of the transmission line. The condition that the TEM mode should propagate along the transmission line is that the gap between the two rods is less than a half-wavelength in height and width. This is a minimum requirement to create a PMC surface. Under this condition, the space in the gap between the quarter-wavelength long rods becomes a PMC surface.

However, in the actual phase shifters shown in Figs. 3 and 5, the surface of the structure comprised of the gaps between the WI rods, and the tops of the rods has a different property to a PMC surface, and can be considered to have

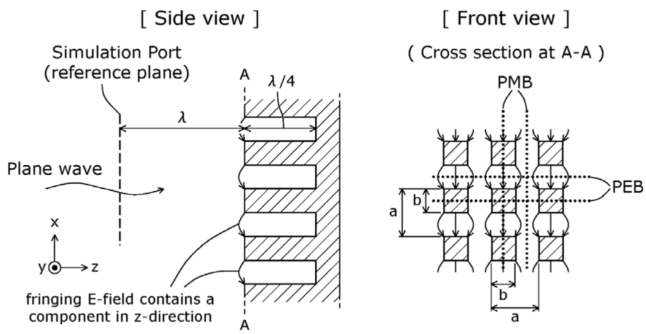

Fig. 6 Geometry for the surface reflection phase of the WI rods.

characteristics intermediate between a PMC and a PEC surface. This is the reason why the surface of the WI rod structure is referred to as PMC-like and not as a PMC. Thus it is essential to carry out a primary study to estimate how the surface of the WI rods approaches a PMC surface.

Figure 6 shows the geometry used to assess the phase of the reflection from the WI surface when a plane wave with an E-field in the x-direction impinges upon an infinitely extended WI metal surface, in which the rods are a quarter-wavelength in height. In Fig. 6, the front view depicted on the right-hand side of the figure shows the cross section A-A in the side view. With the incidence of a plane wave, the E-field between the WI rods is excited as shown in the front view of Fig. 6. When the E-field is symmetrical around the equivalent PMB (Perfect Magnetic Boundary) and the equivalent PEB (Perfect Electric Boundary) in Fig. 6, an electromagnetic analysis can be applied to the area enclosed by the boundaries.

In the analysis, the position of a simulation port (reference plane) is determined as follows. The input admittance at the surface of the quarter-wavelength WI rods is written as

$$Y_{in} = -jY_o \cot \frac{2\pi f L}{v_o} + j2\pi f C \tag{3}$$

where Y_o is the characteristic admittance between the rods for a transmission line in the TEM mode, f is the operating frequency, L is the length of the rods, v_o is the velocity in vacuum, and C is the fringing capacity. The fringing capacity C is caused by the fringing E-field, which contains a component in the z-direction and is distributed in the area around the surface of the WI rods. From this fact, we can determine the position of the simulation port in such a manner that the port is located at one wavelength from the surface of the rods, including the phase change resulting from fringing E-field, as shown in Fig. 6.

Figures 7 and 8 show the phase of the reflection from the surface of the WI rods calculated using the High-Frequency Structure Simulator (HFSS). In the calculation, the WI metal plate is assumed to be lossless, which means that the reflection magnitude is equal to 0 dB (not shown in the figure). In the figures, 'a' is the period between the rods and 'b' is their width.

As can be seen in the figure, the reflection phase from

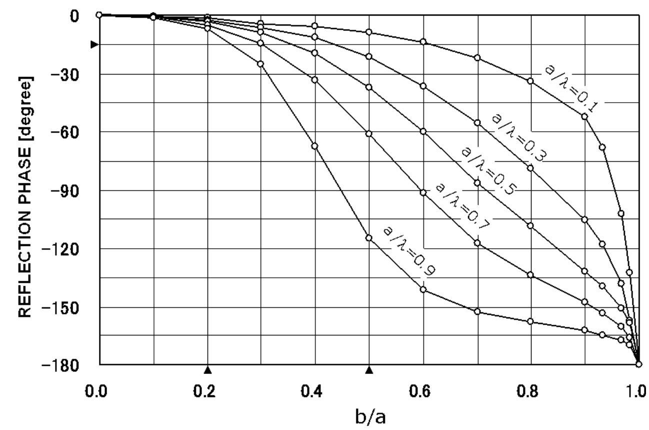

Fig. 7 Calculated surface reflection phase of the WI rods as a function of b/a.

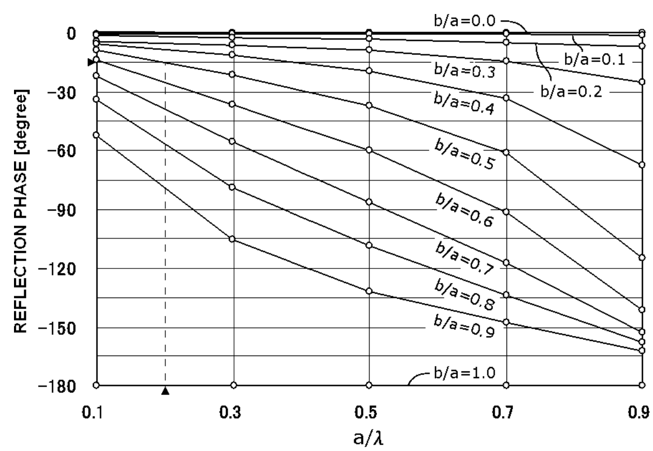

Fig. 8 Calculated surface reflection phase of the WI rods as a function of a/λ.

the surface of the structure varies significantly as b/a and a/λ is changed. If we define a criterion such that the PMC-like surface should have a reflection phase of less than −15 degrees, the combination of ($b/a \leq 0.2$ for any a/λ) and ($b/a \leq 0.5$ and $a/\lambda \leq 0.2$) are acceptable. Although there are a number of combinations that fulfill these requirements, the combination ($b/a = 0.5$ and $a/\lambda = 0.2$) provides a practical structure for fabrication from the following reasons.

(a) The relaxed tolerance for processing the WI structure can reduce the manufacturing cost. The dimension of $b/a = 0.5$ gives the most relaxed tolerance in the process of forming both WI rod and the gap between WI rods.

(b) The final application of the WI structure would be a phase shifter used for phased array antennas. Phased array antennas possess a plural phase shifter, and thus the structure presented in this paper is required to have a small area (a squared). Furthermore, a thinner WI rod would deteriorate mechanical reliability in forming and fabrication process. Therefore, under the conditions that the length of WI rod is a quarter-wavelength to create a PMC-like surface and $b/a = 0.5$, there may be a suitable value for a/λ. The dimension of $a/\lambda = 0.2$ allows the ratio of the width to length of

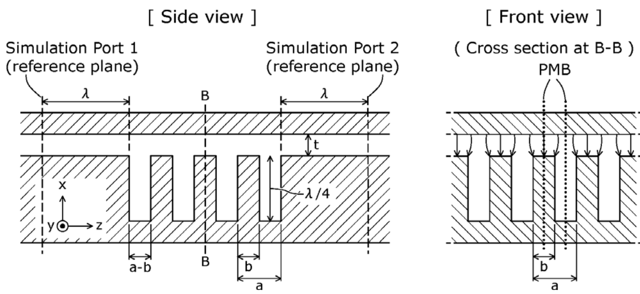

Fig. 9 Geometry for the transmission characteristics of a WI waveguide.

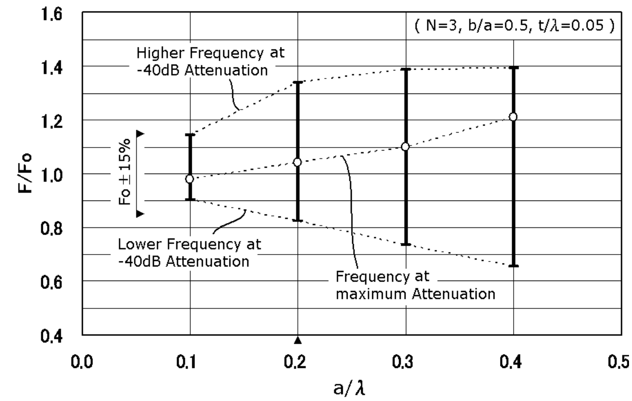

Fig. 10 Band width for −40 dB isolation in a WI waveguide as a function of a/λ.

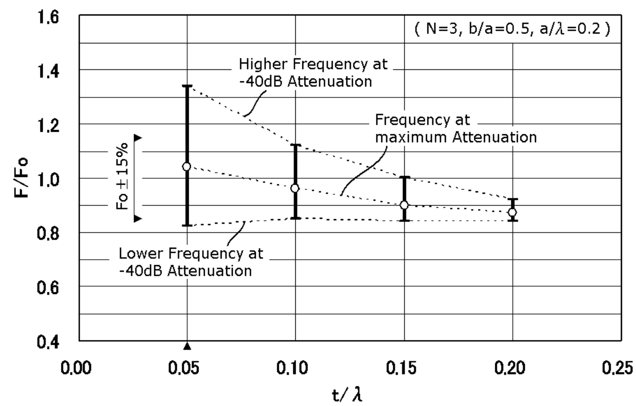

Fig. 11 Band width for −40 dB isolation in a WI waveguide as a function of t/λ.

WI rod to be equal to 0.4, resulting in a reasonable choice for mechanical reliability.

The consideration mentioned above is particularly important for mass-production and for low cost and high reliability.

3.2 Evaluation of the Number of Waffle Iron Stages

In the proposed variable phase shifter, the WI structure is utilized as a band elimination filter in order to return the electromagnetic wave to the radiation element, resulting in a good isolation between adjacent phase shifters. Although conventional methods [8], [9] can be used for the design of a WI filter with the height of the rods less than a quarter-wavelength, the rods used in the variable phase shifter studied in this paper should be a quarter-wavelength in height in order that the surface of the waffle structure has PMC-like characteristics. For this reason, electromagnetic analysis was adopted.

Figure 9 shows the geometry used for analyzing the transmission characteristics of the WI waveguide. In Fig. 9, the front view shows the cross section at B-B in the side view. In the geometry both the upper metal and the periodic WI structure extend to infinity in the y-direction. Figure 9 shows the situation where an electromagnetic wave in the TEM mode propagates from port 1 to port 2 with the E-field being excited in the x-direction. When the electromagnetic wave propagates, the E-field is distributed between the tops of the WI rods and the upper metal plate, as shown in the front view. Since the E-field is symmetrical about the equivalent PMB as shown in Fig. 9, electromagnetic analysis can be applied to the area enclosed by equivalent boundaries. In the analysis, the range of the distance 't' between the top of the rods and the upper metal plate is determined from the following study.

With the assumption that the surface of the WI structure is a PMC, and under the condition that the distance $t > \lambda/4$, a TE mode with E-field in the y-direction, as shown in Fig. 9, is able to propagate between the tops of the rods and the upper metal plate. The wavelength of this TE mode can be calculated from the following equation.

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\lambda/4t\right)^2}} \tag{4}$$

Therefore, to eliminate the TE mode, the simulation is limited to the range $t < \lambda/4$.

Figures 10, 11, and 12 show the results calculated using the HFSS in such a manner that the results accommodate the −40 dB isolation requirement in the desired bandwidth, where the master parameters selected are those that the study in the previous section showed would provide a practical structure; these are $b/a = 0.5$, $a/\lambda = 0.2$ and $N = 3$, where N represents the number of WI rods between port 1 and port 2 (Fig. 9 shows the case for $N = 3$). F_o is the frequency corresponding to the case where the WI rods are a quarter-wavelength in height. In the calculation, the WI structure is assumed to be lossless, which means the magnitude of the reflected wave (i.e. the ability to return the electromagnetic wave to the radiation element) with −40 dB isolation is less than −0.0005 dB.

As can be seen from Figs. 10, 11, and 12, the bandwidth for −40 dB isolation varies significantly as a/λ, t/λ and N are changed. If the parameters $a/\lambda = 0.2$, $t/\lambda = 0.05$ and $N = 3$ are selected, a bandwidth of $F_o \pm 15\%$ is available, which is adequate for general purposes, except for special systems, in which a larger bandwidth is needed, such as UWB (Ultra Wide Band).

Although the area of the phase shifter can be reduced

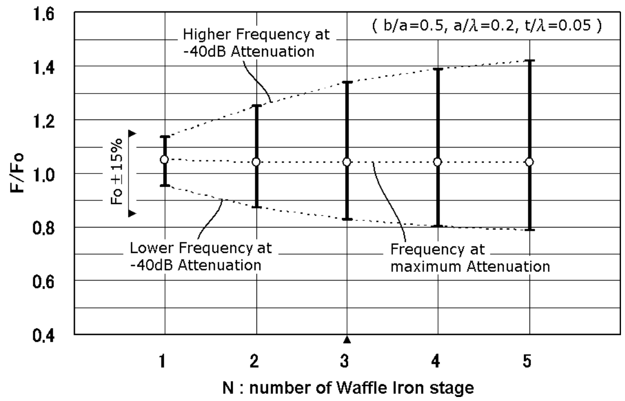

Fig. 12 Band width for −40 dB isolation in a WI waveguide as a function of N.

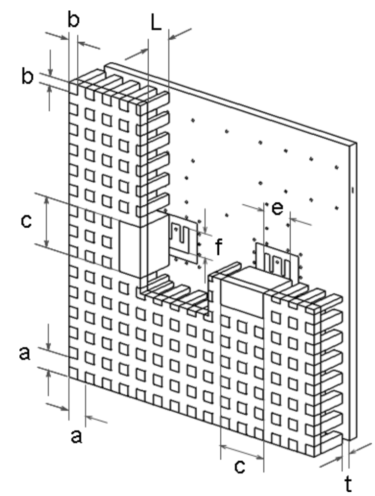

Fig. 13 Structure of the fabricated phase shifter.

by decreasing a/λ, Fig. 10 shows that as a/λ gets smaller, the −40 dB isolation bandwidth is reduced. On the other hand, t/λ has little affect on the area of the phase shifter, and Fig. 11 shows that the smaller that t/λ is, the larger the −40 dB isolation bandwidth. It is found from this consideration that reducing t/λ is an effective way to reduce the area of the phase shifter without affecting the isolation.

4. Experiments of 1-Port and 2-Port Phase Shifters

To verify the theoretical investigations described above, 1-port and 2-port phase shifters were fabricated and tested in the 5 GHz band. The structural parameters were determined by the procedure described in the previous sections, and are as follows: $b/a = 0.5$, $a/\lambda = 1/6\,(\leq 0.2)$, $t/\lambda = 1/30\,(\leq 0.05)$, and $N = 3$. In some applications, a wide frequency range would be desirable for a phase shifter, and thus we have attempted to use an E-shaped patch antenna [13] with wideband characteristics as a radiation element.

The structure of the fabricated phase shifter is shown in Fig. 13, and the specific dimensions are listed in Table 1. The TRL calibration lines were fabricated on the feed circuit layer of the substrate, which were printed at the same time as the fabrication of the whole phase shifter circuit. Using the standard THRU-line calibration method, a set of S-parameters of $MAG(S11) \leq -50$ dB, $MAG(S21) \leq \pm 0.05$ dB, $ANG(S21) \leq \pm 1$ deg was obtained, ensuring good calibration conditions. After conducting the whole calibration procedure, the performance of the phase shifter was measured.

Figure 14 shows the simulated and measured return loss of the radiation element without the WI metal structure. A return loss of less than −10 dB between 4.7 GHz to 5.3 GHz was obtained. However the measured bandwidth is wider than the calculated one. A possible cause of this discrepancy may be inadequate modeling of the feed structure of the radiation element in the calculation.

Figures 15 and 16 show the simulated and measured characteristics of the 1-port phase shifter. WI metal position, d, is equal to zero when the center of the radiation element and WI-L are coincident with each other. The sign of d agrees with the arrow shown in Fig. 5. In Fig. 16, the WI metal structure is moved a distance of ±30 mm, and a phase change of more than 250 degrees is achieved with an insertion loss less of than 2 dB at 5.0 GHz when the WI position is moved from −25 mm to +10 mm. The reason for the insertion loss observed in the figures is due to the loss in the radiation element, a part of which arises from the enhancement of a resonating current because the radiation element is operated in a half-wavelength resonant mode.

Figures 17 and 18 show the measured characteristics of the 2-port phase shifter. The phase change of $S21$ is similar to the 1-port phase shifter in shape, which implies that the hybrid coupler is well designed. A phase change of more than 250 degrees is achieved with an insertion loss of less

Table 1 Specific dimensions of the fabricated phase shifter in the 5 GHz band.

Center Frequency	5.0 GHz
WI-rod pitch [a]	10.0mm
Cross sectional area of WI-S [b]	5.0mm * 5.0mm
Cross sectional area of WI-L [c]	25.0mm * 25.0mm
WI-rod length [L]	15.0mm
Distance of WI and Substrate [t]	2.0mm
Area of Radiation element [e] * [f]	19.3mm * 12.5mm
Permittivity of Substrate	3.8 (at 1GHz)
Tangent of loss angle	0.004 (at 1GHz)
Total thickness of Substrate	3.0mm

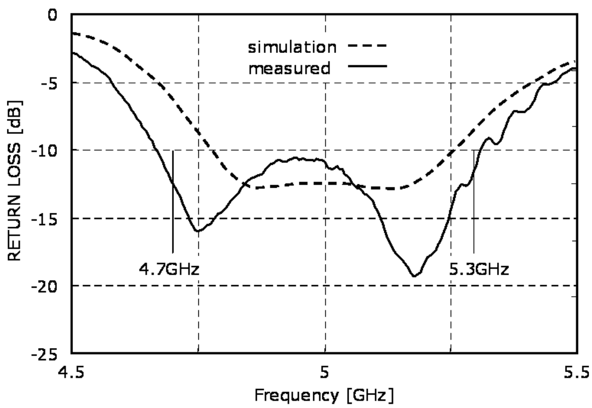

Fig. 14 Simulated and measured return loss of the radiation element without the WI metal structure.

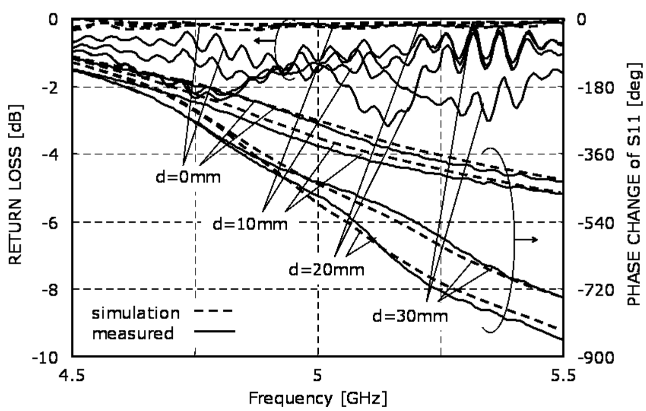

Fig. 15 Simulated and measured performance of the 1-port phase shifter as a function of frequency.

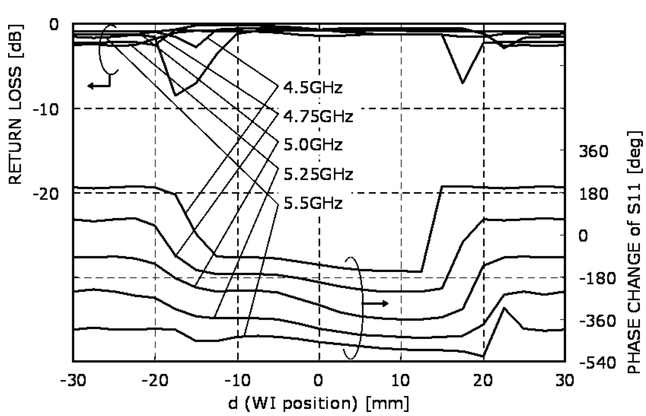

Fig. 16 Measured performance of the 1-port phase shifter as a function of WI position.

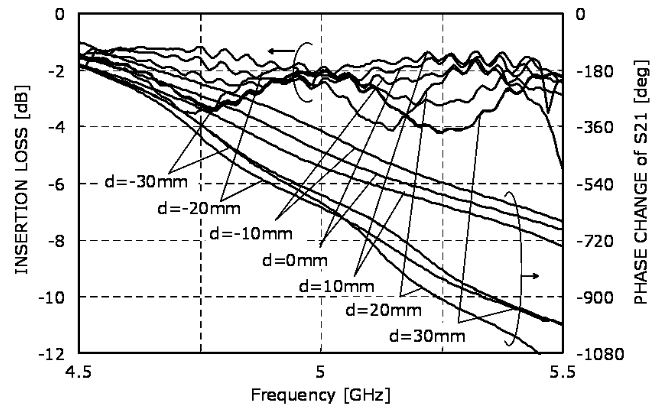

Fig. 17 Measured performance of the 2-port phase shifter as a function of frequency.

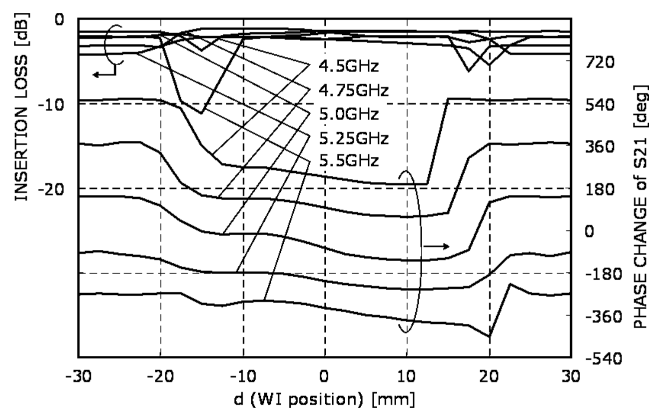

Fig. 18 Measured performance of the 2-port phase shifter as a function of WI position.

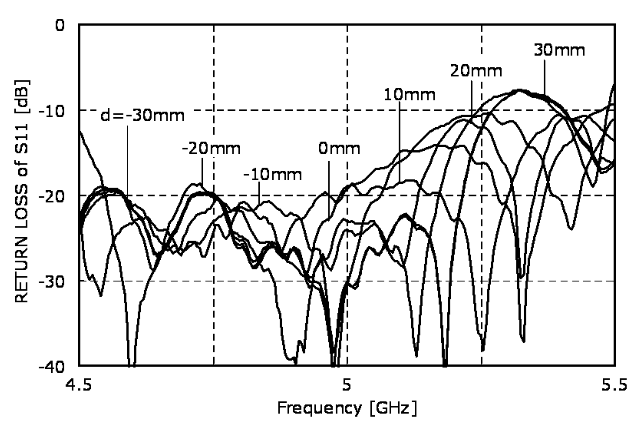

Fig. 19 Measured matching performance of the 2-port phase shifter.

than 3 dB at 5.0 GHz. Fig. 19 shows the impedance matching performance of the 2-port phase shifter. As can be seen from Fig. 19, the 2-port phase shifter has a return loss of about −20 dB for all WI positions at 5.0 GHz. The total performance of the 2-port phase shifter at 5.0 GHz is summarized in Fig. 20. It can be seen from Fig. 20 that the 2-port phase shifter has large phase changes while maintaining sufficiently small insertion and return losses when the WI metal plate moves.

5. Applications to Phased Array Antennas

As one of the applications of the proposed phase shifter, a phased array antenna employing the 2-port phase shifters [12] is demonstrated in this section. Figure 21 shows the

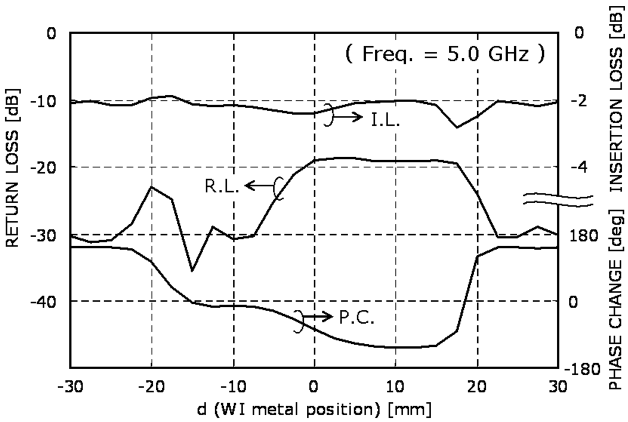

Fig. 20 Summary of the performance of the 2-port phase shifter at 5.0 GHz as a function of WI position.

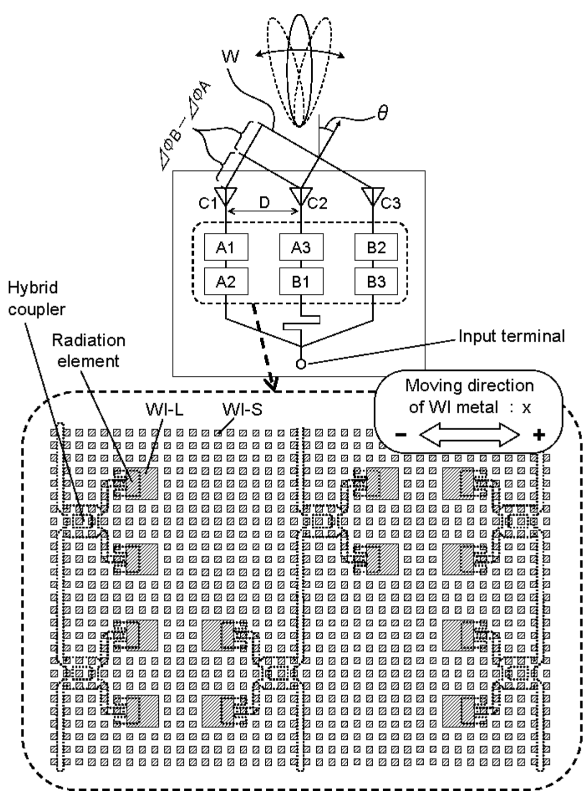

Fig. 21 Structure of the phased array antenna and circuit diagram.

configuration of the phased array antenna. In Fig. 21, the circuit is shown in the upper half of the diagram, and the WI metal structure is shown in the lower half. The phased array antenna has radiation elements C1 to C3, which radiate the electromagnetic wave into the air (note that these radiation elements are different from those in the basic element illustrated in Fig. 2).

There are two groups of phase shifters denoted as A and B. All the phase shifters, A1-A3 and B1-B3, have the same structure, and were made as an integral part of the whole WI metal structure. In either group A or B, the phase shifters give the same phase change. With regard to the

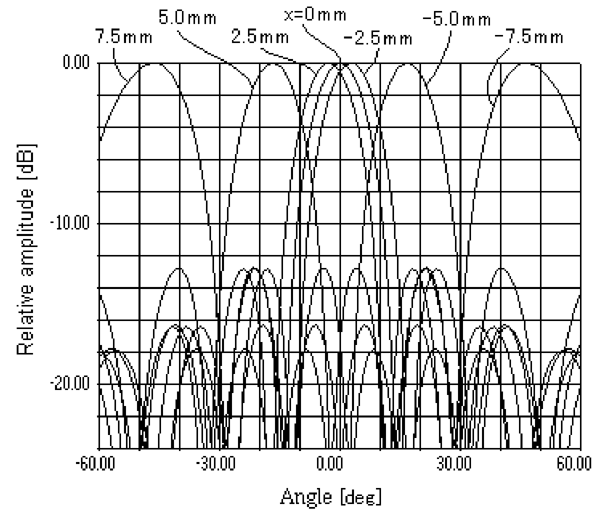

Fig. 22 Simulated radiation patterns of a phased array antenna using 8 elements.

combination of the radiation element and WI-L of the phase shifters, equal and opposite offsets are introduced to the positions of groups A and B. Therefore, when the WI metal moves in the direction shown by the arrow in Fig. 21, the phases associated with groups A and B also change in opposite directions to each other.

The principle of beam steering is explained as follows. Figure 21 shows a state where the WI structure is in the normal position. In Fig. 21, the displacement of WI-L from the radiation elements of groups A and B is symmetrical. In other words, when the WI structure is in the normal position, WI-L for A1-A3 has the same offset from the radiation element as that of B1-B3, but in the opposite direction. This structure produces the same insertion phases and magnitude in A1-A3 and B1-B3. Therefore all of the signals from the input terminal are delivered to the antenna elements C1-C3 in-phase, directing the main beam in the broadside direction of the antenna ($\theta = 0$).

On the other hand, when the WI metal structure is moved in the direction denoted by the arrow in Fig. 21, the phase associated with group A is changed by $\Delta\phi A$, and that associated with the group B is changed by $\Delta\phi B$, and owing to its symmetrical structure the main beam will tilt. The beam direction can be calculated from the following equation [14].

$$\theta = \frac{\pi}{2} - \cos^{-1}\frac{(\Delta\phi B - \Delta\phi A)\,\lambda}{2\pi D} \tag{5}$$

where D is the distance between the antenna elements, and λ is the wavelength in free space.

Figusre 22 shows the simulated radiation patterns of the phased array antenna using 8 antenna elements with the same principle as Fig. 21. In Fig. 22, $D = \lambda/2$, the antenna elements are assumed to have an isotropic radiation pattern, and the measured values of the phase shifter in Fig. 16 are used in the calculation. It can be seen from Fig. 22 that the proposed phased array antenna not only has a beam steering capability with an angular range of more than 45 degrees, but also has stabilized gain during beam steering, when the WI metal structure is moved a distance of 7.5 mm. The total insertion loss amounts to 15.5 dB because the 7 phase-shifters are inserted in series between the input terminal and each antenna element.

The large amount of insertion loss, mentioned above, can be reduced by decreasing the number of phase shifters with enhanced phase changes. Another solution to reduce the insertion loss is to use a waveguide type radiation element with a small loss, as in the basic element in Fig. 2. These trials will be left for the subject of future work.

6. Conclusion

A new type of variable phase shifter using a movable WI metal structure has been proposed. From a study of the principle and the design, estimates of the structural dimensions, b/a, a/λ, N, and t/λ, for a practical device were obtained. The 1-port and 2-port phase shifters were fabricated and experiments in the 5 GHz band were conducted. Phase shift ranges of more than 250 degrees with less than 2 dB and 3 dB insertion losses were obtained. Furthermore, the characteristics of a phased array antenna were evaluated using the measured data of a 2-port phase shifter, and we showed that the proposed phased array antenna would not only have a large steering range but also have stabilized gain during beam steering.

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