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

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1. Introduction

Recently there has been considerable interest in low-cost and easy to mass-product beam steering antenna for vehicle radar or millimeter-wave video transmission systems. This trend has required a simply structured phase shifter, which includes the liquid crystal material [1], the movable dielectric bricks [2], and the ferroelectric materials [3]. In this paper, a new type of phase shifter and phased array antenna adopting a movable waffle-iron (denote as WI hereinafter) metal has been proposed. To verify this concept, the phase shifter has been experimented in the 5GHz band, and the antenna characteristics has been evaluated using measured data of the phase shifter.

2. Principle of Phase Shifter

Up to the present, WI or a corrugated waveguide with periodic structures have been used for filters utilizing their band elimination characteristics [4, 5]. Furthermore, the periodic structure is used for the EBG (Electromagnetic Band Gap) as one of the applications of Meta material technologies in the literatures [6] and [7].

There is some information in the literatures [6, 7] such that the EBG surface has PMC (Perfect Magnetic Conductor) -like characteristics. Furthermore, it is shown that the corrugate-slab surface of quarter-wavelength height has the same characteristics as PMC. Based on the background mentioned above, we have proposed a new type of phase shifter from the points of view listed in the followings:

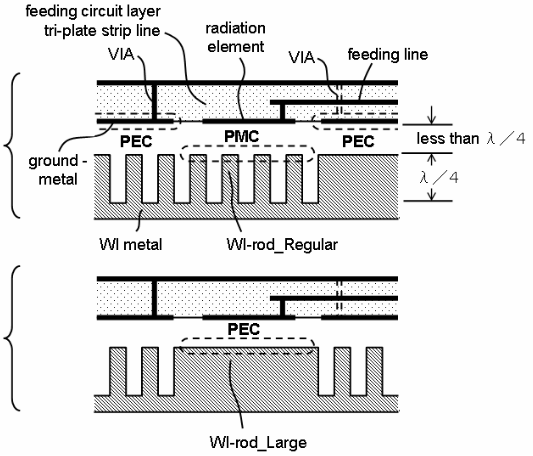

Fig. 1 Cross-sectional view of the variable phase shift element

(1) The WI-rod surface of quarter-wavelength height shows PMC-like characteristics. (2) A parallel-plate waveguide employing PMC and PEC (Perfect Electric Conductor) with the distance of less than quarter-wavelength has band elimination characteristics. (3) Changing the cross-sectional area of WI-rod larger, a surface of WI-rod changes from PMC to PEC gradually. (4) Surface reflection coefficients between PMC and PEC differ in 180 degrees.

Fig. 1 shows the cross-sectional view of variable phase shift element. Fig. 2 shows the schematic of 2-ports phase shifter using a 3dB hybrid coupler and a pair of variable phase shift elements [8]. Fig. 3 shows the cut-away view of 2-ports phase shifter.

As shown in Fig. 1, the variable phase shift element has a structure of parallel-plate waveguide composed of WI-metal (PMC) which has the rods of quarter-wavelength height and ground-metal (PEC), with the distance between PMC and PEC being less than quarter-wavelength. There is also a radiation element on the ground-metal, and the ground-metal is co-owned by the parallel-plate waveguide and the feeding circuit layer of tri-plate stripline. The cross-sectional area of WI-rod_Large is larger than the radiation element in order to make its surface change to PEC. In Fig. 1

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and Fig. 3, the WI-rod of which cross-sectional area is smaller than the radiation element is denoted as WI-rod_Regular.

The principle of phase shifter is explained as follows; Fig. 1A shows that WI-rod_Regular is situated in front of the radiation element, whereas Fig. 1B shows that WI-rod_Large is situated in front of the radiation element. As in Fig. 1A, the RF energy radiated into the parallel-plate waveguide from the radiation element spreads toward surrounding area. However, WI metal has band elimination characteristics so that the RF energy returns back to the radiation element with low return loss.

In a similar manner, in Fig.1B, the RF energy radiated into the parallel-plate waveguide returns back to the radiation element with low return loss. While it is known that the surface reflection coefficients between WI-rod_Regular (PMC) and WI-rod_Large (PEC) differ in 180 degrees [6, 7].

Furthermore in the intermediate state between Fig. 1A and Fig. 1B, where the radiation element stretches over both WI-rod_Regular and WI-rod_Large, the surface reflection coefficient also has an intermediate value.

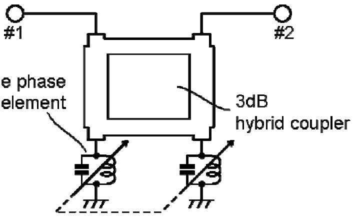

Fig. 2 Schematic of the 2-port phase shifter

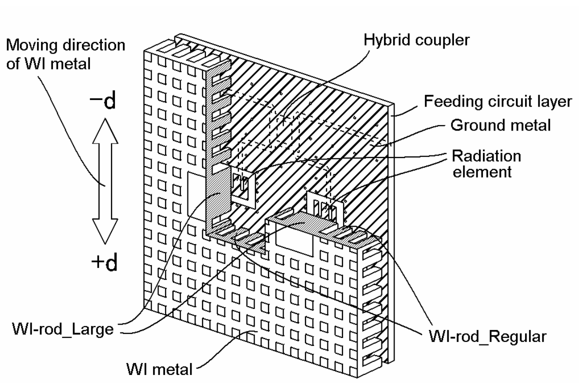

Fig. 3 Cut-away view of the 2-port phase shifter

Consequently, if the WI metal is moved continuously between the two states, the continuous phase shift characteristics with low return loss and large phase shift ranges could be obtained.

The 2-port phase shifter is composed of a 3dB hybrid coupler and a pair of variable phase shift elements as in Fig. 2. Fig. 3 shows the actual structure of 2-port phase shifter, in which the hybrid coupler is fabricated on the feeding circuit layer. For the 2-port phase shifter as shown in Fig. 3, there is the WI-rod_Reglar section between the two WI-rod_Larges, and then the electromagnetic coupling between the two phase shift elements is very small because of the band elimination characteristics of the WI section.

Furthermore, in the condition that a pair of WI-rod_Larges is moved in the same value, the reflection coefficients of the two phase shift elements also change in the same value. Consequently, 2-port phase shifter has a performance of large phase shift ranges with the impedance matching of both ports kept a good condition.

3. Experiment of 2-Port Phase Shifter

In general applications a wide frequency range is required for the phase shifter, so that we have adopted the wide band E-shaped patch antenna as a radiation element [9].

The specifications of the phase shifter are as follows. The center frequency is 5.0GHz, the cross-sectional area of WI-rod_Regular and WI-rod_Large are 5.0mm × 5.0mm and 25.0mm × 25.0mm respectively, WI-rod height is 15.0mm, the distance of WI-metal (PMC) and ground-metal (PEC) in the parallel-plate waveguide is 2.0mm, the area of radiation element is 19.3mm × 12.5mm, the relative permittivity and the tangent of loss angle of feeding circuit layer are 3.8 and 0.004 at 1GHz respectively, and the thickness of feeding circuit layer is 3.0mm. On the substrate for feeding circuit layer, the TRL calibration lines were fabricated simultaneously with the printed layout of phase shifter. Then for a standard THRU-line, ensuring MAG(S11)<−50dB, MAG(S21)< ±0.05dB, ANG(S21)< ±1deg using TRL calibration method, the phase shifter has measured.

Fig. 4 and Fig. 5 show the measured return and insertion characteristics of 2-port phase shifter, where d [WI position] equal to zero when the center of radiation element and WI-rod_Large are equally overlapped, and the sign of d agrees with Fig. 3. As in Fig. 5, the phase change of more than 250 degrees is achieved with the insertion loss less than 2.5dB at 5.0GHz when WI metal moves with the distance of 30mm (–25mm to +10mm). It is supposed that the insertion loss is caused by the loss of radiation element, and the main loss factor may be attributed to the enhancement of resonance current because the radiation element is operated in a half-wavelength resonant mode.

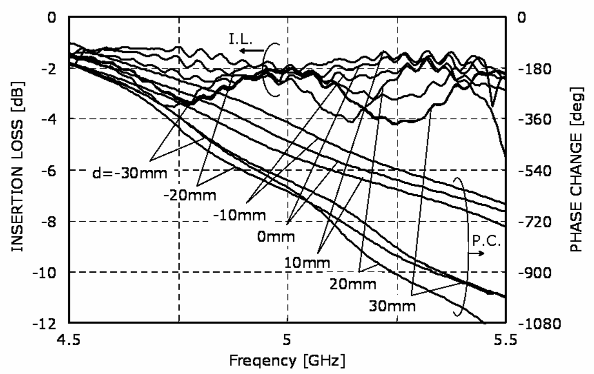

Fig. 4 Measured insertion loss and phase change characteristics of the 2-port phase shifter as a function of frequency

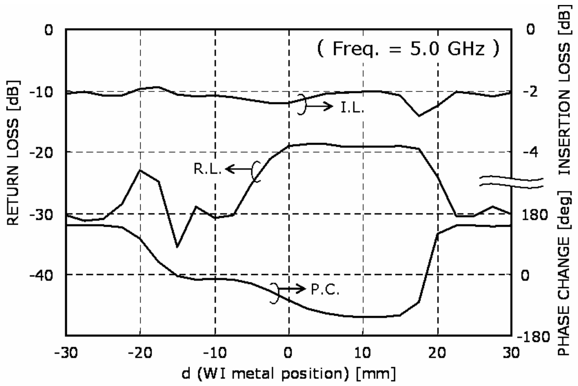

Fig. 5 Measured return loss, insertion loss and phase change characteristics of the 2-port phase shifter as a function of WI-metal position

4. Applications to Phased Array Antennas

Fig. 6 shows the principle of phased array antenna employing 2-port phase shifters [8]. The principle of beam steering is explained as follows.

All of the phase shifters R1-R3 and L1-L3 enclosed with dotted line have the same structure, and the whole WI metal has been made as an integral part. Fig. 6 shows a state that the WI metal is in the normal position, where the WI-rod_Large is symmetrically displaced from the radiation element between the two groups of R1-R3 and L1-L3. In other words, when the WI metal is in the normal position, the position of WI-rod_Large for R1-R3 and L1-L3 is offset to the radiation element with the same distance and opposite direction, and then all of the insertion phases also produce the same values. Therefore all of the signals from an input terminal are delivered to antenna elements A1-A3 with in-phase, so that the main beam is directed in the broadside direction of the antenna ($\theta = 0$).

On the other hand in a state that WI metal is moved to the direction denoted with the arrow in Fig. 6, the offset of WI-rod_Large and the symmetrical structure result in the difference in the phase shift value of R1-R3 ($\Delta\phi R$) and L1-L3 ($\Delta\phi L$), leading to the changes in the main beam direction.

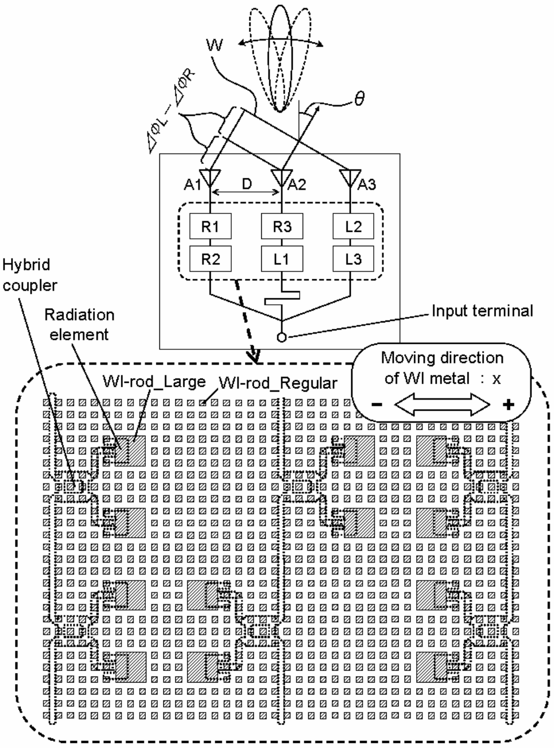

Fig. 6 Principle of the phased array antenna

Consequently the beam direction is described with the equation shown below [10].

$$\theta = \frac{\pi}{2} - \cos^{-1}\frac{(\Delta\phi L - \Delta\phi R)\lambda}{2\pi D}$$

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

Fig. 7 shows the simulated radiation patterns of phased array antenna, which is developed using 8 antenna elements with the same principle as Fig. 6. Where $D = \lambda/2$, the antenna element is isotropic, and the measured values of phase shifter in Fig. 5 are applied to the calculations.

It can be seen from Fig. 7 that the proposed phased array antenna has not only beam steering ranges more than 45 degrees when the WI metal moves with the distance of 7.5mm, but also a stabilized gain during the beam steered.

Whereas the total insertion loss amounts to 15.5dB because 7 phase shifters in series are inserted between an input terminal and each antenna element.

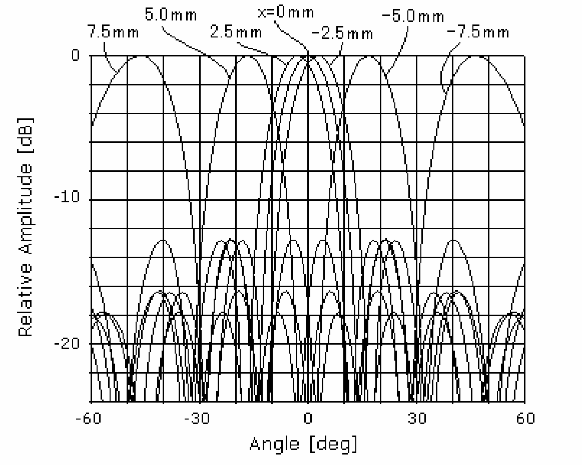

Fig. 7 Simulated radiation patterns of the phased array antenna using 8 elements

Therefore a decrease of insertion loss will be the subject in further work.

5. Conclusion

The 2-port variable phase shifter adopting a movable waffle iron metal has been experimented in the 5 GHz band, and the phase shift ranges more than 250 degrees with less than 2.5dB insertion loss is obtained. Furthermore the characteristics of phased array antenna has been evaluated using measured data of phase shifter, and the proposed phased array antenna has not only a large steering ranges more than 45 degrees when the WI metal moves with the distance of 7.5mm, but also a stabilized gain during the beam steered.

For further work, it is necessary that the hybrid coupler and feeding line will be fabricated using a waveguide structure, and the radiation element will be changed to low loss type like a horn antenna for the millimeter wave applications.

References

[1] H. Kamoda, T. Kuki, H. Fujikake and T. Nomoto, “Millimeter-wave Beam Former Using Liquid Crystal, ” Proc. 34th European Microwave Conf., pp.1141-1144, Amsterdam, 2004.

[2] J. Cha and Y. Kuga, “A Mechanically Steerable Array Antenna Using Controllable Dielectric Phase Shifters for 77GHz Automotive Radar Systems, ” IEEE AP-S Int. Symp., Albuquerque, NM, 2006.

[3] J. Modelski and Y. Yashchyshyn, “Semiconductor and Ferroelectric Antennas, ” Proc. APMC2006, Vol.2, 1059-1065, Dec.2006.

[4] E.D. Sharp, “A High-Power Wide-Band Waffle-Iron Filter, ” IEEE Trans. Microwave Theory Tech., vol. MTT-11, pp.111-116, March 1963.

[5] G. Matthaei, L.Young and E.M.T. Jones, Microwave Filters, Impedance-Matching Networks, and Coupling Structures, pp.390-409, McGraw-Hill, 1964.

[6] F. Yang and Y. Rahmat-Samii, “Reflection Phase Characterizations of the EBG Ground Plane for Low Profile Wire Antenna Applications, ” IEEE Trans. Antennas Propagat., vol.51, no.10, Oct.2003.

[7] D. Sievenpiper, L. Zhang, R.F.J. Broas, N.G. Alexópolous and E. Yablonovitch, “High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band, ” IEEE Trans. Microwave Theory Tech. vol.47, no.11, Nov.1999.

[8] JP PAT. PA2006-353564

[9] F. Yang, X.X. Zhang, X. Ye and Y. Rahmat-Samii, “Wide-Band E-Shaped Patch Antennas for Wireless Communications, ” IEEE Trans. Antennas Propagat., vol.49, no.7, July 2001.

[10] J.D. Kraus, Antennas Second Edition, pp.485-499, McGraw-Hill, 1988.