OFFSET BEAM PLANAR ANTENNA IN SIMPLE PHASE SHIFTER EMPLOYING TRIANGULAR DIELECTRIC PLATE ON FEEDLINES

Naoki HONMA, Tamami MARUYAMA, and Toshikazu HORI
Nippon Telegraph and Telephone Corporation
1-1 Hikari-no-oka, Yokosuka, Kanagawa 239-0847, Japan
E-mail: honma@wslab.ntt.co.jp

1. Introduction

To radio-communicate using directive antennas, the direction of the beam must be adjusted when the antenna direction differs from the desired direction. When the antenna positions are stationary, there is no need to control the beam dynamically. When the beam adjustment is achieved by phase controlling, a bit phase shifter is generally applied to control the beam. However in this case, a bit phase shifter is not suitable because it is very lossy [1]. Incorporating the shifter makes the feedline configuration more complex and there is no need for dynamic phase control. On the other hand, in a manual variable phase shifter, when incorporated with an antenna feedline, there is a problem in that control is difficult and the antenna becomes large. When applying a delay line to shift the phase, although it establishes an offset beam with a very simple structure, it is impossible to change the direction of the beam, since the phase difference is fixed completely.

To establish a variable phase shift using a simple configuration, the method of controlling the phase shift by overlaying a dielectric plate on the line was adopted in 1974 [2], and the thickness and length of the dielectric plate was optimized [3]. However, an arbitrary thickness and length could not be selected in these methods due to the reflection at the dielectric edge. It is difficult to obtain an arbitrary phase shift. These methods are not suitable to control the beam direction freely, since it is not easy to obtain the optimum phase shift.

This paper proposes a new simple planar array antenna configuration with a simple phase shifter comprising a triangular dielectric plate on the feedlines. The triangular shape of the dielectric plate enables easy shifting of the beam direction. To avoid reflection at the dielectric edge, we propose to taper the edge of the dielectric plate. This shape enables us to employ an arbitrary dielectric plate form such the proposed triangular plate.

This paper discusses two points and indicates the effectiveness of the proposed antenna and method of designing the antenna.

- The relation between the beam offset angle and the dielectric shape.
- The taper form optimizing method at the edge of the dielectric plate

2. Antenna configuration

The structure of the antenna is shown in Fig. 1. Term α is the offset angle of the beam from the normal line of the antenna plane. One isosceles-triangle-shaped dielectric plate is attached to the microstrip lines, where β is the angle between the two equal sides of the isosceles triangle. The first important point of this configuration is the triangular shape of the dielectric plate. This shape enables the beam direction to be shifted because the lines are given the appropriate phase shift by the dielectric plate.

The second important idea of this paper is adopting a tapered dielectric plate edge configuration to suppress the reflection at the edge of a dielectric plate. The desirable amount of phase delay can be obtained. Although there is a method to avoid the reflection by employing a half-wavelength dielectric plate on the microstrip line [3], there is a problem in that it was hard to obtain an arbitrary amount of phase shift because of the restriction on the dielectric plate length. In this paper, since the reflection was suppressed by the taper of the edge of the dielectric plate, the desirable amount of phase delay can be obtained. In order to examine the designing method, antennas in a simple four-element structure were used.

3. Design method of a triangular dielectric plate considering offset beam angle

Fig. 2 shows the dielectric phase shifter on the parallel microstrip lines. In this paper, for the sake of simplicity, line spacing d_l and element spacing d_r shall be regular intervals, and the dielectric plate is in the form of an isosceles triangle. Offset beam angle α is obtained as

$$\alpha = \sin^{-1}\left\{2\frac{d_l}{d_r}\tan\frac{\beta}{2}\cdot\left(\sqrt{\varepsilon_{re}}-\sqrt{\varepsilon_{re0}}\right)\right\} \qquad (1)$$

where β is the angle between the two equal sides of the isosceles triangle. The effective dielectric constant, ε_{re0}, of the microstrip line and effective dielectric constant ε_{re} of the multilayer microstrip line are determined by substrate dielectric constant ε_{r1}, the overlay plate of dielectric constant ε_{r2}, substrate thickness h_1, overlay plate thickness h_2, strip conductor width w, and strip conductor thickness t. To obtain the values of ε_{re0} and ε_{re}, we employed the variational method [4] [5].

Formula (1) indicates that α is independent of the wavelength, if ε_{re0} and ε_{re} are independent of the frequency. When $d_l = d_r$, α is determined by only β and $(\sqrt{\varepsilon_{re}}-\sqrt{\varepsilon_{re0}})$. By using (1), β can be determined easily.

To obtain a larger value of α, the feedlines must have a longer redundant length to attach the dielectric plate, when ε_{re0} and ε_{re} are fixed. Then the redundant length must be determined. From Formula (1), we obtain the overlay length, L_m, as follows

$$L_m = \frac{(m-1)d_r\sin\alpha}{\sqrt{\varepsilon_{re}}-\sqrt{\varepsilon_{re0}}} + L_1 \quad (m = 1, 2, \cdots) \qquad (2)$$

where m is number of lines and L_1 is first overlay length. The redundant length of microstrip lines must be at least L_m. Formula (2) indicates that adopting a high dielectric constant plate enables us to shorten the redundant length.

4. Taper form optimizing method at the edge of the dielectric plate

The effect of the phase shift was larger with a high dielectric constant plate, however the reflection in the boundary also increased. Therefore, we propose a method that circumvents this problem by tapering both sides of the isosceles-triangle-shaped dielectric plate. Since reflection was reduced with a long taper, the redundant section of the microstrip line for the dielectric plate must also be long. As a result, the dielectric loss and conductor loss increase.

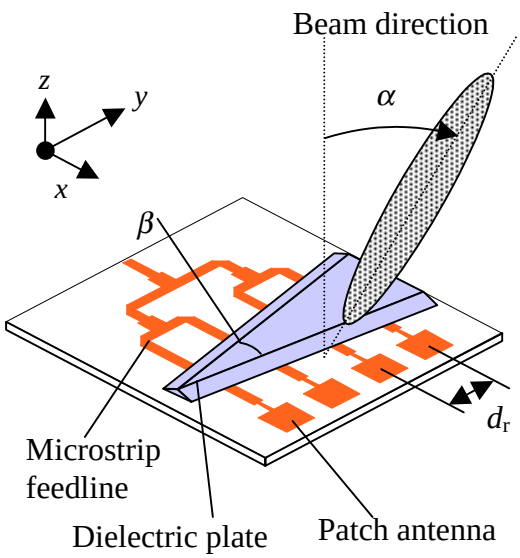

Fig. 1. Antenna configuration.

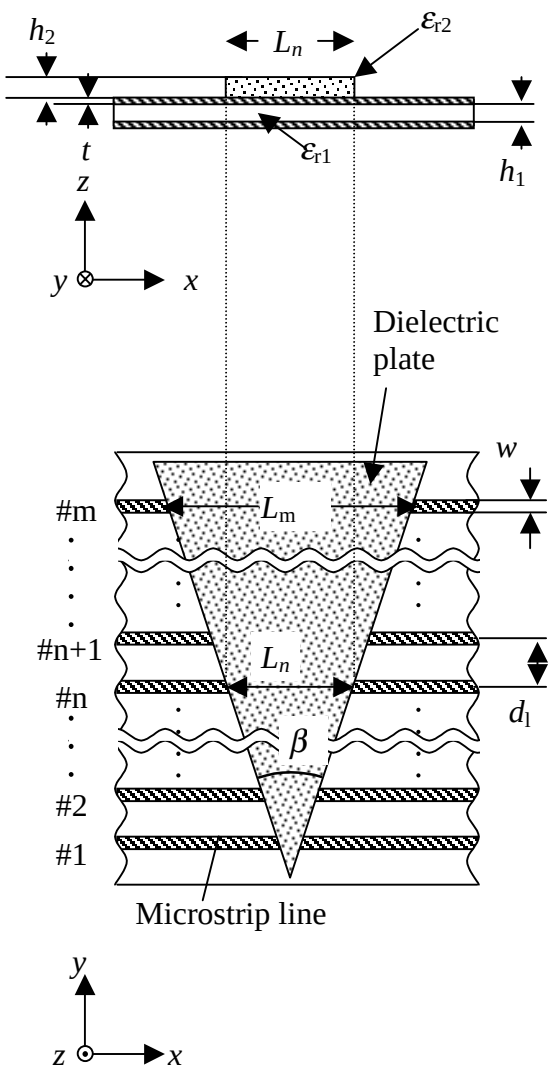

Fig. 2. A triangular dielectric plate on the microstrip lines.

On the other hand, a shorter taper results in a smaller reduction effect of the reflection. Thus, a suitable taper length is considered in the following.

A cross-sectional view (xz plane) of the taper is shown in Fig. 3, where ε_{r1} is the substrate dielectric constant, ε_{r2} is the overlay plate of the dielectric constant, h_1 is the substrate thickness, and h_2 is the overlay plate thickness. The characteristic impedance, $Z(h')$, of the line in the taper section changes continuously, where h' is the height of dielectric plate. Now, we obtain $Z(h')$ by approximation assuming that the line property is constant because strictly deriving $Z(h')$ is difficult. The characteristic impedance of the multilayer microstrip line can be calculated by an integral equation derived from the variational method. When the taper is linear, it is $h' = h_2 x/l_t$, therefore, the reflection coefficient of the taper is obtained as

$$\Gamma(l_t) = \frac{1}{2}\int_0^{h_2} e^{-\frac{2j\beta x l_t}{h_2}h'} \frac{d}{dh'}\{\ln Z(h')\}dh' \tag{3}$$

where l_t is length of the taper. By using Formula (3), the return loss property of the taper can be obtained. Fig. 4 shows the return loss property of the taper length, where λ_g is the effective wavelength of the microstrip. To validate this approximation, the results of FDTD analysis were added. We found that similar results were obtained and that this formula was effective in analyzing the taper property of this structure.

The local minimum of the return loss was found at $l_t = \lambda_g/2$. At this point, the return loss was improved by more than 10 dB compared to $l_t = 0$. It was revealed that the optimized taper achieved a high level of suppression of reflection., where $h_1 = h_2 = 1.6$ mm, $w = 5.0$ mm, $t = 36$ μm, $\varepsilon_{r1} = 2.2$, and $\varepsilon_{r2} = 10.0$.

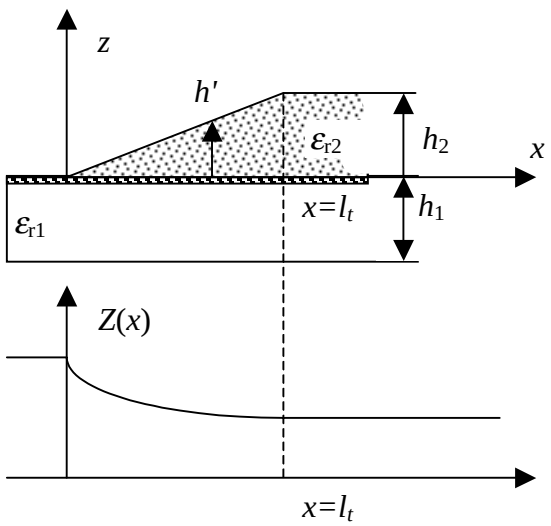

Fig. 3. Taper configuration and sketch of the characteristic impedance of microstrip.

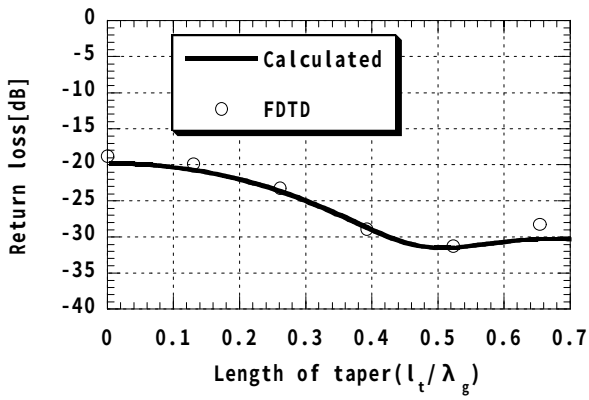

Fig. 4. Return loss of microstrip line versus l_t .

5. Assessment of proposed antenna and design method

In order to verify the design, the antenna configuration shown in Fig. 1 was analyzed by the FDTD method. The simulation results of the beam offset angle and directive gain of the antenna in the 5-GHz band are shown in Fig. 5. The beam offset angle of FDTD and that of Formula (1) differ by less than 1 ° . These results indicate the validity of this antenna and design method. Here $h_1 = h_2 = 1.6$ mm, $w = 5.0$ mm, $t = 36$ μm, $\varepsilon_{r1} = 2.2$, $\varepsilon_{r2} = 5.0$, and $d_l = d_r = 30$ mm. The radiation pattern simulated by FDTD is shown in Fig. 6. The radiating pattern applied by the phase shifter with a taper showed that the undesired radiation was suppressed. These results mean that the taper of the dielectric edge had two effects: reduction of reflection and suppression of undesired radiation.

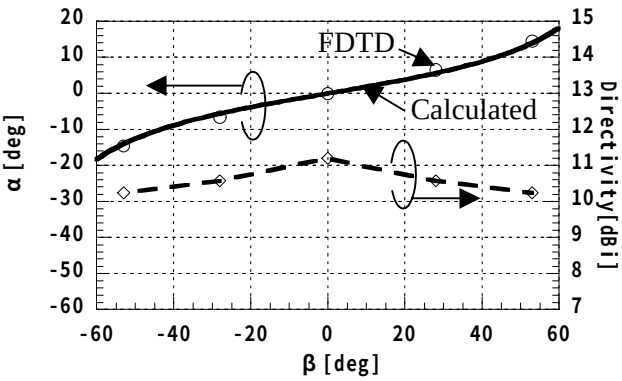

Fig. 5. Offset beam angle α and directivity versus β.

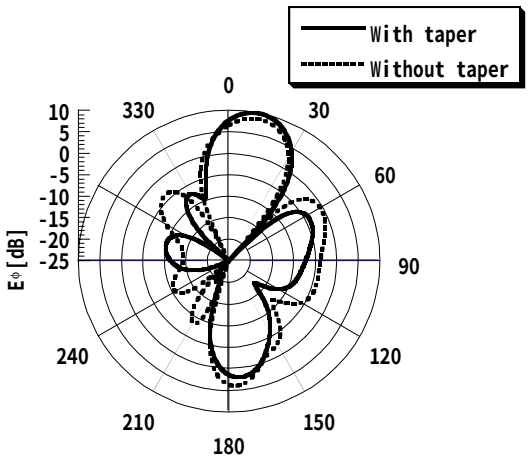

Fig. 6. Comparison of antenna Radiation pattern for β = 28.1 ° (H-plane).

6. Conclusion

We proposed a new beam offset antenna that has a very simple configuration employing a dielectric plate on the feedlines. The dielectric plate was formed into a triangle and the edges were tapered to add optimal phase shift to the lines to shift the beam direction. Moreover, we determined the design method of this antenna. The following were clarified:

- We described the formula that denotes the relation between the offset beam angle and dielectric plate shape, and compared the results with the FDTD analysis. Consequently, we verified good agreement with an accuracy within ±1 °. Moreover, we revealed the redundant length of the feedline appropriate for the dielectric plate. By using this derived formula, the design of this antenna can be determined.
- We proposed a means to suppress the reflection in a boundary by casting the edge of a dielectric plate in the shape of a taper. Furthermore, we clarified the optimum length of the taper and obtained good results that indicate that the return loss was improved by more than 10 dB at the $\lambda_g/2$ length taper.

Furthermore, as a result of the radiation pattern simulation, we found that undesired radiation at the edge of the dielectric plate was suppressed by adopting the taper. Based on the results presented, we established the validity and the design method of this antenna.

Acknowledgment

The authors thank Dr. Hideki Mizuno of Nippon Telegraph and Telephone Corporation for his constant encouragement and advice.

References

[1] Aikawa et al., “Monolithic Microwave Integrated Circuit”, IEICE, Jan. 1997 (in Japanese).

[2] Y. S. Lee, “Mode Compensation Applied to Parallel-coupled Microstrip Directional Filter Design”, *Trans. Microwave Theory Tech.*, Vol. MTT-22, pp. 66-69, Jan. 1974.

[3] M. A. Gouker et al., “A Microstrip Phase-Trim Device Using a Dielectric Overlay”, *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-42, pp. 2023-2026, Nov. 1994.

[4] A. K. Verma et al., “Dielectric Loss of Multilayer Microstrip Line”, *Microwave Opt. Technol. Lett.*, Vol. 17, pp. 368-370, Apr. 1998.

[5] A. Taketomi, K. Sawaya, S. Adachi, S. Ohsima, N. Yaoi, “A Method for Measuring Surface Impedance of Superconductor and Dielectric Characteristics of Substrate by Using Strip Line Resonator”, *IEICE Trans. Electron.*, Vol. E77-C(8), pp. 1234-1241, Aug. 1994.