Proceedings of ISAP'04, Sendai, JAPAN

Power Dividing Characteristics of a Short-Slot Directional Coupler in a Single-Layer Dielectric Substrate with Air Region Near the Waveguide Side Walls

*Shin-ichi Yamamoto, Jiro Hirokawa and Makoto Ando

Tokyo Institute of Technology, Dept. of Electrical and Electronic Eng.,
2–12–1, O-okayama, Meguro-ku, Tokyo, 152–8552, Japan,
E-mail: shin-y@antenna.ee.titech.ac.jp

1 Introduction

The authors have proposed a beam switching antenna consisting of a Butler matrix and a slot array integrated on a single-layer dielectric substrate[1, 2]. Short-slot directional couplers are used to construct the hybrids and the crossing couplers in the Butler matrix also in a single-layer. The length of the coupler is determined by the difference between the phase constants of the TE_{10} and TE_{20} modes in the coupled region. This paper proposes a method to reduce the coupler length by removing dielectric near the side walls as shown in Figure 2. The dielectric removal enhances the above-mentioned difference in the phase constants and results in length reduction of the coupled region. The experiment results of prototype couplers are reported.

2 Miniaturization of the coupler

Post-wall waveguides are arranged in a fiberglass-reinforced PTFE substrate with a thickness of 3.2 mm and a dielectric constant of $\varepsilon_r = 2.17$. The design frequency is 25.6 GHz. The post radius is 1.2 mm and the typical post spacing is 2.4 mm.

In the short-slot coupler[4], the coupling is controlled by the accumulated phase difference between the TE_{10} and TE_{20} modes that propagate in the coupled region. The power to Port#2 and #4 from Port#1 is proportional to $\cos(\beta_1 - \beta_2)\ell/2$ and $\sin(\beta_1 - \beta_2)\ell/2$, respectively, where the phase constants of the TE_{10} and TE_{20} modes in the coupled region are β_1 and β_2. The coupled length ℓ necessary for realizing the specified value of $(\beta_1 - \beta_2)\ell/2$. The length decreases for larger differences between the phase constants.

As shown in Figure 1(a), the dielectric constant near the side walls of the coupled region is reduced from ε_{r1} of the dielectric substrate to ε_{r2}. Figure 1(b) shows the phase constant versus the width w of ε_{r2} calculated by the Finite Element Method simulator Ansoft HFSS. The reduction of the dielectric constant near the side walls produces a large decrease in the phase constant of the TE_{20} mode since the TE_{20} field is strong there, but it produces only a small decrease in the TE_{10} mode since the TE_{10} field is weak there. There are many ways to reduce the dielectric constant near the side walls. In this paper, for instance, it is done by cutting rectangular holes in the dielectric near the side walls.

ISBN: 4-88552-207-2 C3055©IEICE

3 Design and characteristics of the coupler

The reflection from the coupler primarily occurs at both ends of the coupled region due to the TE_{10} mode. The reflection of the TE_{10} mode at each end is about -10 dB while that of the TE_{20} mode is around -20 dB or less. An approximate simple condition for the reflection cancellation of the TE_{10} mode at both ends is given by

$$1 + e^{-j2\beta_1 \ell} = 0. \tag{1}$$

The relation between the phase constants of the two modes is determined in accordance with the following equations

$$\begin{cases} (\beta_1 - \beta_2)\dfrac{\ell}{2} = \dfrac{\pi}{4} & \text{(for Hybrid)} \\ (\beta_1 - \beta_2)\dfrac{\ell}{2} = \dfrac{\pi}{2} & \text{(for Cross Coupler)} \end{cases} \tag{2}$$

which give the desired coupling. Therefore

$$\begin{cases} \beta_2 = \dfrac{2n}{2n+1}\beta_1 = \dfrac{2}{3}\beta_1, \dfrac{4}{5}\beta_1, \ldots & \text{(for Hybrid)} \\ \beta_2 = \dfrac{2n-1}{2n+1}\beta_1 = \dfrac{1}{3}\beta_1, \dfrac{3}{5}\beta_1, \ldots & \text{(for Cross Coupler)} \end{cases} \tag{3}$$

$\beta_2 = 2\beta_1/3$ is derived for the hybrid to satisfy these conditions and $\beta_2 = 3\beta_1/5$ is for the cross coupler. The width w is determined from Figure 1(b), and the slot length ℓ is determined by equation (2). The hybrid and the cross coupler are designed with these values as initial parameters. ℓ and w are modified by Ansoft HFSS to obtain the coupling of 3 dB for the hybrid and 0 dB for the cross coupler and reflection suppression at each input port. In the hybrid, the coupled length ℓ is 8.02 mm, which is 51% of the conventional value, for $w = 1.3$ mm and $d = 1.5$ mm. In the cross coupler, ℓ is 12.70 mm, which is 57% of the conventional value, for $w = 1.82$ mm, $d = 1.0$ mm.

Figures 4 and 5 show the measured characteristics of the hybrid and the cross coupler, respectively. Note that they include the reflections from the waveguide transformers at the ports. The reflection at each four port should be same. The figures show the envelopes of measured values of reflection for 12 different measurement errors and a manufacture errors. Reflection is -15 dB or less at the maximum. The dividing ratio of the hybrid which is the ratio of S_{21} and S_{41} is -0.29 dB. Isolation of the hybrid (S_{31}) and the cross coupler (S_{21} and S_{31}) are 23.0 dB and 19.0 dB, respectively. Each measured value is smaller than the calculated one due to losses in the post-wall waveguides. Insertion losses of the hybrid and the cross coupler are 0.55 dB and 0.88 dB, respectively.

4 Conclusion

A method to reduce the size of a short-slot directional coupler by changing the dielectric constant near the side walls in the coupled region is proposed. The coupled length can be reduced by 51% for the hybrid and by 57% for the cross coupler, respectively. The dividing ratio of the hybrid is −0.3 dB. Isolation of the couplers is more than 19 dB. Insertion losses of the hybrid and the cross coupler are 0.55 dB and 0.88 dB, respectively.

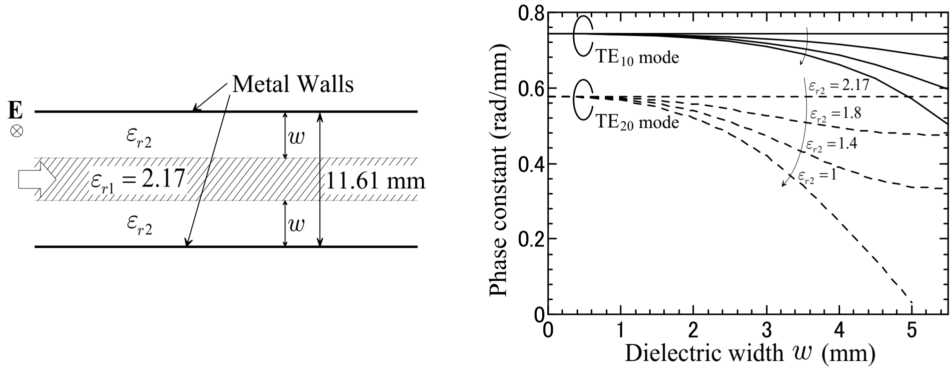
References

[1] S. Yamamoto, J. Hirokawa and M. Ando, "A Beam Switching Slot Array with a 4-Way Butler Matrix Installed in Single Layer Post-Wall Waveguides," IEICE Trans. on Communications, vol.E86–B, No.5, pp.1653–1659, May 2003.

[2] S. Yamamoto, J. Hirokawa and M. Ando, "A beam-swithcing slot array with a 4-way Butler matrix using narrow post-wall waveguides," IEICE Spring Natl. Conv. Rec., p.96, B-1-96, March 2003.

[3] J. Butler and R. Lowe, "Beam-Forming Matrix Simplifies Design of Electronically Scanned Antennas," Electron. Des., 9, 8, pp.170–173, April 1961.

[4] H.J. Riblet, "The Short-Slot Hybrid Junction," Proc. IRE, vol. 40, pp. 180–184, Feb. 1952.



(a) Analysis model (b) Phase constant versus dielectric width w

Figure 1: Phase constant versus dielectric width

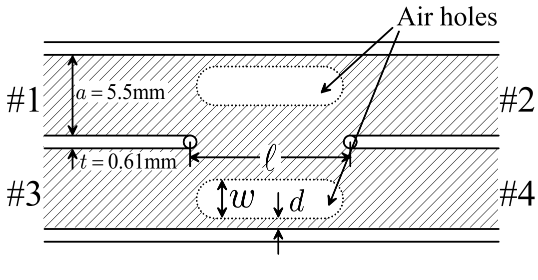


Figure 2: Analysis structure of the coupler

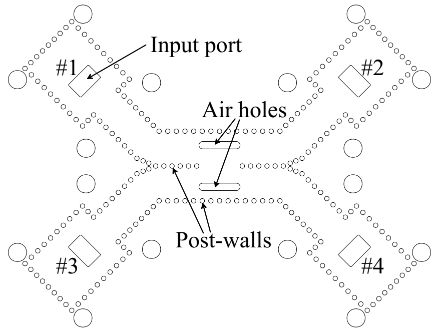
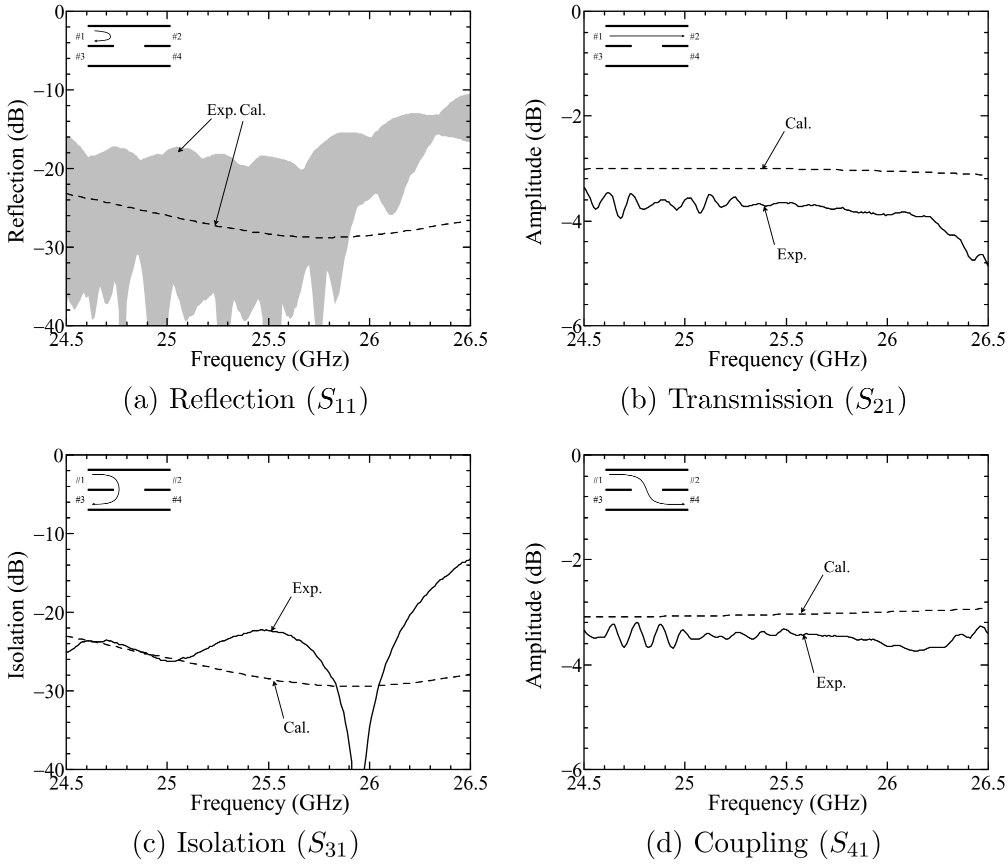


Figure 3: Structure of the coupler for experiments



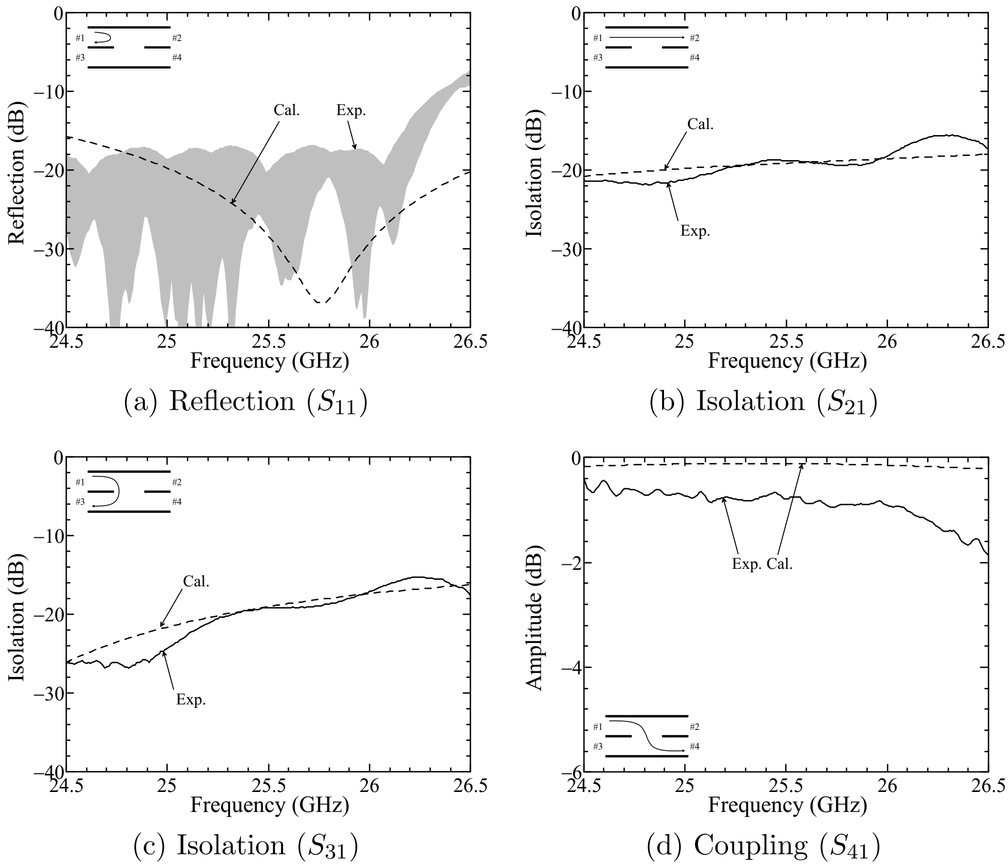
(a) Reflection (S_{11})

(b) Transmission (S_{21})

(c) Isolation (S_{31})

(d) Coupling (S_{41})

Figure 4: Characteristics of manufactured hybrid



(a) Reflection (S_{11})

(b) Isolation (S_{21})

(c) Isolation (S_{31})

(d) Coupling (S_{41})

Figure 5: Characteristics of manufactured cross coupler