Experimental Study of Dielectric Waveguide Y-Junctions for Millimeter-Wave Integrated Circuits

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Abstract —**Symmetric and asymmetric Y-junctions have been fabricated from rectangular dielectric image line, and the transmission and reflection characteristics have been measured in the 20–26-GHz range. The tested symmetric Y-junction operates as a near 3-dB power divider for the junction half-angle below ~20°. The maximum allowable junction angle of the symmetric Y-junction is discussed, which is very important for millimeter-wave integrated-circuit applications. It is shown that the asymmetric Y-junction can be used as a directional coupler because of the controllable splitting ratio and high isolation. The results for the asymmetric Y-junction with a gap are also presented.**

I. Introduction

Millimeter-wave integrated circuits using dielectric waveguides [1] have been investigated extensively under the stimulus of the rapid development of integrated optics [2]. Dielectric waveguide Y-junctions [3]–[7] are important devices in such integrated circuits, which play the role of beam splitters (or power dividers) and recombiners. In integrated optics, Y-junctions are also used in active devices [8], [9] such as Mach–Zehnder interferometric modulators and switches using an electrooptic effect. Although Y-junctions at optical wavelengths are investigated extensively, there are a few studies [10], [11] at millimeter wavelengths. The output waveguides of the Y-junction at optical wavelengths are usually bent at an angle below 1°–2° so that the radiation loss can be kept at less than an acceptable level. However, such a small angle is impractical for millimeter-wave integrated-circuit applications. In order to make the devices containing Y-junctions as small as possible, the junction angle must be enlarged. Although the maximum allowable junction angle at millimeter wavelengths seems to be larger than that at optical wavelengths because of the higher dielectric constant ratio between the guiding and surrounding media, a sufficient study has not yet been made. Although the symmetric Y-junction can be used as a power divider, it is not suitable for other applications such as monitoring of the power launched into the dielectric waveguide. For wide applications, the study of not only a symmetric structure but an asymmetric structure is needed.

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This paper discusses the symmetric and asymmetric Y-junctions made of a rectangular dielectric image line suitable for millimeter-wave integrated circuits. The transmission and reflection characteristics are measured as a function of the junction angle in the *K*-band. It is found that the output waveguides of the symmetric Y-junction can be bent through 20°–30° for typical material with $\epsilon_r = 2.25$. In the asymmetric Y-junction, the splitting ratio of output waveguides can be controlled by changing the junction angle, and the isolation between output waveguides is very high. Therefore, the asymmetric Y-junction can be used as a directional coupler for monitoring of the power and for reflection measurements. This paper also proposes the asymmetric Y-junction with a gap to reduce the reflection at the junction.

II. Experiments

In this section, we examine the transmission characteristics of symmetric and asymmetric Y-junctions as shown in Fig. 1. The Y-junctions treated here are made of a rectangular dielectric image line. These Y-junctions are usually operated in the single-mode range. In that case, a tapered section is inserted to provide a smooth transition, as shown in Fig. 1(a). We consider here the special case of $L = \infty$, where the width of the input waveguide is $2a/\cos\theta$. This symmetric Y-junction presents a good approximation to one with the long tapered section.

A. Experimental Procedure

We describe the fabrication of Y-junctions and a method for measuring the transmission and reflection characteristics, which are similar to those in a previous paper [10]. The dielectric material of waveguides used here is polypropylene ($\epsilon_r = 2.25$). The cross section $a \times b$ of the output waveguides is 8×4 mm. This waveguide supports only the fundamental E_{11}^y mode at the frequency below 24.1 GHz. The input and output waveguides are separately formed and fixed on a ground plane with adhesive tape. The total length of the input and output waveguides is about 28 cm. The end of the input and output waveguides is tapered at an angle of 9° with each waveguide axis to achieve smooth transitions to and from a metal waveguide.

The fundamental E_{11}^y mode is launched through a metal waveguide system, and the insertion loss between two ports

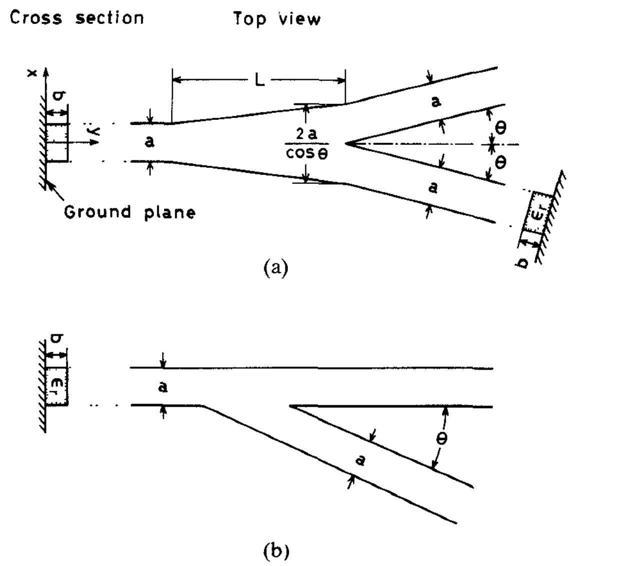

Fig. 1. Y-junction configurations. (a) Symmetric Y-junction with a tapered section. (b) Asymmetric Y-junction.

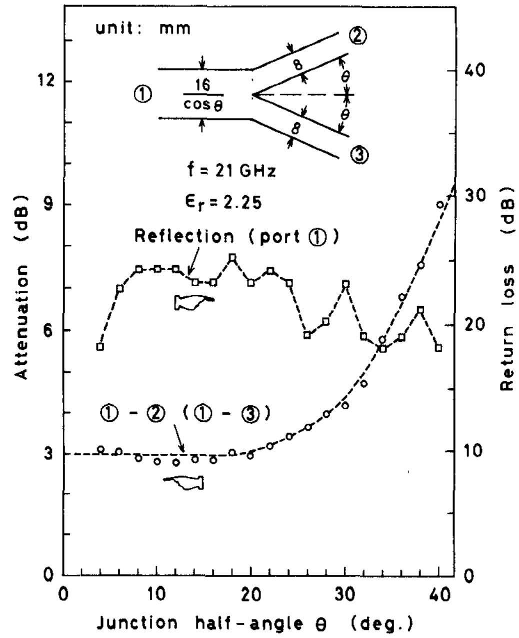

Fig. 2. Measured transmission and reflection characteristics of the symmetric Y-junction as a function of the junction half-angle θ.

and the return loss are measured. The needless losses, such as dielectric and conductor losses, and the transition loss are subtracted from the total insertion loss by the experiment on the insertion loss in the straight waveguide of identical length. It is here assumed that the dielectric loss and conductor loss of each waveguide of the Y-junction are identical with those of the straight waveguide. In these experiments, a reflection-free termination should be achieved at the untested port. The matched termination is fabricated by attaching the absorber (polystyrene foam containing carbon) to the waveguide or by painting aquadag on both sides of the tapered waveguide. The experiments are conducted in the 20–26-GHz range using a mechanically tuned Gunn oscillator.

B. *Results and Discussion*

First, we describe the experimental results for the symmetric Y-junction. Y-junctions with different junction angles were fabricated, and the transmission characteristics were measured to discuss the maximum allowable junction angle. Fig. 2 shows the measured transmission and reflection characteristics as a function of the junction half-angle θ. The operating frequency is 21 GHz. This frequency was chosen from the standpoint of the single-mode operation and the maximum output power of the oscillator. The shown attenuation between input and output waveguides is the average of results for both output waveguides. Note that several measured values are smaller than 3 dB. This is incorrect physically, since the perfect power transmission is 3 dB. This is mainly due to the change in the launching condition and the assumption used for the determination of net power transmission. We believe that this degree of discrepancy is permissible. The attenuation between input and output waveguides increases with the increasing junction angle, as expected. This increase is due to the radiation into the surrounding medium (air), since the reflection into the input waveguide is small. The reflection at the junction unexpectedly increases with decreasing junction angle for $\theta \lesssim 16°$. It is considered that the reflection at the transition is greater than that at the junction in that range. From the standpoint of ray optics, the radiation loss depends on the incident angle of rays (constituent surface waves) in the input and output waveguides. The incident angle ϕ of the ray (defined by the angle between the ray and the waveguide axis) in output waveguides is estimated to be 23.3° by using the effective dielectric constant method [1]. Fig. 2 shows that, for $\theta \lesssim \phi$, the near 3-dB power division is achieved. The author believes that $\theta \lesssim \phi$ can be used as a simple design criterion for the near 3-dB power division. For the large junction angle ($\theta \gtrsim \phi$), the Y-junction with a metal reflector [10] will be useful.

Fig. 3 shows the measured transmission characteristics of the symmetric Y-junction with $\theta = 16°$ as a function of the frequency. The symmetric Y-junction operates as a power divider over the wide frequency range. The difference between two attenuation curves is due to asymmetry of the structure. Although we tried to measure the isolation between output ports, we could not determine it because of the weak transmitted power. The isolation is greater than at least 30 dB over the measured frequency range.

Next, we describe the experimental results for the asymmetric Y-junction. Fig. 4 shows the measured characteristics of the asymmetric Y-junction as a function of the junction angle θ. Note that the attenuation between the two ports does not depend on the direction of propagation. The discrepancy due to the difference in direction of propagation was within about 0.2 dB. The equal power transmission takes place at $\theta \simeq 20°$. For $\theta \gtrsim 20°$, the attenuation between port 1 and port 3 is proportional to the junction angle. The power transmission to port 3 is greater than that to port 2 for $\theta \lesssim 20°$, and the attenuation curves have an optimum at $\theta \simeq 14°$. There are two possible causes

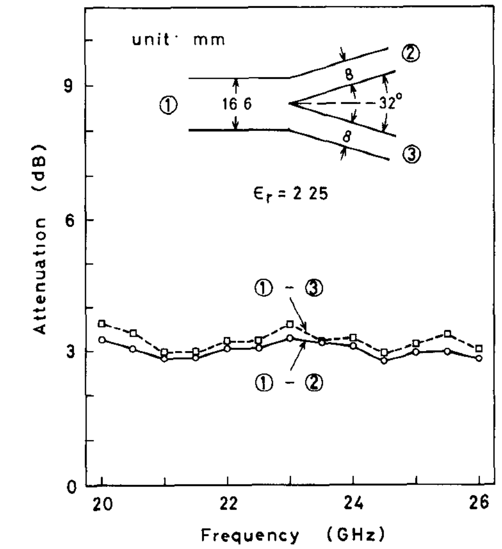

Fig. 3. Measured transmission characteristics of the symmetric Y-junction with $\theta = 16°$ as a function of the frequency.

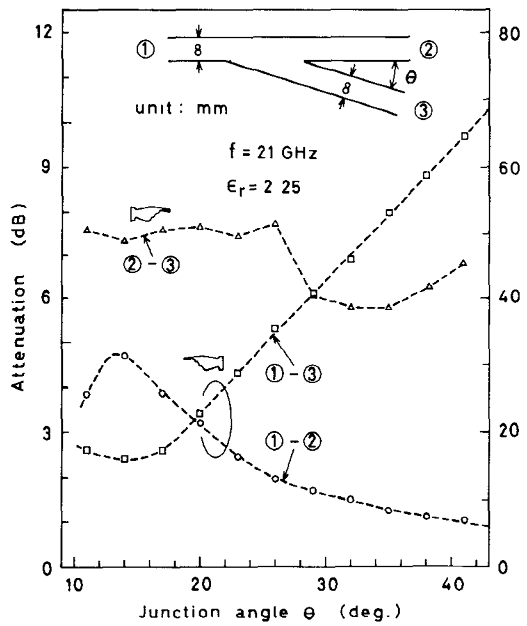

Fig. 4. Measured characteristics of the asymmetric Y-junction as a function of the junction angle θ.

for this interesting phenomenon: the coupling of two guided modes propagating on adjacent output waveguides, and the interference between the lowest order mode and the first higher order mode excited in the tapered section. In order to clarify the true cause, the author [12] has recently investigated theoretically the transmission characteristics of asymmetric Y-junctions with different taper configurations by using the beam propagation method [13]. In the numerical calculation, the weakly guiding waveguide was treated because of the limitation of the method. The numerical results indicate that the coupling of output waveguides causes an oscillatory power splitting when the junction angle is small. The isolation between output ports 2 and 3 is greater than 38 dB. On the other hand, the isolation of

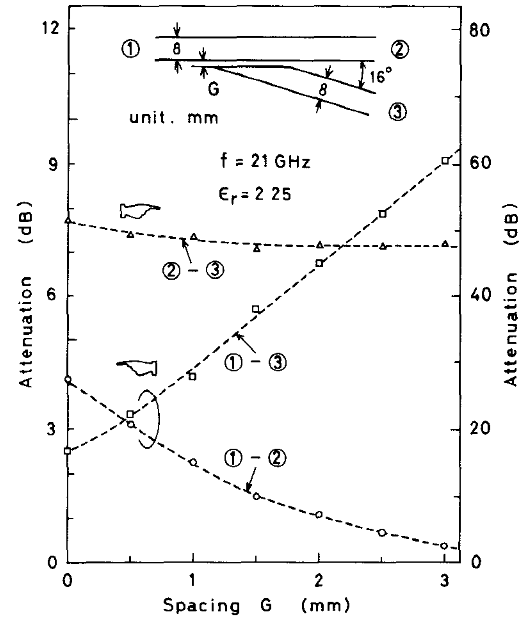

Fig. 5. Measured characteristics of the asymmetric Y-junction with a gap as a function of the spacing G.

the Y-junction with the metal reflector was greater than 20 dB [10]. The metal reflector seems to decrease the isolation because of the current flowing on its surface. When the weak coupling between main waveguide and output waveguide is needed, for example, to monitor the power launched into the dielectric waveguide, the large junction angle should be used. Then, if the reflection due to the junction becomes a serious problem, it can be overcome by introducing a gap at the junction.

Fig. 5 shows the measured characteristics of the asymmetric Y-junction with the gap as a function of the spacing G. The structure is shown in the inset of Fig. 5. The attenuation between port 1 and port 3 is proportional to the spacing G for $G \gtrsim 1$ mm. This is due to the exponential decay of the field in the surrounding medium. On the other hand, the spacing of the gap has little effect on the isolation between output ports 2 and 3 in the measured range. This shows that the reflection-free termination is achieved at the untested port 1. If not so, the isolation must depend on the spacing, since the power transmission from port 1 to port 3 depends on it. We now calculate the power transmitted to ports 2 and 3 when the unit power is launched into port 1. The total transmitted power becomes 0.95, 0.98, 0.99, and 1.03 for $G = 0$, 1, 2, and 3 mm, respectively. Therefore, the radiation and reflection due to the junction decrease with increasing spacing of the gap as expected. The asymmetric Y-junction is very useful for millimeter-wave integrated-circuit applications, since the structure is very compact and the characteristics can be simply controlled by changing the junction angle and the spacing of the gap. For example, it can be used as a directional coupler for monitoring of the power and for reflection measurements.

III. Conclusion

The transmission and reflection characteristics of the symmetric and asymmetric dielectric waveguide Y-junctions have been experimentally discussed for millimeter-wave integrated-circuit applications. If the junction half-angle is smaller than the incident angle of the ray in output waveguides, the symmetric Y-junction operates as a near 3-dB power divider. The characteristics of the asymmetric Y-junction can be controlled by changing the junction angle and by introducing the gap at the junction. The structure is more compact than a distributed directional coupler and the isolation is very high. Therefore, the asymmetric Y-junction can be used as a directional coupler for reflection measurements and for monitoring of the power.

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