Directly Connected Image Guide 3-dB Couplers with Very Flat Couplings

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***Abstract*—The design and evaluation of the directly connected image guide 3-dB directional coupler is described. These couplers have several useful features as a component for millimeter-wave integrated circuits because of broadband and flat coupling characteristics, mechanical stability, and compactness. The bandwidth of the directly connected image guide coupler with proper dimensions and the nearly optimized value of h extends to about 28 percent under the tolerance limits of ± 0.25 dB of deviation in coupling from 3 dB.**

Furthermore, experimental verification has been performed, and, hence, the usefulness of the proposed directly connected couplers with appropriate tapered sections was confirmed, even at frequencies where higher modes could be excited.

I. Introduction

Dielectric image guides, formed by placing a dielectric guide of rectangular cross section on a metal plane, exhibit low propagation losses at millimeter-wave frequencies. Directional couplers in a form suitable for image-guide integrated circuits have been developed [1]–[5]. The 3-dB 90° hybrid coupler is of specific interest for applications such as balanced mixers and balanced amplifiers. The conventional distributed directional couplers with dielectric image lines [1]–[3], rectangular dielectric waveguide [6], or inverted strip dielectric waveguides [7] has the following drawbacks: 1) the size is very large in comparison with the wavelength in millimeter-wave range, and 2) since controlling the spacing of the coupled section of two waveguides is very difficult, it is very difficult to reproduce the coupler performances.

The above problems have been partially overcome in [4] and [5]. Although the design method of a compact and mechanically stable 3-dB coupler in open dielectric waveguide with web registration was shown in [4], an accurate theory was not established and the bandwidth of the coupler is very narrow. It was also reported in [5] that the design process using hollow image guides is more flexible than that for conventional couplers made of image guides placed in parallel because the thickness of the overlay can be adjusted for a desired degree of coupling. But broadening of the bandwidth was not considered in [5].

In this paper, we propose directly connected image guide 3-dB couplers with high performance. This type of coupler is very broadband and reproducible. Furthermore, the proposed couplers are extremely compact in comparison with the previous couplers. They also have good isolation and sufficiently low return loss by forming appropriate tapers in the ends of the coupling section. The degree of coupling can be changed by adjusting the height of the directly connected region. After calculating the dispersion curves and coupling characteristics using the effective dielectric constant method, the directly connected image guide 3-dB couplers were designed and constructed, and their frequency characteristics were measured and compared to those of conventional distributed couplers. The experimental results agree well with theoretical predictions when the length and the taper ratio of the tapered sections are determined experimentally.

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II. High-Performance Coupler Design

A. Dispersion Characteristics of Directly Connected Image Guides

In order to make the design process more flexible than that of other couplers, the directly connected image guide shown in Fig. 1 is considered. In region I or II, the hybrid eigenmodes can be classified into E^x_{pq} and E^y_{pq} groups. The effective dielectric constant approach was adopted since its accuracy is good enough for most engineering applications, especially for the dispersion characteristics [8]. The steps in the analysis are summarized below.

First, to obtain the effective dielectric constant ϵ_{eI} or ϵ_{eII}, we solve the eigenvalue equation of the structure shown in Fig. 2(a). This is as follows:

$$\tan(k_y t) = \frac{\epsilon k_0}{\epsilon_0 k_y} \tag{1}$$

where t is h for region I or b for region II, k_y is the propagation constant in the y direction, and k_0 is the free-space wave-number, i.e.

$$k_y = \sqrt{\omega^2 \mu (\epsilon - \epsilon_0) - k_0^2}. \tag{2}$$

When (1) is solved for k_y, the effective dielectric constant ϵ_{eI} or ϵ_{eII} is given by

$$\epsilon_{e\,\substack{\mathrm{I}\\\mathrm{II}}} = \epsilon - \left(k_{y\,\substack{\mathrm{I}\\\mathrm{II}}}/k_0\right)^2. \tag{3}$$

The original structure given in Fig. 1 may be modeled by the hypothetical one shown in Fig. 2(b). Due to the sym-

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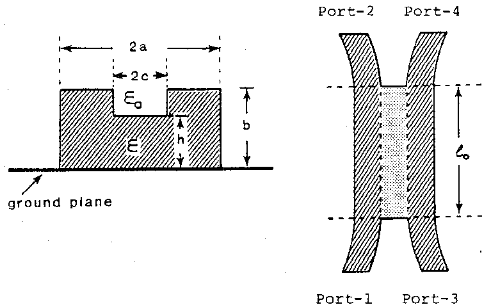


Fig. 1. Directly connected image guide.

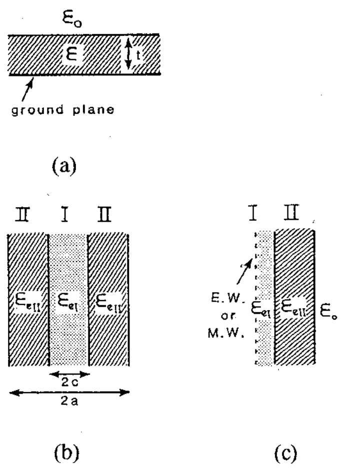


Fig. 2. Analytical process for the effective dielectric constant method. (a) Dielectric slab on the ground plane, (b) Hypothetical structure with effective dielectric constants, and (c) One half of (a) due to symmetry.

metry of the structure, it is necessary to consider only half of the structure given in Fig. 2(c). The eigenvalue equations are obtained as follows:

$$\tanh(\eta_1 c) = \frac{\eta_2}{\eta_1} \cdot \frac{\eta_2 \tan\{\eta_2(a-c)\} - \eta_0}{\eta_2 + \tan\{\eta_2(a-c)\}},$$

$$\text{for even mode } (E_{11}^y, E_{31}^y, \cdots) \quad (4)$$

and

$$\coth(\eta_1 c) = \frac{\eta_2}{\eta_1} \cdot \frac{\eta_2 \tan\{\eta_2(a-c)\} - \eta_0}{\eta_2 + \tan\{\eta_2(a-c)\}},$$

$$\text{for odd mode } (E_{21}^y, E_{41}^y, \cdots) \quad (5)$$

where

$$\eta_0 = \sqrt{\beta_{e_o}^2 - \omega^2 \mu \epsilon_0}, \qquad \eta_1 = \sqrt{\beta_{e_o}^2 - \omega^2 \mu \epsilon_{eI}},$$

$$\eta_2 = \sqrt{\omega^2 \mu \epsilon_{eII} - \beta_{e_o}^2}$$

and, β_e and β_o are the propagation constants for the even and odd modes, respectively.

Fig. 3 shows the dispersion curves for the directly connected image guides when a, b, and c are 4, 2, and 1.5 mm, respectively, and h takes the values 0, 1, or 2.5 mm, while Fig. 4 shows those when a, b, and c are 3, 1.5, and 1 mm, respectively, and h is 0 or 1.25 mm. The structure with $h = 0$ corresponds to a coupling structure for a conventional distributed directional coupler.

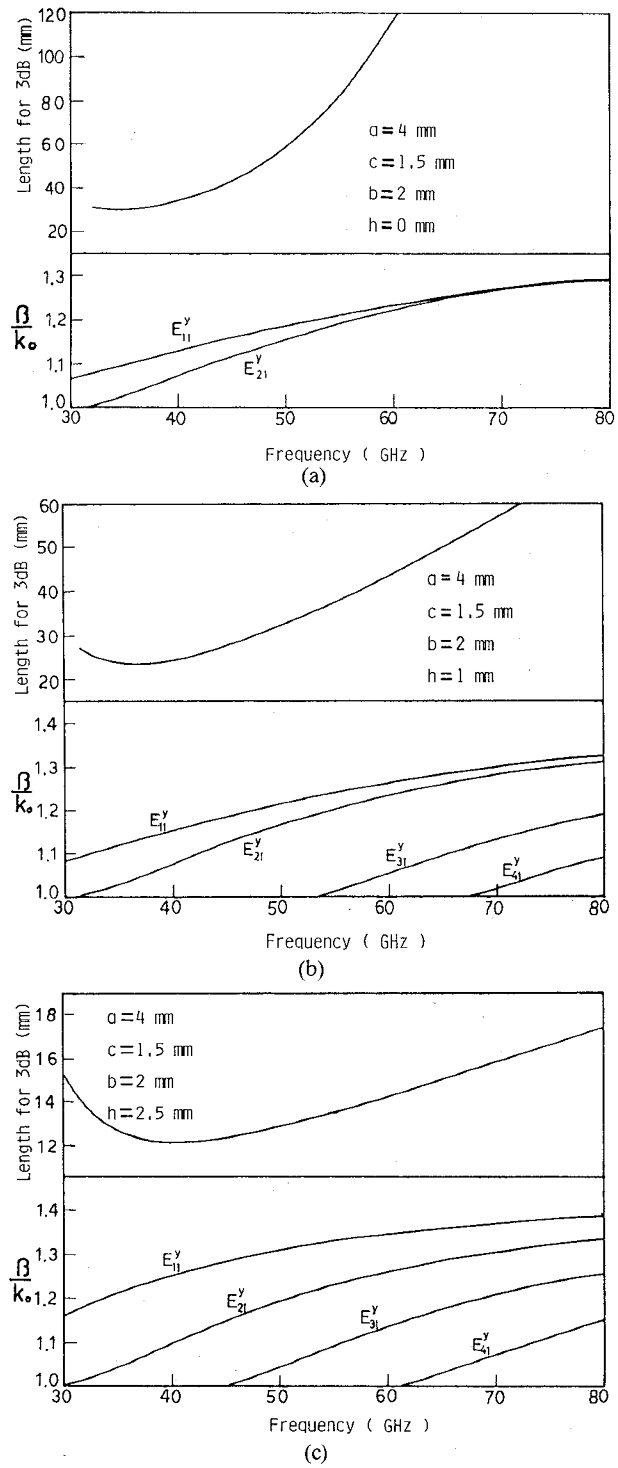


Fig. 3. Dispersion curves and coupling length for 3-dB directional couplers for the directly connected image guide ($a = 4$, $c = 1.5$, $b = 2$ mm) with dielectric constant ϵ_r of 2.1, (a) with $h = 0$ mm (conventionally distributed coupled image guide), (b) with $h = 1$ mm, and (c) with $h = 2.5$ mm.

B. Coupler Design

Since a directly connected image guide can be regarded as two image guides coupled tightly by connection with dielectric material, there exist symmetric and antisymmet-

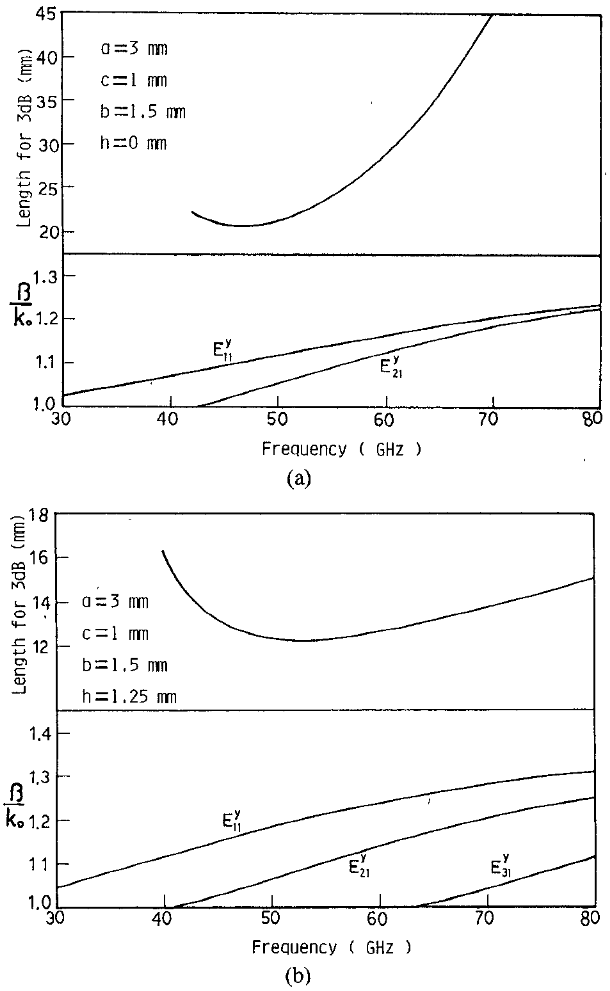


Fig. 4. Dispersion curves and coupling length for 3-dB directional couplers for the directly connected image guide ($a = 3$, $c = 1$, $b = 1.5$ mm) with dielectric constant ϵ_r of 2.1, (a) with $h = 0$ mm (conventionally distributed coupled image guide), and (b) with $h = 1.25$ mm.

ric modes above a certain frequency as shown in Figs. 3 and 4. For certain frequencies, only the lowest even and odd modes exist. In this frequency band, we can design a directional coupler in single-mode operation using the lowest even-mode E_{11}^y and the lowest odd-mode E_{21}^y.

Though there is leakage due to discontinuities and irregularities in region I [8], it may be suppressed by adopting an appropriate taper at the ends of the connected region I. Assuming that the directly connected image guide is lossless and matched at all ports, the coupling length for a 3-dB directional coupler is

$$L_{3\mathrm{dB}} = \frac{\pi}{2(\beta_e - \beta_0)} \tag{6a}$$

since the length L needed to transfer the total power of the incident wave to the neighboring line is given by

$$L = \frac{\pi}{\beta_e - \beta_0}. \tag{6b}$$

Then, the scattering coefficients for the coupler are expressed as follows:

$$|S_{21}| = \left|\cos\frac{\beta_e - \beta_0}{2} l_{\mathrm{eff}}\right|$$
$$|S_{41}| = \left|\sin\frac{\beta_e - \beta_0}{2} l_{\mathrm{eff}}\right| \tag{7}$$

where l_{eff} is the effective coupling length of a coupler [7].

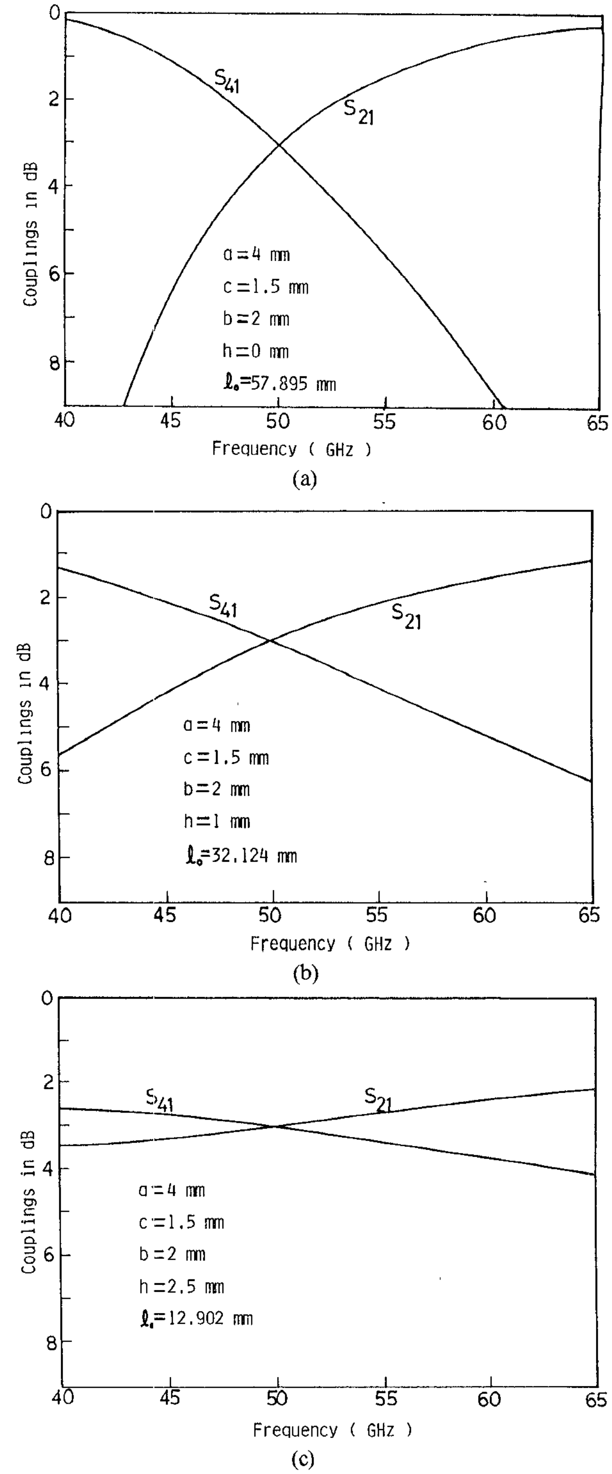


Fig. 5. Calculated frequency characteristics for the directly connected image guide ($a = 4$, $c = 1.5$, $b = 2$ mm), (a) with $h = 0$ mm (conventional distributed coupler), and (b) with $h = 1$ mm, and (c) with $h = 2.5$ mm.

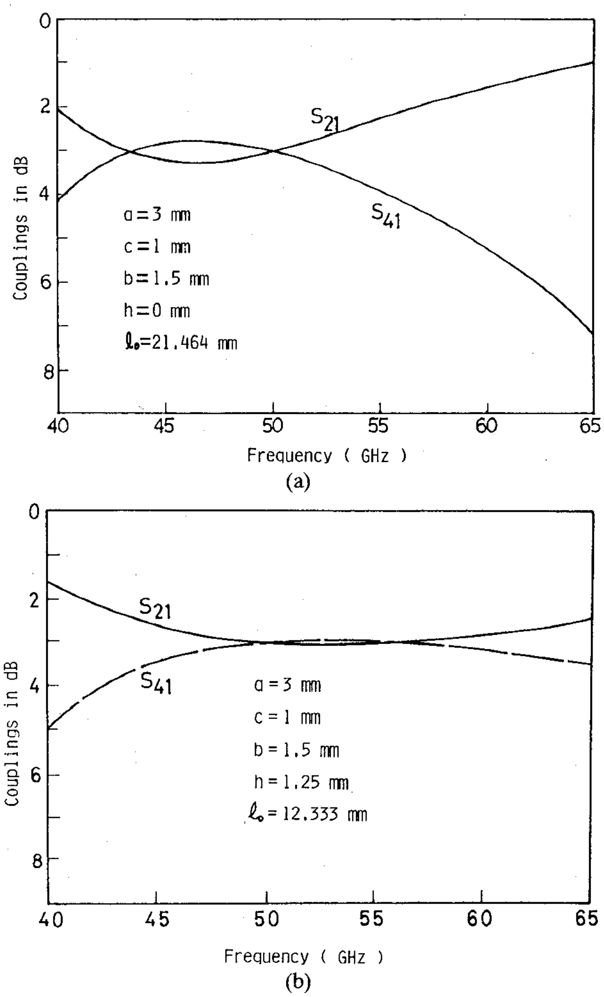
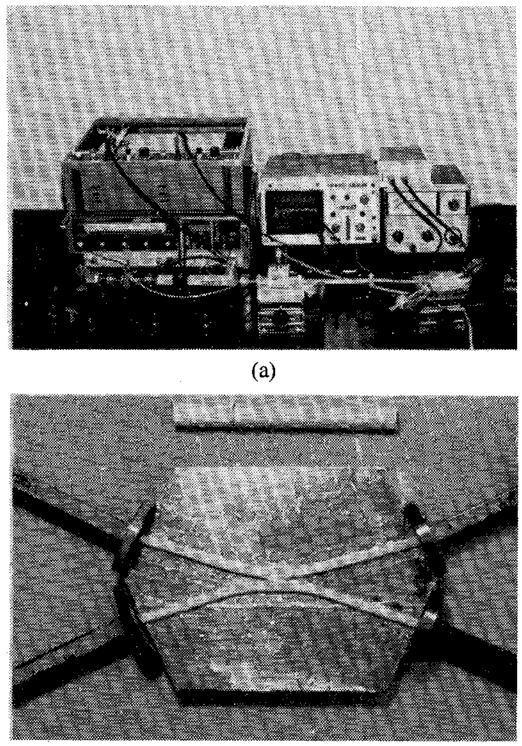


Fig. 6. Calculated frequency characteristics for the directly connected directional couplers ($a=3$, $c=1$, $b=1.5$ mm), (a) with $h=0$ mm (conventional distributed coupler), and (b) with $h=1.25$ mm (nearly optimized value of h).

The coupling lengths for 3-dB couplers calculated by (6a) are shown in Figs. 3 and 4 with dispersion curves. Figs. 5 and 6 show the calculated frequency characteristics for the couplers at the center frequency of 50 GHz with the same dimensions as those in Figs. 3 and 4. From Fig. 5, we can see the bandwidth of the directly connected image guide coupler with $h=2.5$ mm extends to 24 percent in the tolerance limit of ± 0.43 dB of deviation in coupling from 3 dB, while that of the coupler with $h=1$ mm is 16.3 percent. When, on the other hand, the coupler is a conventional one with $h=0$ as shown in Fig. 5(a), the coupler is extremely narrow band and has a bandwidth of only 3 percent. Therefore, the higher the value of h takes, the broader the bandwidth, and the shorter the length of the coupler. However, higher modes may propagate within the operating bandwidth if h becomes larger than 1 mm, as shown in Fig. 3 for the center frequency of 50 GHz.

Similarly, the coupling characteristics become broader and flatter as h becomes higher in the case when a, b, and c take the values 3, 1.5, and 1 mm, as shown in Fig. 6. But, for single-mode operation, the optimum value of h is about 1.25 mm because higher modes can be excited in a certain frequency range when h is greater than 1.25 mm. Therefore, there is an optimum value of h for the broad-band design of a directly connected image-guide coupler. It is seen from Fig. 6 that the coupler with a nearly optimum value of h has an extremely broad bandwidth of 28.1 percent, whereas the conventional one has a bandwidth of 10.2 percent in the tolerance limit of ± 0.25 dB of the deviation in coupling from 3 dB.



(a)

(b)

Fig. 7. The measuring setup and directly connected image line directional coupler. (a) Experimental setup. (b) The directly connected image guide coupler with dimensions of $a=4$, $b=2$, $c=1.5$, and $h=2.5$ mm (shown in Fig. 8(c)).

III. Experimental Results

It is known that the single-mode operation is important in obtaining satisfactory performance in structures similar to those considered here. However, it is expected that the effect of higher modes in the coupling section can be removed by appropriately tapering the junctions between arms and coupling section. In order to confirm this, first, experiments were performed on three couplers with parameters given in Fig. 5. For the case shown in Fig. 5(c), the experimental results for a coupler with tapered sections are compared with those for a coupler without tapered sections. In the experiments, all the guides were fabricated of Teflon with dielectric constant ϵ_r of 2.1. In Fig. 7, photographs of a directional coupler measuring setup and a directly connected image guide coupler are shown.

Fig. 8 shows the experimental results for the three cases. In Fig. 8(a) and (b), corresponding to single-mode operation, the results agree well with the numerical predictions given in Fig. 5(a) and (b). It can be seen that the bandwidth of the directly connected coupler is broader and that the coupling length is shorter than the conventional one.

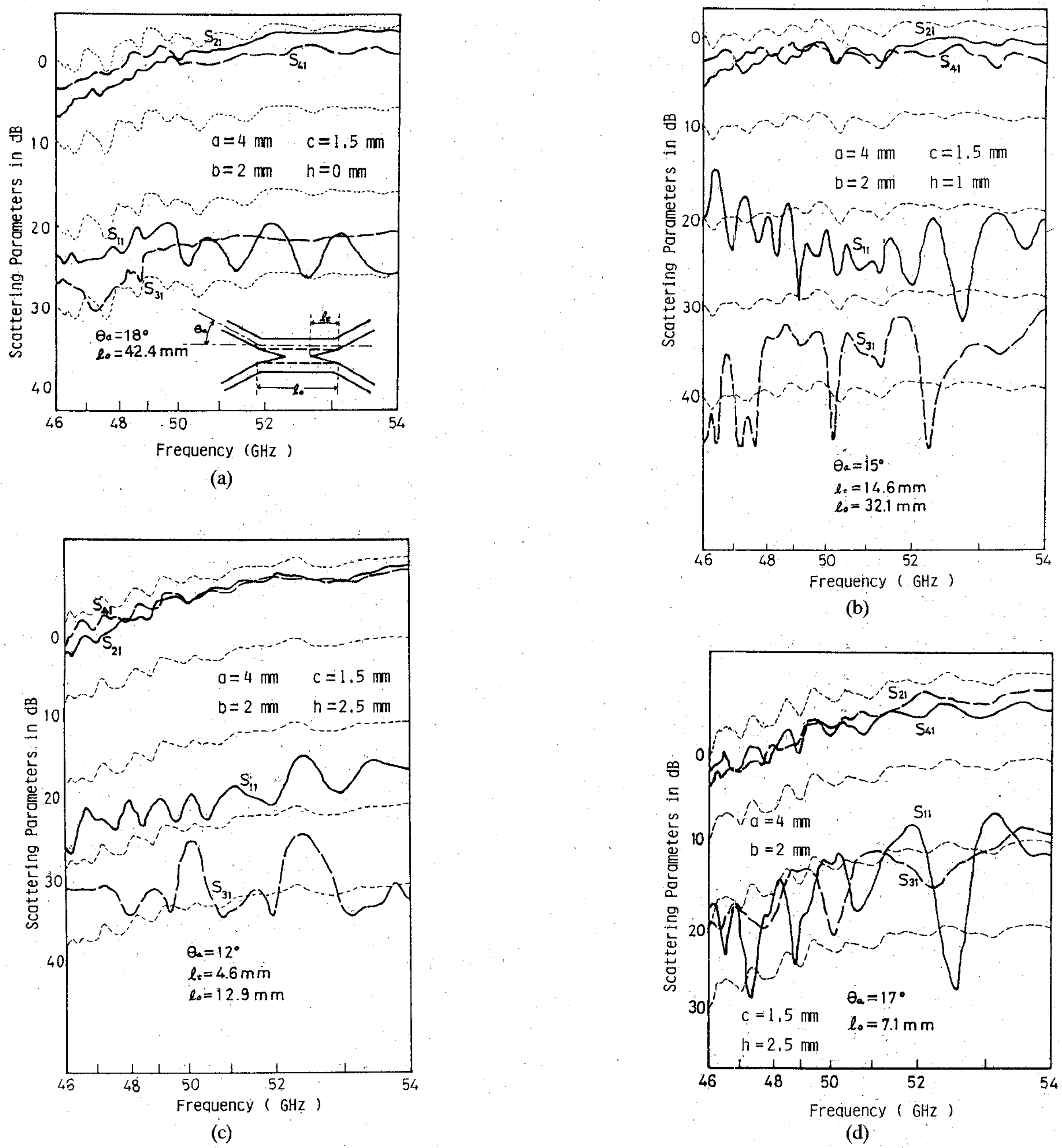
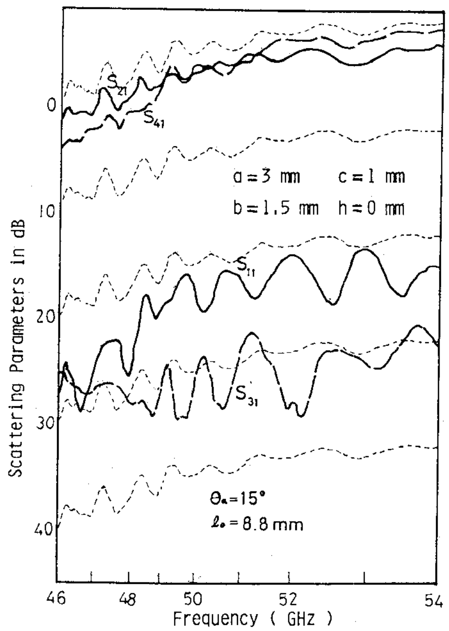
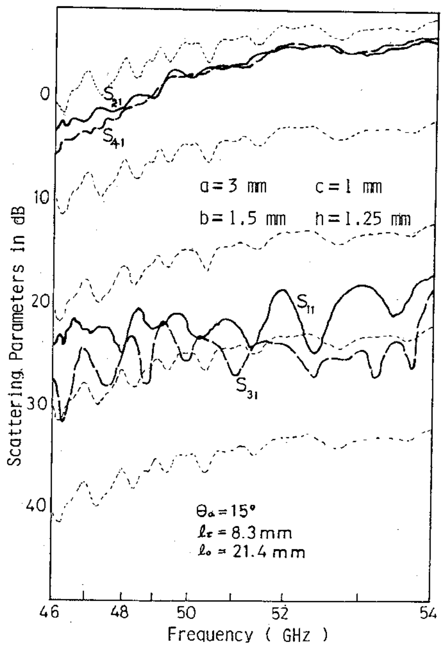


Fig. 8. Measured frequency characteristics for the directly connected directional couplers ($a = 4$, $c = 1.5$, $b = 2$ mm), (a) with $h = 0$ mm (conventional distributed coupler), (b) with $h = 1$ mm and with tapered sections, (c) with $h = 2.5$ mm and with tapered sections, and (d) with $h = 2.5$ mm and without tapered sections.

Since, on the other hand, the coupler shown in Fig. 5(c) is not under single-mode operation, there is a possibility of high insertion and return losses due to higher mode excitation, even though the bandwidth is broad. However, it is confirmed in Fig. 8(c) that the higher modes are rarely excited if an appropriate taper is included in the section between the main arm and coupling section. Fig. 8(d) shows the frequency characteristic for the coupler shown in Fig. 5(c) without tapered sections. From Fig. 8(d) and 8(c), it is seen that the coupling characteristics become flatter in both cases, but that the insertion loss and return loss increase in the version without tapered sections. It is conjectured that the improvement in performance of a directly connected coupler including tapers at the ends of the coupling section is not only due to suppression of higher modes, but also due to the decrease of mismatches of the fundamental modes from discontinuity at the ends. This has been confirmed from the period of the ripples evident in Fig. 8(d). Therefore, the period of the ripples in measured frequency characteristics agrees very well with the estimated one from the distance between the ends of the coupling section. In this case, the tapered sections may play a very important role in preventing the effect of higher modes and the mismatches of the fundamental modes at the ends of the directly connected region. Furthermore, one can draw a very important conclusion that, even though there is a possibility that higher modes could be excited in the directly connected image guide, they are



(a)



(b)

Fig. 9. Measured frequency characteristics for the directly connected image guide coupler ($a = 3$, $c = 1$, and $b = 1.5$ mm), (a) with $h = 0$ mm (conventional distributed coupler) (b) with $h = 1.25$ mm of nearly optimized value and with tapered sections.

not necessarily excited when the appropriate taper is inserted. As a consequence, the measured frequency characteristics for the directly connected image guide coupler with the dimension of $a = 4$, $b = 2$, $c = 1.5$, and $h = 2.5$ mm shown in Fig. 8(c) also agree well with the prediction shown in Fig. 5(c), and the bandwidth is 24 percent in a tolerance limit of ± 0.43 dB on the deviation in coupling from 3 dB, while the corresponding bandwidth of the conventional coupler is only 3 percent, as shown in Figs. 5(a) and 8(a).

The frequency characteristics of the directly connected image guide couplers were then compared with conventional ones within the constraint of single-mode operation. As in the above case, the bandwidth and the coupling length become broader and shorter, respectively, as the value of h is increased. Since the optimum value of h is 1.25 mm with the constraint of single-mode operation, the couplers with $h = 0$ and $h = 1.25$ mm were fabricated and tested while $a = 3$, $b = 1.5$, and $c = 1$ mm were used for the both couplers. Fig. 9 shows the experimental results which agree well with theory. It is seen that the coupler with a nearly optimum value of h is extremely broadband.

In all experiments, the tapers are linear and the length of the tapers and the angle of the arms are shown in Figs. 8 and 9, where the coupling lengths l_0 of directly connected couplers were fabricated as the theoretical coupling lengths L_{3dB} for 3-dB couplers in (6a). The lengths l_t of the tapered sections and the angles θ_a from the extension lines of the straight coupling section to the connecting arms were determined experimentally. It is noteworthy that the use of an effective coupling length [7], which includes the additional coupling effect of the connecting arms, is not needed as a result of making appropriate tapers at the ends of the directly connected coupling region. Therefore, the effect of the additional couplings between the connecting arms is canceled out with the reducing effect of coupling in the tapered sections. Furthermore, the couplers with directly connected image guides have improved mechanical stability and require shorter bends or smaller angles from the extension line of the straight coupled section to each connecting arm because the two coupled main guides can be separated further from each other than in conventional couplers. Although the lengths of tapered sections and the angles of connecting arms were determined by experiments here, it should be desired to study them theoretically in the future.

On the other hand, the typical overall insertion losses of the directly connected image guide couplers are about 0.8 dB, which are equivalent to the insertion loss of a straight image line with the total length of coupler, mainly transition loss from metallic waveguide.

IV. Conclusion

Directly connected image guide couplers have been proposed and studied theoretically and experimentally, and a comparison of propagation constants and coupling characteristics made with the conventional distributed image guide couplers. It is concluded that the directly connected image guide coupler is extremely broadband, has very flat coupling characteristics, and is a useful component for millimeter-wave integrated circuits. Furthermore, it is confirmed experimentally that the performance of the directly connected image guide coupler is improved by including appropriately tapered sections, even at frequencies where higher modes could be excited.

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