Reduced-Size Branch-Line and Rat-Race Hybrids for Uniplanar MMIC's

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Abstract—**A new method of miniaturizing branch-line 90° hybrids and 180° rat-race hybrids is proposed. The method utilizes combinations of short high-impedance transmission lines and shunt lumped capacitors. The new hybrids are fabricated on GaAs substrates and the validity and effectiveness of the method are confirmed through experiments at 25 GHz and 11 GHz. The fabricated hybrids demonstrate excellent design accuracy even at high frequencies, with a circuit size that is more than 80 percent smaller than conventional hybrids. These hybrids are particularly suitable for uniplanar MMIC's where necessary shunt connections are easily made.**

I. Introduction

HYBRID couplers play important roles as 90° and 180° power dividers or power combiners in such microwave circuits as balanced mixers, image-rejection mixers, and balanced amplifiers. Among them, coupled-line couplers, branch-line 90° couplers, and rat-race 180° couplers are widely used in microwave integrated circuits. They utilize the favorable characteristics of quarter-wavelength transmission lines.

However, the sizes of "quarter-wavelength" couplers are too large for monolithic microwave integrated circuit (MMIC) applications, since a large circuit area results in high chip cost. The lumped-element approach [1], [2], which uses spiral inductors and lumped capacitors, is one of the solutions to this problem. However, the design of lumped-element circuits must be somewhat empirical, and it needs precise inductor models based on careful measurements of test elements. Moreover, the design becomes difficult at frequencies above 20 GHz. Gupta and Getsinger [3] presented a quasi-lumped-element branch-line coupler, which uses lumped capacitors and short-circuited transmission lines employed as inductor elements. Their coupler is free from the uncertainty caused by lumped inductors, but its layout is inconvenient for tight integration.

In this paper, a new size-reduction method for hybrid couplers is proposed which utilizes combinations of short high-impedance transmission lines and shunt lumped capacitors. With this method, a 3 dB branch-line coupler can be developed using transmission lines of, for example, only 1/8 and 1/12 of a wavelength, and the area occupied by the coupler can be over 80 percent smaller than that of the conventional coupler. Advantages of the size-reduction method proposed here are (1) small circuit size due to short line length, (2) excellent design accuracy even at high frequency bands, and (3) good compatibility with uniplanar MMIC's [4], [5] proposed by the authors. This paper describes the design of a branch-line 90° hybrid, followed by experimental results at 25 GHz and 11 GHz. Transmission loss caused by conductor losses of high-impedance coplanar waveguides is also discussed. Next the design and the performance of a 25 GHz reduced-size rat-race 180° hybrid are presented.

II. Size-Reduction Method

The quarter-wavelength transmission line shown in Fig. 1(a) is a key element in conventional hybrid couplers. It consists of distributed series inductance and shunt capacitance. The aim of this study is to obtain a smaller circuit which is equivalent to the quarter-wavelength transmission line. A transmission line shorter than a quarter of a wavelength has a lower inductance and capacitance. Our approach is to offset the inductance drop by increasing the characteristic impedance of the line and to offset the capacitance loss by adding lumped capacitors, as shown in Fig. 1(b).

Let us examine the compatibility between the circuits in Fig. 1(a) and (b). The admittance matrices $[Y_a]$, $[Y_b]$ of the circuits in Fig. 1(a) and (b) are

$$[Y_a] = \frac{1}{jZ_0}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{1}$$

$$[Y_b] = \begin{bmatrix} \dfrac{\cos\theta}{jZ\sin\theta} + j\omega C & \dfrac{1}{jZ\sin\theta} \\ \dfrac{1}{jZ\sin\theta} & \dfrac{\cos\theta}{jZ\sin\theta} + j\omega C \end{bmatrix} \tag{2}$$

where Z_0, Z, θ, and ω are the characteristic impedance of the quarter-wavelength line, the characteristic impedance of the shortened line, the electrical angle of the shortened line, and the angular frequency, respectively. Comparing these two equations, we obtain

$$Z = Z_0/\sin\theta \tag{3}$$

$$\omega C = (1/Z_0)\cos\theta. \tag{4}$$

This relation is illustrated in Fig. 2. The electrical length θ can be made shorter, as can be seen in the figure, if the higher characteristic impedance Z is adopted and the

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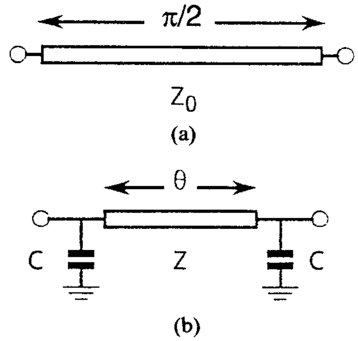

Fig. 1. (a) Quarter-wavelength transmission line. (b) Shortened transmission line equivalent to the quarter-wavelength transmission line.

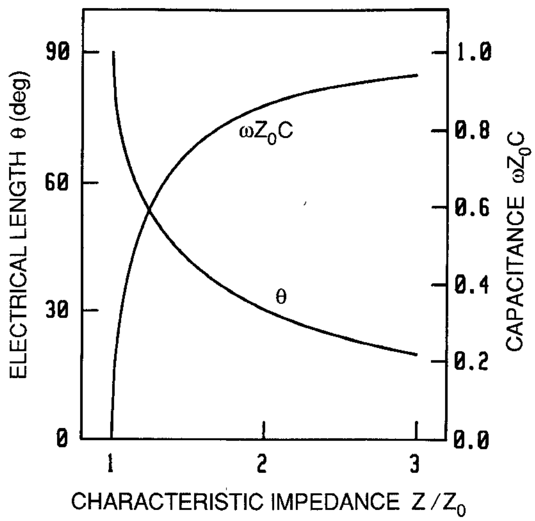

Fig. 2. Equivalent condition of the shortened transmission line.

lumped capacitance C is increased. The limit of $\theta = 0$ corresponds to purely lumped elements. This method can halve the length of the transmission line, 1/8 of a wavelength, for instance, by increasing the characteristic impedance by a factor of $\sqrt{2}$. This method requires the added capacitors to be grounded. Since uniplanar MMIC's have ground planes on their top side, they are especially suitable for this method.

III. 90° Branch-Line Hybrid

A. *Design of 90° Branch-Line Hybrids*

A circuit diagram of the well-known branch-line hybrid is shown in Fig. 3(a). The size of this circuit is easily reduced using the method described above. The characteristic impedances of the lines used in the conventional branch-line hybrid are Z_0 and $Z_0/\sqrt{2}$. If the characteristic impedance in the reduced-size hybrid is Z, the electrical length of the branch-line θ_1, the electrical length of the through-line θ_2, and the capacitance C are

$$\theta_1 = \arcsin y \tag{5}$$

$$\theta_2 = \arcsin \frac{y}{\sqrt{2}} \tag{6}$$

$$\omega C Z_0 = (1 - y^2)^{1/2} + (2 - y^2)^{1/2} \tag{7}$$

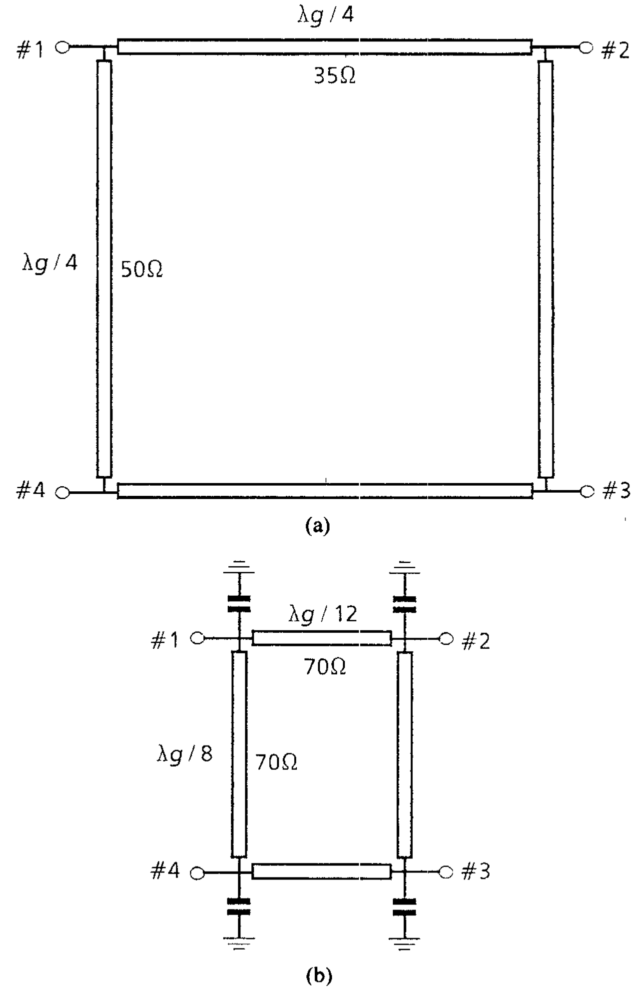

Fig. 3. (a) Circuit diagram of the conventional branch-line hybrid. (b) Circuit diagram of the reduced-size branch-line hybrid.

where $y = Z_0/Z$. When $y = 1/\sqrt{2}$, for example, $\theta_1 = 45°$ and $\theta_2 = 30°$. In other words, if the characteristic impedance is increased to 70.7 Ω, the line lengths become 1/8 of a wavelength and 1/12 of a wavelength respectively, as shown in Fig. 3(b). Line impedances higher than 70.7 Ω lead to shorter transmission lines, of course. However, the line width of the coplanar waveguides must be larger and the effects of junction discontinuities become large. Calculated phase differences between S_{31} (coupling) and S_{21} (direct) are shown in Fig. 4 compared with those of the conventional (quarter-wavelength) hybrid and the purely lumped hybrid. The bandwidth of the reduced-size hybrid is a little wider than that of the purely lumped hybrid but narrower than that of the quarter-wavelength hybrid.

B. *Loss in the Reduced-Size Coupler*

It may be thought that the use of high-impedance coplanar waveguides will result in large insertion losses. In fact, the transmission loss of coplanar waveguides increases rapidly as the center conductor becomes narrow. On the other hand, conductor loss of the lines with higher

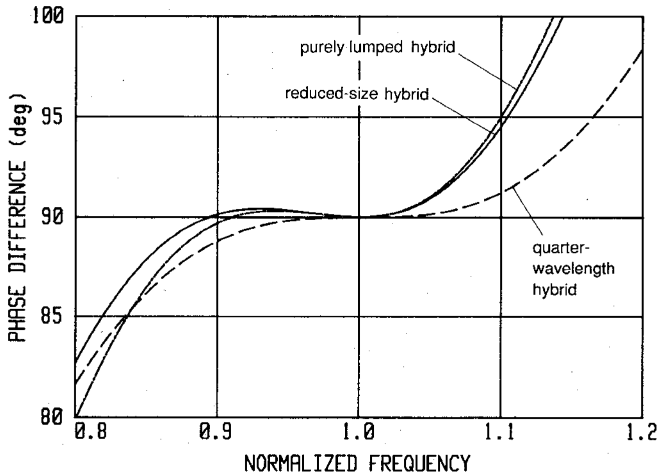

Fig. 4. Calculated phase differences between S_{21} and S_{31} of the reduced-size hybrid, the conventional hybrid, and the purely lumped hybrid.

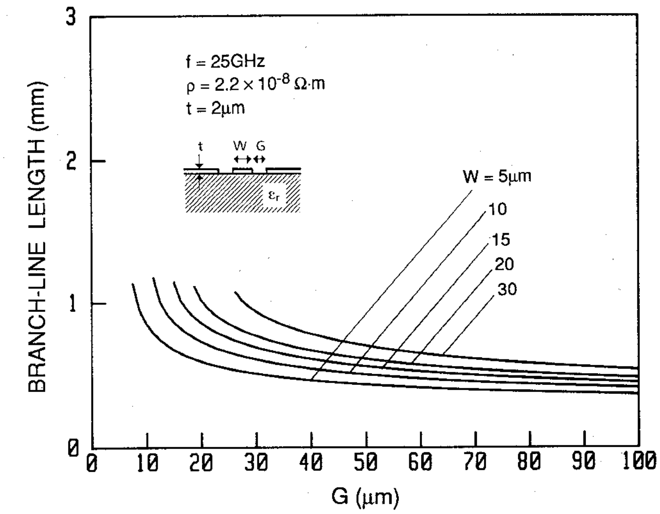

Fig. 6. Branch-line length of the 25 GHz reduced-size branch-line hybrid as a function of conductor gap G of the coplanar waveguide.

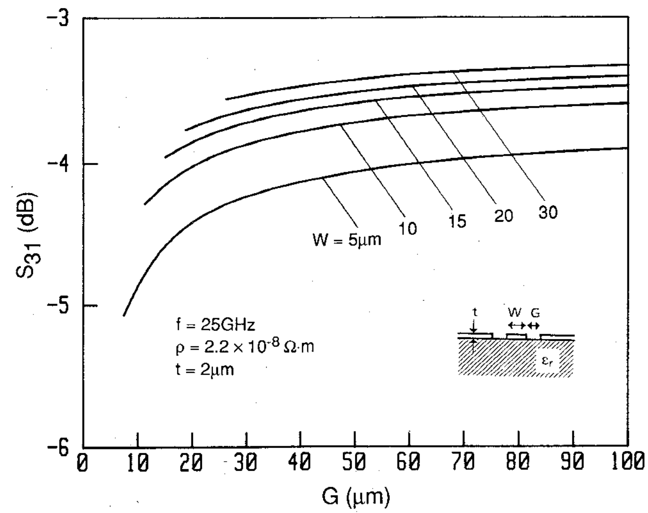

Fig. 5. Calculated insertion losses of the 25 GHz reduced-size branch-line hybrid as a function of conductor gap G of the coplanar waveguide.

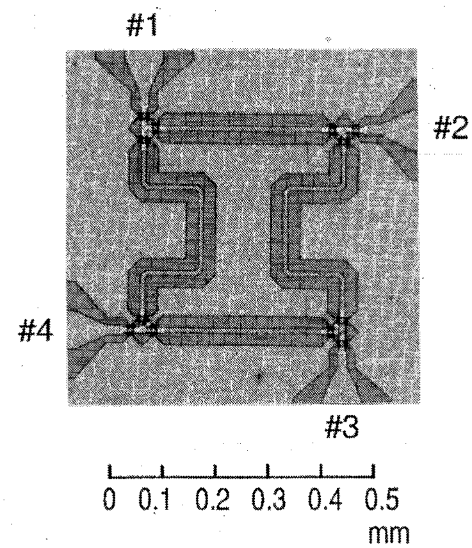

Fig. 7. Photomicrograph of the fabricated 25 GHz reduced-size branch-line hybrid.

impedance is smaller in principle because of the lower currents on them. In this section, ohmic losses of the reduced-size branch-line hybrid are discussed quantitatively.

Conductor losses of the coplanar waveguides can be evaluated [6] using Wheeler's incremental inductance rule [7]. S parameters of the hybrid are calculated using the evaluated attenuation constant and the complex characteristic impedance due to conductor losses. The resultant calculated insertion losses of the 25 GHz hybrids are plotted in Fig. 5 as a function of the conductor gap G of the coplanar waveguides for several values of the center conductor width W. Metals 2 μm in thickness and 2.2×10^{-8} $\Omega \cdot$m in conductivity are assumed, and the dielectric constant of the substrate is 12.6. Associated branch-line lengths are shown in Fig. 6. The narrow widths W and the wide gaps G lead to short line lengths, and narrow W values result in large insertion losses, as expected. It is worth noting that the losses decrease as the gap G increases. This means that the size-reduction method proposed here does not degrade the insertion loss properties of the hybrids when the conductor width W is kept constant.

C. Experimental Results

The 25 GHz and 11 GHz reduced-size branch-line hybrids were designed and fabricated on semi-insulating GaAs substrates. Fig. 7 shows a photomicrograph of the 25 GHz hybrid. All the transmission lines are 70 Ω coplanar waveguides with a 10 μm center conductor width and their lengths are 1/8 and 1/12 of a wavelength. Air bridges are used at the coplanar waveguide junctions in order to equalize potentials of the grounds. Metal—insulator—metal (MIM) shunt capacitors are located at the corners of inner ground metal. The insulator film is Si_3N_4. The size of the fabricated hybrid is 500 μm $\times$ 500 μm. This is more than 80 percent smaller than a conventional branch-line hybrid.

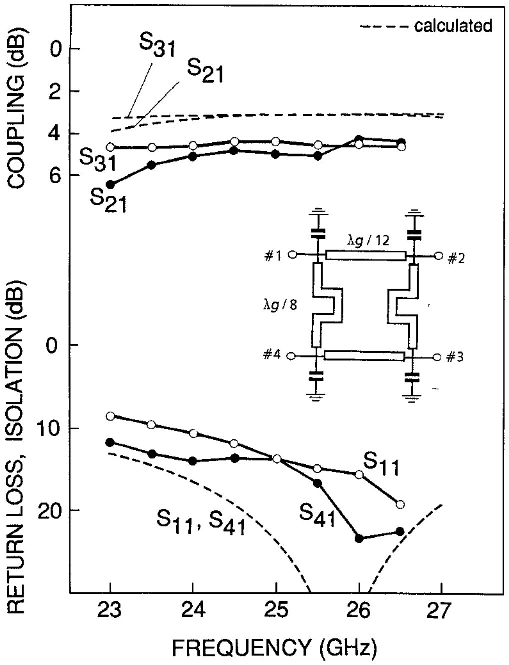

Fig. 8. Measured performance of the 25 GHz reduced-size branch-line hybrid.

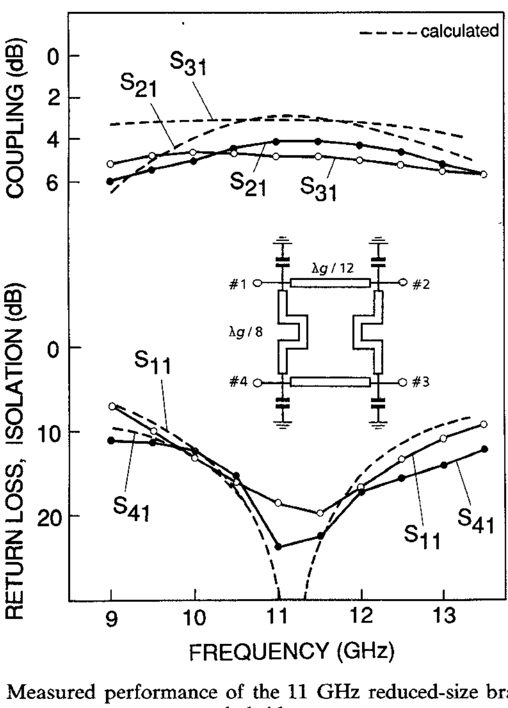

Fig. 9. Measured performance of the 11 GHz reduced-size branch-line hybrid.

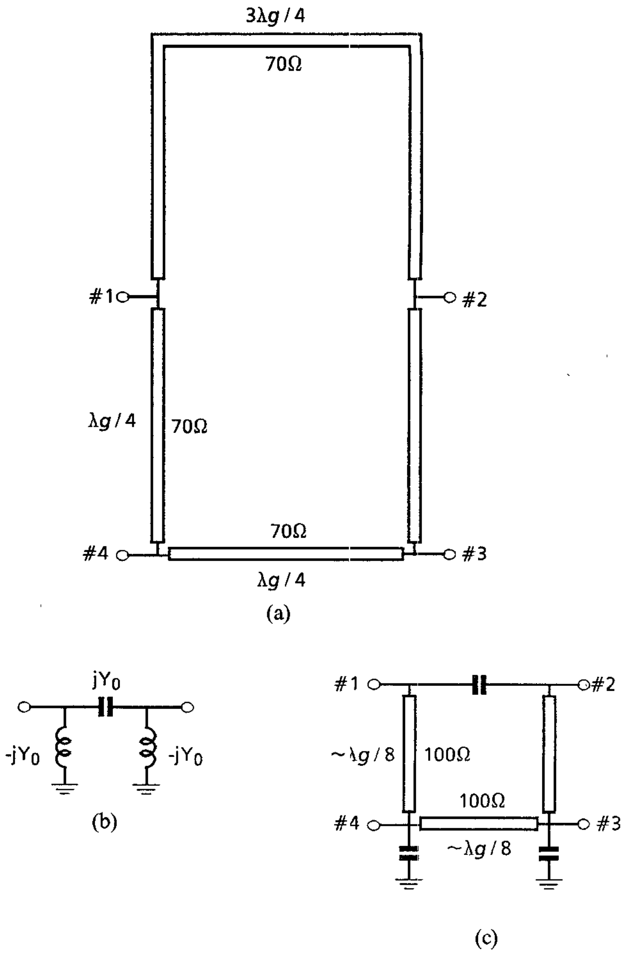

Fig. 10. (a) Circuit diagram of the conventional rat-race hybrid. (b) Circuit equivalent to 3/4 wavelength transmission line. (c) Circuit diagram of the reduced-size rat-race hybrid.

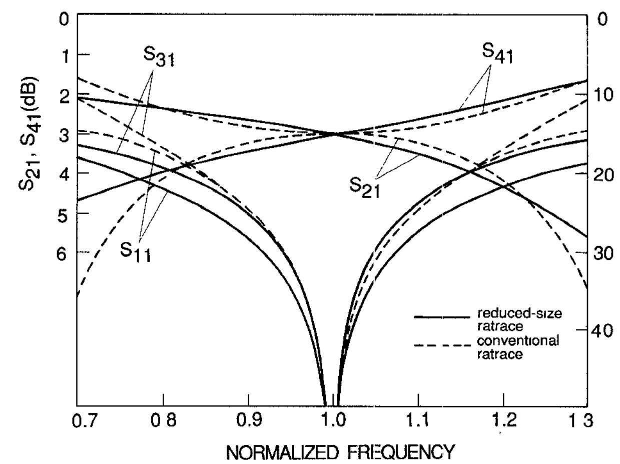

Fig. 11. Calculated frequency response of the reduced-size rat-race hybrid and the conventional rat-race hybrid.

The measured performance of the fabricated 25 GHz hybrid is shown in Fig. 8. The measurements were made using microwave wafer probes. The calculated values are also plotted in the figure. The hybrid shows equal power splitting performance and good isolation. The larger loss measured in the experiment is mainly due to the conductor loss discussed above. Additional loss is caused by surface and edge roughness of the metal, inferior metal conductivity, and the dielectric loss of the substrate, which were not taken into account in the calculations. An 11 GHz hybrid was also fabricated and tested. The results are shown in Fig. 9. Its center conductor width is also 10 μm and its performance is similar to that of 25 GHz hybrid. The obtained experimental results confirm the validity and effectiveness of the method proposed here.

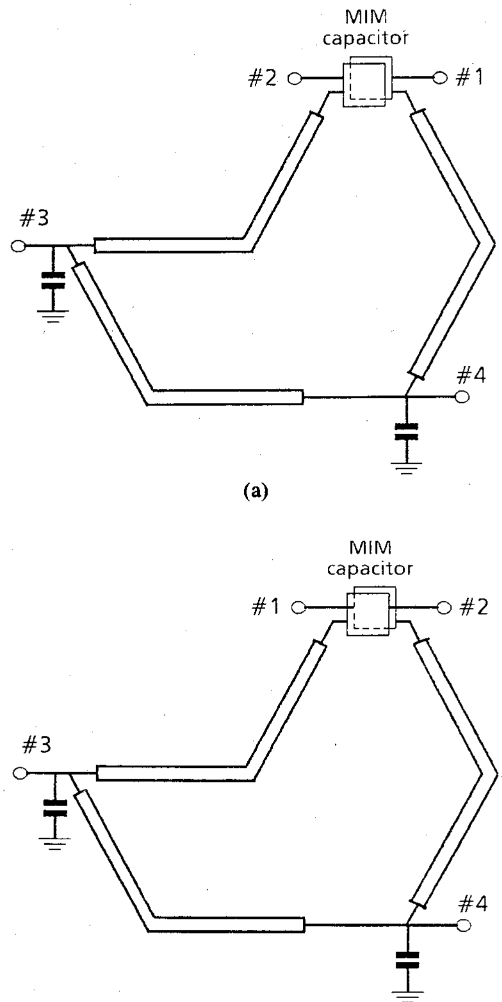

Fig. 12. Port interchange in the reduced-size rat-race hybrid: (a) usual port layout; (b) port layout convenient for mixer applications.

IV. 180° Rat-Race Hybrid

A. Circuit Design

The 180° hybrids have the capability of dividing and combining signals in 0° and 180°, and have many applications. The 180° hybrids which can be used in MIC's and MMIC's are a rat-race hybrid, a reverse-phase hybrid ring [8], and slotline magic T's [4], [9]–[11]. They utilize transmission lines of a quarter of a wavelength or longer, or active elements. Size reduction of the rat-race hybrid was tried using the method employed for the branch-line hybrid.

The traditional rat-race hybrid consists of $1/4$ and $3/4$ wavelength lines, as shown in Fig. 10(a). The $1/4$ wavelength lines can be shortened to $1/8$ wavelength by increasing their characteristic impedance up to 100 Ω and adding lumped capacitors. On the other hand, the $3/4$ wavelength line can be replaced by the π network shown in Fig. 10(b) [2]. Moreover, the shunt inductances in Fig. 10(b) and the shunt capacitances added to $1/8$ wavelength lines almost cancel each other. Finally, the rat-race hybrid can be replaced by the circuit shown in Fig. 10(c) with optimized line lengths and capacitances. Fig. 11 shows the calculated frequency responses of the circuit in Fig. 10(c) compared with those of the conventional rat-race hybrid.

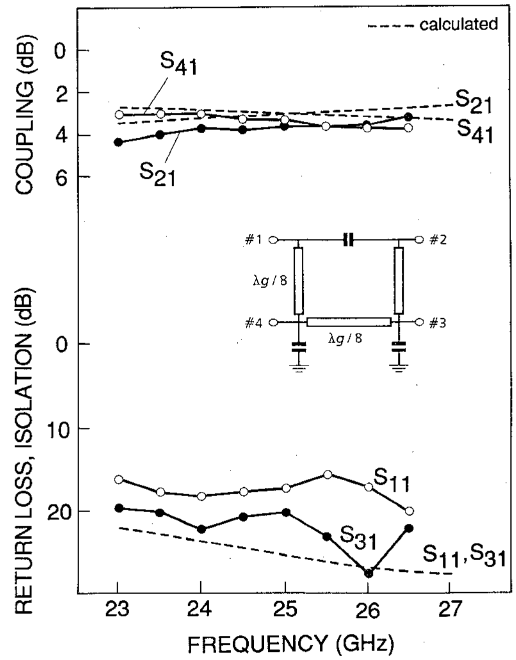

Fig. 13. Measured performance of the 25 GHz reduced-size rat-race hybrid.

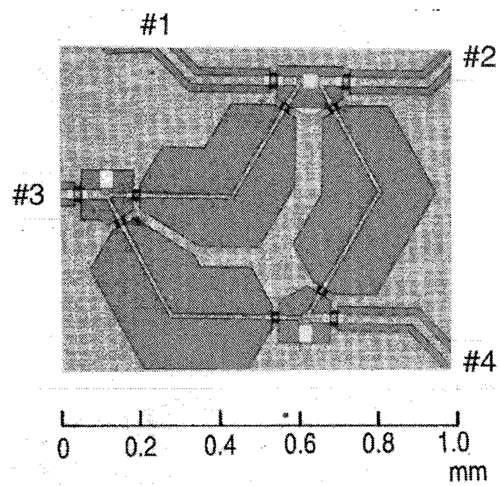

Fig. 14. Photomicrograph of the fabricated 25 GHz reduced-size rat-race hybrid.

Another advantage of the reduced-size rat-race proposed here is its flexible port arrangement. Fig. 12 illustrates the port interchange possible in this reduced-size rat-race. The lines can cross at the position of the lumped MIM capacitor without any performance deterioration. This convenient port layout is highly effective, especially for mixer applications.

B. Experimental Results

The reduced-size rat-race hybrid was fabricated and tested at 25 GHz. It consists of 100 Ω coplanar waveguides and MIM capacitors. The center-conductor width of the coplanar waveguides is 10 μm. The measured performance is shown in Fig. 13. The calculated performance is also plotted in the figure. Insertion loss is smaller than that of the branch-line hybrid because the characteristic impedance of the lines is higher. Fig. 14 shows the layout of the fabricated 25 GHz hybrid. The size reduction is noticeable because all lines used are just 1/8 wavelength.

V. Conclusions

A new method of reducing the size of branch-line 90° hybrids and 180° rat-race hybrids has been proposed and confirmed through experiments at 25 GHz and 11 GHz. The size of fabricated hybrids is more than 80 percent smaller than that of conventional hybrids. The proposed method does not use lumped inductors and, consequently, has the advantages of excellent design accuracy even at high frequencies. These hybrids are particularly suitable for uniplanar MMIC's because shunt connections are easily available on the uniplanar structure.

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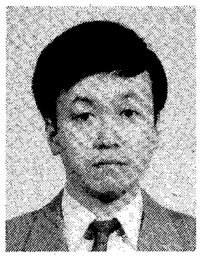

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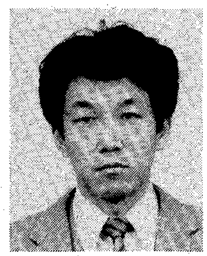

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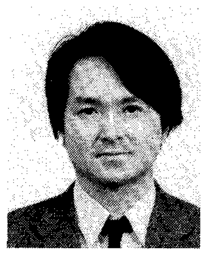

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