# Computation of Coplanar-Type Strip-Line Characteristics by Relaxation Method and Its Application to Microwave Circuits

TAKESHI HATSUDA, MEMBER, IEEE

*Abstract*—**The characteristics of new strip lines [i.e., a single strip-conductor coplanar-type strip line (S-CPS), a two symmetrical strip-conductor coplanar-type strip line (T-CPS), and a coupled strip-conductor coplanar-type strip line (C-CPS), which consists of single two-center strip conductors or coupled strip conductors and ground plates on a dielectric substrate and outer ground conductor] are calculated by the relaxation method. The effect of the outer ground conductor and side wall on these lines is analyzed and the characteristic impedance and phase–velocity ratio are determined. The characteristic impedance is determined experimentally and the maximum values of the discrepancies compared with the calculated value of each of the lines are 2.0–3.0 percent.**

**Application examples of the coplanar-type strip line to microwave transistor amplifier and parallel-coupled filter are shown.**

**A transistor amplifier of small size, light weight, wide bandwidth, and improved reliability is achieved.**

**A parallel-coupled filter small in size (reduction ratio is more than 50 percent), with good frequency symmetry and featuring easy resonance frequency fine tuning is obtained.**

## I. INTRODUCTION

MICROWAVE circuits used in a communication satellite, for example, require light weight, small size, and high reliability, so the strip line is suited to these needs. The characteristic impedance and phase–velocity ratio of conventional triplate strip lines are determined by the thickness of the dielectric substrate and its relative dielectric constant, by the width of the strip conductors, and by the height of the line. In order to obtain a smaller line when using the same dielectric substrate and the same height of line, or to obtain a more versatile line, different types of new lines must be considered.

The coplanar waveguide (CPW) is very attractive and it is analyzed in open boundary by using conformal mapping [1]. But closed boundary lines are needed for high-gain amplifier circuits, and lines having side walls can help to miniaturize microwave circuits.

In this paper, three new types of strip lines [i.e., the single strip-conductor coplanar-type strip line (S-CPS), which has a center strip conductor and ground plates on dielectric substrate as shown in Fig. 1(a), the two symmetrical strip-conductor coplanar-type strip line (T-CPS), which is shown in Fig. 1(b), and the coupled strip-conductor coplanar-type strip line (C-CPS), which is shown in Fig. 1(c)] are analyzed by the use of the relaxation method [2]–[10].

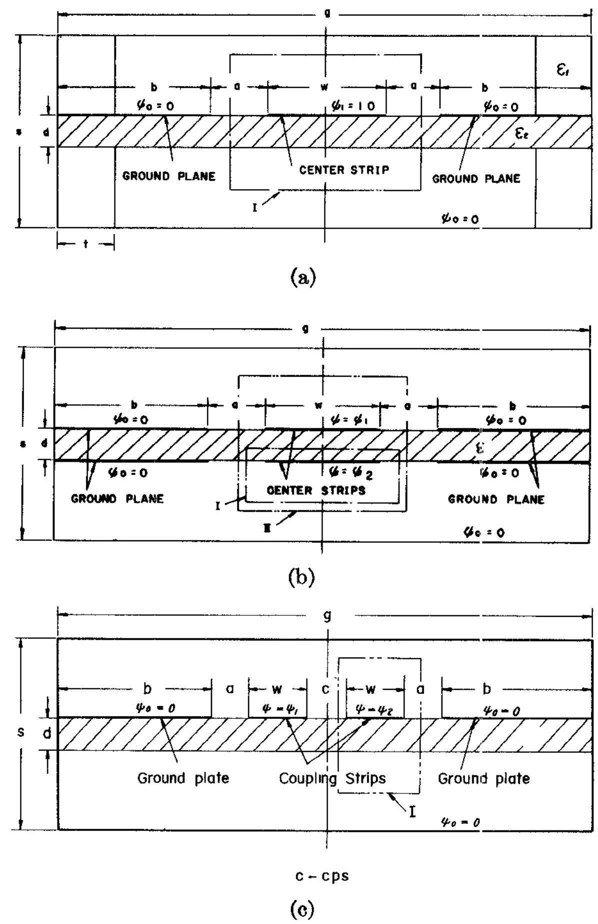


Fig. 1. (a) Single strip-conductor coplanar-type strip line (S-CPS). (b) Two symmetrical strip-conductor coplanar-type strip line (T-CPS). (c) Coupled strip-conductor coplanar-type strip line (C-CPS).

As one example of application of S-CPS, a transistor amplifier for an on-board satellite transponder has been developed. The resulting amplifier is small in size, light in weight, and has more resistivity to shock and vibration, with good operational performance. Other advantages achieved are wider amplifier bandwidth, a simpler more reliable technique of grounding the emitter lead of a transistor, and easier construction of a bypass capacitor than by conventional techniques used with conventional triplate strip line and microstrip.

A four-stage amplifier and an isolator were assembled into a simple compact package, resulting in high perform-

Manuscript received December 28, 1973; revised April 21, 1975.
The author is with the Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Yokosuka-shi, Kanagawa, Japan.

ance stability and miniaturization of the amplifier assembly.

Another application is the parallel-coupled bandpass filter using C-CPS. The resulting bandpass filter has good frequency symmetry because of the small difference between even- and odd-mode phase–velocity ratio, compared with the conventional suspended triplate strip line. Small filter size is achieved because of the smaller value of the phase–velocity ratio and mainly by the fringing capacitance between the ground plates and the edge of the resonator. The effect of side wall and other circuits near the filter is smaller than in a conventional type.

## II. COPLANAR-TYPE STRIP LINES

The characteristic impedance and phase–velocity ratio of conventional triplate strip lines are determined by the thickness of the dielectric substrate and its relative dielectric constant, by the width of the strip conductors, and by the height of the line. In order to obtain a smaller line when using the same dielectric substrate and same height of line, or to obtain a more versatile line, different types of new lines must be considered.

The new types of strip lines (S-CPS, T-CPS, and C-CPS) are analyzed by the use of the relaxation method.

The parameters in Fig. 1(a) are as follows: $s$ is the height of the line; $g$ is the width of the line; $w$ is the width of the center strip conductor; $d$ is the thickness of the dielectric substrate; $\epsilon_2$ is the relative dielectric constant of the dielectric substrate; $t$ is the width of the supporting dielectric (Teflon); $\epsilon_1$ is the relative dielectric constant of the supporting dielectric; $a$ is the distance between the center strip conductor and the ground plate; $b$ is the width of the ground plate; I is the integrating path; and $\psi$ is the potential of conductor. In Fig. 1(b), $\epsilon$ is the relative dielectric constant of the dielectric substrate, and I and II are the integrating paths. In Fig. 1(c), $c$ is the gap between coupling strip conductors.

As shown in Fig. 1(a), the dielectric substrate is supported by another dielectric (Teflon, whose relative dielectric constant is $\epsilon_1 = 2.1$). This is used as a shock absorber and also for maintaining the same potential ($\psi_0 = 0$) at the ground plate and the outer ground conductor by putting copper foil between the Teflon and the ground plate.

## III. CHARACTERISTICS OF THE SINGLE STRIP-CONDUCTOR COPLANAR-TYPE STRIP LINE (S-CPS)

Characteristics of the strip line shown in Fig. 1(a) can be determined by solving the two-dimensional problem presented by boundary conditions of a potential for an inner strip conductor, where $\psi_1 = 1.0$ of a potential for the ground plate and the outer ground conductor where $\psi_0 = 0$. The solution of such an inhomogeneous transmission line is determined from Laplace's equation

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} = 0. \tag{1}$$

In the relaxation method [2]–[10], (1) is expanded to a simultaneous difference equation. Because of symmetry, only half of the area of Fig. 1(a) needs to be considered. The analysis of CPS differs only slightly from that of [11] and [12] (i.e., the conventional strip line, where $b = 0$ in Fig. 1).

In the calculation, the thickness of the strip conductor is considered as zero, because this thickness is actually very small when compared with the dielectric substrate thickness.

### A. *Effect of Side Wall and Outer Ground Conductor*

The coplanar strip line is characterized by ground plates and shielding by an outer ground conductor. The effects of the side wall and the outer ground conductor of the S-CPS are examined first. The characteristics of the S-CPS depend upon parameter $b/[(w/2) + a]$, as shown in Fig. 2. In this calculation, $s = 4.3$ mm, $d = 0.61$ mm, $\epsilon_2 = 9.4$, and $\epsilon_1 = 1.0$.

As seen in Fig. 2, characteristic impedance $Z_o$ and phase–velocity ratio $v/v_0$ asymptotically approach constant values when the ratio $b/[(w/2) + a]$ is larger than 1.0–1.5. This is the merit of S-CPS, i.e., the effect of side wall and other circuits near the center strip conductor is smaller than in a conventional type.

When $b$ becomes zero, the values of $Z_o$ and $v/v_0$ become the values one obtains with the conventional single strip-conductor strip line [11], [12].

The effect of changes of the value of $s$ is shown in Fig. 3. The conventional type (i.e., $b = 0$) with $w/g = 0.18$ is also shown in Fig. 3. The computation parameters are $g = 10.7$ mm, $d = 0.61$ mm, $\epsilon_2 = 9.4$, $\epsilon_1 = 2.1$, $w/g = 0.18$, and $a/g = 0.06$. The variation of $Z$ is smaller, but $v/v_0$ is larger in the S-CPS than in the conventional type. In the S-CPS, values of $Z_o$ and $v/v_0$ tend to become constant when $d/s$ becomes small (i.e., $s$ becomes large). The $d/s$ ratio corresponding to $s = 4.3$ mm, $d = 0.61$ mm ($\nabla$ symbol in Fig. 3) is used in the following calculations. The effect of $s$ is seen to be small for such a ratio ($d/s = 0.142$).

### B. *Characteristic Impedance and Phase–Velocity Ratio of S-CPS*

Strip-line dimensions of $s = 4.3$ mm, $g = 10.7$ mm, $d = 0.61$ mm, $\epsilon_2 = 0.94$, $t = 1.5$ mm, and $\epsilon_1 = 2.1$ are computed.

In Fig. 4, $Z_o$ and $v/v_0$ versus $a/s$ of S-CPS are shown when $w/s$ assumes constant values of 0.143, 0.286, and 0.429. The point (symbol $\cdot$) shows the values of a conventional type. When the value of $a$ becomes small, $Z_o$ and $v/v_0$ become small.

Table I shows a comparison of $Z_o$ and $v/v_0$ for conventional type and S-CPS. The reduction ratio of S-CPS is 40–50 percent of $Z$ and 25–30 percent of $v/v_0$. This reduction ratio becomes large when $a/s$ becomes smaller.

In Fig. 5, $Z_o$ and $v/v_0$ versus $w/s$ of the S-CPS are shown when $a/s$ assumes constant values of 0.143, 0.286, and 0.429. The top solid-line curve in Fig. 5 shows the characteristics with no Teflon, and the dashed-line curves show

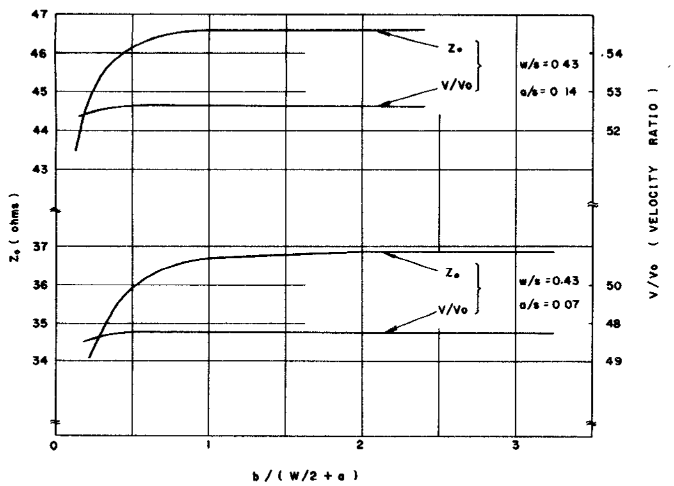


Fig. 2. $Z_o$ and $v/v_0$ of S-CPS versus $b/(w/2 + a)$.

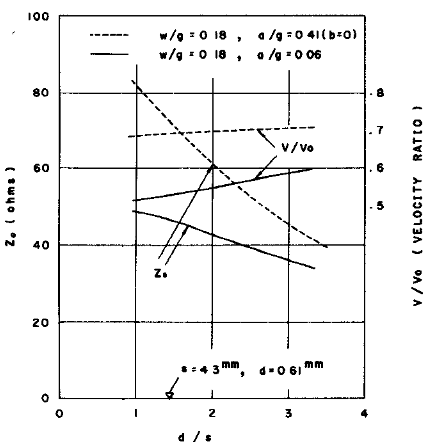


Fig. 3. $Z_o$ and $v/v_0$ of conventional type and S-CPS versus $d/s$.

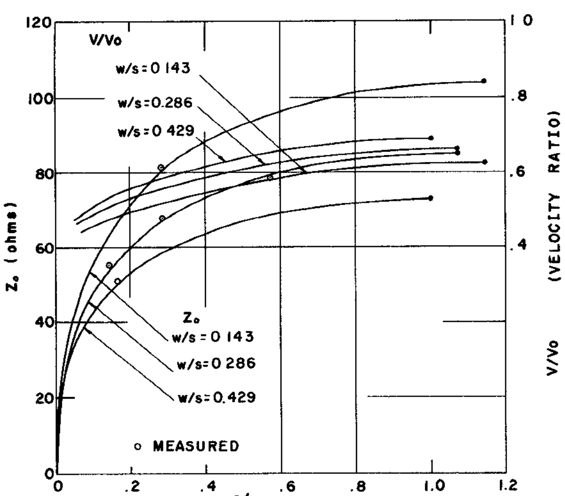


Fig. 4. $Z_o$ and $v/v_0$ of S-CPS versus $a/s$ for $w/s$ const.

TABLE I

Reduction Ratio of $Z_0$ and $v/v_0$ for S-CPS

| | $w/s$=0 143 | | | $w/s$=0. 286 | | |
|---|---|---|---|---|---|---|
| | Conventional Type | S-CPS $a/s$=0. 143 | Reduction Ratio (percent) | Conventional Type | S-CPS $a/s$=0 143 | Reduction Ratio (percent) |
| $Z_o$ | 104 Ω | 64 Ω | 38 | 85. 5 Ω | 42 3 | 50 |
| $v/v_0$ | 0 63 | 0 47 | 25 | 0 67 | 0. 47 | 30 |

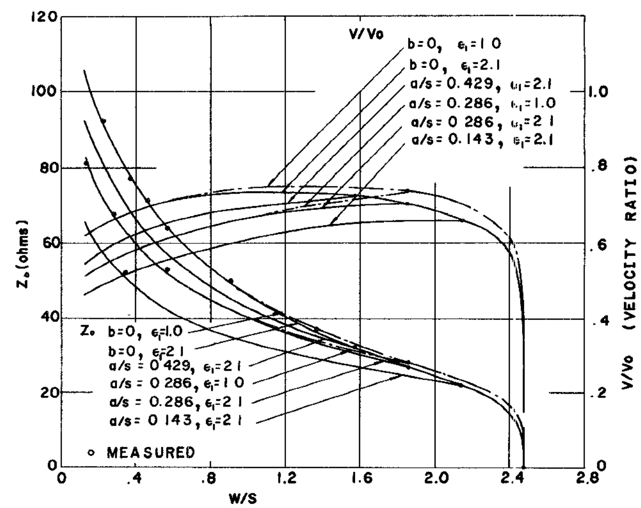


Fig. 5. $Z_o$ and $v/v_0$ of S-CPS versus $w/s$ for $a/s$ const.

the characteristics of a conventional type (i.e., $\epsilon_1 = 1.0$). The ratios of $w/s$ and $v/v_0$ for 50-Ω transmission line of S-CPS compared with the conventional type of strip line are shown in Table II. The effect of Teflon on the S-CPS is also shown in Fig. 5. The effect is smaller than for the conventional type.

### C. *Equipotential Diagram of S-CPS*

Fig. 6 shows the calculated result of a half-area of equipotential diagram where $s = 4.3$, $g = 10.7$, $d = 0.61$, $t = 1.5$ mm, $\epsilon_2 = 9.4$, $\epsilon_1 = 2.1$, $w/s = 0.429$, and $a/s = 0.143$.

From Fig. 6, the following can be seen.

1) The field is concentrated by the existence of ground plates. This explains why $Z_o$ and $v/v_0$ approach constant values when the $b$ becomes larger than a certain value.

2) The equipotential area did not expand in the supporting dielectrics (Teflon), so the effect of the Teflon is small.

3) The characteristic change caused by the influence of other circuits (for example, a biasing circuit in a transistor amplifier) on the ground plates assumes a small value in S-CPS.

4) In the case of other parallel lines near the center strip conductor, the coupling of these lines is small due to the existence of ground plates.

## IV. CHARACTERISTICS OF THE TWO SYMMETRICAL STRIP-CONDUCTOR COPLANAR-TYPE STRIP LINE (T-CPS)

As shown in Fig. 1(b), T-CPS has two center strip conductors and ground plates on both sides of a dielectric substrate. The following are advantages of this type of line.

1) It is smaller than S-CPS.

2) By using both sides of the dielectric substrate, three-dimensional utilization of the line can be achieved.

3) In a conventional-type strip line, values of $Z_o$ and $v/v_0$ are determined from the thickness of dielectric sub-

TABLE II
REDUCTION RATIO OF $w/s$ AND $v/v_0$ FOR S-CPS 50-Ω LINE

| | $w/s$ | Reduction Ratio (percent) | $v/v_0$ | Reduction Ratio (percent) |
|---|---|---|---|---|
| Conventional Type | 0.9 | | 0.73 | |
| $a/s=0.286$ | 0.64 | 29 | 0.62 | 15 |
| $a/s=0.143$ | 0.36 | 60 | 0.51 | 30 |

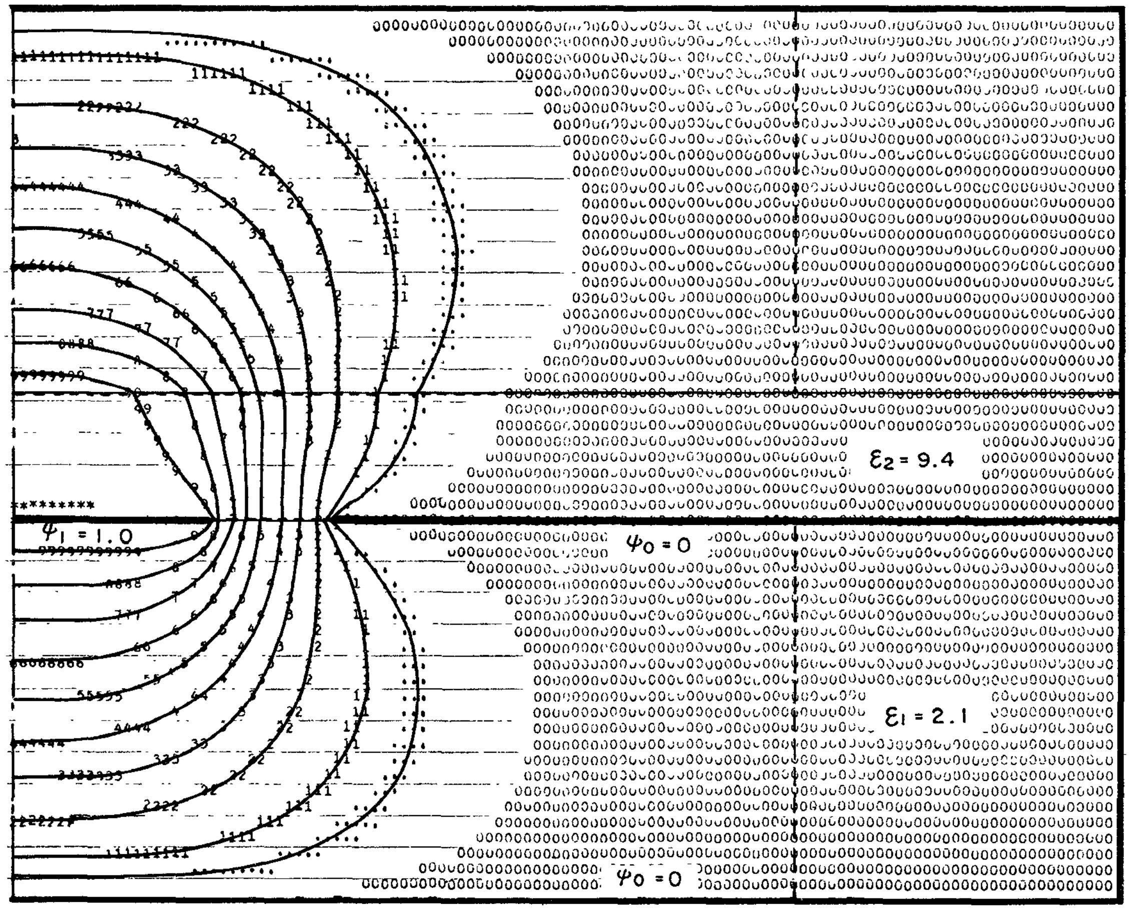


Fig. 6. Equipotential diagram of S-CPS.

strate and its dielectric constant, the height of line ($s$), and the width of the center strip conductor ($w$). However, in CPS, the values of $Z_o$ and $v/v_0$ can be changed by changing the distance between center strip conductor and ground plate ($a$), so this line has more design flexibility for filters or directional couplers.

Computer programs were developed for two modes, i.e., 1) $\psi_1 = \psi_2 = 1.0$ and $\psi_0 = 0$ for the even mode, and 2) $\psi_1 = 1.0$, $\psi_2 = -1.0$, and $\psi_0 = 0$ for the odd mode, where $\psi_1$ and $\psi_2$ are the potentials of the upper and lower strip conductors, respectively. Four characteristic impedances and four phase–velocity ratios are defined, i.e., $Z_{0e}{}^{I}$, $Z_{0e}{}^{II}$, $(v/v_0)_e{}^{I}$, and $(v/v_0)_e{}^{II}$ for the even-mode case and $Z_{0o}{}^{I}$, $Z_{0o}{}^{II}$, $(v/v_0)_o{}^{I}$, and $(v/v_0)_o{}^{II}$ for the odd-mode case.

Notations I and II indicate the integrating path, where I encloses one strip conductor and II encloses two strip conductors in Fig. 1(b), $e$ denotes even mode and $o$ denotes odd mode. In the symmetrical strip conductor case

$$Z_{0e}{}^{II} = Z_{0o}{}^{I}/2$$

$$(v/v_0)_e{}^{I} = (v/v_0)_e{}^{II}$$

and

$$Z_{0o} = \infty .$$

Computer programs were developed for the quarter-area of Fig. 1(b) because of the symmetry of the line.

The characteristic impedance and phase–velocity ratio versus $w/s$ of T-CPS, when $a/s = 0.143$ and 0.286, are shown in Fig. 7. The upper curves of Fig. 7 show the characteristics of the conventional strip line.

Table III shows a comparison of $Z_o$ and $v/v_0$ for the conventional type and for the even mode of T-CPS ($Z_{0e}{}^{II}$ and $(v/v_0)_e{}^{II}$). From Tables II and III the reduction ratios of T-CPS (even-mode case) are larger than for S-CPS.

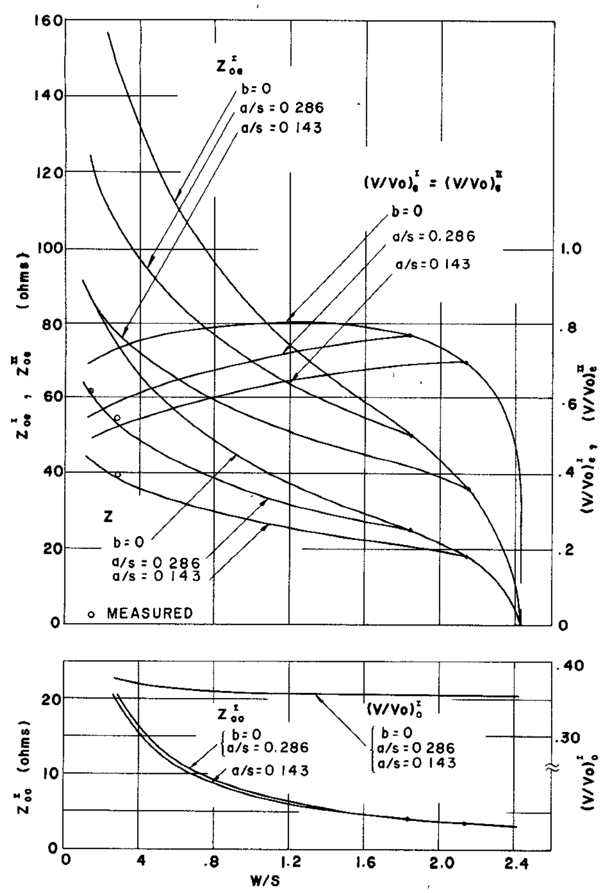


Fig. 7. $Z_o$ and $v/v_0$ of T-CPS versus $w/s$ for $a/s$ const.

TABLE III
REDUCTION RATIO $Z_{0e}{}^{II}$ AND $(v/v_0)_e{}^{II}$ FOR T-CPS

| | $w/s$=0 286 | | |
|---|---|---|---|
| | Conventional Type | T-CPS $a/s$=0. 143 | Reduction Ratio (percent) |
| $Z_{0e}{}^{II}$ | 74 Ω | 28 Ω | 62 |
| $(v/v_0)_e{}^{II}$ | 0 74 | 0 47 | 36 |

Reduction ratios $w/s$ and $(v/v_0)_e{}^{II}$ for a 50-Ω transmission line, compared with the T-CPS and conventional type, are shown in Table IV. From Tables II and IV, it is apparent that the reduction ratios $w/s$ and $v/v_0$ for the T-CPS are larger than for the S-CPS.

## V. CHARACTERISTICS OF THE COUPLED STRIP-CONDUCTOR COPLANAR-TYPE STRIP LINE (C-CPS)

C-CPS has two coupled strip conductors and ground plates on a dielectric substrate, as shown in Fig. 1(c).

Computer programs were developed for two modes, i.e., 1) $\psi_1 = \psi_2 = 1.0$ and $\psi_0 = 0$ for the even mode, and 2) $\psi_1 = 1.0$, $\psi_2 = -1.0$, and $\psi_0 = 0$ for the odd mode, where $\psi_1$ and $\psi_2$ are the potentials of the coupled strip conductors, respectively.

Two characteristic impedances and two phase-velocity ratios are determined, i.e., $Z_{0e}$, $Z_{0o}$, $(v/v_0)_e$, and $(v/v_0)_o$.

The effect of the side wall and the ground plate is also

TABLE IV
REDUCTION RATIO $w/s$ AND $(v/v_0)_e{}^{II}$ FOR T-CPS 50-Ω LINE

| | $w/s$ | $(v/v_0)_e{}^{II}$ |
|---|---|---|
| Conventional Type | 0 75 | 0. 79 |
| $a/s$=0 286 | 0 36 | 0 60 |
| Reduction Ratio (percent) | 52 | 24 |

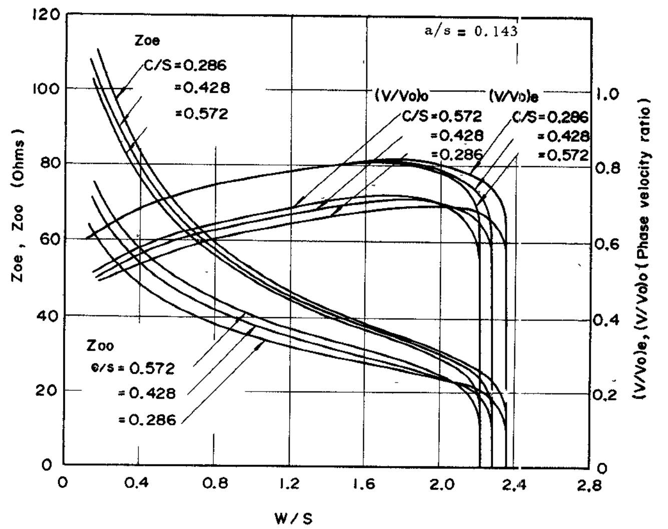


Fig. 8. $Z_{0e}$, $Z_{0o}$, $(v/v_0)_e$, and $(v/v_0)_o$ of C-CPS versus $w/s$ for $c/s$ const.

smaller than that of a conventional coupled strip line, as S-CPS and T-CPS.

In Fig. 8, $Z_{0e}$, $Z_{0o}$, $(v/v_0)_e$, and $(v/v_0)_o$ versus $w/s$ of C-CPS are shown when $c/s$ assumes constant values of 0.286, 0.428, and 0.572 and $a/s$ assumes a constant value of 0.143. (Other parameters are $s = 4.3$, $g = 10.7$, $d = 0.61$ mm, and $\epsilon = 9.35$).

From Fig. 8, the following is seen.

1) The characteristic impedance and phase-velocity ratios are smaller than that of a conventional coupled strip line, especially in the even-mode case. This means that the resonator length of the filter and coupler and the width of the strip conductor become small.

2) The differences between the phase-velocity ratios of the even mode and odd mode become smaller than in a conventional coupled strip line.

By using these charts, the filter and coupler design can be accomplished.

## VI. EXPERIMENTAL RESULTS OF THE CHARACTERISTIC IMPEDANCE OF S-CPS AND T-CPS

The circular dots plotted in Figs. 4, 5, and 7 are measured points. Experimental strip lines were made from gold-plated Cr–Au thin film. The coaxial to strip line connection was achieved by an omni spectra miniature (OSM) adapter. The characteristic impedances $Z_o$ of the S-CPS and $Z_{0e}{}^{II}$ of the T-CPS were measured by a time domain reflectometer. The maximum value of the differences from the calculated value is 3 percent in the S-CPS in Figs. 4

and 5 and 3.5 percent in the T-CPS in Fig. 7. This is considered to be due to the uncertainty in the value of the relative dielectric constant of the substrate, equipment construction errors, and measuring errors.

## VII. ACCURACY OF CALCULATION

The accuracy of the results can be checked by comparison with the results of [13], and is shown in Table V, where the program T-CPS (even-mode case) is computed by setting $b = 0$ (i.e., conventional type). It is seen that the value of the error of $Z_{0e}^{II}$ is 1.49 percent, when mesh points of height $s$ are 80 points, $w/s = 0.2$, and $g/s = 3.0$. The accuracy in regard to $(v/v_0)_e^{II}$ is better than $Z_{0e}^{II}$, as shown in Table V. In the calculation of the CPS, as in Figs. 5 and 10, the mesh points of $a$ are 84 points, $g/s = 2.48$ and error becomes small.

## VIII. EXAMPLES OF CPS APPLICATION TO MICROWAVE CIRCUITS

In this section, a microwave transistor amplifier using S-CPS and a parallel-coupled filter using C-CPS are described.

### A. *Microwave Transistor Amplifier*

Various microwave transistor amplifiers have already been reported, such as the balanced transistor amplifier [14] and single-transistor-cascaded type [15]–[18]. In this section, a transistor amplifier using S-CPS for a communication satellite use is described. In designing the amplifier configuration, special attention is paid to the realization of light weight, small size, and survival against shock and vibration.

In S-CPS, as shown in Fig. 1(a), it is easy to ground transistor leads and bypass capacitors by effective use of the ground plates. The characteristic impedance and phase–velocity ratio become small by setting the ground plates near the center strip conductor.

The major problems in designing transistor amplifiers are the design of matching circuits and achievement of good transistor grounding methods. The former is calculated by computer-aided design (CAD) [19], [20] and the latter is somewhat easier in CPS. The transistor emitter is grounded on ground plates set near the emitter, as shown in Fig. 9. The RF bypass capacitor (which has an electrode for face bonding) can easily be soldered on the terminals of the biasing inductance and ground plates.

Fig. 9 shows experimental results achieved for single- and two-stage amplifiers. From these results one sees that the 3-dB bandwidth is more than 3 GHz (1.2–4.3 GHz) and the gain is 5 dB and 11 dB, respectively. The transistor is a V-578 transistor (NEC) of n-p-n silicon epitaxial-planar type.

TABLE V
ACCURACY OF THE RELAXATION METHOD COMPARED WITH [13]

| $w/s$ | $g/s$ | Results of [13] | | Results of Relaxation Method and Error | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $Z_0$ (Ω) | $v/v_0$ | Mesh ($s\times g$) | $Z_{0e}^{II}$ Ω | Error (percent) | $(v/v_0)_e^{II}$ | Error (percent) |
| 0 2 | 2 0 | 95. 7 | 0. 8965 | 100×200 | 94 912 | 0 82 | 0. 89611 | 0. 044 |
| 0 2 | 2 0 | 95 7 | 0. 8965 | 80×160 | 94 648 | 1 09 | 0 89604 | 0 051 |
| 0 2 | 3 0 | 97 0 | 0 9008 | 100×300 | 95 780 | 1 25 | 0 90081 | 0 001 |
| 0 2 | 3 0 | 97 0 | 0 9008 | 80×240 | 95 554 | 1 49 | 0 90098 | 0. 019 |
| 0 333 | 2 0 | 81 2 | 0 9109 | 60×120 | 79 823 | 1 69 | 0 90942 | 0. 162 |
| 0 333 | 3 0 | 81 8 | 0 9153 | 60×180 | 80 785 | 1 24 | 0 91566 | 0 039 |
| 0 466 | 2. 0 | 69 9 | 0 9209 | 60×120 | 69. 472 | 0 61 | 0 91846 | 0 178 |
| 0 466 | 3 0 | 70 9 | 0 9259 | 60×180 | 70. 511 | 0 54 | 0 92587 | 0 003 |

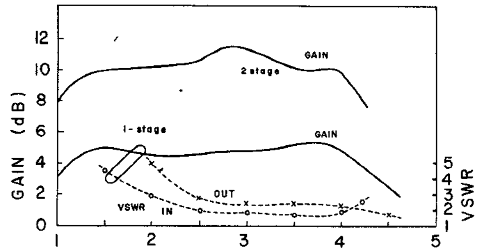


Fig. 9. Characteristics of single- and two-stage wide-band transistor amplifiers.

A four-stage amplifier was constructed by cascading two-stage amplifiers, using a matching circuit. An isolator is added to the output port to improve the output VSWR and for ease of cascading subsequent amplifiers or other passive circuits. The isolator has a bandwidth greater than 1 GHz and VSWR less than 1.5:1. The four-stage amplifier and isolator are mounted in a single compact package as shown in Fig. 10, with the center strip conductors and ground plates electrically connected by soldering or thermal compression bonding. With this packaging technique: 1) high performance stability is achieved by reducing the number of coaxial connectors; 2) amplifier blocks, as well as other circuits [for example, filters and automatic gain control (AGC)], can be connected or replaced as desired; and 3) miniaturization of the amplifier assembly is obtained.

Fig. 11 shows the characteristics of the four-stage amplifier. This amplifier has a bandwidth greater than 1 GHz (3.2–4.2 GHz), a gain of 22 dB ± 0.2 dB, an input VSWR smaller than 3.0:1, and an output VSWR smaller than 1.6:1. Amplifier weight is 70 g.

Merits of the amplifier using S-CPS follow.

1) By using CPS, the electrical field is concentrated near the center strip conductor, so signal injection to the transistor chip and impedance matching can be achieved smoothly. And the emitter lead inductance becomes small due to the existence of a ground plate. As a result, wide-bandwidth characteristics are realized.

2) Grounding can be accomplished reliably in a narrow space so the amplifier size becomes small and the number of soldered portions can be decreased, resulting in high subsystem reliability.

3) Low-impedance matching circuits (i.e., parallel capacitors) can be realized by getting near the ground plates to center strip conductor. Small size can also be achieved.

4) Due to the existence of a ground plate, the effect of other circuits on the amplifier characteristics becomes smaller than in a conventional-type strip line.

### B. *Parallel-Coupled Filter Using C-CPS*

By using a characteristic impedance and phase–velocity ratio chart like Fig. 8 and the design formula of a parallel-

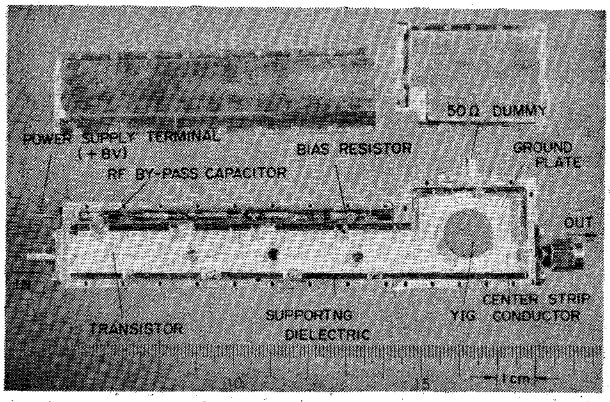


Fig. 10. Four-stage transistor amplifier.

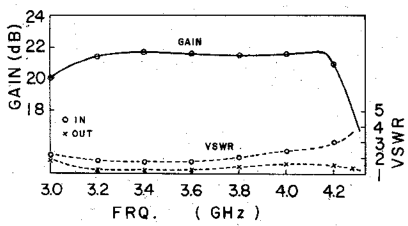


Fig. 11. Characteristics of the four-stage transistor amplifier.

coupled filter, the demensions of a parallel-coupled filter are determined. Fig. 12 shows the pattern of a parallel-coupled filter using C-CPS.

Fig. 13 shows an example of the characteristics of this filter.

In Fig. 13, four values of the length of resonator ($l$) and gap distance between the edge of the resonator and the ground plate ($G$) are chosen as follows. Parameters of filter ① are $l = 24.2$ mm, $G = 0.8$ mm; parameters of filter ② are $l = 24.2$ mm, $G = 0.8$ mm; parameters of filter ③ are $l = 19.6$ mm, G = 1.5 mm; and parameters of filter ④ are $l = 24.2$ mm, $G = 0.3$ mm. Alumina ceramics were put in the gaps. Lines were made from silver-plated Cr–Au thin film.

From Fig. 13, the following is seen.

1) The filter symmetry in the frequency characteristic is better than that of a conventional suspended triplate strip line because of the small difference of the phase-velocity ratio between the even mode and the odd mode of C-CPS.

2) The resonator length and width of line become small because the characteristic impedance and phase–velocity ratio are smaller in C-CPS than in conventional coupled strip line.

3) The resonator length can be further shortened by using a small gap distance between the resonator edge and ground plate ($G$). In Fig. 13, $G$ values of 0.3 mm, 0.8 mm, and 1.5 mm are shown. In the case of $G = 0.3$ mm and $l = 24.2$ mm the reduction ratio is about 50 percent, compared with a conventional suspended triplate strip-line coupled filter. This reduction ratio can be increased by using a small value of $G$.

Such capacitive loading by narrowing the gap distance between the resonator edge and the ground plate can only done by using C-CPS (i.e., the fringing capacitance of a conventional type of filter is smaller in value than for C-CPS).

4) Due to the existence of a ground plate, the effect of a side wall or of other circuits on the filter characteristics becomes smaller than in a conventional strip-line filter. Also the side wall can be near the strip conductor, so the filter becomes small in size.

5) The filter resonance frequency can be shifted lower by putting a dielectric (for example, Teflon or alumina ceramics) in the gap between resonator edge and ground plate as shown in the curve ④ in Fig. 13. The reduction ratio can thereby be increased. This shows that resonance frequency fine tuning is easy in this type of filter.

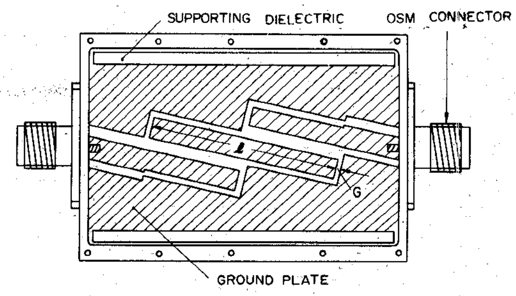


Fig. 12. C-CPS parallel-coupled filter.

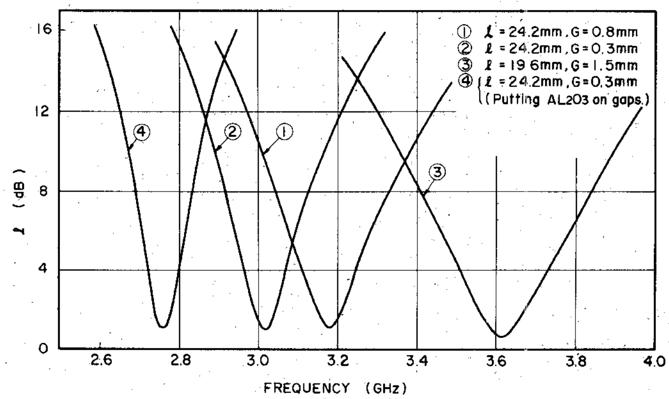


Fig. 13. Characteristics of C-CPS parallel-coupled filter.

## IX. CONCLUSION

Using the relaxation method, the characteristics of the S-CPS and the T-CPS are obtained. Merits of the CPS are the following. 1) The CPS is a shielded-type transmission line, so it is suitable for use in high-gain transistor amplifiers or other active circuits. 2) The characteristic impedance and phase–velocity ratio become small, compared with the conventional-type line, due to the existence of ground plates. 3) It is easy to connect shunt elements, for example, in the circuits in transistor amplifiers. 4) It can be used in nonreciprocal magnetic-device applications, similar to the CPW [1] and slot line [21]. 5) The effect of side wall and other circuits near the center conductor is smaller than for a conventional type. 6) The effect of variation of distances is smaller than for a conventional type. 7) When the T-CPS is used as coupled line, the difference between even- and odd-mode phase–velocity ratio is smaller than for the conventional type, so directional couplers and filters which have good characteristics can be achieved. 8) It is easy to use together with the CPS and conventional-type line.

Examples of application of S-CPS in a transistor amplifier and C-CPS in a parallel-coupled filter, respectively, are shown.

A transistor amplifier small in size, light in weight, with wide bandwidth and more reliability is achieved.

A parallel-coupled filter small in size, with good frequency symmetry and easy resonance frequency fine tuning is obtained.

There are many other CPS applications, for example, microwave tunnel-diode amplifier, mixer, coupler [22], attenuator, and nonreciprocal circuits at microwave frequencies.

The relaxation method analysis is a quasi-TEM approximation. Thus it has a high-frequency limit, so another method should be considered at high frequencies.

## ACKNOWLEDGMENT

The author wishes to thank Dr. R. W. Beatty and Dr. S. Shimada for their helpful comments about CPS. The author also wishes to thank S. Morimoto, Director of the Satellite Communication Section, H. Fuketa, Staff Engineer of the Satellite Communication Section, and N. Sinji, Staff Engineer of the Radio Propagation Section for their valuable discussions. He also wishes to thank H. Sakamoto and M. Kaji, members of the Satellite Communication Section in the Yokosuka Electrical Communication Laboratory, and members of the Computation Section and the Electronic Circuit Section in the Musashino Electrical Communication Laboratory, for their cooperation.

## REFERENCES

[1] C. P. Wen, "Coplanar waveguide: A surface strip transmission line suitable for nonreciprocal gyromagnetic device applications," *IEEE Trans. Microwave Theory Tech.* (*1969 Symposium Issue*), vol. MTT-17, pp. 1087–1090, Dec. 1969.
[2] R. V. Southwell, *Relaxation Methods in Theoretical Physics*, vol. 1. New York: Oxford, 1946.
[3] H. E. Green, "The numerical solution of some important transmission-line problems," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Microwave Filters*), vol. MTT-13, pp. 676–692, Sept. 1965.
[4] M. V. Schneider, "Computation of impedance and attenuation of TEM-lines by finite difference methods," *IEEE Trans. Microwave Theory Tech.* (*1965 Symposium Issue*), vol. MTT-13, pp. 793–800, Nov. 1965.
[5] J. W. Duncan, "The accuracy of finite-difference solutions of Laplace's equation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 575–582, Oct. 1967.
[6] D. H. Sinnott, "The use of interpolation in improving finite difference solutions of TEM mode structures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 20–28, Jan. 1969.
[7] D. H. Sinnott, G. K. Cambrell, C. T. Carson, and H. E. Green, "The finite difference solutions of microwave circuit problems," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Computer-Oriented Microwave Practices*), vol. MTT-17, pp. 464–478, Aug. 1969.
[8] T. Hatsuda and T. Matsumoto, "Computation of impedance of partially filled and slotted coaxial line," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-15, pp. 643–644, Nov. 1967.
[9] T. Hatsuda *et al.*, "Computation of characteristic impedance of inhomogeneous slotted coaxial lines by relaxation method," *J. Inst. Electron. Commun. Jap.*, vol. 51-B, pp. 91–99, Apr. 1968; also *J. Inst. Electron. Commun. Eng. Jap.* (in Japanese), vol. 51-B, pp. 156–163, Apr. 1968.
[10] T. Hatsuda, "Computation of the characteristics of coplanar-type strip lines by the relaxation method," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-20, pp. 413–416, June 1972.
[11] T. Hatsuda and T. Kimura, "Computation of single strip conductor and symmetrical and asymmetrical two strip conductor strip-line characteristics by relaxation method," *Rev. Elec. Commun. Lab.*, vol. 20, pp. 36–46, Jan.–Feb. 1972.
[12] ——, "Computation of single strip conductor and symmetrical and asymmetrical two strip conductor strip-line characteristics by relaxation method," *J. Inst. Electron. Commun. Eng. Jap.*, vol. 54-B, pp. 467–474, 1971.
[13] D. L. Gish and O. Graham, "Characteristic impedance and phase velocity of a dielectric-supported air strip transmission line with side walls," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 131–148, Mar. 1970.
[14] K. M. Eisele, R. S. Engelbrecht, and K. Kurokawa, "Balanced transistor amplifier for precise wideband application," in *Dig. Tech. Papers, 1965 Int. Solid-State Circuits Conf.*, vol. 8, pp. 18, 19.
[15] A. Ayaki, E. Igarashi, and Y. Kajiwara, "A 4-GHz multistage transistor amplifier," *IEEE Trans. Microwave Theory Tech.* (*1969 Symposium Issue*), vol. MTT-17, pp. 1072–1077, Dec. 1969.
[16] T. Hatsuda, "A wide band transistor amplifier at the 4 GHz band for communication satellite use," in *Proc. 9th Int. Symp. Space Technology and Science* (Tokyo, Japan, 1971), pp. 749–756.
[17] ——, "A wide band transistor amplifier at the 4 GHz band for communication satellite use," Tech. Group on Microwaves, Inst. Elec. Commun. Eng. Jap., Paper MW 71-5, 1971.
[18] W. Baechtold, "*Q*-band GaAs F.E.T. amplifier and oscillator," *Electron. Lett.*, vol. 7, pp. 275–276, 1971.
[19] T. W. Houston and L. W. Read, "Computer-aided design of broad-band and low-noise microwave amplifiers," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Computer-Oriented Microwave Practices*), vol. MTT-17, pp. 612–614, Aug. 1969.
[20] T. N. Trick and J. Vlach, "Computer-aided design of broadband amplifiers with complex loads," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 541–547, Sept. 1970.
[21] S. B. Cohn, "Slot line on a dielectric substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 768–778, Oct. 1969.
[22] C. P. Wen, "Coplanar-waveguide directional couplers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 318–322, June 1970.