Traveling-wave microwave power divider composed of reflectionless dividing units

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***Abstract*— We propose a new waveguide type traveling-wave microwave power divider that is adequate for high power applications. The divider is composed of multiple stages of reflectionless dividing units, each having two output ports. Design formulas for reflectionless equal-power dividing are first derived. Structural parameters for wideband design of two- to six-stage dividers are then obtained by means of numerical analyses based on an equivalent circuit. Comparison of experiments at X-band shows good qualitative agreement with the analyses. Typical measured bandwidth for relative divided powers deviation of less than ± 0.5 dB was 2.7 GHz, and that for -20 dB return loss was more than 3.2 GHz for the four-stage (eight-way) divider.**
The divider presented here has excellent features; the bandwidth for equal-power dividing decreases very little and the bandwidth for low return loss increases with increasing number of the dividing stages. It also has advantages of low insertion loss and flexibility over the number of the dividing stages.

***Index Terms*— Microwave, power dividing, power combining, traveling-wave operation.**

I. Introduction

POWER combining is indispensable in realizing high-output solid-state microwave power amplifiers for systems such as in satellite communication or broadcasting [1], [2]. Power combining of microwave amplifiers usually operates in three stages: dividing the input signal, amplifying the divided signals, and combining the powers. Efficient power combining requires microwave multiple-port power dividers and combiners with low insertion loss and wideband characteristics.

Several kinds of dividers and combiners have been hitherto proposed and realized: "tree" structure in which a number of 3 dB hybrids are connected in the shape of a tree [3], [4], "N-way" structure which provides N branches in a single step [5]–[13], and "chain" structure in which a number of hybrids are successively connected [14]. A "tree" structure is easy to construct and has been widely used, but as the number of ports increases the configuration becomes more complicated and the insertion loss also increases. An "N-way" structure can provide a number of branches and many useful "N-way" dividers and combiners have been developed. A "chain" structure can exhibit a wideband traveling-wave operation with flexibility of increasing or decreasing the number of branches. However, it has scarcely been studied mainly because of necessity of a number of divider/combiner stages with different coupling coefficients.

Recently, the authors proposed a waveguide type divider/combiner of multiple-port ladder structure which is useful particularly for high-power applications [15]–[17]. Although the structure looks like the "chain" structure and it has moderately wideband characteristics, it does not represent an exact traveling-wave operation because each divider/combiner stage is not reflectionless. In this paper, we propose a new waveguide type multiple-port power divider of chain structure, which exhibits wideband traveling-wave operation by realizing local cancellation of reflections at each dividing stage. The divider is composed of many dividing units having a pair of coaxial branch ports and a short, narrow waveguide section. The divider provides advantages of low insertion loss, wideband characteristics, and wide selection of the number of branches.

In the following section, an equivalent circuit is introduced and design formulas are given for equal-power and reflectionless dividing. Section III is devoted to numerical analysis on the optimum design of a divider. After the scattering matrix of the narrow section is derived by means of the mode matching method, structural parameters of the dividing units are obtained through numerical analysis on the equivalent circuit. Design and characteristics of a wideband divider system are then discussed. In Section IV experimental results on the dividers are described and compared with the theory.

II. Structure and Design of the Divider

In a traveling-wave divider of chain structure, an input power should be divided equally among N successive branch ports with no reflection. Fig. 1 shows the traveling-wave divider of chain structure discussed in this paper. It is composed of N dividing units each of which consists of a waveguide section with a coaxial probe-pair followed by a thin narrow section. Each unit is numbered starting with the last unit. Since the reflected waves, caused by the probe-pair and by the narrow section in each dividing unit, can be canceled out with each other, it is possible that each unit has no reflection at its input port. Thus, globally, traveling-wave behavior can be exhibited with this divider structure.

Fig. 2 shows an equivalent circuit for the structure. Consider a unit $\#k$, and let the equivalent admittances looking toward the narrow section at the port-pair be $y_k = g_k + jb_k$, and the equivalent admittance of the coaxial probe-pair be $y_{pk} =$

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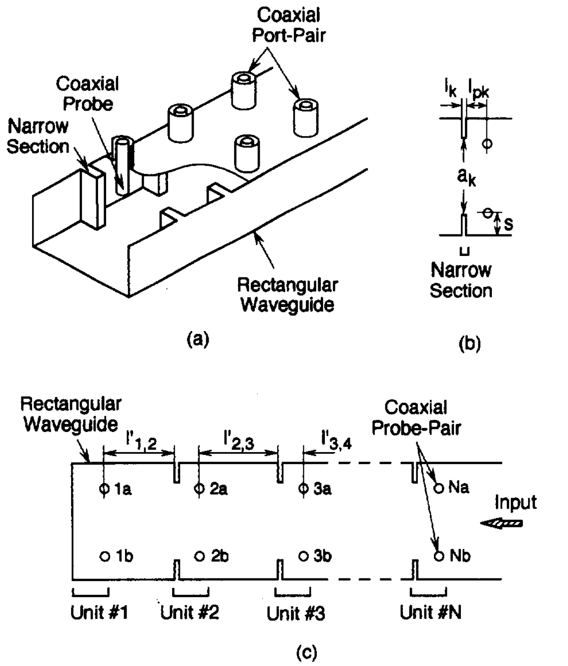


Fig. 1. Traveling-wave divider. (a) Aspect. (b) Dividing unit (unit $\#k$). (c) Construction of the divider.

$g_{pk}+jb_{pk}$, where all the conductances and susceptances are normalized by the characteristic admittance of the waveguide, Y_0. Assuming that the left side of unit $\#k$ is in the matched condition, requirement of no reflection at the input of the unit is written as

$$g_k+g_{pk}=1, \quad b_k+b_{pk}=0 \quad (2\le k\le N).$$

Because the ratio of the power delivered to the two output branch ports to the power transmitted to unit $\#(k-1)$, which we call the "power-dividing ratio," must be $1:(k-1)$ for equal power dividing, we have

$$\frac{g_{pk}}{g_k}=\frac{1}{k-1}. \tag{1}$$

From these equations, the design formulas for equal-power and reflectionless dividing are given as

$$g_k=\frac{k-1}{k} \quad (2\le k\le N), \tag{2}$$

$$g_{pk}=\frac{1}{k} \quad (2\le k\le N), \tag{3}$$

and

$$b_k+b_{pk}=0 \quad (2\le k\le N). \tag{4}$$

III. Numerical Analysis

A. Scattering Matrix of a Narrow Section

For discussion of the design of the dividing units which satisfy (2)~(4), the expression of the scattering matrix of a narrow section should be obtained.

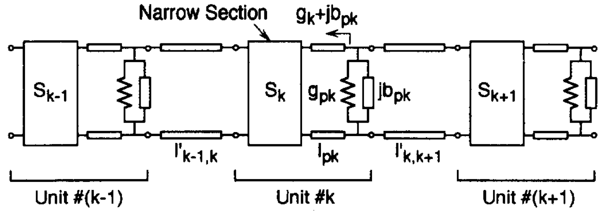


Fig. 2. Equivalent circuit.

Referring to Fig. 3, let the incident waves of TE_{i0} modes ($i=1,3,\ldots,M$; M is an odd number) to boundary I from region A and B be $\mathbf{a}_A^{I}=[a_{A1},a_{A3},\ldots,a_{AM}]^t$ and $\mathbf{a}_B^{I}=[a_{B1},a_{B3},\ldots,a_{BM}]^t$, respectively and the reflected waves be $\mathbf{b}_A^{I}=[b_{A1},b_{A3},\ldots,b_{AM}]^t$ and $\mathbf{b}_B^{I}=[b_{B1},b_{B3},\ldots,b_{BM}]^t$, respectively. Similarly, let the incident waves to boundary II from region B and C be $\mathbf{a}_B^{II}$ and $\mathbf{a}_C^{II}$, respectively, and the reflected waves be $\mathbf{b}_B^{II}$ and $\mathbf{b}_C^{II}$, respectively. We represent the scattering property of boundary I as

$$\begin{bmatrix}\mathbf{b}_A^{I}\\ \mathbf{b}_B^{I}\end{bmatrix}=\mathbf{S}^{I}\begin{bmatrix}\mathbf{a}_A^{I}\\ \mathbf{a}_B^{I}\end{bmatrix}, \quad \mathbf{S}^{I}=\begin{bmatrix}\mathbf{S}_{11}^{I} & \mathbf{S}_{12}^{I}\\ \mathbf{S}_{21}^{I} & \mathbf{S}_{22}^{I}\end{bmatrix}. \tag{5}$$

Then the scattering matrix for boundary II, $\mathbf{S}^{II}$, can be written, from the symmetry of the structure, as

$$\mathbf{S}^{II}=\begin{bmatrix}\mathbf{S}_{11}^{II} & \mathbf{S}_{12}^{II}\\ \mathbf{S}_{21}^{II} & \mathbf{S}_{22}^{II}\end{bmatrix}=\begin{bmatrix}\mathbf{S}_{22}^{I} & \mathbf{S}_{21}^{I}\\ \mathbf{S}_{12}^{I} & \mathbf{S}_{11}^{I}\end{bmatrix}. \tag{6}$$

$\mathbf{S}^{I}$ and $\mathbf{S}^{II}$ can be calculated using the mode matching method. Considering that $\mathbf{b}_B^{I}$ is transformed to $\mathbf{a}_B^{II}$, and $\mathbf{b}_B^{II}$ to $\mathbf{a}_B^{I}$ by the narrow section (Region B) of length l, we obtain the scattering matrix of the narrow section as

$$\mathbf{S}_c\equiv\begin{bmatrix}\mathbf{S}_{11}^{I} & \mathbf{O}\\ \mathbf{O} & \mathbf{S}_{22}^{II}\end{bmatrix} + \begin{bmatrix}\mathbf{S}_{12}^{I}\mathbf{D} & \mathbf{O}\\ \mathbf{O} & \mathbf{S}_{21}^{II}\mathbf{D}\end{bmatrix}\begin{bmatrix}\mathbf{E}\mathbf{S}_{11}^{II}\mathbf{D} & \mathbf{E}\\ \mathbf{F} & \mathbf{F}\mathbf{S}_{22}^{I}\mathbf{D}\end{bmatrix}\begin{bmatrix}\mathbf{S}_{21}^{I} & \mathbf{O}\\ \mathbf{O} & \mathbf{S}_{12}^{II}\end{bmatrix}, \tag{7}$$

where $\mathbf{O}$ is the null matrix and $\mathbf{D}$, $\mathbf{E}$ and $\mathbf{F}$ are given by

$$\mathbf{D}=\begin{bmatrix}e^{-\gamma_1 l} & & 0\\ & \ddots & \\ 0 & & e^{-\gamma_M l}\end{bmatrix}, \tag{8}$$

$$\mathbf{E}=(\mathbf{I}-\mathbf{S}_{11}^{II}\mathbf{D}\mathbf{S}_{22}^{I}\mathbf{D})^{-1}, \tag{9}$$

and

$$\mathbf{F}=(\mathbf{I}-\mathbf{S}_{22}^{I}\mathbf{D}\mathbf{S}_{11}^{II}\mathbf{D})^{-1}, \tag{10}$$

with γ_i being the propagation constant of TE_{i0} mode ($i=1,3,\ldots,M$) in region B. Then, the reflection coefficient for an incident TE_{10} wave to boundary I, S_{c11}, can be calculated by (7), which in turn gives the equivalent admittance looking toward region B from region A (at boundary I) as

$$\hat{y}=\frac{1-S_{c11}}{1+S_{c11}} \tag{11}$$

This quantity is transformed to $y_k=g_k+jb_k$ by the line of length l_{pk}.

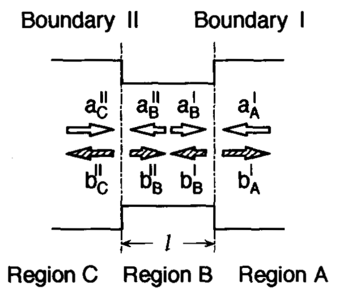


Fig. 3. Scheme for the analysis.

TABLE I
OPTIMUM VALUES OF THE STRUCTURAL PARAMETERS AND THE BANDWIDTH OF THE DIVIDING UNITS

k	2	3	4	5	6
g_k	1/2	2/3	3/4	4/5	5/6
b_k	−0.522	−0.311	−0.221	−0.172	−0.141
a_k[mm]	14.90	16.84	17.87	18.55	19.03
l_k[mm]	1.0	1.0	1.0	1.0	1.0
βl_{pk}[rad]	$\pi/8$	$\pi/8$	$\pi/8$	$\pi/8$	$\pi/8$
B_d[GHz]	4.2	≥ 4.8	≥ 5.0	≥ 5.0	≥ 5.0
B_r[GHz]	2.2	3.0	≥ 4.3	≥ 4.5	≥ 4.6

B. Design of Dividing Units

Based on the equivalent circuit shown in Fig. 2 and using the scattering matrix of the narrow section given in the previous section, numerical analysis was carried out for each dividing unit. This analysis yielded the relation among the structural parameters a_k, l_k and l_{pk}, for which g_k satisfies the condition (2) at a specified frequency. Thirty TE_{i0} modes ($i = 1, 3, \ldots, 59$) of both the incident and reflected waves in the waveguide were taken into account in the analysis using the mode matching method. The admittance of the probe-pair was determined so as to satisfy the condition (3) and (4), and no frequency dependence of the admittance was assumed.

Numerical design was carried out for X-band dividers with the design frequency 9.0 GHz. In order to describe wideband characteristic of a dividing unit, we define the width of a band in which deviations of both the delivered power and the transmitted power from the desired values are within ± 0.5 dB as B_d, and a set of values for a_k, l_k and l_{pk} was chosen so as to maximize the bandwidth B_d. The results are shown in Table I. It is noticed in the table that values of l_k and βl_{pk} (β is the phase constant of TE_{10} mode in the waveguide) are chosen as 1.0 mm and $\pi/8$, respectively, independent of k. This is because, then, almost the maximum B_d can be obtained merely by adopting these values for every k. The reason why $\beta l_{pk} \simeq \pi/8$ gives the wideband characteristics is that frequency dependent admittance $\hat{y}$ can be transformed to an admittance of much less frequency dependence by the line of length l_{pk}. The width of a band in which the reflection coefficient of a dividing unit is less than −20 dB, B_r, is also given in the table for $k = 2 \sim 6$ and it is seen that B_d and B_r increase with k because the power-dividing ratio decreases with increasing k (see (1)).

TABLE II
OPTIMUM VALUES OF $l'_{k-1,k}$

k	3	4	5	6
$l'_{k-1,k}$[mm]	5.4	6.0	7.0	7.0

Considerable physical demension tolerances are shown by the numerical analysis. For example, for unit #3, deviation of 0.1 mm in one of the parameter values of a_3, l_3 and l_{p3} causes the deviation within 0.5% in the transmitted power through the unit and the maximum return loss as small as −44 dB.

C. Wideband Design of the Divider

A divider system is constructed using the dividing units described above in the manner that unit #k is connected to unit #$(k-1)$ with the line of length $l'_{k-1,k}$. Although the lengths of the connecting lines between $(k-1)$-th and k-th units, $l'_{k-1,k}$'s, are arbitrary at the design frequency because no reflection exists on the connecting line, $l'_{k-1,k}$ is chosen so as to maximize the bandwidth B_d through numerical analysis based on the equivalent circuit of Fig. 2, assuming unit #1 is perfectly matched. Table II shows the optimum values of $l'_{k-1,k}$.

As for unit #1, it is required to have a good matching characteristic. In the following, we consider three types for unit #1: A) a unit of the perfect matching characteristic, B) a unit of a simple structure as shown in Fig. 1(c), and C) a unit with a matching iris (see Fig. 7(c)).

Type A has the ideal matching characteristic at every frequency. Type B consists of a probe-pair whose conductance is unity and a shorting plate which should cancel out the susceptance of the probe-pair. For this probe-pair, the one whose admittance is $y_{p1} = 1.0 + j0.74$ was chosen because this gave the widest bandwidth of $B_r = 1.1$ GHz for unit #1 among realizable probe-pairs in the experiment. For type C, a large bandwidth $B_r = 4.9$ GHz was obtained for an optimized composition of a probe-pair whose admittance is $y_{p1} = 1.37 + j0.41$ and a capacitive iris.

The values of B_d and B_r for the three types of the dividers of $N = 2 \sim 6$ are given in Table III, where the columns of $N = 1$ indicate the characteristics of unit #1's. $l'_{1,2}$'s were taken as 5.4 mm in case B and 5.6 mm in case C so as to maximize B_d's for the dividers of $N = 2$. Typical frequency characteristics of the dividers are shown in Fig. 4, for cases A and B in which Type A and B is used as unit #1, respectively.

As for B_d, the bandwidths of case B is the narrowest as is expected, but the difference among the bandwidths decreases with increasing number of the stages N. Also, the bandwidth little decreases as the number of stages increases in all the cases. As for B_r, it has a tendency to increase with N. This is because reflection by a unit diminishes with increasing unit number k, and because the incident wave to unit #1 is diminished when N increases and poor frequency

TABLE III
VALUES OF B_d AND B_r OF THE DIVIDERS. (a) FOR THE CASE IN WHICH UNIT #1 IS REFLECTIONLESS (CASE A). (b) FOR THE CASE IN WHICH THE SIMPLE STRUCTURE SHOWN IN FIG. 4 IS USED AS UNIT #1 (CASE B). (c) FOR THE CASE IN WHICH A PROBE-PAIR WITH A MATCHING IRIS IS USED AS UNIT #1 (CASE C)

(a)

N	1	2	3	4	5	6
B_d[GHz]	–	4.20	2.85	3.00	3.00	2.95
B_r[GHz]	∞	1.85	3.65	5.05	5.70	6.05

(b)

N	1	2	3	4	5	6
B_d[GHz]	–	2.80	2.65	2.75	2.85	2.80
B_r[GHz]	0.8	3.15	4.80	5.80	4.45	5.10

(c)

N	1	2	3	4	5	6
B_d[GHz]	–	3.80	3.15	3.00	3.05	2.85
B_r[GHz]	4.9	2.15	3.80	5.05	5.65	6.05

characteristic of unit #1 becomes less important. Additionally, it is seen in Table III that case B has the largest value of B_r for $N = 2 \sim 4$. In case B, both unit #1 and #2 have relatively narrow bandwidth, and proper value of $l'_{1,2}$ can make the reflection by both the units partially cancel with each other to widen the frequency characteristic of the combination of these two units. It should be noted in Table III that case C shows excellent wideband characteristics comparable with case A though unit #1 of type C has the structure of easy fabrication.

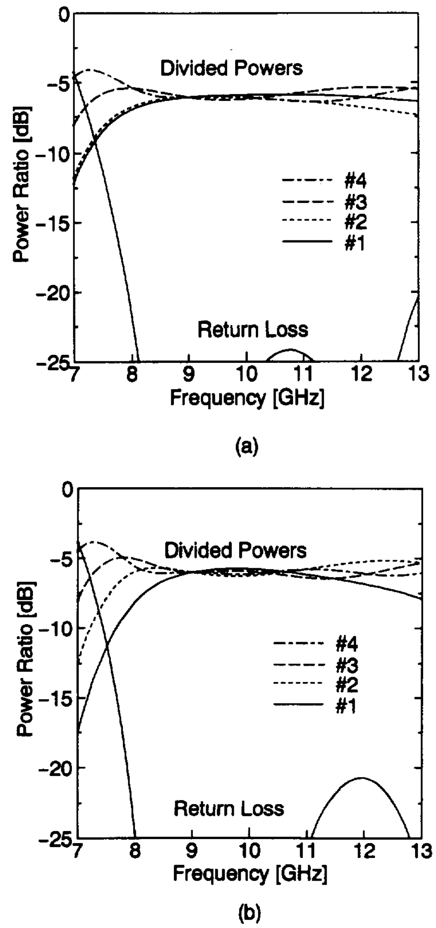


Fig. 4. Frequency characteristics of the four-stage (eight-way) divider. (a) Case when unit #1 is reflectionless (case A). (b) Case when the simple structure is used as unit #1 (case B).

IV. EXPERIMENTS

A. Admittances of Narrow Sections

Experiments were carried out at X-band for four- to eight-way ($N = 2 \sim 4$) dividers whose designs were given in Tables I and II. Measured results on the frequency characteristics of the admittance looking at the position of probe-pair toward each narrow section with matched termination, y_k, agreed well with the corresponding calculated results. A typical result is shown for unit #3 in Fig. 5.

B. Characteristics of Dividing Units

Measurements on the characteristics of the dividing units of the optimum design given in Table I were carried out. The structure of the probe-pair whose admittance y_{pk} realizes the conditions (3) and (4) was determined experimentally with the position and the length of the probe-pair varied. The structural parameters are given in Table IV. Fig. 6 shows the measured results of the power passing through the unit #2 and the reflected power of the unit, together with the corresponding calculated results based on the equivalent circuit of Fig. 2. The frequency at which reflected power takes the minimum is seen about 1 GHz higher than the design frequency of 9.0 GHz. The reason is considered that the higher modes in the line between the narrow section and the probe-pair affect the admittances y_k and y_{pk}. The values of B_d and B_r for the dividing units of $k = 2 \sim 4$ are listed in Table V. The bandwidths almost agree with the corresponding calculated results shown in Table I.

C. Characteristics of the Dividers

So as to construct a divider system, the dividing units were successively connected by the lines whose lengths are listed in Table II.

A commercially available coaxial-waveguide converter with sufficiently wide frequency characteristics (HP X281C; Measured VSWR was less than 1.03 over the X-band) was substituted for unit #1 of type A. Measured bandwidths

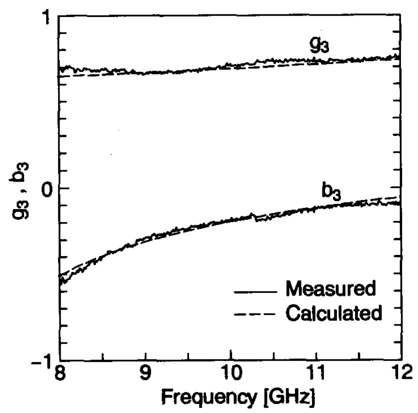


Fig. 5. Admittance of a narrow section ($k = 3$).

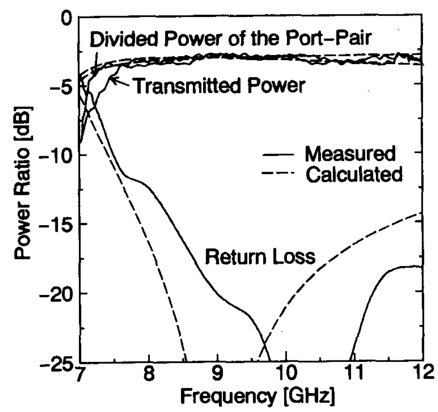


Fig. 6. Characteristics of a dividing unit ($k = 2$).

TABLE IV
STRUCTURE OF THE PROBE-PAIRS USED IN THE EXPERIMENT

k	2	3	4
s [mm]	4.0	3.6	3.4
d_p [mm]	5.8	5.2	5.0
g_{pk}	0.51	0.33	0.25
b_{pk}	0.53	0.31	0.22

TABLE V
MEASURED B_d AND B_r OF THE DIVIDING UNITS

N	2	3	4
B_d [GHz]	≥ 4.1	≥ 4.3	≥ 4.8
B_r [GHz]	2.0	≥ 3.4	≥ 3.6

TABLE VI
MEASURED B_d AND B_r OF THE DIVIDER

(a)

N	2	3	4
B_d [GHz]	4.54	2.72	2.77
B_r [GHz]	2.28	2.79	≥ 3.48

(b)

N	2	3	4
B_d [GHz]	≥ 2.79	1.98	2.10
B_r [GHz]	≥ 2.99	≥ 2.88	2.93

(c)

N	2	3	4
B_d [GHz]	4.26	2.88	2.67
B_r [GHz]	2.80	≥ 2.80	3.17

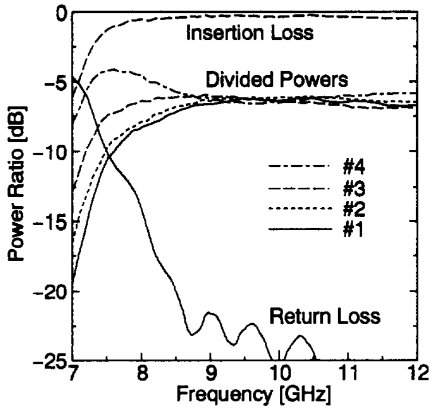
B_r's of unit #1 of type B and C were 1.2 GHz and 3.8 GHz, respectively. Fig. 7 shows measured power dividing characteristics and return losses of the four-stage dividers for cases A$\sim$C.

The measured values of B_d and B_r for the dividers of $N = 2\sim4$ are also shown in Table VI. The measured result qualitatively agrees with the calculated, indicating equal-power dividing over sufficiently wide frequency range with return loss much less than -20 dB. The insertion losses were less than 0.1 dB in the band of B_d for $N = 2$ and 3, though insertion loss of 0.2 dB appeared for $N = 4$.

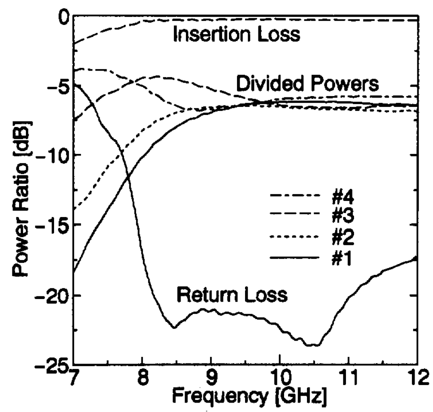
D. Isolation

In order to investigate the isolation characteristics of the dividers, power transmission coefficients among ports were measured. Fig. 8 shows the typical measured data of isolations for the four-stage divider using unit #1 of type B. The isolation between the paired ports of unit #1, 1a and 1b, shows the worst isolation of 6.0 dB, and all the other isolations even between the paired ports in the other divding units are better than about 10 dB in the frequency range of B_d. In the four-stage divider using unit #1 of type C, almost the same isolation characteristic was obtained, except poorer isolation between ports 1a and 1b. It is considered that in unit #1 of type C, these ports interact with each other because a standing wave occurs due to the capacitive iris when port 1a or 1b is excited.

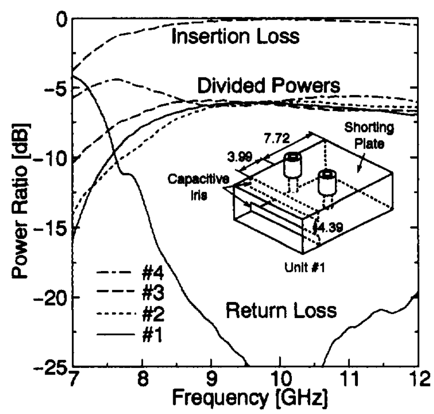
Isolation is important for the divider performance when the load VSWR of each output port is not small enough. Isolation between certain two output ports, say port $\#k$ and port $\#l$



(a)



(b)



(c)

Fig. 7. Measured results on the four-stage divider. (a) HP X281C (for case A), (b) simple structure shown in Fig. 1 (case B; $y_{p1} = 1.0 + j0.74$), and (c) the structure with a probe-pair and a matching iris (case C; $y_{p1} = 1.37 + j0.41$) are used as unit #1.

is represented by the scattering matrix element S_{kl}. When the reflection coefficient of the load of port $\#k$, $\Gamma_L^{(k)}$ is small, the maximum deviation of the output power of port $\#l$ can be estimated by $2|\Gamma_L^{(k)}||S_{kl}|$, while the reflection coefficient at the input port is givin by $|\Gamma_L^{(k)}|/2N$. For a eight-way divider, by using the values of $|S_{kl}|$'s in Fig. 8, the mismatch of the load

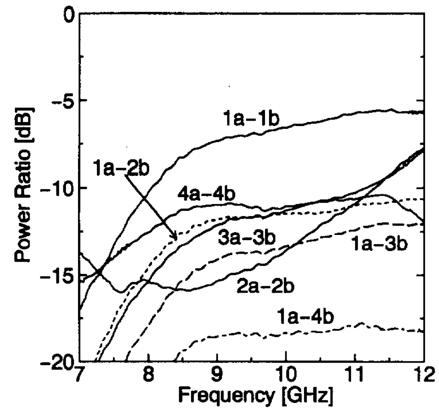


Fig. 8. Worst case isolation of the four-stage (eight-way) divider of case B. 1a, 1b, 2a, ..., etc. denote the port number (cf. Fig. 1).

VSWR = 1.5 gives rise to output power deviation of 18% in the worst case (port 1a–1b), and deviation less than 12% in the other cases, and input return loss of −32 dB.

V. Conclusion

We have proposed a new waveguide type traveling-wave power divider which is useful particularly for high-power applications. We have shown that the divider has the advantages of both wideband and low insertion loss characteristics. Since the divider has a chain structure, it is easy to increase/decrease the number of dividing ports.

In principle, the divider is composed of reflectionless dividing units, each having two output branch ports. The portion of $k \geq 2$ of the divider have been designed to have the maximum bandwidth under the assumption that unit #1 has ideally no reflection. Three cases have been discussed for unit #1; unit #1 of the ideal characteristic (case A), the one with a simple structure(case B) and the one with a matching iris (case C). For dividers having three or more dividing units, numerical analyses have shown that the dividers of cases B and C can have almost comparable performance with case A, whereas the performance is more sensitive to adjustment errors in case B and C than in case A. In the experiments, the dividers have not necessarily shown such wideband characteristics as in the analyses for the case of B and C because of this sensitivity. Typical measured bandwidths B_d and B_r are as wide as 2.8 GHz and more than 3.5 GHz, respectively, for the four-stage (eight-way) divider with unit #1 of type C.

As revealed both analytically and experimentally, the divider has an excellent feature that the bandwidth concerning equal power dividing little decreases and the bandwidth concerning return loss rather increases with increasing number of the dividing stages.

The problem of the poor isolation between paired ports in unit #1 will be avoided by using unit #1 with a single output port though it requires to modify the design. Furthermore, it is necessary to discuss the combiner operation of the divider structure developed in this paper. These are the next important subjects to be studied.

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