the input reflection coefficient of the junctions was well below −30 dB in the same frequency range. Thus it can be concluded that the corner shaped junctions in the Fig. 9(b) coupler cause severe radiation losses, while at the same time the low-input reflection and high-directivity values are preserved.

The radiation losses of the curved arms were also measured [9] in a separate experiment and found to be well below 1 dB for frequencies above 27 GHz because of the large curvature radius of the arms.

The overall losses of the dielectric image line directional couplers could not be measured exactly; they range below 2 to 1 dB in the case of the Fig. 9(a) coupler and below 6 to 3 dB in the case of the Fig. 9(b) coupler.

VI. Conclusion

It is shown that it is possible to calculate the coupling properties of uniform coupled dielectric image lines and directional couplers on the basis of dielectric image lines at reasonable accuracy. Some design features for directional coupler structures are also discussed.

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On an Ultrabroad-Band Hybrid Tee

UDO BARABAS

***Abstract*—A hybrid tee is investigated which consists of two broad-band line transformers and a lumped branching point. The branching point forms a bridge circuit, the resistances of which are determined by six lines and their load resistors. The bandwidth is wider than three decades, extending from 2.4 MHz to 5 GHz, and is determined by the transformers. In a special version, the upper cutoff frequency can be shifted to about 12 GHz. The isolation between opposite lines is greater than 40 dB.**

I. Introduction

A HYBRID junction can be defined as a "waveguide arrangement (including coaxial transmission lines), with four branches which, when the branches are properly terminated, has the property that energy can be transferred from any one branch into only two of the remaining three" [1]. In common usage of such junctions, this energy is equally divided between the two branches. Many interesting arrangements of "hybrid tees," as they are also called, have been described. Familiar forms of the hybrid tee for radio frequencies are the magic tee and the hybrid ring, the former consisting of waveguides, the latter being composed of coaxial transmission lines [2]. In a different approach [3], a long gradual taper is required. Good performances over bandwidths exceeding a decade have been obtained. Another approach [4] used a 3-dB asymmetric coupled-transmission-line directional coupler and a Schiffman phase shifter. There, good performance over an octave bandwidth (2–4 GHz) was achieved. Again, another way of realizing hybrid tees is based on 3-dB directional couplers with phase shifters between them [5], [6]. The bandwidth is about four octaves (35–588 GHz) [5] and 8–12 GHz [6], respectively. In a further configuration [7], the hybrid consisted essentially of a coaxial junction with a shielded loop, the axis of which was located at the center of the tee. With such a circuit a bandwidth of approximately 10 percent at about 3 GHz was measured. The isolation between shunt and series arms was in the order of 40 dB. Another rigid coaxial and stripline hybrid tee [8] had a bandwidth of one octave at a frequency of

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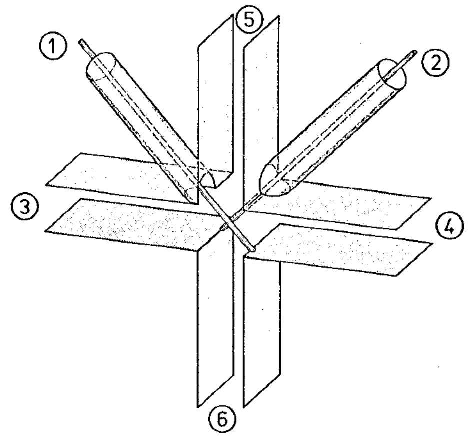

Fig. 1. Illustration of the branching point of the hybrid tee. The dielectrics of the semirigid coaxial cables and that between the conductors of the striplines are not shown.

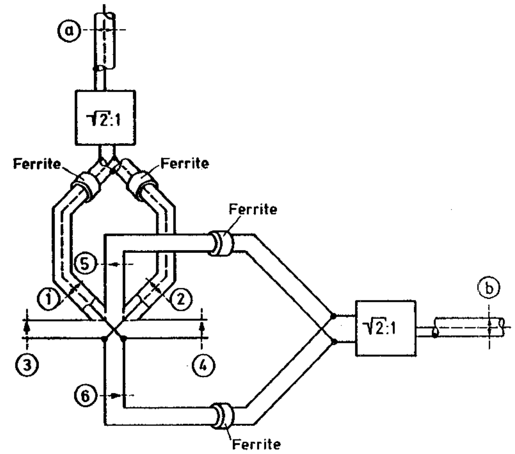

Fig. 3. Circuit of the hybrid tee (magic tee).

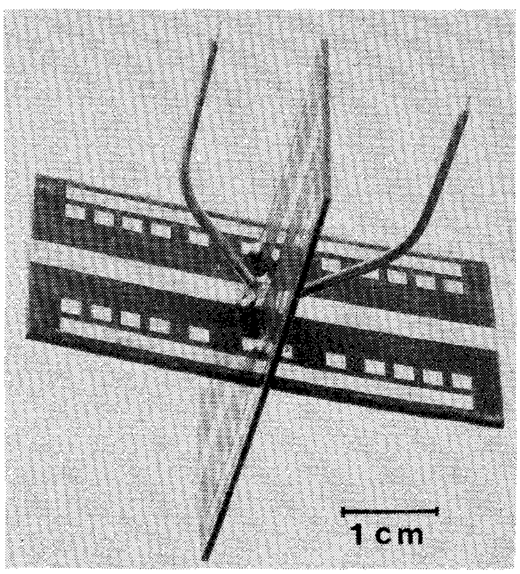

Fig. 2. Photo of the branching point. The substrate is 1 mm thick and the outer diameters of the coaxial semirigid cables are 1.2 mm.

200 MHz; the isolation between opposite ports was found to be 45–50 dB in the transmission frequency range. A further stripline hybrid tee, using two dual stripline bandpass filters [9], also exhibited a one-octave frequency bandwidth, while the isolation was higher than 20 dB. A hybrid tee developed from a balun [10] again showed an octave bandwidth.

In this paper a different kind of hybrid tee [11], [18] is analyzed which consists of both a lumped branching point [12], [13], constituting a bridge circuit, and two (transmission line) broad-band transformers [16]. The resistances of the bridge circuit are formed by six lines (four microstriplines and two coaxial semirigid cables) and their load resistors, with all lines having the same characteristic impedance (see Figs. 1 and 2). Two lines each of the six lines (lines (1) and (2), (3) and (4), and (5) and (6), respectively) are combined to three pairs of lines. The lines of each pair are symmetrical to one another. Two of the three pairs are joined and then connected to the broad-band transformers (see Fig. 3).

The resulting circuit is a 4-port hybrid tee employing no transmission lines with defined lengths related to a particular transmitted wavelength. This circuit is thus extremely suited for broad-band (pulse) applications. Analogous to the nomenclature of a waveguide hybrid tee, lines (3) and (4) are the colinear lines; (a) is the sum line, and (b) is the difference line.

This paper serves the theoretical approach of this kind of hybrid tee by analyzing the branching point (a 6-port one) and its symmetry properties in connection with a suitable combination of some lines of the branching point with broad-band transformers. Furthermore, a modification of the hybrid tee is proposed. This modification leads to an essentially increased upper cutoff frequency between the colinear lines and the two output lines of the resulting circuit.

II. Analysis of the Hybrid Tee

All input lines of the hybrid tee are matched in the transmission frequency range of the broad-band transformers if all lines have the same characteristic impedance. The transmission ratio of the transformers is $(V_{in} : V_{out}) = (\sqrt{2} : 1)$, matching the input lines (a) and (b) to the shunted lines (1) and (2) or (5) and (6), respectively. Providing line (a) with an input signal, this signal—equally divided—reaches the branching point via lines (1) and (2). In the branching point the two arriving identical signals are again equally divided and coupled into the lines (3), (4), (5), and (6). The lines (1) and (2) are isolated from each other. Fig. 4 shows the equivalent circuit of the branching point, with the six lines represented by their characteristic impedances $Z_{0n} (n = 1–6)$. It can be seen that in the lines (5) and (6) the arriving signals are superimposed to zero, and in the lines (3) and (4) to the full amplitude, being as high as in the lines (1) and (2). If the lines (3) and (4) are terminated to be matched, the hybrid tee operates as a power divider. In case of mismatched terminations in the lines (3) and (4), reflected

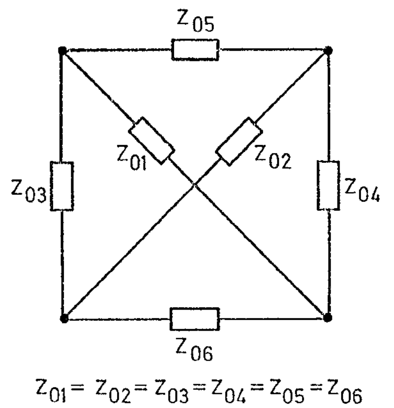

Fig. 4. Equivalent circuit of the branching point; the six lines are represented by their characteristic impedances Z_{01}–Z_{06}.

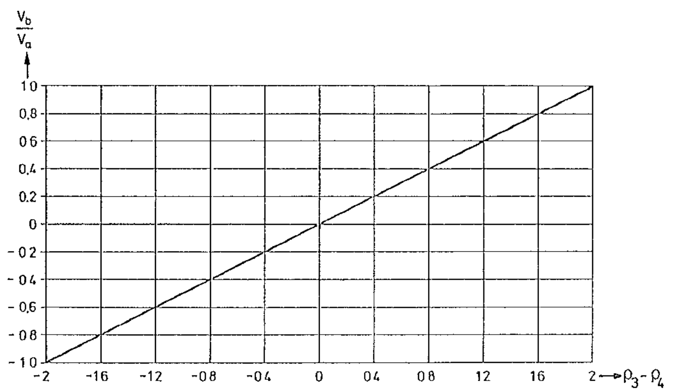

Fig. 5. Voltage ratio V_b/V_a of the hybrid tee as function of the reflection coefficients ρ_3 and ρ_4 in the lines (3) and (4), respectively.

signals return to the branching point, reaching it at the same time, provided that lines (3) and (4) have the same lengths. The sum of the reflected voltages is equally divided and is coupled into the lines (1) and (2), thus returning to the signal source in line (a). In each of the output lines (5) and (6), the reflected voltages are superimposed to half the value of their difference (see Fig. 5).

An input signal which enters line (b) reaches only the lines (3) and (4) but with opposite polarity (180° out of phase). Considering their polarity, half of the sum of the here reflected voltages is coupled into the lines (1) and (2), thus reaching the output line (a).

To deduce the scattering matrix of the hybrid tee, the 6-port branching point is regarded at first. In its most general form, the scattering matrix $[S]$ of the branching point is

$$[S]=\begin{bmatrix} s_{11} & \cdots & s_{1m} & \cdots & s_{16} \\ \vdots & & \vdots & & \\ s_{n1} & \cdots & s_{nm} & & \vdots \\ \vdots & & & & \\ s_{61} & & \cdots & & s_{66} \end{bmatrix}. \qquad (1)$$

The scattering coefficients are unknown and unrelated. Under certain conditions (isotropy and lossless case) it is possible to determine all the scattering coefficients by deductive reasoning.

1) Because of the reciprocity of the 6-port we have

$$s_{nm}=s_{mn}, \qquad \text{with } n,m=1\text{–}6 \text{ and } n\neq m. \qquad (2)$$

2) The lines (1) and (2), (3) and (4), and (5) and (6), respectively, are decoupled from each other.

$$s_{12}=s_{21}=s_{34}=s_{43}=s_{56}=s_{65}=0. \qquad (3)$$

3) All input lines are matched, therefore,

$$s_{nn}=0, \qquad \text{with } n=1\text{–}6. \qquad (4)$$

4) If one line is provided with an input signal, all output signals are equal, showing a voltage amplitude of half of the input voltage amplitude. The reference planes of the output lines, at which the scattering coefficients are determined, are moved so that the phase angles of the transfer coefficients become zero.

$$s_{31}=s_{41}=\ \ s_{51}=-s_{61}=0.5 \qquad (5)$$

$$s_{32}=s_{42}=-s_{52}=\ \ s_{62}=0.5 \qquad (6)$$

$$s_{13}=s_{23}=\ \ s_{53}=\ \ s_{63}=0.5 \qquad (7)$$

$$s_{14}=s_{24}=-s_{54}=-s_{64}=0.5. \qquad (8)$$

With regard to (1)–(8), the scattering matrix of the branching point can now be written as follows:

$$[S]=0.5\begin{bmatrix} 0 & 0 & 1 & 1 & 1 & -1 \\ 0 & 0 & 1 & 1 & -1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & -1 & -1 \\ 1 & -1 & 1 & -1 & 0 & 0 \\ -1 & 1 & 1 & -1 & 0 & 0 \end{bmatrix}. \qquad (9)$$

By connecting lines (1) and (2) or (5) and (6), respectively, with transformers as shown in Fig. 3, this circuit obtains the properties of a hybrid tee (magic tee) (see Fig. 3). The output signals of the branching point in the lines (1) and (2) (b_1 and b_2) and (5) and (6) (b_5 and b_6), being the input signals of the transformers, are equal to one another. Therefore, with respect to the transformers, it follows that $a_1=a_2$ and $a_5=a_6$. By moving the reference planes of the transformer input and output lines in such a way that the phase angles of the transfer coefficients are also zero, the following systems of equations are valid for the assumed case of ideal transformers:

$$\begin{bmatrix} b_a \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} a_a \\ a_1 \\ a_2 \end{bmatrix} \qquad (10)$$

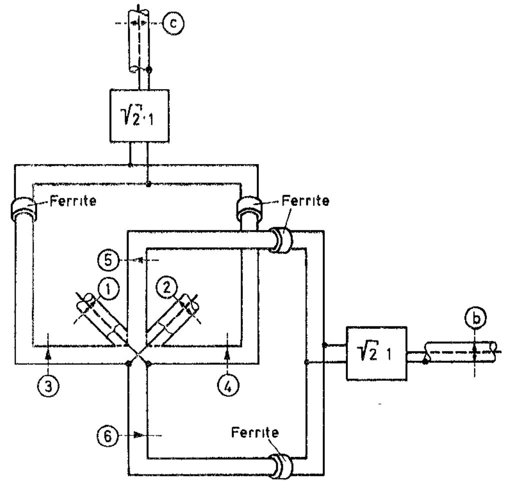

Fig. 6. Hybrid tee, represented in another possible configuration.

and

$$\begin{bmatrix} b_b \\ b_5 \\ b_6 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} a_b \\ a_5 \\ a_6 \end{bmatrix}. \tag{11}$$

By cascading these two transformers with the branching point (Fig. 3) we obtain the scattering matrix of a hybrid tee and thus the complete system of equations as follows:

$$\begin{bmatrix} b_3 \\ b_4 \\ b_a \\ b_b \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} a_3 \\ a_4 \\ a_a \\ a_b \end{bmatrix}. \tag{12}$$

The general properties of a hybrid tee (magic tee) are known and have been presented previously [14].

As can be seen from Figs. 1 and 2, the lines of the branching point are arranged in a three-dimensional form; therefore, one might advantageously change its lines within the hybrid tee. By connecting other pairs of lines to the transformers as shown in Fig. 3, the sum, difference, and colinear lines are rotated. In Fig. 6 line (3) is combined with (4) and (5) with (6). In this circuit, line (c) is the sum line, (b) is the difference line, and both lines (1) and (2) are the colinear lines. In a further configuration, the sum line can be represented by line (c), the difference line by line (a), and the colinear lines by the lines (5) and (6).

For some applications, in which the hybrid tee is operated only in one direction, a modification of the hybrid tee is recommended. Here the transformer in the output line has to be omitted. In this case two output lines result. If these output lines are both equally terminated and equally long, the principal behavior of the circuit is not changed. This operation has two advantages: first, the limitation in bandwidth between the colinear lines and the output, caused by the transformer in the output lines, is removed, and, secondly, further circuits in the colinear and the output lines can be positioned closely to the branching point. If the impedances of these circuits do not match the characteristic line impedances, no essential delay time exists between the networks. Therefore, reflections may be neglected. This operation of the branching point can be calculated in a quasi-stationary consideration. Employing the basic circuit of Fig. 3 and the equivalent circuit of the branching point of Fig. 4, the currents in the lines (3), (4), (5), and (6) are calculated as a function of the applied voltage $V_a/2$ (measurable across a load $Z_L = Z_a$) connected with line (a) yielding with $Z_1 = Z_2 = Z_5 = Z_6$

$$i_3 = \frac{1}{Z_1 + Z_3} \frac{V_a}{\sqrt{2}} \tag{13}$$

$$i_4 = \frac{1}{Z_1 + Z_4} \frac{V_a}{\sqrt{2}} \tag{14}$$

$$i_5 = i_6 = \frac{1}{2} \frac{Z_3 - Z_4}{(Z_1 + Z_3)(Z_1 + Z_4)} \frac{V_a}{\sqrt{2}}. \tag{15}$$

Here, Z_3 is the internal impedance of the circuit in line (3), Z_4 that of line (4), and so on. The input signal source providing line (a) is matched by the transformer, and $Z_1 = Z_2 = Z_a$ is valid. If power matching between the networks in the output lines (5) and (6) (with $Z_5 = Z_6$) and the branching point is required, one must provide (see Fig. 7)

$$Z_5 = Z_6 = \sqrt{\frac{Z_1 Z_4 (Z_1 + Z_3) + Z_1 Z_3 (Z_1 + Z_4)}{2Z_1 + Z_3 + Z_4}}. \tag{16}$$

III. Construction and Experimental Results of the Hybrid Tee

The broad-band transformers were implemented by line transformers which employ micro-semirigid cables (Fig. 8) [11], [15]–[17]. These transformers limit the operating frequency range of the hybrid tee. The upper cutoff frequency of the tee was measured at 5 GHz and the lower cutoff frequency at 2.4 MHz. The upper cutoff frequency of the transformer is essentially determined by the structure (spacing extension) of the connection "point" of the transformer lines. To get a high upper cutoff frequency, both ends of the transformer lines must be connected in a space-saving design. In addition to this, the connections were performed in two stages: first of all, the coaxial lines were connected to only few-millimeter-long microstriplines. Then the microstriplines themselves were combined in a spacing T junction. Fig. 9 shows the input and output connection of the transformer lines. It is known that a well-dimensioned junction from a coaxial line to a microstripline has the behavior of a low-pass filter with a cutoff frequency of more than 10 GHz. The spacing T junction also has an upper cutoff frequency of

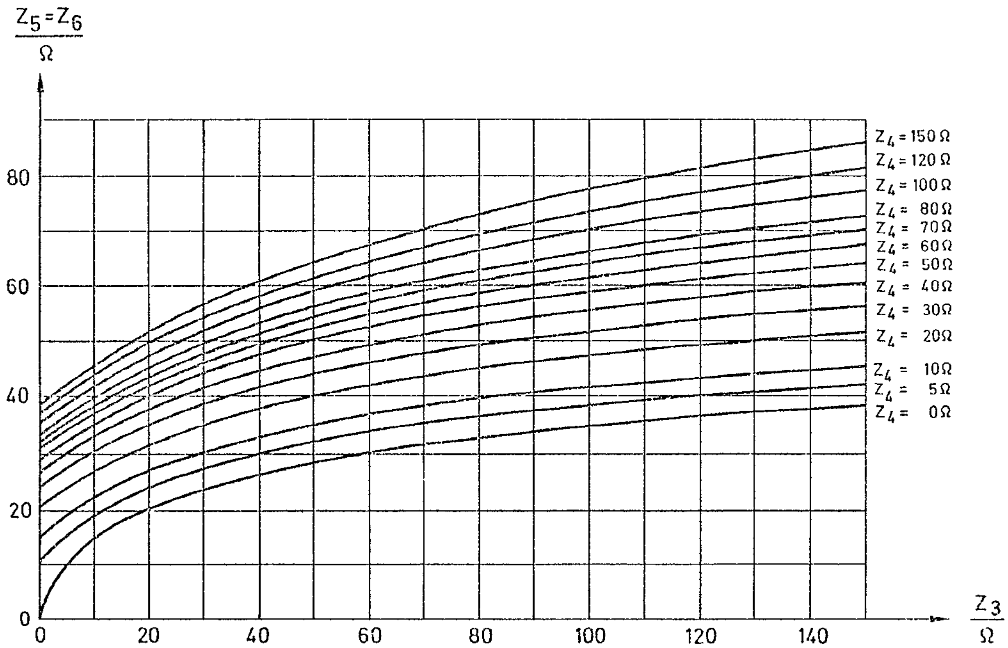

Fig. 7. Load resistances in the output lines (5) and (6) for a quasi-stationary consideration in order to obtain power matching with the branching point, circuited with different resistances in the lines (3) and (4).

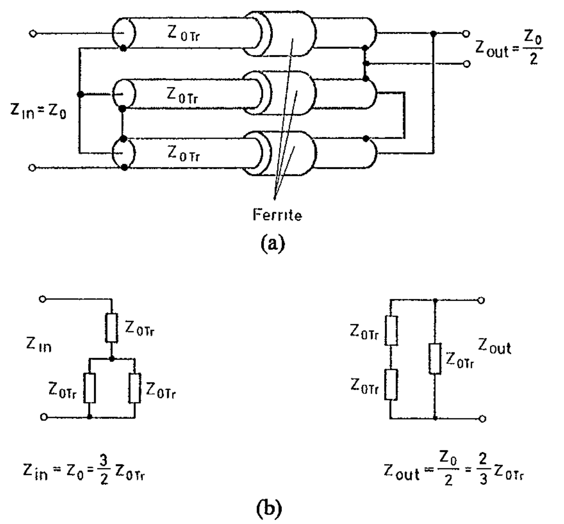

Fig. 8. (a) Broad-band line transformer having a transmission ratio of $Z_{in}:Z_{out}$ of approximately 2:1. Z_{0Tr} and Z_0 are the characteristic impedances of the transformer lines and the input or output lines, respectively. (b) Equivalent circuits of the transformer input and output.

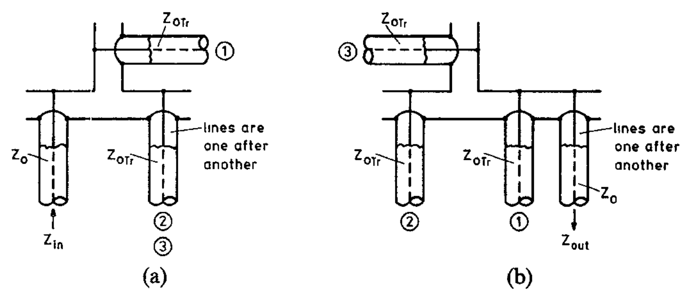

Fig. 9. Mechanical design of the line connection at the input (a) and the output (b) of the transformer.

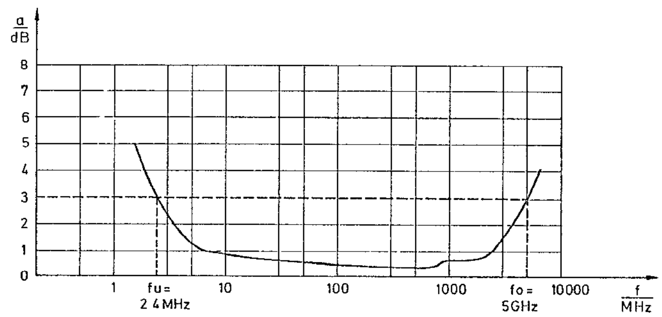

Fig. 10. Attenuation of the hybrid tee as function of the frequency.

more than 10 GHz, as will be shown in the example of the higher upper cutoff frequency of the more complex structure of the branching point.

The lower cutoff frequency is determined by the inductances of the short-circuit loops which are caused by different connections of the transformer lines at the input and output of the transformer [15]–[17]. To enlarge these inductances, the transformer lines were provided with ferrite beads (Valvo, Ferroxcube, 3B, and 4B1). The insertion loss in the transmission region obtained between input (a) or (b) and line (3) or (4) was approximately 0.6 dB (see Fig. 10).

As can be seen from Fig. 8, it is not possible to match simultaneously the input and output lines of the transformers. If the input line has to be matched, the characteristic impedance of the lines of the transformers must have the value $Z_{0Tr} = Z_0(2/3)$, and if the two output lines are

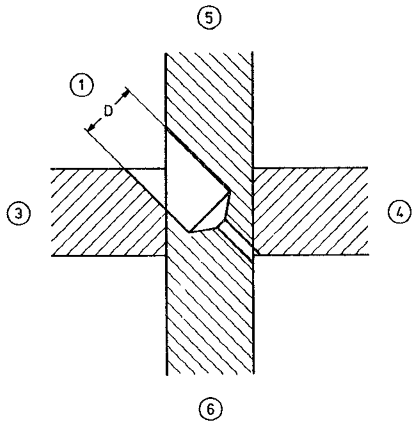

Fig. 11. Cross-sectional view of the branching point with drilled holes for mounting the coaxial lines.

matched it must be $Z_{0Tr}=(Z_0/2)(3/2)$. With $Z_0=50\ \Omega$, a compromise is given for $Z_{0Tr}=35\ \Omega$; the modulus of the reflection coefficients for the input and output lines is then about 0.03.

The lines (1) and (2) were also realized by micro-semi-rigid cables (UT 47 SP). The branching point was made up of two crossed teflon plates, glass-fiber reinforced, and copper covered. The thickness of the teflon substrate is 1 mm, carrying striplines with a characteristic impedance of 50 Ω. For mounting lines (1) and (2), diagonal holes were drilled through the branching point. Good results were obtained by mounting the lines (1) and (2) as shown in Fig. 11, which is a cross-sectional view of the branching point. Both the teflon substrates (hatched) and the holes for mounting the line (1) are shown. At first, the thin hole was drilled for the inner conductor of line (1) (see Fig. 1). Then a larger hole with the diameter D was drilled approximately halfway into the branching point. D is as large as the outer diameter of the shield of line (1). Line (2) was also plugged in such a hole. The bridge circuit can be compensated by balancing the electric field components inside the branching point by a definite placing of the lines (1) and (2) in the holes. Thus an isolation of more than 40 dB between opposite lines was obtained.

The branching point itself was demonstrated to have an operating range up to about 12 GHz between the lines (3)–(6) and approximately 7 GHz from the lines (1) and (2) to the lines (3)–(6). The cutoff frequency of about 12 GHz is caused by the electric field distortion at the branching point. The dimension of the branching point of 1 mm in the direction of propagation of the electric fields is not negligible at these high frequencies. At 12 GHz the wavelength in the teflon substrate is 17.25 mm; thus the branching point can no longer be regarded as lumped. Exact computations on three-dimensional structures like the branching point are not possible. The other upper cutoff frequency of 7 GHz is, firstly, also caused by the field distortion and, secondly, by the not negligible self-inductances of the inner conductors of lines (1) and (2) inside the branching point (see Fig. 1). At a thickness of the dielectric of 1 mm, the inner conductors passing diagonally through the branching point are approximately $\sqrt{2}$ mm long. A simple calculation, combining the measured two upper cutoff frequencies of the branching point and the upper cutoff frequency of the measuring system, leads to total (equivalent) inductances for the inner conductors of about 2 nH.

By the transformers, e.g., see Fig. 3, the conductors of the lines (1) and (2) or (5) and (6), respectively, were connected thus causing short circuits. This is the reason for a second lower cutoff frequency of the hybrid tee. As the lines (1), (2), (5), and (6) are long enough to be provided with many ferrite beads, the lower cutoff frequency can be shifted into the kilohertz range. Therewith this frequency is much smaller than that of the transformers, and it is not significant. At the wavelength $\lambda=2l$ (l: length of the lines (1), (2), (5), and (6), respectively), resonants occur [16], [17]. These resonants are damped by the losses caused by the ferrite beads. With increasing l, the resonant frequencies are decreased, which in turn cause an enlarging of the frequency-dependent permeability of the ferrite beads. With $l \geqslant 10$ cm, these resonants are not measurable (see Fig. 10). The choice of the ferrite beads is not critical. Here, toroidal ferrite beads (Valvo, Ferroxcube, 3B, and 4B1) with an outer diameter of 3.5 mm and an inner diameter of 1.3 mm were used.

IV. Applications

For illustration, an application of the hybrid tee will be described here. The hybrid tee can be used as an essential component in short-pulse regenerators. A clocked diode differential regenerator (DDR) [19] is one such application. Additional required components in the DDR are step-recovery diodes (SRD's), mounted in the lines (3) and (4). By omitting the transformer in the output lines (5) and (6), the high cutoff transfer frequency of approximately 12 GHz between lines (3) or (4) and (5) or (6) becomes available, and, therefore, the short switching transients of the SRD's (of about 50 ps) can be fully transferred to both output lines. At a bit rate of 1 Gbit/s, output pulses with a halfwidth of less than 100 ps (at a voltage gain of 20 dB in a single stage) were obtained [19]. The input pulse width amounted to 750 ps; thus a significant pulse narrowing with gain was achieved. The two output signals might feed a following DDR (or any other amplifier) in a push-pull mode.

Because of the short output pulses available through the DDR's, multiplexing of PCM-type signals up to several gigabits per second is possible. In a multiplexer application the DDR's essentially operate as pulse narrowing stages, generating an output pulse width nearly independent of the input pulse width. In such a multiplexer [20], [21], four input channels with a bit rate of 1.12 Gbit/s were combined to a multiplexed RZ-format output bit stream at 4.48 Gbit/s. In a feasibility study, an RZ-format output bit rate of 7.84 Gbit/s was reached (see Fig. 12). The width of the output pulses was about 100 ps and

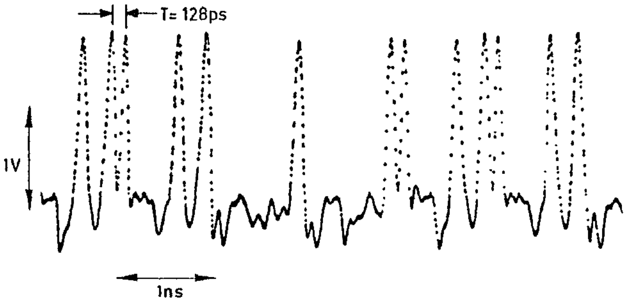

Fig. 12. Output signal of the 1.12-Gbit/s (input) to 7.84-Gbit/s (output) multiplexer which contains hybrid tees and step-recovery diodes.

their amplitude approximately 2 V. The necessary adding circuit which combines the bit stream leaving the DDR's was constructed by using GaAs Schottky-barrier diodes. In a further multiplexer experiment, an NRZ-format output bit stream with a bit rate of 16 Gbit/s at an input bit rate of 1.12 Gbit/s was obtained [22]. The amplitude of the output pulses was 2 V across a load of 50 Ω.

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