Overview of Quasi-Planar Transmission Lines

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(Invited Paper)

Abstract —**A number of quasi-planar transmission lines are reviewed in terms of the general propagation characteristics including useful features, precautions in practice, and some design information. Transmission lines discussed in this paper include coplanar waveguides, finlines, suspended stripline, and microslab waveguides. Attenuation characteristics of some of these lines are compared. In addition, the problems of discontinuity characterizations are included.**

I. Introduction

ALTHOUGH the majority of microwave and millimeter-wave integrated circuits have been fabricated with the microstrip line, the search continues for an alternative transmission medium which would present a potential advantage over the microstrip line or supplement it. For instance, the suspended stripline with a quartz substrate has been used for receiver applications at 230 GHz [1]. With the advent of monolithic microwave integrated circuits, a renewed interest is evident in the coplanar waveguide. However, in contrast to microstrip lines, a relatively limited amount of information is available on these transmission lines. It is true that there are still many problems with microstrip lines, particularly with regard to the high-frequency characterization of microstrip discontinuities. Nevertheless, the situation of the microstrip line is far better, in terms of both theoretical and experimental characterizations, than the suspended stripline and coplanar waveguide. Finlines are somewhat better than these two in terms of the amount of information.

The objective of this paper is to review the nature of these quasi-planar transmission lines. Collection of most of the basic information for each transmission line has been attempted. However, it is not possible to cover all the relevant publications. In the first part of the paper, each transmission line will be described in terms of its physical nature and propagation characteristics. Next, comparisons are made of the attenuation characteristics. General comparisons will also be provided. A few attempts to characterize discontinuities appearing in these transmission lines will then be mentioned.

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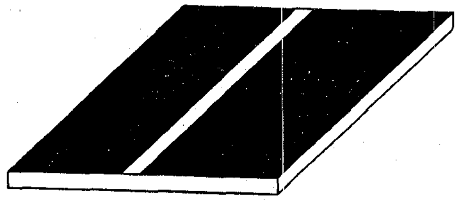

Fig. 1. Slot line.

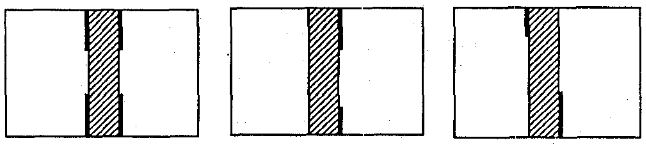

Fig. 2. Bilateral, unilateral, and antipodal finlines.

II. Finlines and Slot Lines

The slot line (Fig. 1) was proposed by Cohn, who also provided an analysis method [2]. He has pointed out that the guided mode has a region of elliptical polarization and hence is suited for applications with a ferrite material. The slot line was not widely used in comparison with other quasi-planar transmission lines, particularly the finline, which happened to have a similar configuration on the substrate. However, the slot line mode plays an important role, as we will see later in other quasi-planar transmission lines such as coplanar waveguides.

The finline was invented by Meier [3] as an alternative to the microstrip line at millimeter-wave frequencies. It was considered to be compatible with batch-processing techniques and superior to microstrip lines in a number of aspects at millimeter-wave frequencies. There are three types of finlines: unilateral, bilateral, and antipodal, as shown in Fig. 2. They are basically printed ridge waveguides and hence they can have a wider single mode spectrum than a corresponding waveguide in which the finline is housed. One consequence of this configuration is that a transition to the standard waveguide is quite easily fabricated. Usually, the finline electrodes are tapered down so that a planar "horn" is formed on the substrate. On the other hand, a transition from the antipodal finline to a microstrip line can be made easily. One of the fins is tapered down to a center strip while the width of the fin on the other side of the substrate is gradually increased to form the ground plane of the microstrip line.

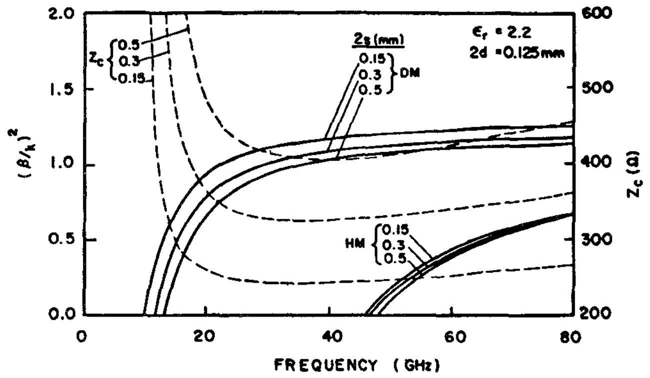

Fig. 3. Dispersion characteristics of a finline (from [6]).

The propagation characteristics of the finlines have been studied by a number of research groups [4]–[6]. These works have treated idealized structures and computed the phase constant and the characteristic impedance. Fig. 3 shows typical examples of the propagation characteristics for the dominant and the second-order modes calculated by the spectral-domain method [6]. The characteristic impedance is calculated on the basis of the voltage–power definition, in which the voltage across the slot and the power transmitted are used. Although this definition is not unique, it is perhaps the most suitable and is widely used for finlines. The characteristic impedance is usually higher than 100 Ω, although the antipodal configuration can find a lower impedance. In addition to these fundamental characteristics, both the dielectric loss α_d and the conductor loss α_c have been computed and the results are shown in Fig. 4 [7]. It is generally agreed that the measured values of finline attenuation are about three times the predicted values, due to surface roughness and other factors.

In an actual realization of finlines, one often uses a small groove in the top and bottom walls of the waveguide housing in which the finline is accommodated. The effect of these grooves may not be negligible. In addition, the thickness of the fin metallization can affect the propagation characteristics of the finline. These problems have been studied recently [8], [9]. It was pointed out that the effects of the grooves and the metallization thickness become increasingly important as the frequency is increased.

III. Suspended Striplines

Fig. 5 shows the cross section of the suspended stripline and its twin, the inverted stripline. Usually, these configurations are placed in a shielding waveguide. In that instance, the difference between these two ceases to exist. These structures provide a way to reduce the attenuation in a microstrip line at higher frequencies and yet retain some of the features of the microstrip line such as the quasi-TEM nature of the dominant-mode propagation. Like the case for microstrip lines, the characteristic impedance is usually based on the power–current definition. From the analysis point of view, these configurations can be treated in a unified manner as strip transmission lines containing multiple layers of dielectric materials. Therefore, once a generalized analysis algorithm is developed, it can be used for a number of stripline configurations, including the microstrip line [10].

The suspended (and inverted) striplines have a number of useful features. First, the attenuation due to the dielectric material is reduced, because the substrate is usually used for supporting the strip and the greater part of the electromagnetic field is located in the air. The loss characteristics will be compared with other quasi-planar and planar transmission lines shortly. This also makes the modal dispersion small and the effective dielectric constant relatively small. The low dispersion nature is useful for broad-band applications and the low effective dielectric constant relaxes the mechanical tolerance of the structure as the physical size is allowed to be large. Second, it is possible to use both sides of the substrate. For instance, a broadside coupled stripline can be fabricated which is suitable for filter configuration due to a strong coupling between the two strips facing each other through the substrate. Another example of this feature is the electromagnetically coupled patch antenna shown in Fig. 6. Furthermore, two surfaces can be used for different types of printed transmission lines, such as the unilateral finline on one side and the suspended stripline on the other. On the other hand, there is a lower limit to the realizable characteristic impedance in the case of a shielded suspended stripline. This is because the size of the shield case, which limits the maximum width of the strip, is designed in such a way that the higher order waveguide-type modes are cut off.

Usually, the substrate of the suspended stripline is supported mechanically with grooves in the sidewalls of the waveguide-type housing. In many theoretical efforts, the effect of these supporting grooves is neglected. The results of these analyses are usually acceptable for design. It is found that groove effects can be significant for a shallow groove. In such a case, these effects cannot be neglected for precise filter design based on the suspended stripline. The significance of these effects can be reduced by the use of a waveguide housing with very low sidewalls [11].

IV. Coplanar Waveguide

The coplanar waveguide (in Fig. 7) was invented by Wen [12] as a planar transmission line which is made of a center strip on the surface of a substrate with two ground planes placed adjacent and parallel to the strip. To date, the coplanar waveguide has been used much less frequently than the microstrip line. However, with the advent of monolithic microwave and millimeter-wave integrated circuits, there is renewed interest in the coplanar waveguide. All three conductors in the coplanar waveguide are on the same side of the substrate. Since the dominant mode is quasi-TEM, there is no low-frequency cutoff. This mode is a balanced mode. Because of the existence of three separate conductors, the coplanar waveguide is suitable for accommodating MESFET's and other three-terminal devices. However, heat removal from an active device is not easy. An additional ground plane may be placed on the other side of the substrate as shown in Fig. 8. This modi-

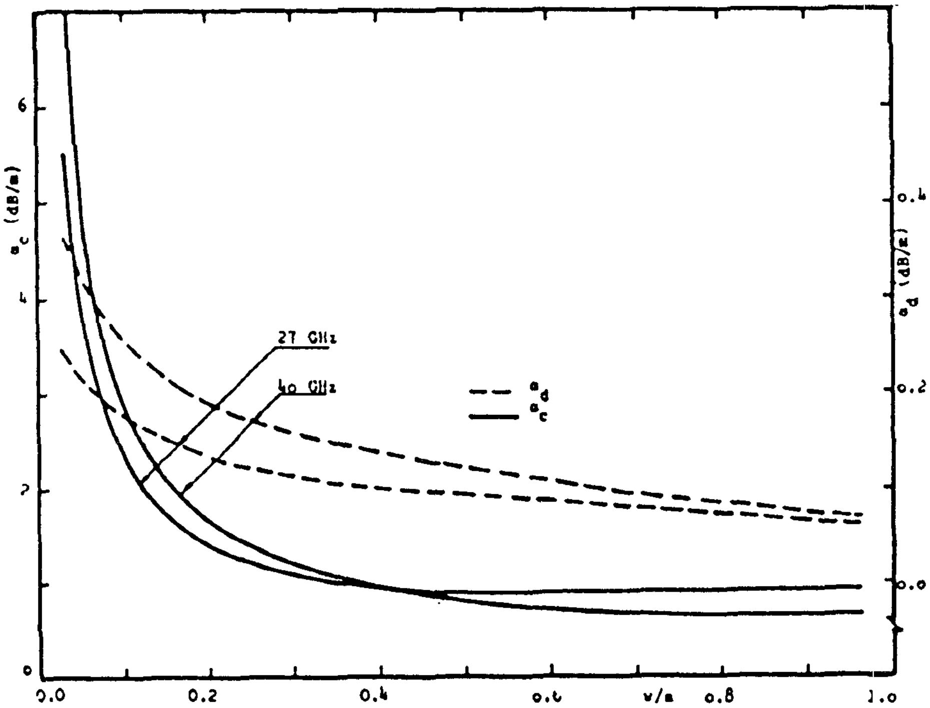

Fig. 4. Conductor loss α_c and dielectric loss α_d of unilateral finline.

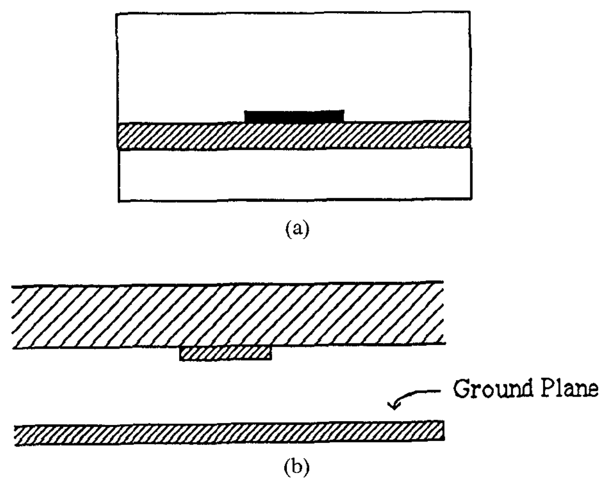

Fig. 5. (a) Suspended stripline and (b) inverted stripline.

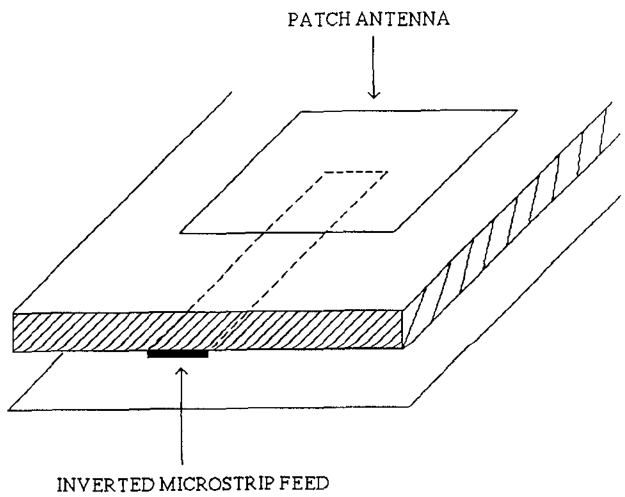

Fig. 6. Electromagnetically coupled patch antenna.

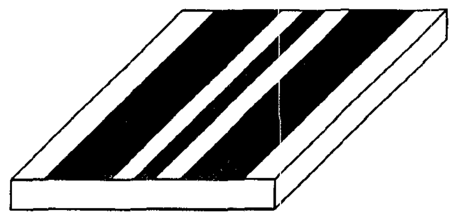

Fig. 7. Coplanar waveguide.

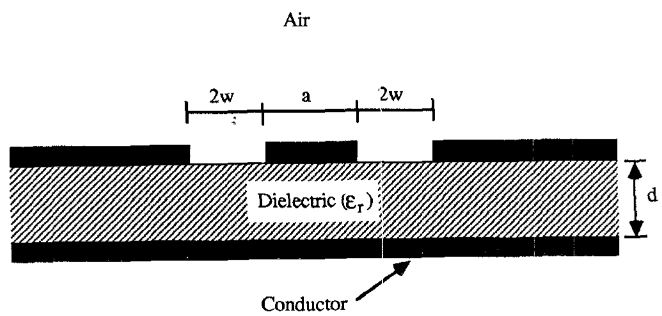

Fig 8. Conductor-backed coplanar waveguide.

fied structure is called the conductor-backed coplanar waveguide [13].

Since there are gaps on both sides of the center strip in the coplanar waveguide, this configuration may be thought of as two coupled slot lines. The coupled slot line mode may be excited in the coplanar waveguide as an unbalanced mode if, for example, the structural symmetry is broken. To prevent excitation of the coupled slot line mode, air bridges between the two ground planes are often used so that the RF potentials of the two ground planes are kept equal. Because of the balanced nature of the

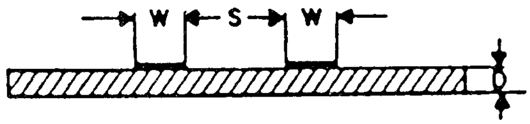

Fig. 9. Coplanar strips.

coplanar waveguide mode, the radiation from a short-circuited coplanar waveguide resonator is much smaller than that of the open-ended microstrip resonator [14]. However, a short-circuited half-wave resonator excited by the coupled slot line mode radiates very well. This fact has been advantageously used in fabricating a planar quasi-optical receiver in which the RF signal is received by a coupled slot antenna while the structure operated by the coplanar waveguide mode is used as part of the LO circuit due to its high Q [15].

The propagation characteristics of the coplanar waveguide have been calculated by Wen under a quasi-TEM approximation [12]. More recently, a dynamic full-wave analysis has been carried out by a number of researchers, including Knorr and Kuchler [16]. The characteristic impedance in the reference is based on the voltage–power definition. Losses in the coplanar waveguide have been computed by Gopinath [17] and Jackson [14]. It is pointed out that the coplanar waveguide can have significantly smaller losses than the microstrip line over a wide range of impedance.

As described above, an additional ground plane is often added to the opposite side of the substrate accommodating a coplanar waveguide. This conductor-backed coplanar waveguide provides a mechanism to remove heat from the active devices in the coplanar waveguide circuits. However, this additional conductor causes an added complexity in controlling the guided mode. First, in addition to the two ground planes on both sides of the center strip, the third ground plane on the underside of the substrate must be maintained at the same RF potential. Otherwise, higher order modes may be generated. In addition, it has recently been pointed out that a leakage loss is caused by the wave propagating away from the central coplanar waveguide region [18]. This is heuristically understood if one finds that the ground planes on both sides of the substrate form a parallel-plate waveguide.

V. Other Quasi-Planar Transmission Lines

In addition to the quasi-planar transmission lines described above, there are several lesser known structures. One such structure; shown in Fig. 9, comprises a pair of coplanar strips. This transmission line has been studied by Jansen [10] and by Knorr and Kuchler [16]. The coplanar strips are used more often in high-speed digital circuits than in microwave circuits.

Sequiera and McClintock introduced a Microslab (trademark of the Martin Marietta Corporation) [19] as a low-loss millimeter waveguide. As shown in Fig. 10, the Microslab looks like a modification of the microstrip line. It consists of a conductor strip on a dielectric strip. This dielectric is placed on a double dielectric layer backed by a ground plane. The dielectric permittivities of the dielectric strip and the grounded layer are lower than that of the second dielectric layer. At low frequencies, the waveguiding mechanism is somewhat similar to that of the microstrip line. As the frequency is increased, however, the greater part of the field is in the center guiding layer. Therefore, the conductor loss at higher frequency is reduced. It is expected, therefore, that this quasi-planar waveguide will be usable over a broad frequency range. An analysis based on the mode-matching method and a set of design data are presented for this waveguide in [20]. Fabrication of the Microslab waveguide requires machining and bonding.

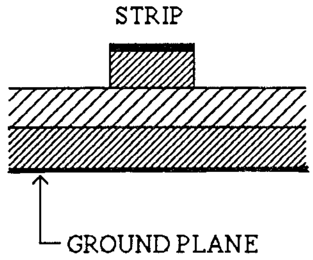

Fig. 10. Microslab waveguide.

VI. Comparison of Losses

The attenuation in the transmission lines is caused by three mechanisms: conductor loss, dielectric loss, and radiation loss. Of these, the radiation loss is typically associated with discontinuities and the bend of the waveguide although, as pointed out by Oliner [18], certain waveguides will be influenced by the inherent leakage phenomena. In this paper, however, we restrict our attention to the conductor loss and dielectric loss. These losses are calculated by perturbation techniques on the assumption that the loss is small. As presented above, the attenuation in the finline has been characterized in [7]. In Fig. 4, it is seen that for a 400 μm gap, the total loss is around 2.5 dB/m over the whole *Ka*-band. In comparison, a typical 50 Ω microstrip line attenuation at 35 GHz is about 25 dB/m while that of a WR 28 waveguide is 0.5 dB/m.

For quasi-TEM-type quasi-planar transmission lines, a simple calculation of the conductor loss based on the incremental inductance rule and of the dielectric loss by a perturbation analysis can provide a comparison of the various lines. Fig. 11 shows the sum of the dielectric loss and the conductor loss for microstrip line, inverted stripline, coplanar waveguide, and conductor-backed coplanar waveguide. It is assumed that the 4-mil (100 μm) thick GaAs substrate has a relative permittivity of 13, and the gold metallization is assumed to be 0.04 mil (1 μm) thick. Other structural dimensions are different from waveguide to waveguide so that all waveguides have a characteristic impedance of 50 Ω. The attenuation is plotted as dB/λ_g, where λ_g is the guide wavelength. As expected, the inverted stripline has the lowest loss. For this configu-

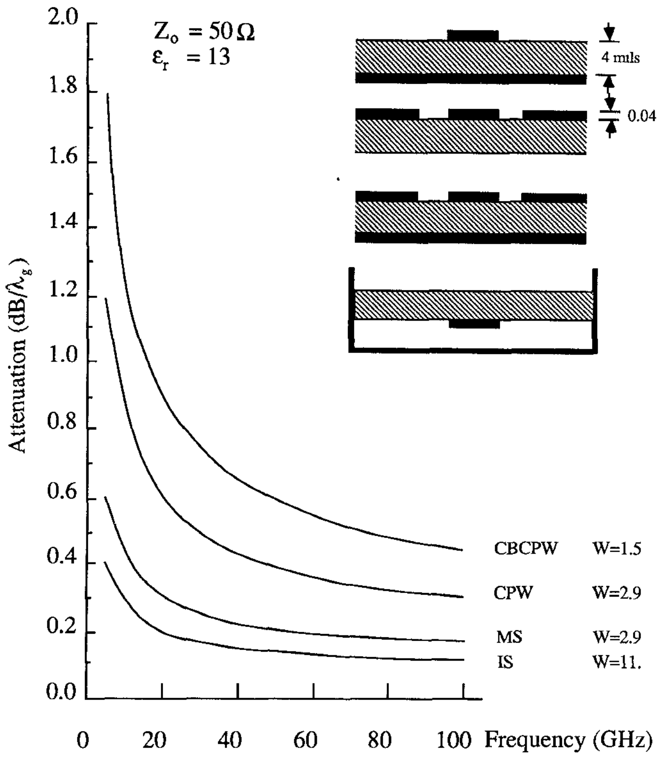

Fig. 11. Attenuation characteristics of quasi-planar transmission lines.

ration, the attenuation of the microstrip line is found to be lower than that of the coplanar waveguide.

VII. Information on Discontinuities

Unlike the microstrip line case, a rather limited number of works have appeared in the literature on the characterization of the discontinuities in other quasi-planar transmission lines. In the case of microstrip lines, there are three levels of characterization of the discontinuity effect. The most primitive one is a quasi-static analysis, in which the discontinuity capacitance and inductance are calculated. The most sophisticated characterization is the full-wave analysis, which includes all the wave phenomena including radiation and leakage from the discontinuity [21], [22]. The third one is the intermediate solution based on the waveguide model [23]. It is interesting to note that such an intermediate model is not easily found for other quasi-planar transmission lines such as slot lines and finlines.

Most of the discontinuities appearing in the quasi-planar transmission structures can be treated as the scattering problem of the incident guided wave along the transmission line. A typical approach for such an analysis is the mode-matching method with a possible improvement [24]. These methods can be applied to a variety of quasi-planar transmission lines. By using this technique, a number of finline discontinuities have been characterized [25]. In the approach, a large number of modes, typically 50 or so, need to be found before the mode-matching procedure is invoked. Another approach is to treat the discontinuity problem as an eigenvalue problem, after a resonator containing the discontinuity is formed, by placing short-circuited walls reasonably far away from the discontinuity. By finding the resonant conditions for a given frequency, the circuit parameters needed to describe the discontinuity effect are extracted. The field analysis to this end can be the spectral-domain method [26] or the transverse resonance technique [27]. Both of these approaches usually presume that the transmission line is enclosed in a waveguide-type housing either by design or as an analytical artifice. Therefore, radiation effects are not immediately obvious in these analyses. In addition, an extreme case is required for obtaining convergent solutions.

TABLE I
Comparison of Quasi-Planar Transmission Lines (MS = Microstrip, SS = Suspended Stripline, CPW = Coplanar Waveguide, CBCPW = Conductor-Backed Coplanar Waveguide, FL = Finline)

	MS	SS	CPW	CBCPW	FL
EFFECTIVE DIEL. CONST.	M	L	M	M	L
DISPERSION	M	L	M	L	H
IMPEDANCE	M	H	M	M	VH*
ATTENUATION	H	L	H	H	M
SERIES ELEMENT	+ +	+ +	+ +	+ +	+
SHUNT ELEMENT	–	–	+ +	+ +	+ +
HEAT SINK	+ +	–	–	+ +	0
INFORMATION ON DISCONT.	+	–	–	– –	0
MONOLITHIC INTEGRATION	+ +	–	+ +	+ +	–

M = moderate, H = high, L = low, VH* = very high except for antipodal finlines.
In ranking preference, availability is in descending order from + +, +, 0, –, – –.

VIII. Concluding Remarks

There still remains a large amount of work to be done for quasi-planar transmission lines. A critical lack of information exists on discontinuities in a quasi-planar transmission line. Therefore, accurate full-wave characterizations of these discontinuities need to be worked out more extensively. Results of such characterizations will be useful in eventually developing computer-aided design (CAD) programs, for instance by means of a lookup table.

In lieu of conclusions, comparisons of various quasi-planar transmission lines are summarized in Table I. For comparison purposes, characteristics of the microstrip line are also included. Entries of this table are often not clear-cut and are quite subjective. However, the results are based on general consensus among many researchers and engineers.

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