Coaxial-Probe to Parallel-Plate Dielectric Waveguide Transition: Analysis and Experiment

G. K. C. Kwan and N. K. Das
Weber Research Institute/Department of Electrical Engineering, Polytechnic University
Route 110, Farmingdale NY11735

Abstract

In this paper, we present a rigorous analysis and experimental results of a coaxial to "parallel plate dielectric waveguide" transition. Coaxial probe has been used in microstrip lines and rectangular waveguides. The present study shows that it is also an effective method to excite the parallel-plate dielectric waveguide. We use here a spectral domain analysis. Applying the method of image, the probe is modeled as an infinitely long thin strip inside a dielectric slab. As experimental results show, efficient excitation can be achieved for such a transition with an insertion loss of about 0.055 dB.

I. Introduction

The "parallel plate dielectric waveguide (PPDW)" consists of a rectangular dielectric strip embedded between two parallel metallic plates.

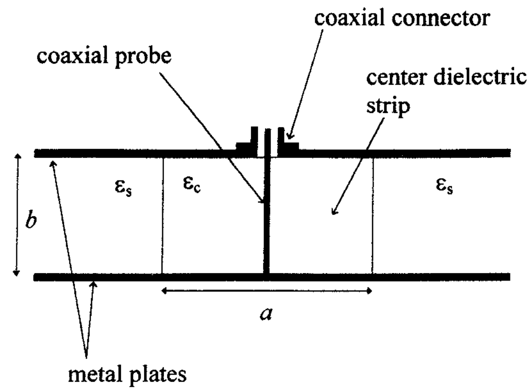

Fig.1 Cross-sectional view of a coaxial to Parallel-Plate Dielectric Waveguide transition. a=width of center dielectric strip, b=thickness of substrate, ε_c=dielectric constant of center dielectric strip, ε_s=dielectric constant of outside dielectric substrate.

A cross-sectional view of the waveguide together with a coaxial probe is shown in Fig.1. Similar geometries have also been used in the H-guide and the NRD guide [1,2]. However, both the H-guide and NRD guide chose to use the higher order modes of this parallel plate structure. In the present study, our focus is on the fundamental TE_{10} mode in this waveguide and its excitation by a coaxial-probe feed. The fundamental mode propagates down to DC, in contrast to the H-guide and the NRD guide where both have cutoff frequencies below which the guides will not operate. This property of the PPDW allows the use of physically thinner (smaller b) substrates for a range of microwave and millimeter-wave frequencies, which is a desirable feature for integrated circuit applications.

In terms of signal transmission, the PPDW, unlike some other waveguide structures with parallel metal planes(striplines, conductor-backed slotline, conductor backed coplanar waveguide), has a critical advantage of confining power within the dielectric strip without radiating or leaking into the parallel plate modes. The metal plates also serve to provide isolation between one layer and the next, which is a major requirement of multilayer microwave integrated circuits. The NRD and H-guide also have the above properties. However, the complexity involved in designing transitions to the NRD and H-guide has always been a major hurdle, where the radiation loss and multimodal excitation problems in these transitions often become

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unavoidable. In the PPDW, although the fundamental mode is non-TEM, its field configuration in the central region is similar to a quasi-TEM line. This feature allows a PPDW to be excited without complex transition geometries. In fact, the coaxial probe is simply placed at the center of the dielectric strip with the center conductor of the probe connected to the opposite metal plate, as shown in Fig.1. Theory and experiments show that, with proper design parameters, radiation loss in such a feeding configuration can be maintained at a negligible level.

II. Spectral-Domain Analysis

In order to incorporate the coaxial probe into a circuit model, we have done a detailed analysis of the probe based on the spectral-domain method [3,4]. Applying image theory to the coaxial to PPDW transition geometry of Fig.1, the problem is transformed into another problem of an infinitely long wire embedded halfway inside a dielectric slab of infinite extent. The wire probe is then approximated by a strip of width W in $\hat{y}$ direction, zero thickness in $\hat{z}$ direction, and infinitely long in the $\hat{x}$ direction. The dielectric slab is parallel to the x-y plane. The Green's function of this geometry can be found from a multilayer Green's function approach [3]. The thin-strip approximation simplifies the present analysis allowing a spectral-domain analysis using multilayer Green's functions.

Using the notation in [3], the Green's function for our equivalent problem is found to be

$$\tilde{\mathbf{G}}_{E_xJ_x}(k_x,k_y)=\tilde{\mathbf{G}}_{E_xJ_x}(0,k_y)= -\frac{\omega\mu}{\beta_{21}}\frac{\beta_{21}\cos(\beta_{21}a/2)+j\beta_{22}\sin(\beta_{21}a/2)}{j\beta_{21}\sin(\beta_{21}a/2)+\beta_{22}\cos(\beta_{21}a/2)}, \qquad (1)$$

using which the expression for equivalent input impedance, *Zin,* seen by the probe can be expressed as,

$$Zin=\frac{b}{4\pi}\int_{-\infty}^{\infty}\frac{\omega\mu}{\beta_{21}}\frac{\beta_{21}\cos(\beta_{21}a/2)+j\beta_{22}\sin(\beta_{21}a/2)}{j\beta_{21}\sin(\beta_{21}a/2)+\beta_{22}\cos(\beta_{21}a/2)} \cdot\text{sinc}^2(k_yW/2)dk_y. \qquad (2)$$

Equation (2) assumes a uniform current distribution on the current strip. *Zin* is evaluated numerically with extraction of the poles of the Green's functions. The poles in the integrand of (2) corresponds to the guided fundamental mode of the PPDW. The residues contributed by the poles are calculated analytically, and then added to the rest of the integration computed numerically.

III. Impedance Computation

The input impedance, *Zin,* of a practical probe configuration has been computed and the results are plotted in Fig.2. The probe has a diameter 1.27mm. Width of the strip, W, in our probe model is taken to be the value of the probe diameter times π/2. PPDW dimensions are a=14.4mm, b= 5.08mm, ε_c=10.8, ε_s=1.0. The

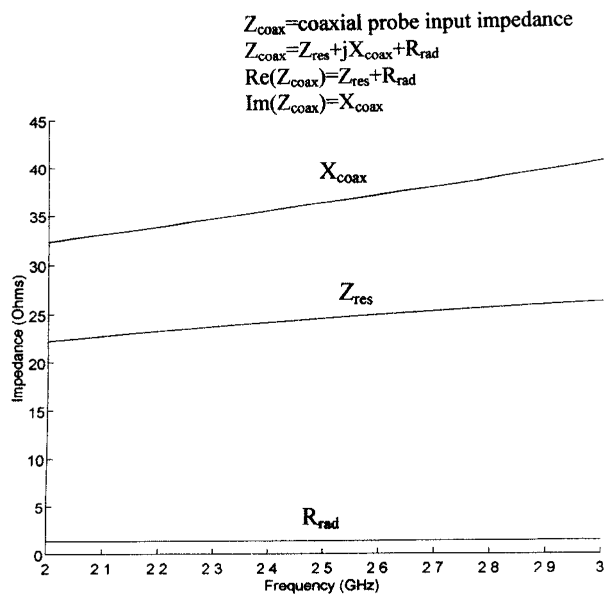

Fig.2 Input impedance of coaxial-PPDW transition. PPDW dimensions: a = 14.4mm, b = 5.08 mm, ε_c = 10.8, ε_s = 1.0. Diameter of coaxial probe = 1.27mm.

real part of the spectral integral corresponds in part to radiation loss due to parallel plate modes and in part to wave guidance along the PPDW. The part due to wave guidance by PPDW, Z_{res}, in this case, is approximately 23 Ohms at 2.5 GHz. It may be noted, that Z_{res} is approximately half of the characteristic impedance of PPDW, Z_g, defined in the next section (slight difference due to the finite width of the probe W). The factor of half is due to the fact that the calculation for the probe impedance is done for the case of a probe inside a PPDW which is infinitely long on both sides of the probe.

IV. Circuit Model

In order to make general use of any waveguide, its characterization in terms of the transmission-line theory is very desirable. Also, without a circuit model for its transitions and devices, the waveguide will have limited application. Simple circuit theory prove to be quite satisfactory here in predicting the PPDW's performance with a probe excitation, despite the non-TEM nature of its fundamental mode. It turns out that the electric field at the center of the waveguide across the parallel plates can be used to define the voltage of the PPDW. The characteristic impedance can be defined as $Z_g = V^2/2P$, where V is the peak voltage and P is the average power propagating down the waveguide. This characteristic impedance has been used throughout our circuit modeling and simulations, giving excellent agreement with experiments. Based on the input impedance found for the coaxial probe, a self-consistent circuit model was derived for a coaxial-PPDW-coaxial transition (see Fig.4) as shown in Fig.3. In this equivalent circuit, both the probe reactance as well as the effects of radiation are accurately accounted for. It may be seen in Fig.2, that R_{rad}, which is contributed by the radiation loss of the probe to the outside parallel-plate medium, is significantly low (a few ohms), suggesting very high efficiency of the probe excitation.

V. Experiment

A prototype for the coax-PPDW-coax transition is shown in Fig.4. Short-circuit plates are placed inside the PPDW layer to create short-circuit stubs for the PPDW. The stub lengths, L_1 and L_2, are chosen so as to give an open circuit at the

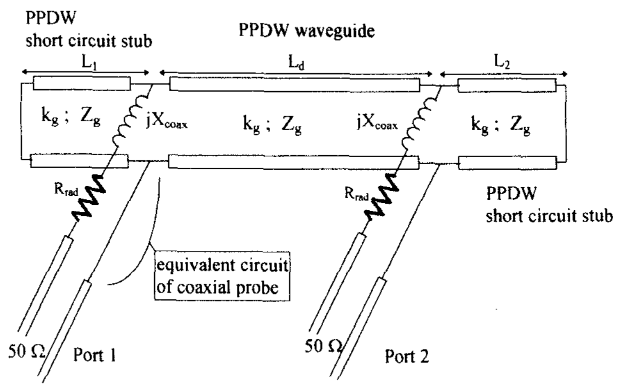

Fig.3 Equivalent circuit for a coax-PPDW-coax transition of Fig.4

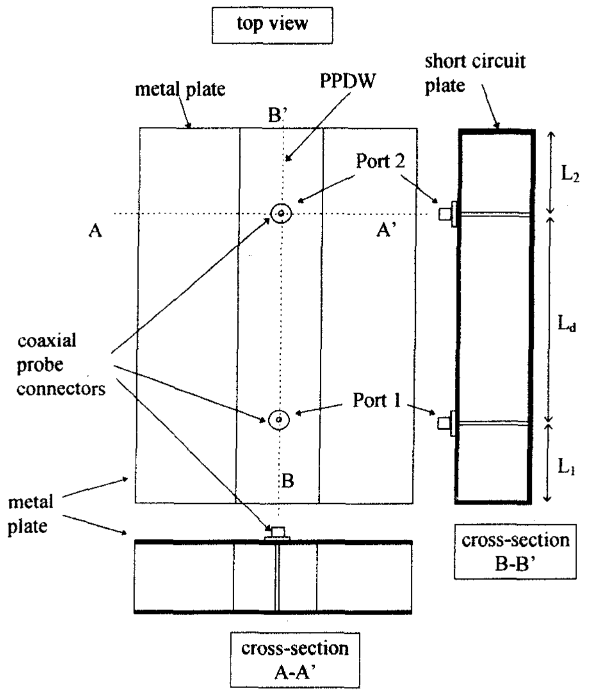

Fig.4 Dervice geometry of coax-PPDW-coax transition used for measurement.

location of the coaxial probe at the frequency of interest. The PPDW guide is designed to have a characteristic impedance of approximately 50 ohms at this frequency. Finally, measurement of the S_{21} of the coax-PPDW-coax transition is done on a network analyzer and the results are compared with the theoretical computation in Fig.5 (insertion loss) and Fig.6 (Smith Chart plot of S_{21}). Calculated S_{21} with material loss is found to be -1.89 dB at 2.5 GHz while calculated S_{21} without loss is -1.52 dB. Therefore, calculated losses in the conductor and dielectric strip of the waveguide itself is 0.37 dB. Measurement at this frequency show 0.48 dB of total insertion loss, which is actually better than the calculation. If one excludes the above calculated material loss of 0.37 dB in the waveguide, the experimental value of 0.48 dB total insertion loss translates to 0.11 dB of radiation loss due to two coaxial probes at the two ports, or equivalently only 0.055 dB (negligible) of radiation loss per one coaxial probe.

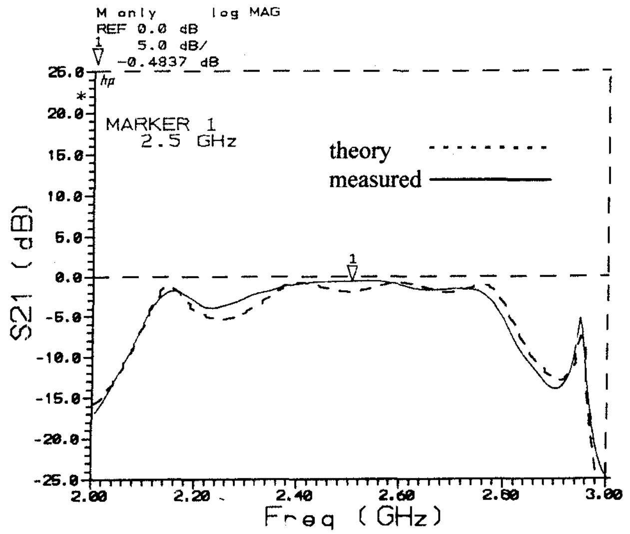

Fig.5 Measured and computed insertion loss of coax-PPDW-coax transition. PPDW dimensions. L_1=L_2=38mm, L_d=140mm, a = 14.4mm, b = 5.08 mm, ε_c = 10.8, ε_s = 1.0. Diameter of coaxial probe = 1.27mm.

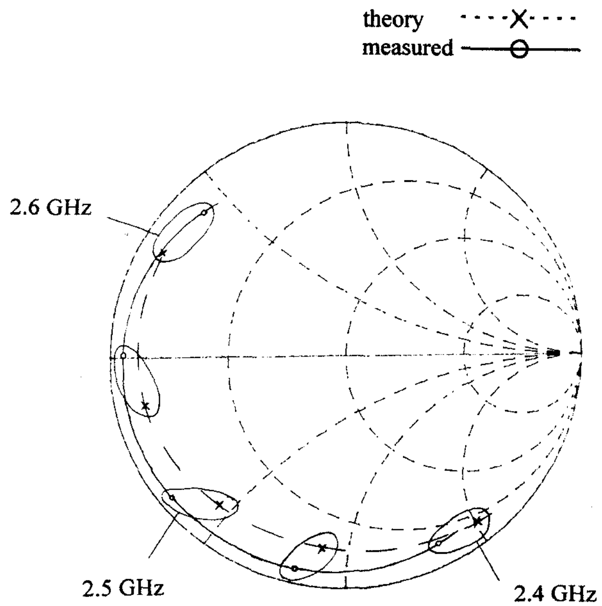

Fig.6 Measured and computed Smith Chart plot of S_{21} of coax-PPDW-coax transition. PPDW dimensions. L_1=L_2=38mm, L_d=140mm, a = 14.4mm, b = 5.08 mm, ε_c = 10.8, ε_s = 1.0. Diameter of coaxial probe = 1.27mm.

VI. Conclusion

We show that the coaxial probe is a simple and efficient method of exciting the PPDW, i.e. the fundamental mode in the parallel-plate dielectric waveguide. Analysis is rigorous and the results have also been verified in experiments. An insertion loss of only 0.055 dB per transition has been experimentally achieved for the coaxial to PPDW transition.

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