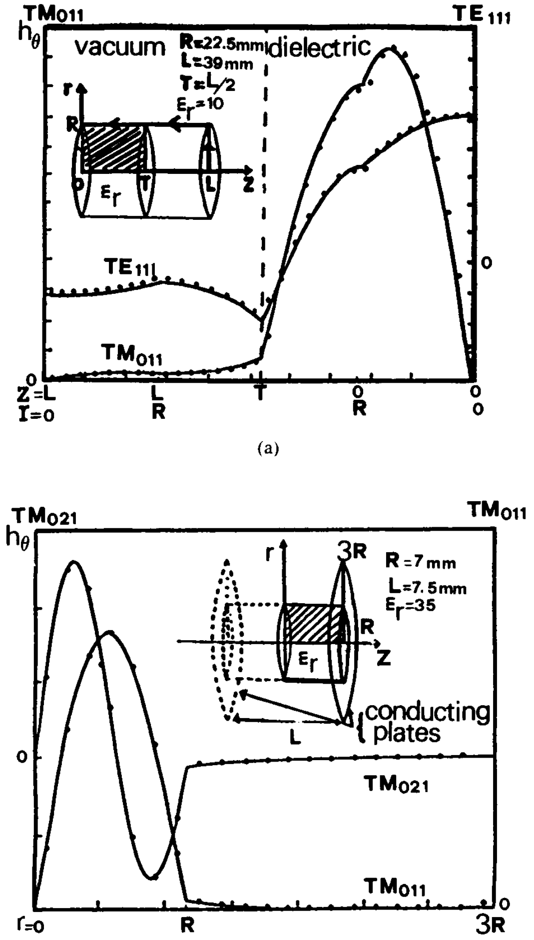

(a)

(b)

Fig. 2. The distribution of the h_θ field component at the metallic surface for (a) the TM_{011} and TE_{111} modes on dielectric-loaded cavity and (b) the TM_{011} and TM_{021} modes on shielded dielectric resonator.

IV. Conclusions

The numerical results obtained in studying several systems confirm the validity of the method and its wide fields of applications. Theoretically it is worth noting the simplicity and generality of the formulation, which allow such problems as unbound systems to be tackled, something that is difficult with other techniques. The complexity of the numerical procedure is not excessive and the consideration of a low number of intervals in the boundary partition leads to quite accurate results (errors in frequency being less than 1 percent).

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An Experimental Investigation of the Microstrip Step Discontinuity

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Abstract —**Measurements of a cascade of microstrip step discontinuities are compared with results of an electromagnetic analysis and with models available in commercial software. The experimental validation technique, which can be applied to other discontinuities, is described.**

I. Introduction

This paper describes a broad-band validation technique as applied to a step discontinuity. The technique was developed for the validation of the electromagnetic (em) analysis [1]–[3].

While there are many results for the step, most [4]–[11], [17]–[19] specify non-50-Ω *S* parameters. Since the normalizing impedances, which allow conversion to 50 Ω (especially in regard to reflection phase), are rarely specified, it is difficult to compare results. Instead, we compare with the 50-Ω *S* parameters provided by most commercial models.

Koster and Jansen [4] state that measurement of the step "seems hardly feasible with the present state-of-the-art," as the discontinuity effect is small at low frequencies (where accurate measurements are possible) and is difficult to measure at high frequencies. Many validation attempts involve measurement of a single discontinuity at high frequency, resulting in an undesirably large scatter [8]–[14].

Resonance techniques [23] are especially suited to non-50-Ω modeling and could have been applied in the above cases. The technique is useful for generating low-loss two-port discontinuity models. The technique described here is applicable to lossy and multiport validation but not for generating models or for non-50-Ω systems. Our results suggest that the reflection phase of a

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one-port resonator at resonance is more significant than resonant frequencies.

When measurements are difficult, comparisons may be made with previously published theory [17]–[19]. For example, Uzunoglu *et al.* [18] compare results with those of Koster and Jansen [4]. It is difficult to judge which result is superior without measurements. We describe an inexpensive alternative for such situations.

We now make four suggestions concerning validation measurements. First, measurement of a single discontinuity may not be desirable. Likewise, a structure consisting of many uncharacterized discontinuities (e.g., an entire amplifier) is of marginal utility. Instead, we suggest a structure in which the only unknown involves multiple instances of the same discontinuity [6], [7].

Second, measurements can be performed on large structures at low frequencies by scaling the dimensions and frequencies from the desired range of validation to the range over which accurate, low-scatter measurements are possible [16], [20]–[22].

Third, the sensitivity of the composite structure to changes in the discontinuity should be evaluated. This step, which is analogous to the "control" portion of accepted experimental technique, is usually ignored.

Finally, an error analysis needs to be performed before an experiment can be described as complete.

Scaled dimensions can involve thick substrates, which are commercially available as loaded dielectric (e.g., epsilon relative of 12.9 at 12 in × 12 in × 1 in). Any physical substrate introduces an uncertainty in its thickness and dielectric constant. An air "substrate" (as in [16]) eliminates the uncertainty in the dielectric constant and reduces cost while increasing the uncertainty in substrate thickness. While an air substrate is insufficient to ensure validation for general microstrip (and is of little use for modeling), a good microstrip model must be valid for an air substrate in order to be valid in general.

An air substrate provides a strong validity check for the em analysis because the analysis expresses fields in each dielectric layer as a sum of homogeneous rectangular waveguide modes. Filling any layer with dielectric changes only the waveguide mode constants.

II. Experimental Technique

We selected a cascade of four steps in air connected as a short-circuited stub for which we measure the reflection phase. A lossy structure would also require magnitude measurement. Since the embedding structure is unrestricted, multiport discontinuities are easily accommodated.

The stub (Fig. 1) is 17.5 cm long on a 0.5-cm-thick air substrate with steps alternating in width from 0.204 cm to 2.25 cm every 3.889 cm with the last step 1.944 cm from the end. The short to ground is on a narrow, high-impedance line to minimize the short-circuit current and the effect of contact resistance. The input connection is on a narrow line to reduce the input discontinuity. The stub was cut from 3.0-mil-thick beryllium–copper and filed to ±0.001 in. Measurements were made with an HP-8510 automatic network analyzer calibrated directly at port 1 with no connecting cables. The connector electrical length is removed from all measurements.

To model the coax-to-microstrip transition, we measured a uniform 0.204-cm-wide stub to which we fit a circuit theory model. The model fit to within ±2.0°, the residual being viewed as measurement error. The fitted line impedance is 178.9 ± 0.3 Ω (a uniform 2.25-cm-wide stub was also measured, providing 55.0 ± 0.3 Ω). Getsinger [21] describes a related technique.

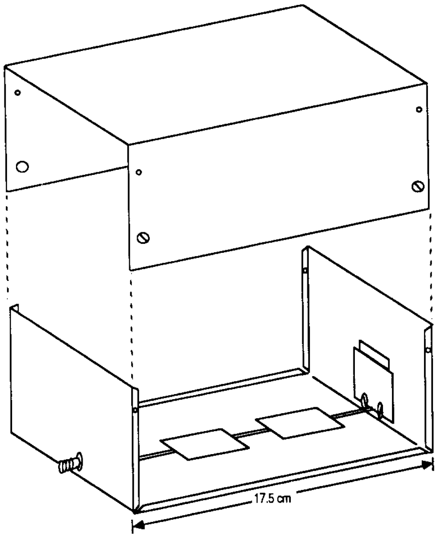

Fig. 1. The embedding structure is a stepped short-circuited stub. The phase of S_{11} depends on four steps going down the length of the stub plus the same four steps again as the reflected wave returns.

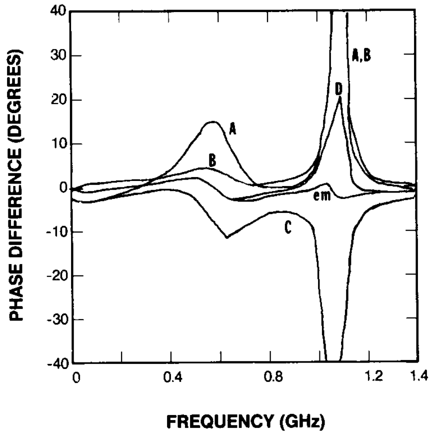

Fig. 2. The phase difference between measured data and the validation model incorporating various step models shows strong sensitivity in the vicinity of the stepped stub resonances. The RMS measurement error is ±2° except at the second resonance (1.1 GHz, ±7°).

We modeled the stepped stub using the above fitted line impedances and port model. This model, the validation model, incorporates the step model to be validated and is independent of the step measurement. Fig. 2 shows the phase differences between the measured data and the validation model for the em and several commercial step models. Maximum differences are off the scale (90° and more) at the stepped stub resonances. The phase differences are difficult to discern on a plot of absolute phases using a 360° scale, and the differences in resonant frequencies are difficult to measure.

An error analysis shows measurement error (±2°) to be the dominant uncertainty except at the second resonance. Here, a ±0.3 Ω uncertainty in either the wide or the narrow line impedance generates a ±4.5° uncertainty in the phase difference. The total RMS uncertainty is now ±7°. Thus, differences of

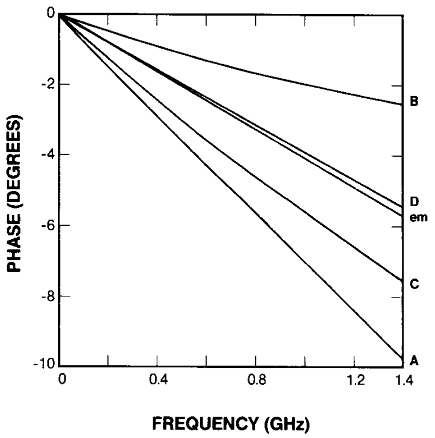

Fig. 3. The S_{21} phase of the commercial step models evaluated covers a four to one range. The letter designations correspond with those in Fig. 2. The step is 2.25 cm to 0.204 cm on an air substrate, 0.5 cm thick.

TABLE I
EM-CALCULATED 50 Ω S PARAMETERS (MAG/ANGLE) FOR THE 2.25 CM TO 0.204 CM STEP

Freq. (GHz)	S11	S21,S12	S22
0.5	0.0171 85.6	0.99985 -2.0	0.0171 90.4
1.0	0.0343 81.1	0.99941 -4.1	0.0343 90.8
1.5	0.0513 76.4	0.99868 -6.2	0.0513 91.2
2.0	0.0678 71.6	0.99769 -8.4	0.0678 91.6

more than about 7° at the second resonance (1.1 GHz) are deemed significant.

The transmission phase of the step models we investigated (Fig. 3) covers a four to one range. Noting this and referring to Fig. 2, we see that this structure is insensitive (relative to measurement uncertainty) to the discontinuity when off resonance (and above 1.4 GHz, not shown), illustrating the importance of checking sensitivity.

III. STEP DISCONTINUITY RESULTS

Since the two ports of the step are physically different, we expect S_{11} and S_{22} to be different. This is true for the em data (Table I) and for most electromagnetic analyses but not for the commercial models.

Table I shows em reflection phase around $+90.0°$, in agreement with most commercial models. The phase of S_{22} (narrow line side) is slowly increasing with frequency. This is expected from Oliner's [15] model, which contains a negative length transmission line. Several results cited in [4] also show a positive phase slope, which Koster and Jansen [4] describe as being of incorrect sign. Most commercial models show a negative phase slope. This problem is unlikely to be resolved through measurement. In addition, the em analysis suggests that the phase slope goes negative when loss is introduced. For the cases considered, metallization loss dominates over dielectric loss, radiation loss, and ground plane loss.

IV. CONCLUSION

We have introduced a simple, inexpensive technique for performing wide-band (multidecade) validation measurements. We emphasize scaling the desired validation frequencies and dimensions so that both the measurement and the fabrication can be performed accurately and inexpensively. The utility of a composite structure (rather than a single discontinuity) is also demonstrated and the sensitivity of the structure to changes in the discontinuity is checked. The technique allows an inexpensive validation to be performed which previously could be realized only with large scatter, if at all.

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