



Fig. 2. The one-port measurement technique.

where p (dimensionless), q , and r (in ohms) are three constants defining the embedding network. p , q , and r can be found from three equations of this sort. These were obtained by connecting three known resistive loads to the end of the shorter length of the TPS cable, and were solved separately for each of the test frequencies. The resistors used were surface-mount metal-film resistors, which have little reactance up to the frequencies of interest. The resistance values used ranged between 10–2200 Ω . Although the equations are simpler if two of the loads are open or closed circuit, it was found that the results were more repeatable if resistances were always used; inductances and capacitances associated with the load, although present, are then practically identical for each measurement.

Once p , q , and r are known, an unknown load Z_{LU} can be calculated by measurement of Γ_{in} and rearrangement of (1). This calculation can be applied to the longer cable as if the extra length of cable were included in the load. The impedance Z_{LU} , thus measured at a point equivalent to the length of the shorter cable, when the longer cable is terminated in a load Z_r , is given by [4]

$$Z_{LU} = Z_0 \frac{\frac{Z_r}{Z_0} + \tanh(\gamma l)}{1 + \frac{Z_r}{Z_0} \tanh(\gamma l)} \quad (2)$$

where l represents the difference in the lengths of the two cables.

Two different loads, Z_{r1} and Z_{r2} , can be connected to the end of the longer cable and the impedances calculated from the measurement are Z_{L1} and Z_{L2} , respectively. This gives two equations of the form of (2), which can be solved for $\tanh(\gamma l)$ (and, thus, γ) and Z_0

$$Z_0^2 = \frac{Z_{L2}Z_{r2}(Z_{r1} - Z_{L1}) - Z_{L1}Z_{r1}(Z_{r2} - Z_{L2})}{(Z_{r1} - Z_{L1}) - (Z_{r2} - Z_{L2})} \quad (3)$$

$$\tanh(\gamma l) = Z_0 \frac{Z_{r1} - Z_{L1}}{Z_{L1}Z_{r1} - Z_0^2} \quad (4)$$

B. Two-Port with Different Length Through Connections

In this technique, only the propagation constant is determined. The technique is more applicable to longer cables, and thus to more accurate measurement of the cable attenuation.

Two baluns are required, and several different lengths of cable are used to connect the balanced sides of the baluns together. The four scattering parameters of the resulting two-port are measured, and then converted to transmission (or cascade) parameters using the

transformation [4]

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{S_{21}} \begin{bmatrix} S_{12}S_{21} - S_{11}S_{22} & S_{11} \\ -S_{22} & 1 \end{bmatrix} \quad (5)$$

This transmission matrix can be considered to be the product of the transmission matrices of the three elements of balun, cable, and balun arranged in cascade fashion. We can define

$$M_{ij} = M_j(M_i)^{-1} \quad (6)$$

where M_i and M_j are the measured transmission matrices with two different transmission cables designated i and j . Marks [5] has shown that the eigenvalues of M_{ij} are the same as those of a measurement without the baluns. Thus, if the eigenvalues of M_{ij} are λ_1 and λ_2 , then the propagation constant can be calculated from

$$\gamma = \frac{\ln(\lambda_1)}{l_i - l_j} = \frac{1}{(l_i - l_j) \ln(\lambda_2)} \quad (7)$$

IV. BALUNS

Various baluns were trialed, including: 1) a 4:9 coax transformer built using "MCX" 75- Ω coax cable, on ferrite toroids [6], [7]; 2) a coax transformer of the same design using "RG-11" 75- Ω coax cable, with no core; 3) no balun; 4) a 1:1 copper-wire Guanella [8] balun wound on various ferrite toroids and rods; 5) a conventional transformer wound on a high-frequency ferrite toroid; and 6) a 1:1 "MCX" coax Guanella balun wound on various ferrite toroids and rods. Each balun was tested for the effectiveness of its balance by direct measurement of the terminal voltages with an oscilloscope, and the level of imbalance was compared with the measurements made using that balun. It was found that while the measurement of Z_o and β were relatively insensitive to imbalance, the measurement of the attenuation in the cable was quite sensitive. This is because once there is an imbalance of the currents on the cable, the cable no longer behaves purely as a transmission line, and begins to radiate. This radiation is indistinguishable (to this technique) from increased line attenuation.

The calculations described are applied separately to each measurement frequency, so the balun need not have a flat response over a large frequency range. There is also no requirement that the balun output impedance closely matches that of the unknown transmission line under test. Similarly, the efficiency of the balun is not a prime requirement for this application, as there is plenty of measurement power available.

It was found that the measurements were more repeatable for higher permeability cores: the higher reactance of the balun at low frequencies results in improved balance [8]. The higher inductance obtained from a toroid core compared to a rod core was also beneficial to the repeatability, as was the tighter coupling, and more consistent impedance of wound coax (compared to wound parallel wires).

The most reliable balun was found to be a simple 1:1 Guanella balun, consisting of 24 turns of "MCX" 50- Ω cable on a 35-mm outside diameter toroid of relative permeability 5000 (initial relative permeability quoted for 25 $^{\circ}\text{C}$, $f \leq 10$ kHz).

V. MEASUREMENT RESULTS

An HP-8753C network analyzer was used for the scattering parameter measurement. 50- Ω n-type connectors were used for unbalanced cables, and direct soldered connections from the balun were used for balanced cables. The frequency scan (0.3–300 MHz) was performed with a 300-Hz intermediate-frequency bandwidth and power of 0 dBm, and the data used was the average of 16 scans. All the resistance values used in the calculations were the dc values of the surface-mount resistors measured with a standard meter.