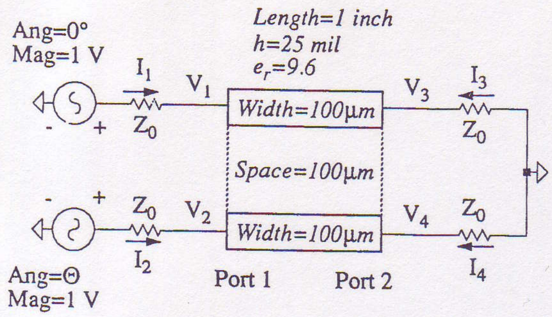

Fig. 5. Schematic of mixed-mode s-parameter simulation of symmetric coupled-pair transmission line.

to be 180° apart. One possible way this can be achieved through a single signal source is with the use of a 180°-3-dB-hybrid splitter/combiner. The construction of the differential reflected and transmitted waves can be also completed through a 180° splitter/combiner. The common-mode stimulus of a coupled two-port requires the input waves at the reference plane to be 0° apart. This can also be achieved through a single signal source with the use of a 0°-3-dB-hybrid splitter/combiner, with the construction of the common-mode reflected and transmitted waves also completed through a 0° splitter/combiner.

The calibration of such a system can be achieved through the extension of VNA calibration theory. Detailed calibration discussion is beyond the scope of this paper, but will be the subject of future work. It is interesting to note, however, that any successful calibration algorithm must correct both magnitude and phase imbalances in the splitter/combiners and signal paths, since any such imbalances will represent errors in the generation and reconstruction of the mixed-mode waves. Also, any calibration will be greatly assisted by requiring one standard for both Z_e and Z_o, which is accomplished when $Z_e = Z_o$, as assumed in this section.

All mixed-mode normalized waves and s-parameters have been discussed with respect to a transmission pair line as a reference. Conceptually, this reference line must be attached to every port of a DUT. However, there is no restriction on the length of these reference lines. Therefore, the reference lines can be of zero length, and the definitions of all mixed-mode quantities will still apply, with one provision. Namely, the generator source impedance and the load impedances must match the characteristic impedance of the reference lines. The use of zero length reference lines is a useful interpretation of the general normalized wave definition of (24) from which the mixed-mode s-parameters are defined.

It it interesting to note that an alternative requirement can be found through which the nodal and mixed-mode waves can be related. One could require the differential-mode and common-mode characteristic impedances to be equal (i.e. $Z_{\mathrm{dm}} = Z_{\mathrm{cm}} = Z_0$). The relationships (25) and (26) will change, however. This alternate requirement may have value in some cases, but the original requirement ($Z_e = Z_o = Z_0$) best relates mixed-mode s-parameters to standard s-parameters.

V. Ideal Mixed-Mode Measurement System and Simulations

Equations (25) and (26) form the basis of an ideal mixed-mode s-parameter measurement system. These equations can be implemented into a microwave simulator, and can provide a quick and simple method of illustrating the usefulness of mixed-mode s-parameters.

The circuit in Fig. 4 was implemented into Hewlett-Packard's MDS. The phase difference, Θ, between the two sources was set to 0° for the common-mode and common-to-differential-mode forward s-parameters. For the forward differential-mode and differential-to-common-mode s-parameters, the phase difference was set to 180°. In each case, the nodal waves were calculated from (25), (26), and (24), and the s-parameters were calculated with the appropriate ratios. The reverse s-parameters were calculated by driving port 2 of the DUT with 50 Ω loads at port 1. ? simulator program.

The first example of mixed-mode s-parameters uses a DUT that is pair of coupled microstrip transmission lines, with symmetric (i.e. equal width) top conductors. This symmetric coupled-pair, and the accompanying circuitry, is shown in Fig. 5. Each runner width is 100 μm with an edge-to-edge spacing of 100 μm. The substrate is 25-mil-thick alumina with a relative permittivity of 9.6 with a loss tangent of 0.001, and the metal conductivity is that of copper, ~5.8 × 10^7 S/m. A one inch section of this line was simulated in MDS as described above, and the mixed-mode s-parameters at 5 GHz are shown in (27) at the bottom of this page. S_{dd}

As expected, each partitioned sub-matrix demonstrates the properties of a reciprocal, passive and (port) symmetric DUT. The differential s-parameters, S_{dd}, show the coupled pair possesses an odd-mode characteristic impedance of 50 Ω (100-Ω-differential impedance), and has low-loss propagation in the differential mode. The common-mode s-parameters, S_{cc}, show the coupled pair posses an even-mode characteristic impedance other than 50 Ω. Actually, the even-mode impedance of the pair is 140 Ω (70-Ω common-mode impedance). Note the cross-mode s-parameters are zero for the symmetric coupled pair indicating no conversion between propagation modes. S_{cc} S_{dc} + S_{cd}

The second example is similar to the first, except the coupled microstrip transmission lines are asymmetric (i.e. unequal widths). This asymmetric coupled-pair, and the accompanying

$$\left[\begin{array}{c|c} S_{dd} & S_{dc} \\ \hline S_{cd} & S_{cc} \end{array}\right] = \left[\begin{array}{cc|cc} 0.001\angle{-141^\circ} & 0.972\angle 9.53^\circ & 0 & 0 \\ 0.972\angle 9.53^\circ & 0.001\angle{-141^\circ} & 0 & 0 \\ \hline 0 & 0 & 0.341\angle{-60.4^\circ} & 0.915\angle{-26.4^\circ} \\ 0 & 0 & 0.915\angle{-26.4^\circ} & 0.341\angle{-60.4^\circ} \end{array}\right] \quad (27)$$

S_{dd} = differential to differential