On S-Parameter Graphs of Multiconductor Lines Via Touchstone File

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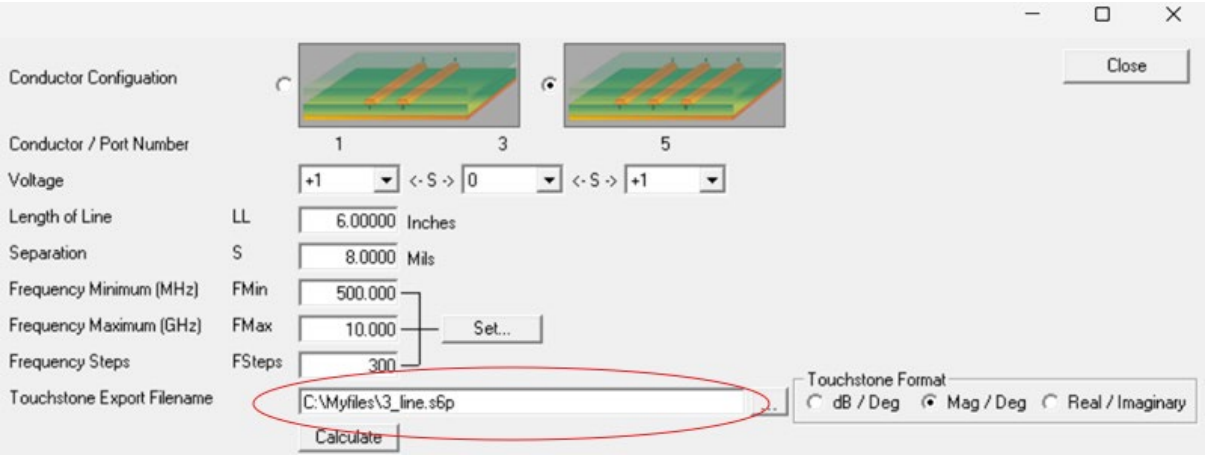
Touchstone file generation is available by adding or browsing to a file location in the optional Multiline Crosstalk dialog in the Si8000m and Si9000e



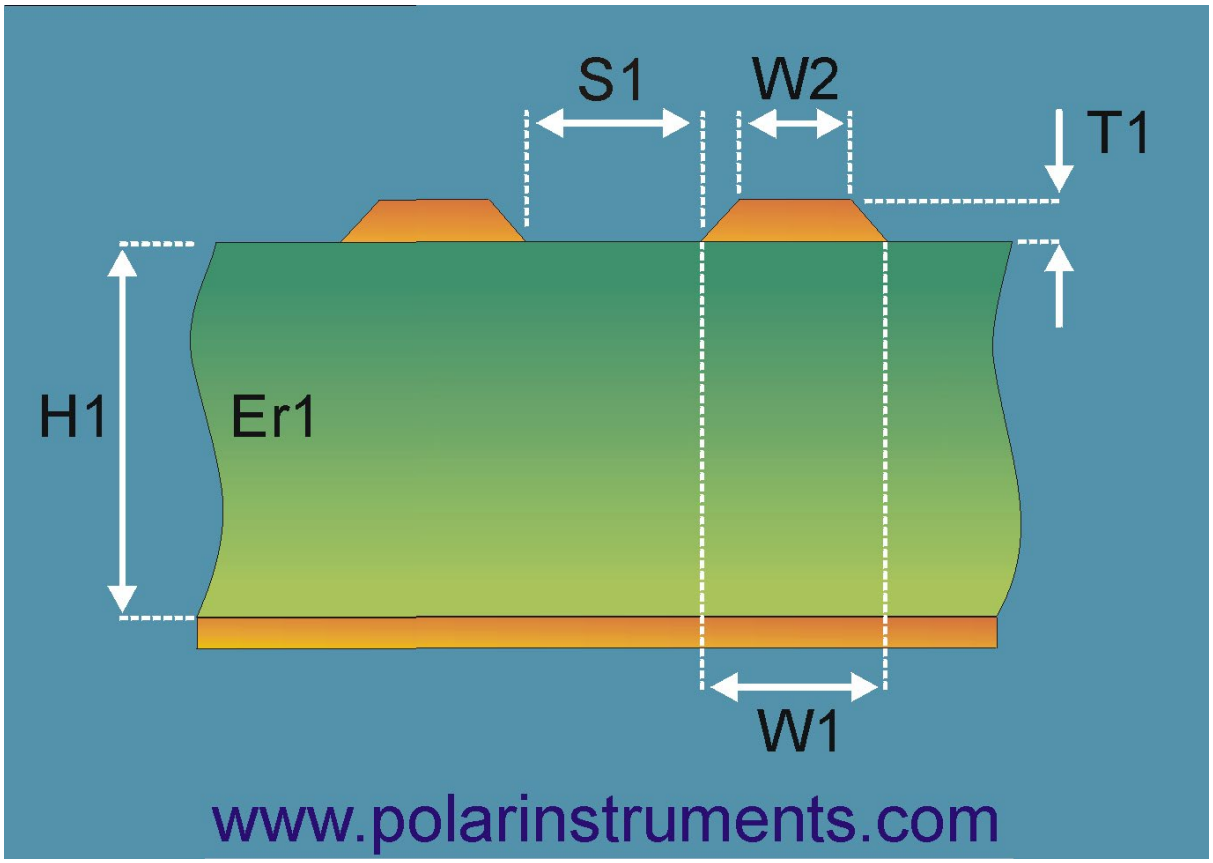
The generated S-Parameters are automatically terminated at the near and far end by the characteristic single-ended impedance of the line (RL).

This note describes the results for the S-parameters of coupled lines. The parameters are defined through:

$$\mathbf{b} = \mathbf{Sa}$$

where the **a** is the vector of input voltages**, b** is the vector of output voltages and **S** is the scattering parameter matrix. The calculation of the S-parameters is given in [1]. In [1], the parameters are defined when the ports are numbered sequentially. For the usual S-parameters presentation, the even numbered ports are opposite the odd numbered ports. The calculated S-parameters, calculated in [1] are rearranged so that the even numbered ports are opposite the odd numbered ports. These parameters are the SP values in the program Also note that the parameters refer to the individual ports and not to a combination of any ports.

Structure 1.



W1 = 177, W2 = 155, H1 = 200, T1 = 30.0, Er1 = 4.2, S1 = 90.6
All dimensions are in micrometers,

This is a microstrip formed of a pair of conductors. The pair of conductors, external to the coupled region, form a differential pair with a differential impedance, $Z_{diff} = 100\,\Omega$.

Dimensions above using the notation used in the Si9000e. These values yield a single ended impedance, at the input to each port, used in the coupled region, of 72.72 Ohms. The following table gives the calculated the modal velocity and impedance values

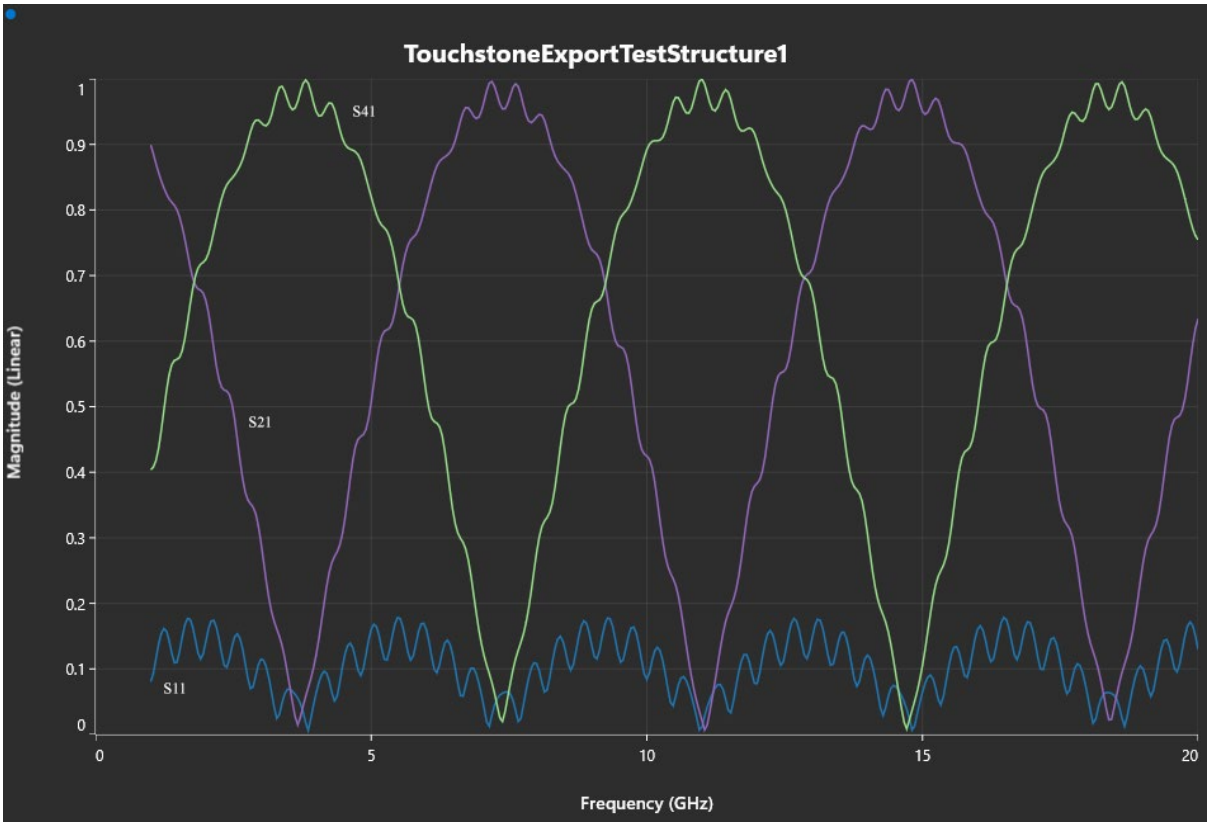
Structure 1

Velocity mode 1 (m/s)	Velocity mode 2 (m/s)	Impedance mode 1 (Ω)	Impedance mode 2 (Ω)	Impedance input line (Ω)
1.9164e8	1.6910e8	50.000	91.985	72.72
		-50.000	91.985	

The modal impedance is a matrix. It is the relation between the nominal line voltage and modal current. In this example there are two modal currents and two line voltages so that the impedance is a 2 x 2 matrix. The negative sign indicates a phase reversal. Using this structure externally as a differential pair, yields an odd mode impedance 50.00 Ω and an even mode impedance 91.985 Ω (as calculated by the Si9000). As noted in the table these impedances, calculated using the coupled line program, are the same as in the table.

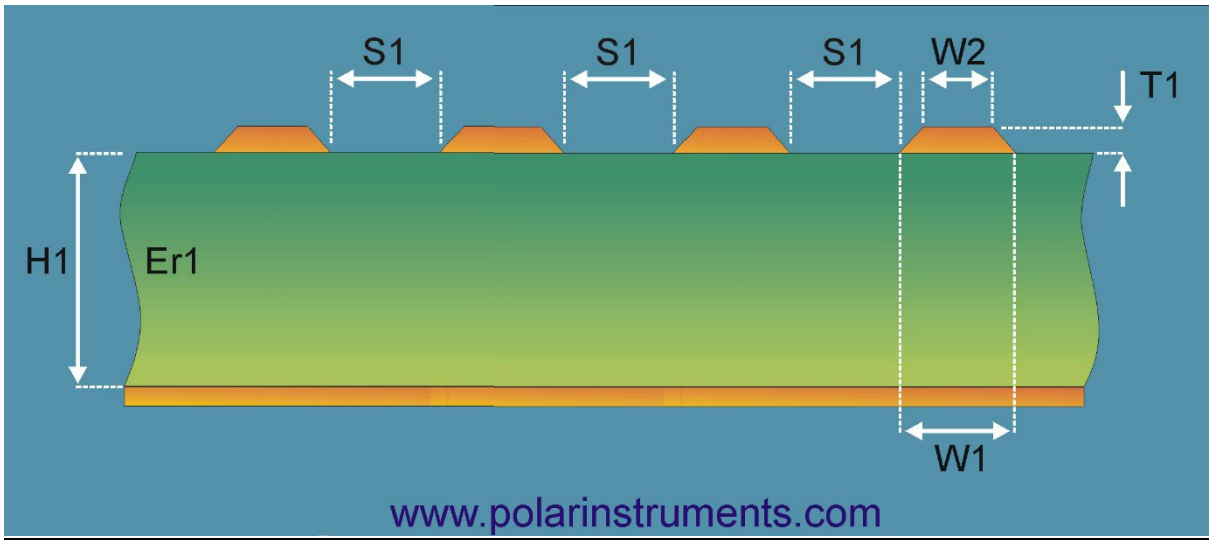
The following graph shows the variation of S11, S21 and S41 with frequency when the coupled length is 200 mm.

The graph of S11 shows the effect of reflections, at the input port 1, caused by the difference in impedance of the external line and the modal impedances in the coupled region. The graph of S21 shows the output at port 2 for an input at port 1. This graph shows that the output varies cyclically in “antiphase” with the output at port 4, S41. These variations are caused by the different phase velocities associated with the two modes. See the table. The small perturbations of the S21 and S41 graphs, are caused by the mis-matched impedances at port 1.



S-Parameters of Structure 1

Structure 2



W1 = 177, W2 = 155, H1 = 200, T1 = 30.0, Er1 = 4.2, S1 = 90.6
All dimensions are in micrometers,

Structure 2 has the same dimensions as structure 1 but there are now 4 parallel conductors each spaced 90.6 µm. The following tables show the results with 4 modes now possible.

Modal Velocity (m/s)

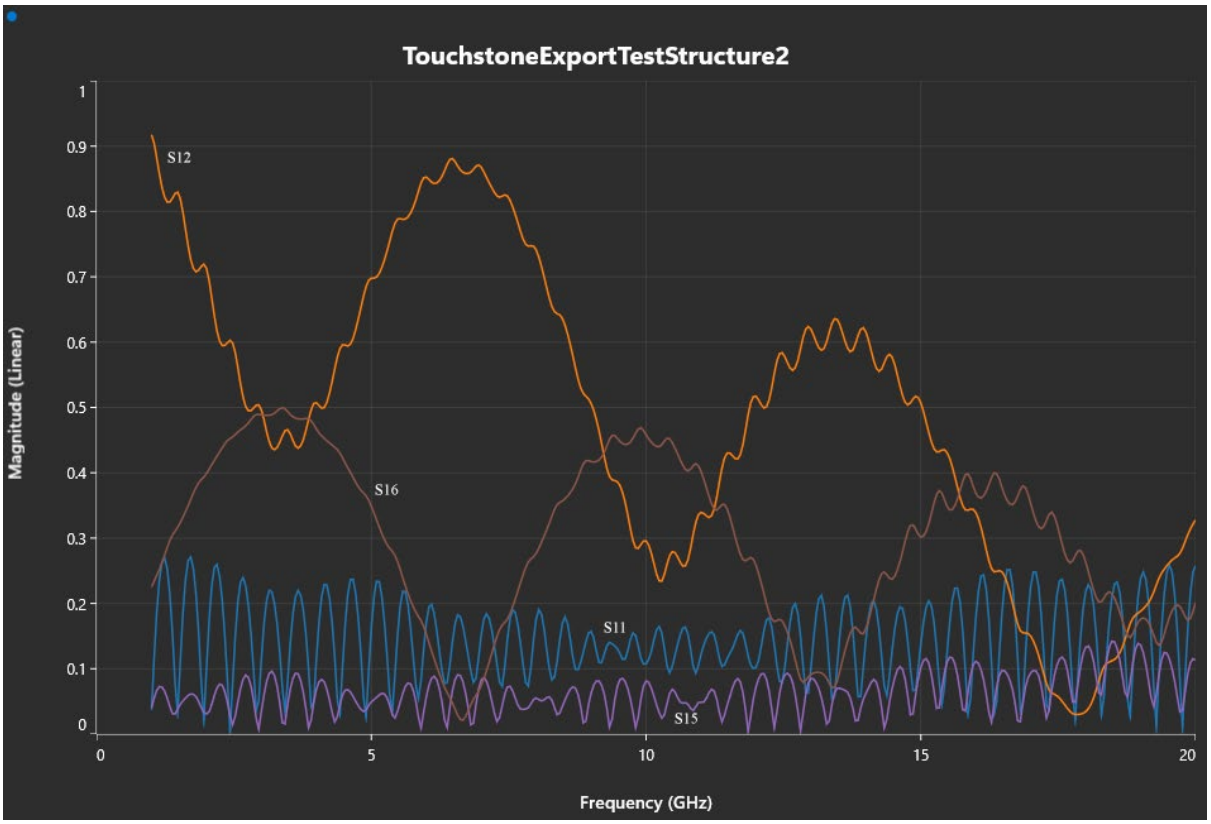
Mode 1	Mode 2	Mode 3	Mode 4
1.7008e8	1.9892e8	1.9263e8	1.9275e8

Modal Impedances (Ω)

Mode 1	Mode 2	Mode 3	Mode 3
82.522	27.965	41.913	54.968
84.369	-140.01	-45.850	145.69
84.369	140.01	-45.850	-145.69
82.522	27.965	41.913	-54.968

The mode impedances occur in pairs either both positive or negative or of opposite sign.

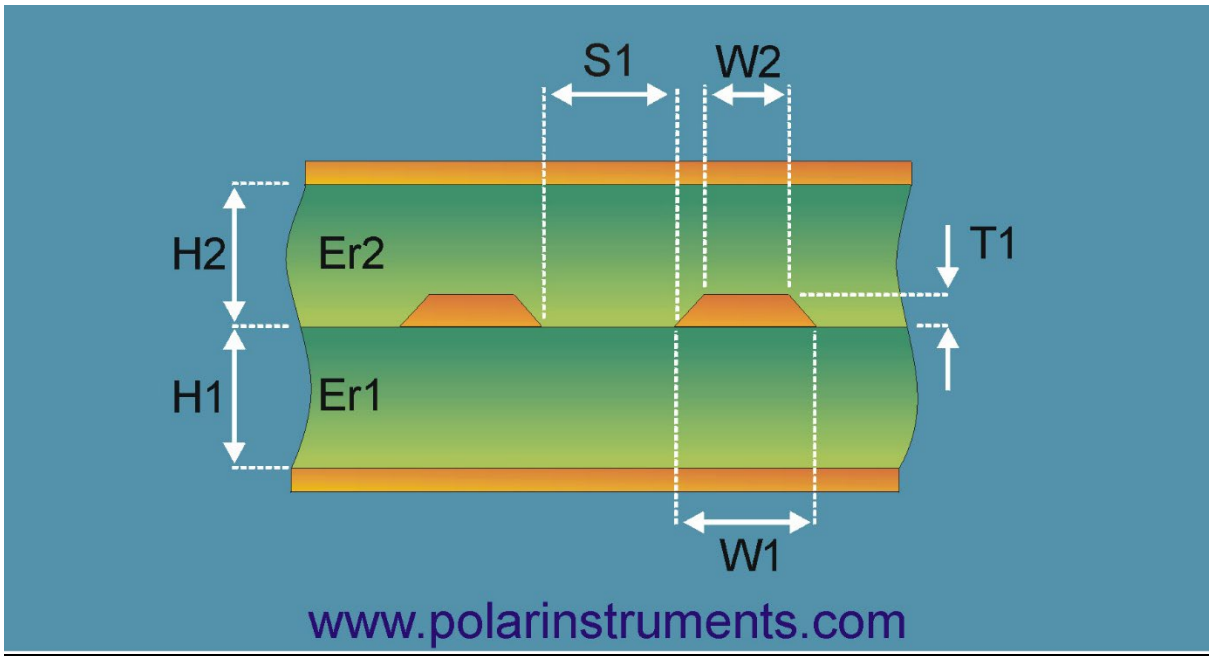
The following graph shows the values of S11, S21, S15 and S61. That is, they are the results of an incident voltage at port 1, on conductor 1, together with the output at ports, 2, 5 and 6. Ports 5 and 6 are conductor 4, the furthest from conductor 1.



S-Parameters of Structure 2

The Structure 2 graphs exhibit similar features as those of Structure 1. First, there is the rapid ripple caused by the mismatch of impedances at the odd numbered ports, which also effects the other S-parameter values. As before, S11 shows a cyclic variation as energy is transferred to the other ports. But because there are now 4 conductors there is both a “slow” transfer of energy, reaching a minimum around 18GHz and a more “rapid” transfer at a period of about 6GHz. If the graph is extended to 40GHz (not shown), the S11 graph slowly increases again. S61 starts by exhibiting a similar property as S21 of Structure 1, starting in antiphase with S21, but it slowly changes its phase position with S21, with increasing frequency as energy is periodically transfer between ports.

Structure 3

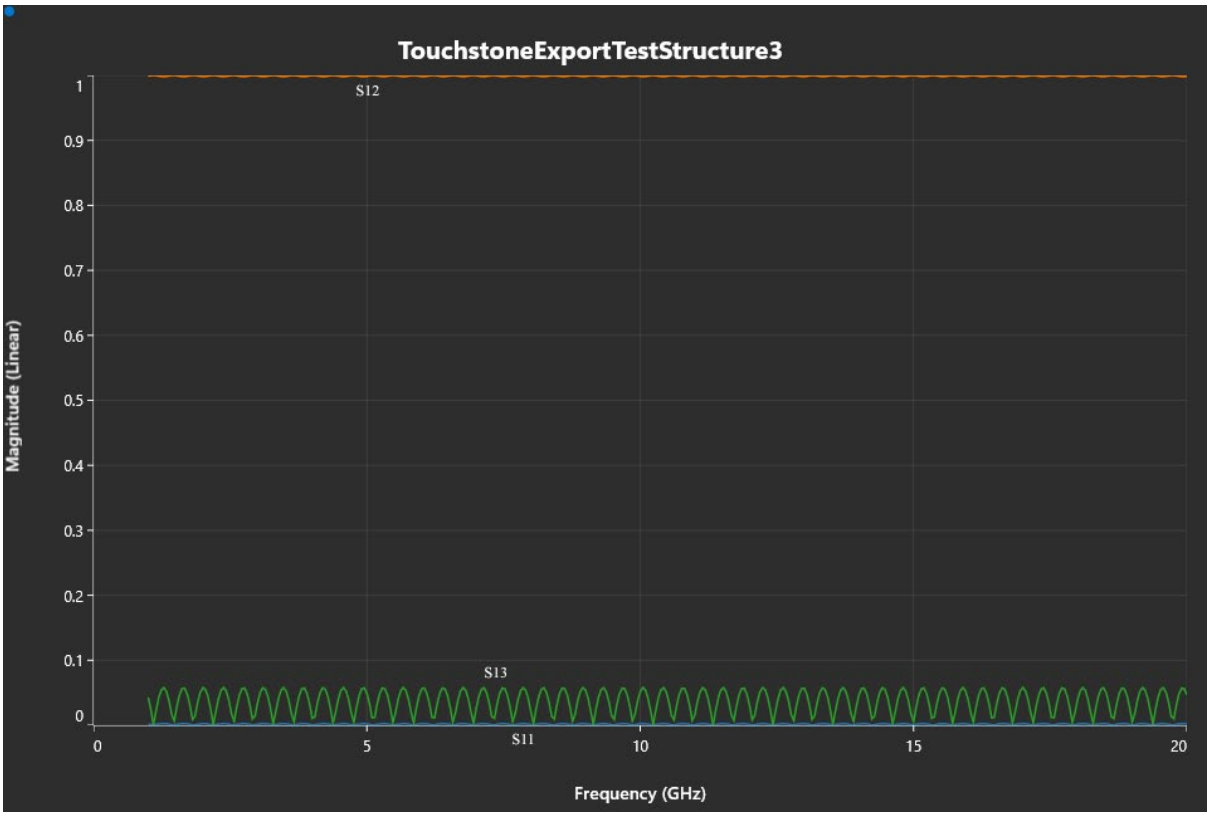


W1 = 177, W2 = 155, H1 = 250, T1 = 30.0, Er1 = 4.2, Er2 = 4.2, H2 = 270, S1 = 334
All dimensions are in micrometers,

This is a 2 conductor stripline structure, externally designed in the same manner as Structure 1, to have an external Zdiff = 100.077Ω. This results in the dimensions above.

Structure 3

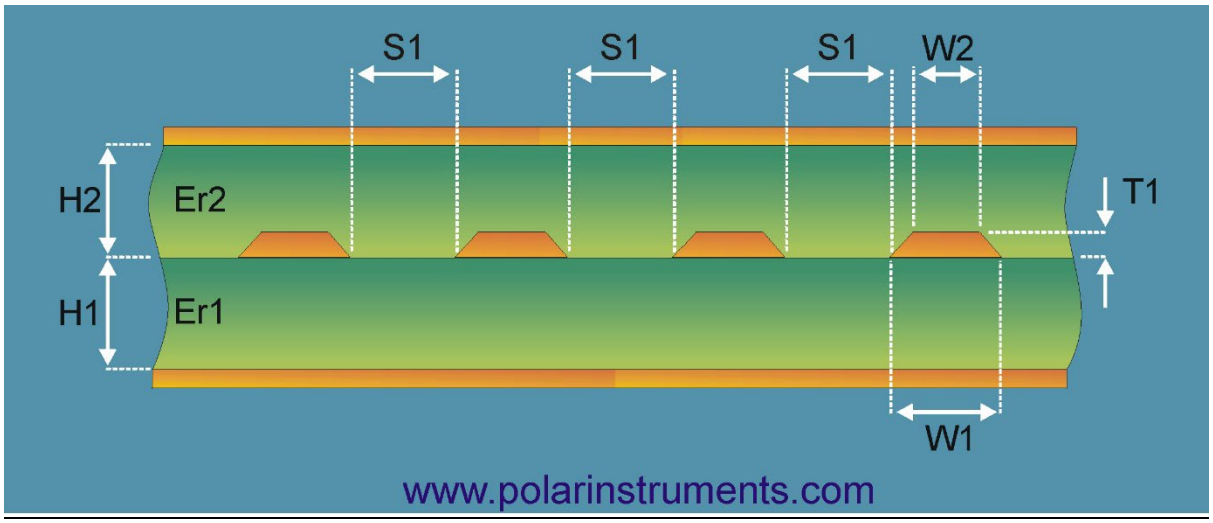
Velocity mode 1 (m/s)	Velocity mode 2 (m/s)	Impedance mode 1 (Ω)	Impedance mode 2 (Ω)	Impedance input line (Ω)
1.4628e8	1.4628e8	48.356	54.996	53.167
		-79.232	35.493	



S-Parameters of Structure 3

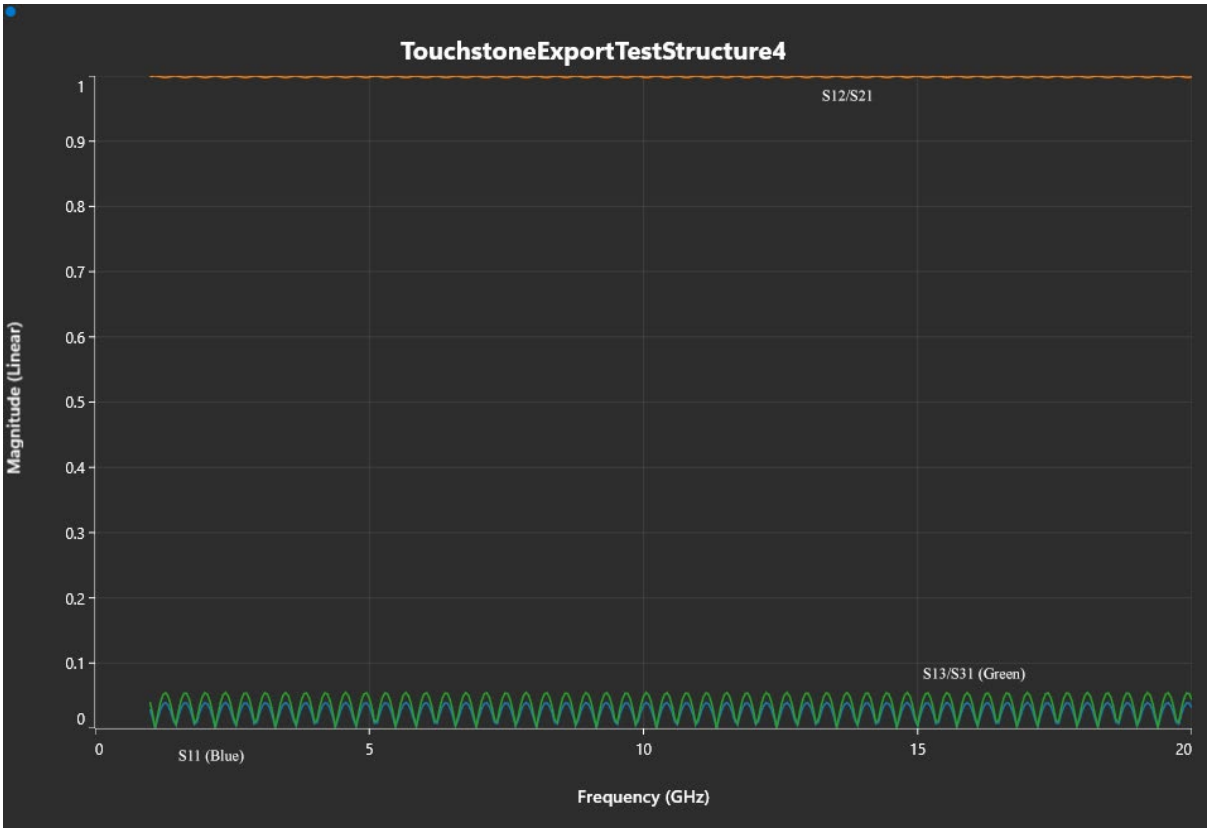
The magnitude of the S-parameters of this structure differs substantially from the microstrip structure of Structure 1 because the velocities of the two modes are now identical. This isn't surprising since both substrate layers have the same constant. Also, the fine structure variations are smaller because the difference in the modal impedances and the single ended line impedance, at the input, is smaller.

Structure 4



W1 = 177, W2 = 155, H1 = 250, T1 = 30.0, Er1 = 4.2, Er2 = 4.2, H2 = 270, S1 = 334
All dimensions are in micrometers,

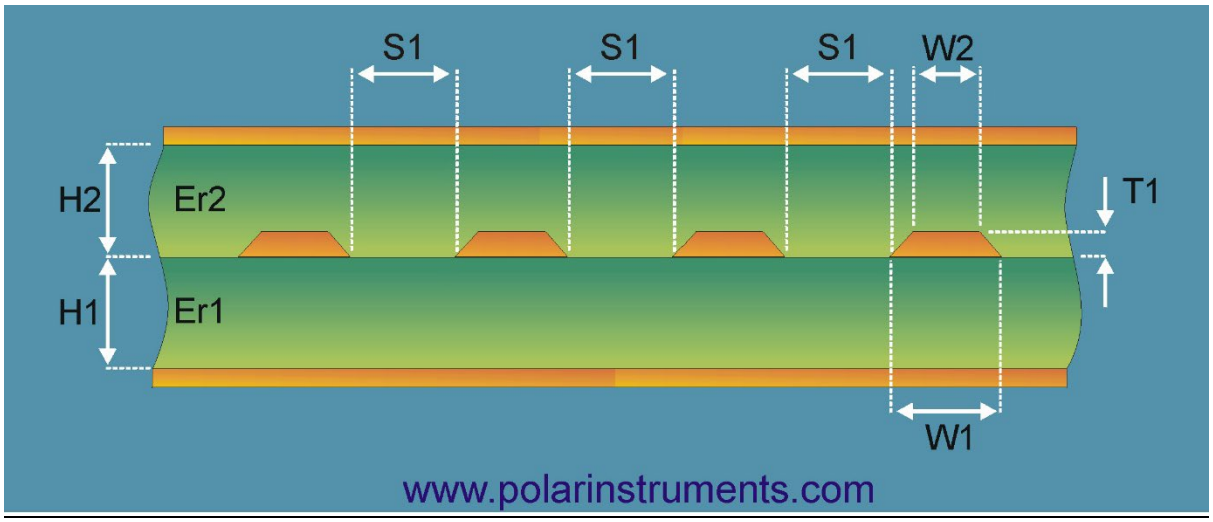
This structure has the same dimensions as Structure 3, but there are now 4 parallel conductors each separated by 334 um. The modal velocities are the same as those of Structure 3.



S-Parameters of Structure 4

The Structure 4 S-parameters are similar to those of Structure 3. Similar comments thus apply.

Structure 5



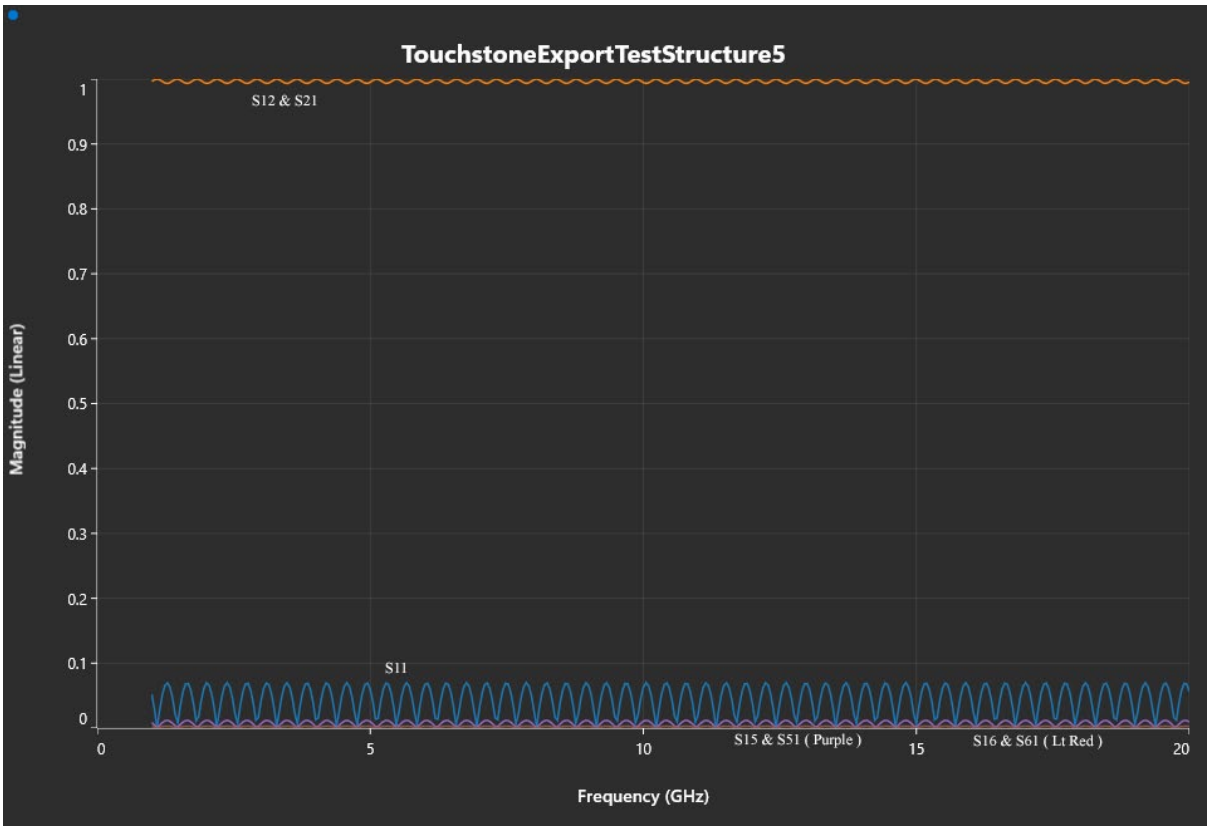
W1 = 177, W2 = 155, H1 = 250, T1 = 30.0, Er1 = 4.2, Er2 = 3.5, H2 = 270, S1 = 224
All dimensions are in micrometers,

The main difference between the parameters of Structures 1 & 2 with those of Structures 3 & 4 is the effects of the different modal velocities. To examine if this effect could be duplicated in a stripline with two different substrates, a further Structure 5, was used. This structure had the same dimensions as those of Structure 4, but with Er2 = 3.5, and S1 adjusted to 224 um so that the differential impedance of the structure was 100 Ohms.

The results are shown in the next graph. The modal velocities (m/s) are shown in the table below.

Structure 5 Velocities

Mode 1	Mode 2	Mode 3	Mode 4
1.5330e8	1.5362e8	1.5354e8	1.5341e8



S-Parameters of Structure 5

As expected, the velocities differ from those of Structure 4 because of the mixed dielectric substrates. However, the different modal values, although there is some variation, are not sufficient to show transfer of energy shown in Structures 1 & 2. The graph does show however a slight increase in the "ripples" caused by the mis-matched impedances between the external lines and the coupled lines.

Discussion

There is a substantial difference between the microstrip, Structures 1 & 2 and the stripline, Structures 3, 4 & 5 results. As mentioned earlier, the large differences in the modal velocities means that at any point the modes get out of phase which results in energy transfer between actual coupled lines. (This is the main principle of a microwave directional coupler). In the case of Structures 3 & 4 the uniform nature of the substrates means that all the modes have the same velocity and remain in phase so there is no modal energy transfer. Structure 5 was introduced with two different substrates. This did produce modal velocities but their difference was insufficient for the phase of the modes, in within the coupled length, 200mm, and frequency range 1 – 20 GHz.

However, there is likely to be a less obvious reason for the difference between the microstrip and stripline results. This concerns the charge and electric field distribution of differential and common mode structures. In the coupled line situation, the charge distribution is used repeatedly to calculate the inter-line capacitances (and inductances) used in the coupled line theory.

The basic impedance calculations (Si9000e) use an image along the centre line between the signal tracks. For differential structures this means there is a virtual charge distribution along this centre line. This charge distribution can be used to estimate the amount of electric field coupling between the two signal tracks. This calculation is readily accomplished by adding a few lines to the original Boundary Element Model. This estimate has been used for the Structures above, with the following results for the percentage amount of charge on the centre line:

Structure 1: 77.6 %

Structure 3: 29.1%.

The higher the percentage the stronger the coupling. Thus, in structures 3, 4 & 5 most of the electric field goes from the signal track directly to the two ground planes. This means the structures are almost operating as uncoupled single-ended striplines. This means that the S-parameters are only weakly coupled.

In microstrip structures the coupling is strong between the signal tracks and are less affected by the presence of the single ground plane. Which also explains, together with the different modal velocities, why the S-parameters exhibit strong coupling effects.

The calculations were calculated for external 100 Ohm differential line structures. The relative dimensions of the conductors will be the same for this impedance, so the graphs will remain the same for smaller or larger structures. The only way that stripline could exhibit a behaviour similar to microstrip is by radically reducing the spacing between the signal tracks, but then the structure will not be a 100 Ohm differential structure.

Acknowledgement

Thanks to Paul Carre for producing the graphics.

Reference

[1] Alan Staniforth: Multiline Scattering Parameters from Chain Parameters, September 2019.