S-Parameters: Microwave goes Mainstream for High-Speed PCB Design

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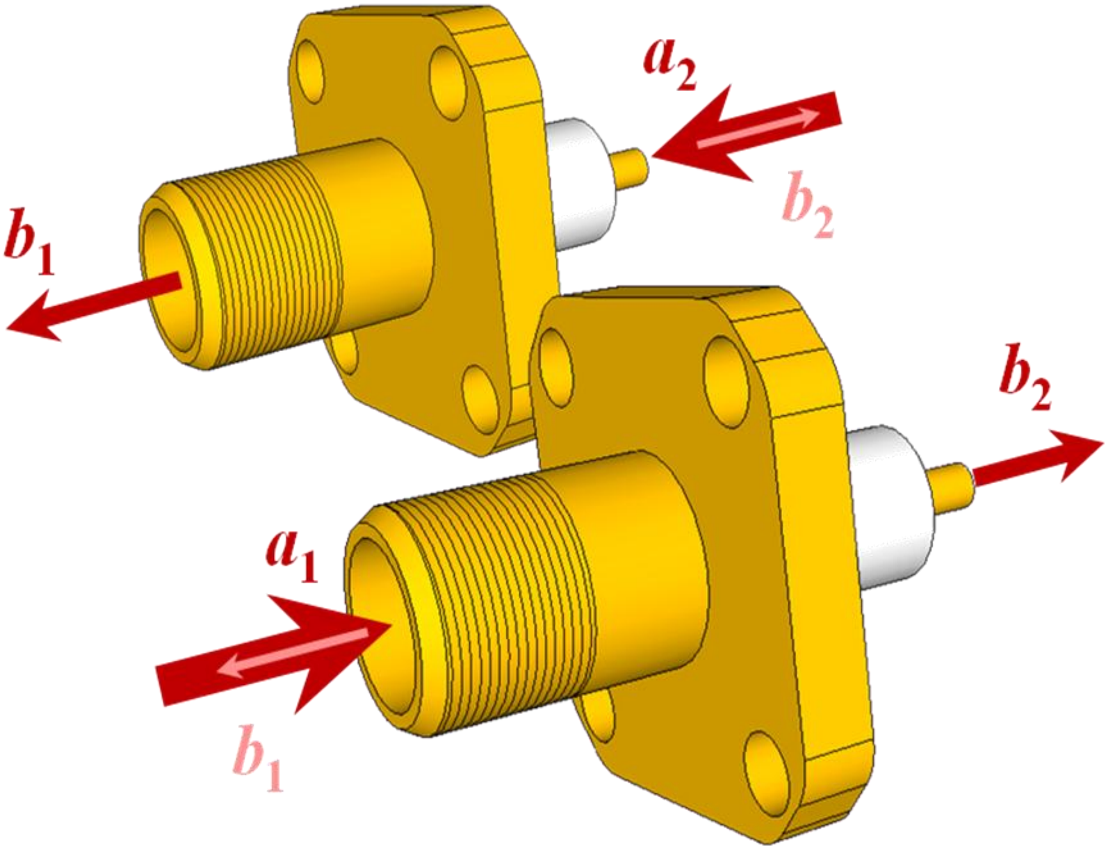


Abstract

Mainstream high-speed PCB design has long followed in the slipstream of RF and microwave engineering. Of necessity, techniques have been simplified and made applicable to wider use: for example IBIS models that describe input/output behaviour without revealing internal design details are published for most high-speed integrated circuits.

Double data rate memory has become the *de facto* standard for PC-based designs, turning every board that uses it into a high-speed design exercise, often involving system-level, multi-board interconnect. For high-speed differential channels, such as USB, common-mode filters and baluns are often employed. At today's bit rates, simple RLC models of such components do not fit the bill, but neither do models that require deep analysis of the physical structures. What is needed is a technique that, as in IBIS, reveals the minimum amount of information about the internal structure

while describing the interface sufficiently to simulate it accurately at frequencies into the multi Gigahertz range.

Luckily, such a technique is ready and waiting: S-Parameters.

This article explains in straightforward terms what S-Parameters are and why they are so useful.

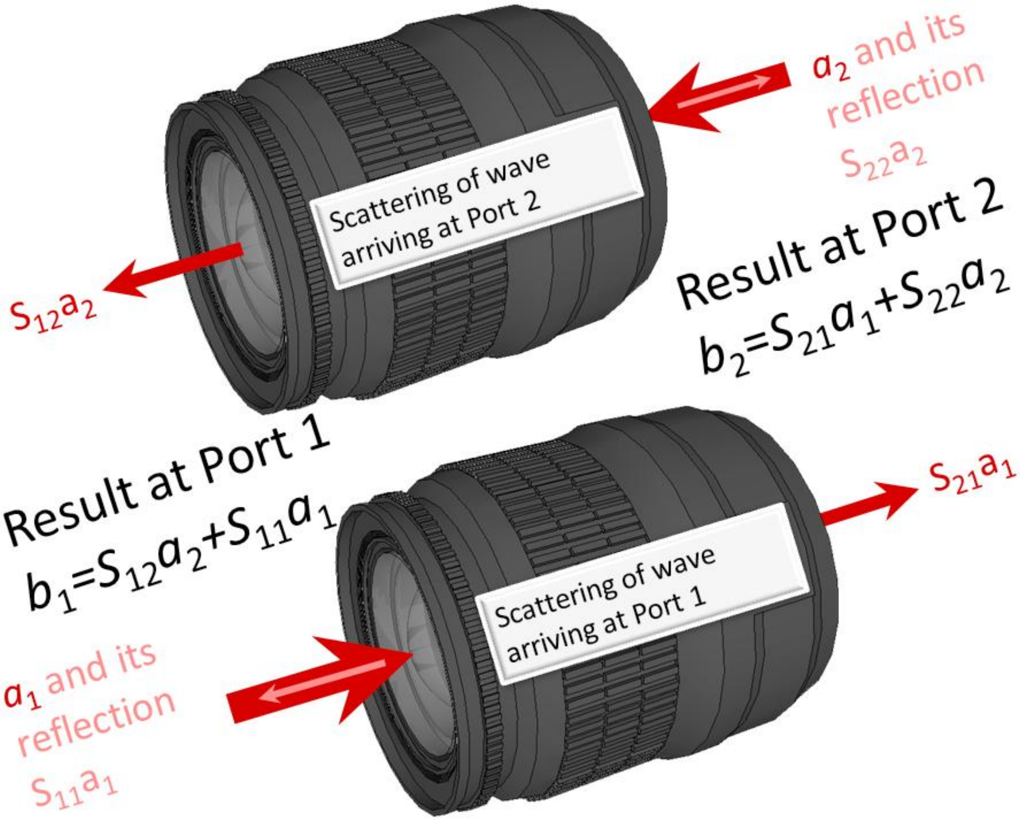
For the purpose of simplicity, the discussion is limited to two-port networks, although this technique is applicable to more complex arrangements.

What S-Parameters Represent

S-Parameters are *Scattering Parameters:* they describe how derivatives of a wave arriving at a circuit network port are scattered to all of the ports, including the one at which the wave arrived. Each S-Parameter names the port to which the wave is scattered first, followed by the port from which it has been scattered. S_{21}, therefore, is the S-Parameter for the wave scattered *to* Port 2 *from* Port 1, representing the transformation in terms of both magnitude and phase.

We shall see how S-Parameters are used in high-frequency electronics circuits, but first imagine that you wanted to describe the behaviour of a lens as shown in Figure 1. This is useful because in the lens, as in high-speed circuits, we are concerned with both transmission and reflection, and the lens is easier to visualise.

Figure 1: Lens Analogy



At high frequencies, the behaviour of a lens is analogous to that of a high-speed circuit such as a filter

You could analyse the physical properties in detail to predict the transmission and reflection of light at various frequencies: a complex task, and if you failed to take account of more subtle effects, your result might not be accurate.

An alternative approach would be to treat the lens as a black box, and merely measure its behaviour at various frequencies.

Let a_1 and a_2 be the incident waves on the left-hand (Port 1) and right-hand (Port 2) sides of the lens respectively.

At each individual frequency, we need to know:

1) The amplitude and phase shift of light transmitted *from* Port 1 *to* Port 2. Let S_{21} represent this transformation, so that the output at Port 2 given input a1 at Port 1 is $S_{21}a_1$.
2) The amplitude and phase of light reflected from Port 1 for input a_1. Let S_{11} represent this transformation, so that the reflection at Port 1 is $S_{11}a_1$.
3) The same information as in 1), but for light transmitted *from* port 2 *to* port 1 ($S_{12}a_2$).
4) The same information as in 2), but for light reflected *from* port 2 ($S_{22}a_2$).

At Port 1 and Port 2, the final results (b1 and b2 respectively) are the sum of the transmitted and reflected waves, so that, expressed in matrix form:

$$\begin{pmatrix} \underline{b}_1 \\ \underline{b}_2 \end{pmatrix} = \begin{pmatrix} \underline{S}_{11} & \underline{S}_{12} \\ \underline{S}_{21} & \underline{S}_{22} \end{pmatrix} \begin{pmatrix} \underline{a}_1 \\ \underline{a}_2 \end{pmatrix}$$

The items in the matrices include magnitude and phase, and can be expressed either as complex numbers or as magnitude and phase angle.

Like visible light, digital electronic signals contain a range of frequencies at various amplitudes and phase angles. If we know S_{11}, S_{12}, S_{21} and S_{22} for a range of frequencies within the limits of operation, we have the means to simulate a circuit such as a filter without the need to know the internal structure, and making no assumptions that might affect simulation accuracy.

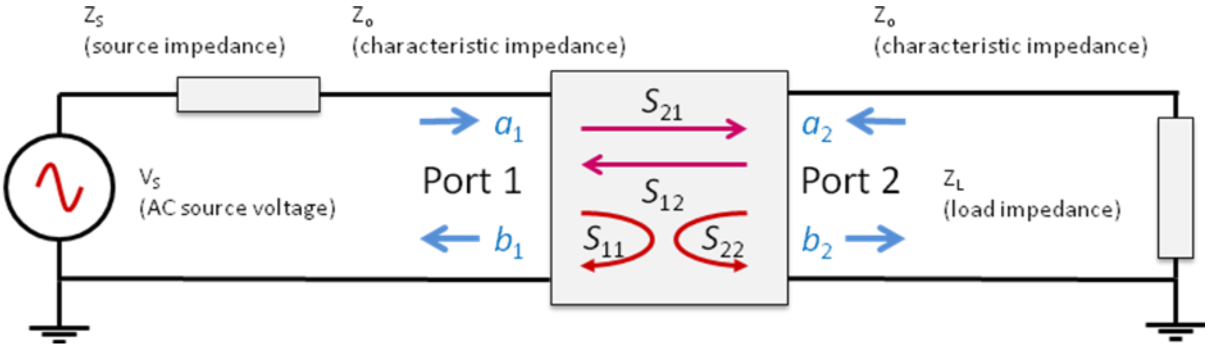
S_{21} is the *forward voltage transmission coefficient*, because if you multiply the incident AC voltage at Port 1 by S_{21}, you get the voltage transmitted to Port 2.

S_{11} is the *input voltage reflection coefficient*, because if you multiply the incident AC voltage at Port 1 by S_{11}, you get the voltage reflected from Port 1.

Measuring S-Parameters

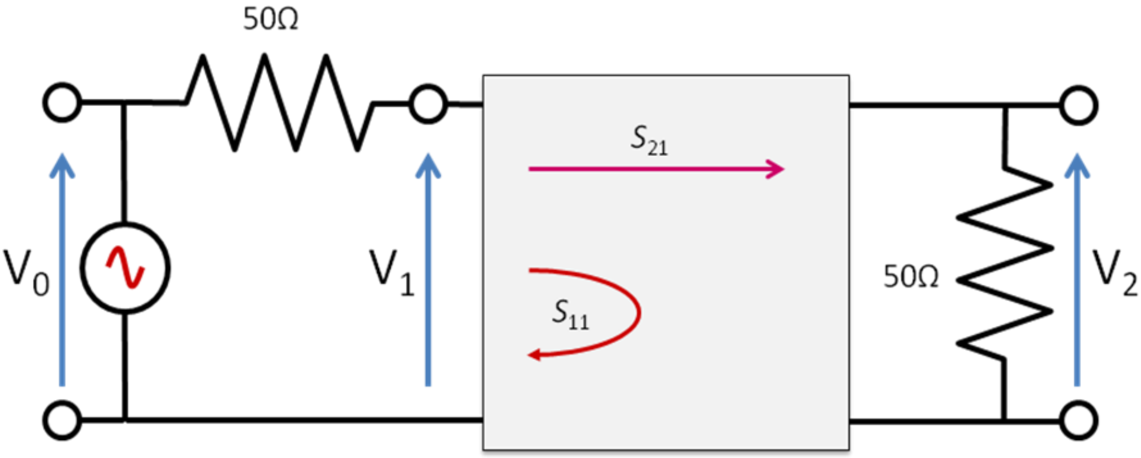
S-Parameters represent the transmission and reflection of waves at a specific frequency, when the network is embedded within long transmission lines with a specific load. These models are automatically adapted for use with different loads. S-Parameter models, in formats such as Touchstone, state the load as which the parameters were measured.

Figure 2: Two-Port Network Embedded within Transmission Lines



S_{21} and S_{11} can be measured by embedding the component to be modelled within a test circuit where the load impedance matches characteristic transmission line impedance. In this way there is no reflection from the far end, so there is no input signal a_2 at Port 2. To find S_{12} and S_{22}, the connections are reversed.

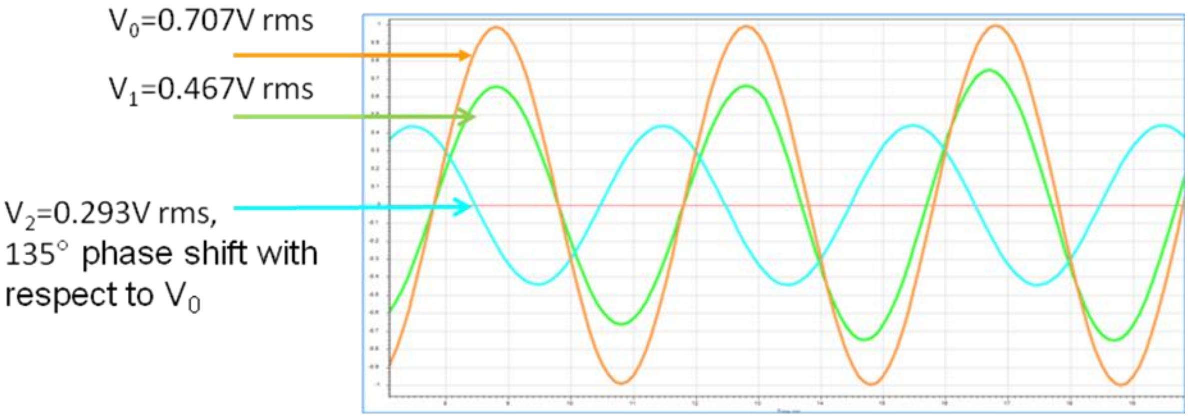
Figure 3: Two-Port Network Test Circuit for Measuring S-Parameters



$$\underline{S}_{21} = \frac{2\underline{V}_2}{V_0} \qquad \underline{S}_{11} = \frac{2\underline{V}_1}{V_0} - 1$$

For instance the measured voltages and derived S11 and S21 for a 2-port network comprising a 200mm length, 100Ω transmission line with negligible loss at 250MHz are shown in Figure 4.

Figure 4: Measured Voltages for S-Parameter Model of 200mm Transmission Line

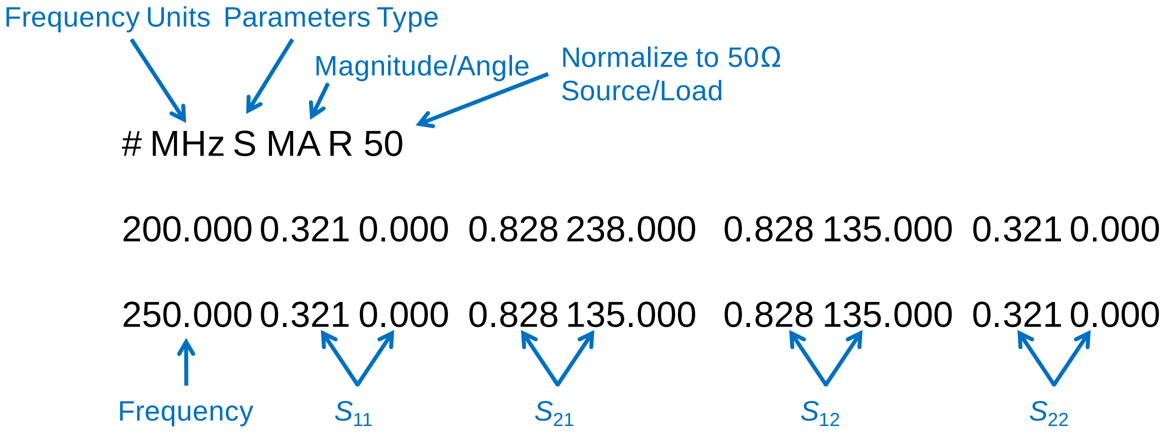


$$\underline{S}_{11}=\underline{S}_{22}=\frac{\underline{b}_1}{\underline{a}_1}=2\left(\frac{\underline{V}_1}{\underline{V}_O}\right)-1=0.321\angle 0^\circ=0.321+j0.000$$

$$\underline{S}_{21}=\underline{S}_{12}=\frac{\underline{b}_2}{\underline{a}_1}=2\left(\frac{\underline{V}_2}{\underline{V}_0}\right)=0.828\angle 135^\circ=-0.585+j0.585$$

In practice, we would need frequency samples covering the applicable range, but for illustration, Figure 5 is a Touchstone format extract containing entries for just two frequency points: the 250MHz parameters we have just derived, and another at 200MHz. This transmission line constitutes a symmetrical network, so S_{11}=S_{22} and S_{12}=S_{21}.

Figure 5: Touchstone Format S-Parameter Model Segment for 200mm Transmission Line



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# MHz S MA R 50

200.000 0.321 0.000  0.828 238.000   0.828 135.000  0.321 0.000

250.000 0.321 0.000  0.828 135.000   0.828 135.000  0.321 0.000
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In practice, S-Parameters will mostly be used for components such as filters and connectors, but the measurement technique and format of the model remains the same. Two requirements commonly apply to S-Parameter models used in high-speed PCB design:

Passivity - The model must not generate more energy that is supplied to it. A passive filter or a connector cannot exhibit gain.

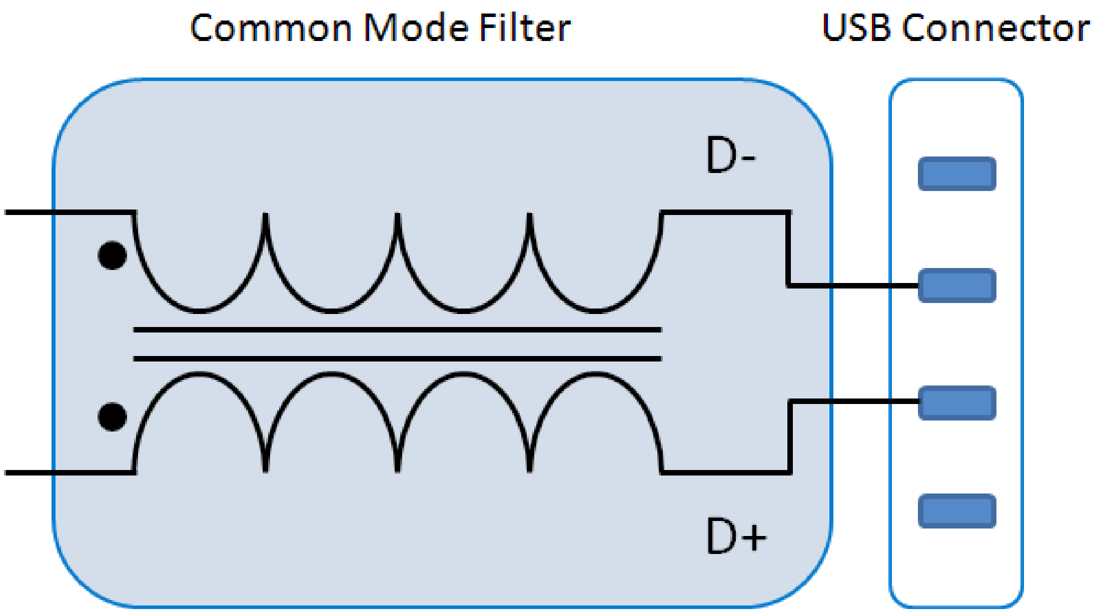
Causality - Determination of causality is more complex, but basically, the response of the model must depend only on its current and previous inputs. This will always be the case with a correctly constructed passive filter or connector model.

Simulation with S-Parameter Models

Most simulation of high-speed digital circuits is performed by time-domain simulators that work in conjunction with design capture and physical layout. The system used to illustrate this article is Zuken *CR-5000 Lightning*, used by many consumer electronics, industrial and aerospace companies to design high-end printed circuit boards. S-Parameter models describe the response at a range of frequencies rather than in the time domain, so they are first transformed into compatible macro-models by importing them into the simulation library via IdEM.

A common-mode filter is sometimes employed in high-speed differential buses such as USB to reduce off-board conducted Electromagnetic Interference (EMI). Differential signals comprise two complementary parts that, ideally, are always exactly opposite in phase. Signals that are in-phase, therefore, can be assumed to be unwanted noise.

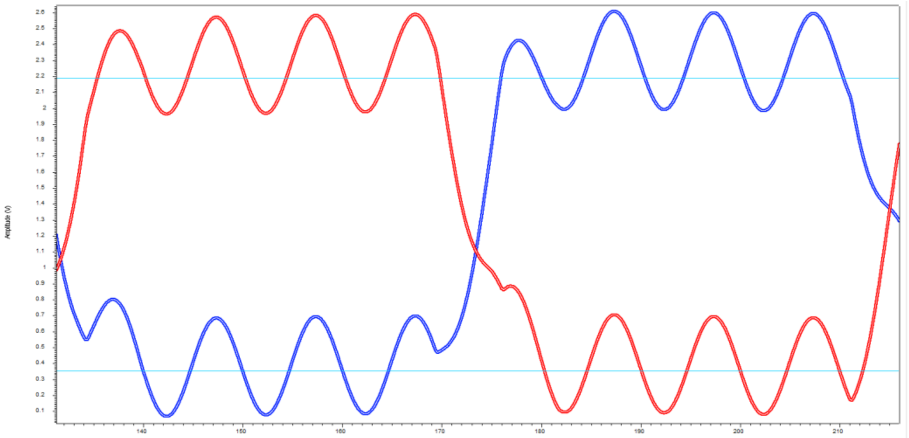
Figure 6: USB Common Mode Filter



Since differential PCB traces are usually routed nearby and in parallel, in-phase noise is often picked up on both sides of the differential pair. The purpose of the Common Mode filter in Figure 6 is, as far as possible, to suppress this noise while allowing the differential signal through.

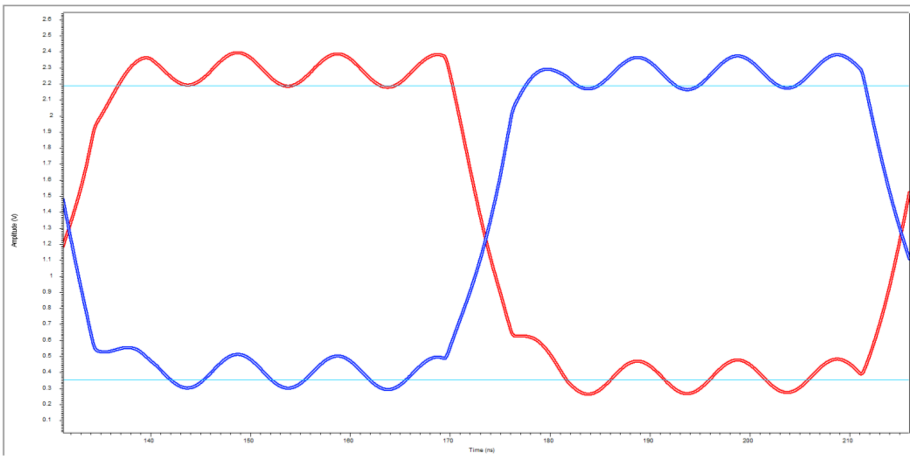
Figure 7 and Figure 8 show confirmation of the effectiveness of this kind of filter using simulation. Crosstalk from a closely-coupled, 1V peak amplitude, 100MHz sine wave signal has been induced equally on the + and – sides of the differential pair.

Figure 7: Differential Pair with Unfiltered In-Phase Noise



In the ideal differential signal, the + (shown in red) and – (shown in blue) waveforms would be exactly opposite in phase. Crosstalk from the 100MHz sine wave, coupled equally to each side of the pair, is in-phase on the two sides. The crossing points of the + and – waves should ideally be central, but the noise has broken this symmetry.

Figure 8: Differential Pair with Filtered In-Phase Noise



After filtering, the noise has been greatly reduced, and the crossing points have become more central.

Summary

With each large increment in bit rate comes a new set of high-speed issues, so that simulation techniques previously only required for RF and microwave applications have to be incorporated into mainstream PCB design flows.

S-Parameters allow accurate modelling of component behaviour without revealing the internal structure and can be derived by measurement alone. The ability to simulate S-Parameter models enhances the accuracy of EDA software for high-speed digital PCB design.

The requirements of fast turnaround and use by non-specialists mean effective designers must employ a combination of known-good templates, embedded constraint management and simulation to achieve the right-first-time results today's market demands.