Product: Vector Network Analyzer ZVB

Measuring Balanced Components with Vector Network Analyzer ZVB

Application Note

Balanced RF components are advantageous compared to traditional single-ended components, since they cause less EMI, and are less susceptible to EMI. This application note describes the fundamental concepts of differential and common mode signals and of mixed-mode parameters, which are essential for balanced components. Techniques for the measurement of mixed-mode parameters are presented. Examples show the features implemented in the ZVB for balanced device measurement.

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Contents

1 Introduction

Traditionally, RF signals have been transmitted via transmission lines that have one of the two line conductors connected to ground. These transmission lines are called unbalanced or single-ended. Among the frequently used line types of the single-ended family are the coaxial line, the microstrip line, and the coplanar line. In microstrip transmission line, for example, one of the two conductors is a metallic strip, the other one is represented by a conductive plane. The two conductors are separated by a dielectric. The conducting plane is assumed to be an ideal ground with equal potential all over the plane. In reality, however, this is not true; circuit components that must be referenced to ground for proper operation cause currents within the ground plane. Finite conductivity and parasitic inductances give rise to differences of potential within the plane. These differences interfere with the desired signal. Furthermore, the strip conductor of the microstrip line might act as an antenna, which is susceptible to interfering electromagnetic fields. Equally, the microstrip line can also be the source of interference that compromises the signal quality of other transmission lines or components.

Such problems can be overcome by using balanced transmission lines, which in general have a symmetric structure. Fig. 1 shows the cross section of a balanced transmission line in planar technology. The line consists of two strip conductors on a dielectric substrate. For the sake of simplicity, there is no ground near to the line.

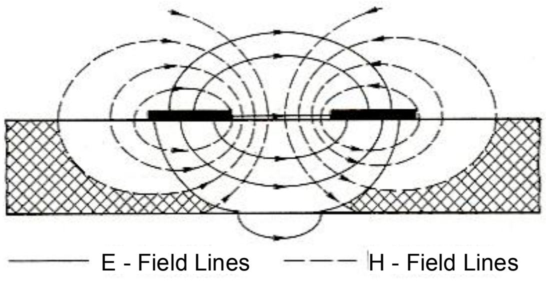


Fig. 1 Cross section of a planar balanced transmission line

The signal is represented by the voltage between the conductors of the balanced line, which is called the differential mode. Ground plane potential is – at least in the ideal case – irrelevant. In reality, however, the ground plane is in almost every case near to the line conductors. Consequently, a second mode exists besides the differential mode. Circuit operation can be disturbed by this mode. A modal analysis is presented below, which shows how the behaviour of balanced transmission lines and components can be measured.

2 Differential and Common Mode

A balanced transmission line with ground plane can be modelled as two coupled single-ended lines. Transmission line theory states that on these two coupled lines there exist two independent modes, which are known as even and odd or, alternatively, common and differential mode. Fig. 2 shows the electric and magnetic field lines of the two modes in the cross section of a planar balanced line.

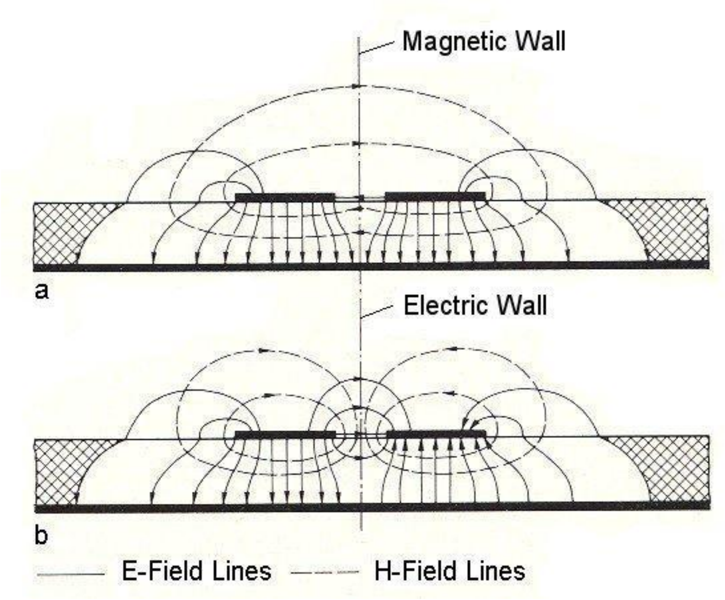


Fig. 2 Cross section of a planar balanced transmission line, with electric and magnetic field lines
a: Even or common mode
b: Odd or differential mode

For common mode, one can imagine a magnetic wall in the vertical symmetry plane, whereas for the differential mode, it is an electric wall.

In general, the characteristic impedances and propagation constants of the two modes are different and there is no fixed relation between them. These parameters depend on the type of the transmission line. The characteristic impedance of the differential mode is Z_d, common mode is Z_c. If the characteristic impedance of the two single-ended lines is Z_0, then Z_d and Z_c can easily be derived. For the differential mode, the voltages are equal in amplitude, but opposite in phase. The voltage doubles, whereas the current remains the same, resulting in $Z_d = 2\ Z_0$. For the common mode, the currents doubles and the voltage remains constant, giving $Z_c = Z_0 / 2$.

A transmission line can be described by wave quantities and S-parameters that refer to single-ended modes, as well as by parameters referring to differential and common modes. Since the latter description is not based on a uniform (e.g. single-ended) mode, the corresponding S-parameters are called mixed-mode parameters. Single-ended and mixed-mode parameter descriptions of a transmission line are equivalent and mutually convertible, as shown below.

The concept of mixed-mode parameters is not restricted to transmission lines, but can be applied to any linear circuit. In Fig. 3 a filter with a single-ended port 1 and a balanced port 2 is shown.

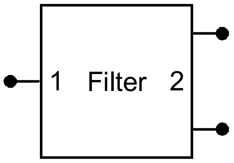


Fig. 3 Filter with a single ended and a balanced port

Its mixed-mode matrix can be written as:

$$S = \begin{pmatrix} S_{ss11} & S_{sd12} & S_{sc12} \\ S_{ds21} & S_{dd22} & S_{dc22} \\ S_{cs21} & S_{cd22} & S_{cc22} \end{pmatrix} \qquad (1)$$

Within the subscripts xyij, x and y stand for the letters s(ingle ended), d(ifferential mode) or c(ommon mode). i and j denote port numbers. The order of letters and numbers is as known from single-ended S-parameters. The first letters and numbers (x and i) represent mode and number of the load port, whereas the second ones stand for source port mode and number. When there is more than one single-ended or balanced port, the parameters are grouped in up to 9 blocks according to their index letter combination. In the S matrix these blocks are arranged as follows:

$$S = \begin{pmatrix} S_{ssij} & S_{sdij} & S_{scij} \\ S_{dsij} & S_{ddij} & S_{dcij} \\ S_{csij} & S_{cdij} & S_{ccij} \end{pmatrix} \qquad (2)$$

The blocks in (2) describe the following characteristics:

- S_{ssij} contains all reflection parameters of the single-ended ports and transmission parameters between them.
- S_{ddij} contains all reflection parameters of the differential modes of the balanced ports and transmission parameters between them.
- S_{ccij} contains all reflection parameters of the common modes of the balanced ports and transmission parameters between them.
- S_{sdij} contains all transmission parameters from a balanced port with differential mode stimulus to a single-ended port.
- S_{dsij} contains all transmission parameters from a single-ended port to the differential mode of a balanced port.
- S_{scij} contains all transmission parameters from a balanced port with common mode stimulus to a single-ended port.
- S_{csij} contains all transmission parameters from a single-ended port to the common mode of a balanced port.
- S_{dcij} contains all transmission parameters from a balanced port with common mode stimulus to the differential mode of a balanced port.
- S_{cdij} contains all transmission parameters from a balanced port with differential mode stimulus to the common mode of a balanced port.

An ideal balanced device is optimized for operation in differential mode and thus rejects all common mode signals. Fig. 4 shows this behaviour for a fully balanced and for a balanced-to-single-ended device.

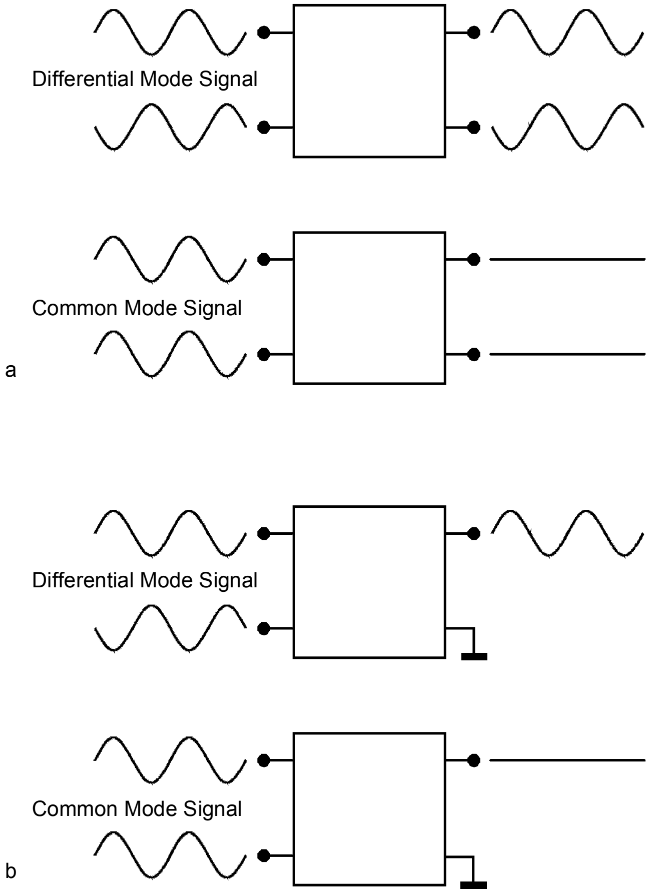


Fig. 4 Ideal balanced devices:
a: Fully balanced
b: Balanced-to-single-ended

For an ideal fully balanced device, the off-diagonal blocks of S-matrix (2) are all equal to zero. An ideal balanced-to-single-ended device, however, has nonzero elements in the S_{sd} and S_{ds} blocks. From a practical point of view, good balanced behaviour can be achieved by designing the circuit symmetric throughout.

Now, let us consider some effects of nonideality. The filter in Fig. 3 is used in order to restrict transmission between the single-ended port 1 and the differential mode of port 2 to a defined frequency band. This desired transmission characteristic is represented by S_{ds21}. However, due to a non-ideal S_{cs21} element some of the signal energy applied to port 1 is converted to common mode at port 2. The load at port 2 will either absorb this signal or reflect it as common or differential mode (see Fig. 5).

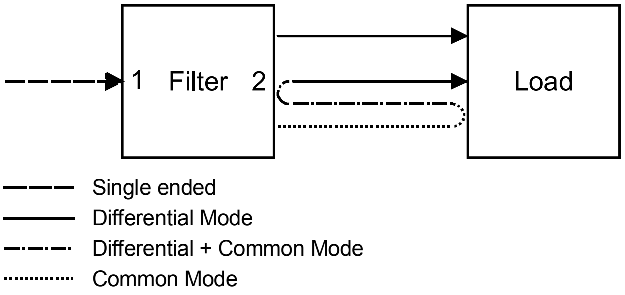


Fig. 5 Forward measurement of the filter of Fig. 3, signal flow

After a second reflection at the filter output (and conversion of the common mode component to differential), both reflected signal components can interfere with the directly transmitted differential signal, which might compromise filter characteristics. This shows that if mode conversion cannot be kept equal to zero, balanced devices should at least have good common mode match.

Signal components that have been converted to common mode once and that remain common mode will not influence the desired transmission characteristics. They can, however, generate EMI, when unwanted signals (e.g. noise) are present at port 1. Conversely, common-mode noise that is picked up and converted to differential mode will lower the signal-to-noise ratio (SNR).

3 Measurement Techniques

Direct determination of the mixed-mode parameters for a DUT would require the measuring instrument to apply pure differential and common-mode stimuli. Furthermore, its receiver would have to be able to distinguish between differential and common-mode responses from the DUT, and finally, well-defined reference planes and balanced calibration standards for these planes would have to be available. Commercially available Vector Network Analyzers (VNAs) do not fulfill these requirements, since their test ports are unbalanced and only one test port can be stimulated at a time. This restriction could be overcome by using balance-unbalance transformers (baluns). In Fig. 6 simple baluns are used in order to measure the differential mode characteristics of a two-port DUT with a VNA. When the differential mode reference impedance is Z_D, the turns ratio n_D of the balun is chosen as

$$n_D = \sqrt{\frac{Z_D}{50\,\Omega}}$$

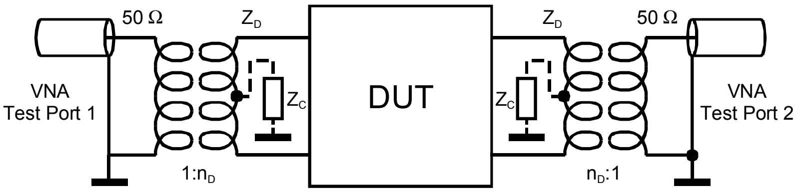


Fig. 6 Measuring the differential mode characteristics of a two-port DUT using baluns

This measurement method, however, has several drawbacks:

- The S-parameters of the DUT are to be determined at its balanced ports. The VNA, when calibrated at its coaxial ports, measures the DUT embedded into baluns. If the characteristics of the balun are not ideal, and additional line lengths have an effect, the measured result can be severely distorted. Direct calibration at the balanced ports in many cases is not an alternative, since balanced calibration standards are not readily available.
- When a simple four-terminal balun is used, the common mode load impedance is an open circuit. Therefore, multiple reflections like those described in Fig. 5 compromise measurement accuracy. This could be improved by providing a center tap at the DUT side winding of the balun and by connecting the common mode reference impedance Z_C between the tap and ground as shown dashed in Fig. 6.
- Common mode characteristics and conversion between differential and common mode cannot be measured.
- The bandwidth of baluns is limited to about 1 GHz.

To measure common mode characteristics, a common mode transformer can be added to the setup of Fig. 6 as shown in Fig. 7.

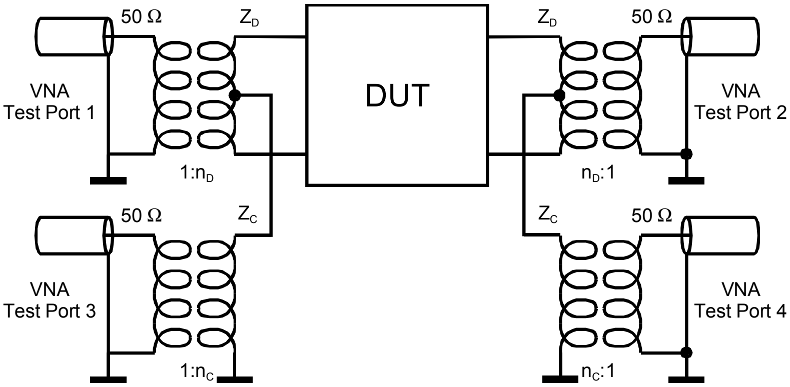


Fig. 7 Differential- and common-mode characterization of a balanced device

The common-mode transformer is connected to the center tap of the differential-mode balun, so that it is possible to measure differential and common modes separately with single-ended VNA test ports. But the problems associated with the non-ideal baluns and with their bandwidth limitation remain.

Therefore, another approach has been chosen. As mentioned before, single-ended characterization of a device is equivalent to mixed-mode characterization. Measuring instruments and accessories, as well as calibration and measurement techniques, are readily available for single-ended multiport measurement. When the single-ended parameters are known, modal decomposition techniques can be used to convert them to mixed-mode. Two different approaches lend themselves for this conversion:

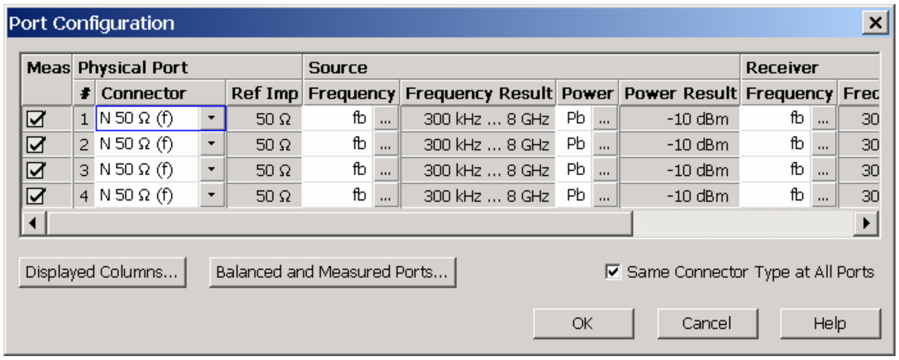
- The single-ended S-parameters are first converted to single-ended Z-parameters. These relate single-ended voltages to single-ended currents. Since there is a linear relation between single-ended and mixed-mode voltages and currents, the single-ended voltages and currents in the matrix equation U = Z * I can be substituted by mixed-mode voltages and currents, resulting in mixed-mode Z-parameters. These Z-parameters can finally be re-converted to mixed-mode S-parameters. This procedure works well for arbitrary reference impedances of single-ended and balanced ports.
- Bockelman and Eisenstadt [1] found a direct matrix relation between single-ended and mixed-mode S-parameters. This implies, however, some restrictions concerning port impedances. If the conditions are not met, additional renormalizations must be performed.

4 ZVB Features for Balanced Device Measurement

The test ports of a ZVB can be configured arbitrarily as single or balanced ports. Any two of the four single-ended test ports available on a ZVB 8 can be put together to form a balanced port. Two different test port numbering schemes exist in parallel:

- The **physical port number** – the number written on the ZVB front panel – denotes the single-ended ports and cannot be changed.
- The **logical port number** is the number to which the indices of measured quantities (e.g. S-parameters) refer. If no balanced ports are defined, the logical port number of a port is equal to its physical port number. The logical number of a balanced port can be assigned by the user. It is specified along with the numbers of its constituent physical ports. The remaining physical ports are automatically renumbered, resulting in a consecutive series of logical port numbers starting with 1.

The port configuration can be set via **MODE: Port Config....** This opens the **Port Configuration** dialog (Fig. 8):

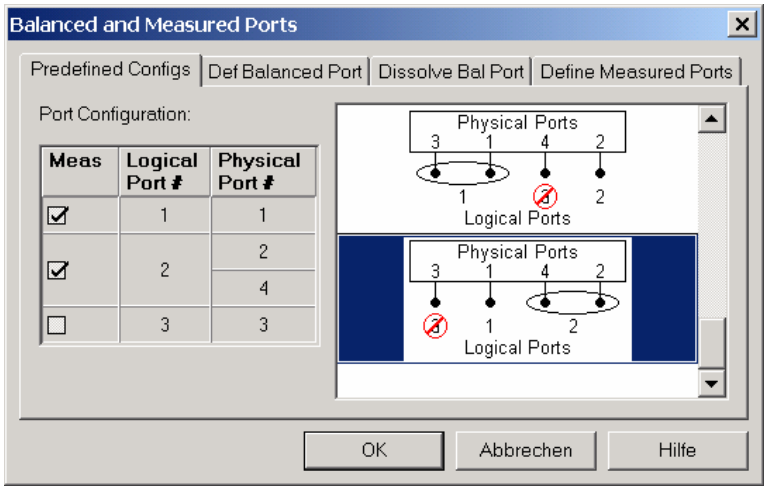


Meas	Physical Port		Ref Imp	Source				Receiver	
	#	Connector		Frequency	Frequency Result	Power	Power Result	Frequency	Frec
☑	1	N 50 Ω (f)	50 Ω	fb ...	300 kHz ... 8 GHz	Pb ...	-10 dBm	fb ...	30
☑	2	N 50 Ω (f)	50 Ω	fb ...	300 kHz ... 8 GHz	Pb ...	-10 dBm	fb ...	30
☑	3	N 50 Ω (f)	50 Ω	fb ...	300 kHz ... 8 GHz	Pb ...	-10 dBm	fb ...	30
☑	4	N 50 Ω (f)	50 Ω	fb ...	300 kHz ... 8 GHz	Pb ...	-10 dBm	fb ...	30

☑ Same Connector Type at All Ports

Fig. 8 Port Configuration dialog

Click on the button **Balanced and Measured Ports...** to open a subdialog for the definition of the balanced port topology:



Port Configuration:

Meas	Logical Port #	Physical Port #
☑	1	1
☑	2	2 4
☐	3	3

Fig. 9 Balanced and Measured Ports dialog

The port configurations that are accessible via the tab **Predefined Configs** (selected per default) cover most practical applications. Fig. 9 shows the appropriate selection for the filter from Fig. 3. For other configurations, each balanced port must be explicitly defined. This can be done via the tab **Def Balanced Port**. Use **Dissolve Bal Port** to break a balanced port up into its physical ports.

The reference impedance of a single-ended port is given by its connector type. The differential and common mode reference impedances of balanced ports, however, can be defined by the user. The default value of the differential mode impedance is $2 * 50\ \Omega = 100\ \Omega$, whereas the common mode impedance is preset to $50\ \Omega / 2 = 25\ \Omega$. Usually, these values must be changed according to the specifications of the DUT.

Since the VNA does not know the number of ports for the DUT, and since it is inefficient to perform a full 4-port system error correction when only a single reflection coefficient is to be measured, the range of measured and corrected test ports must be specified. With the selection shown in Fig. 9, the measured port range is reduced to 1...3. Alternatively to the predefined configurations, the range of measured ports can also be set via the tab **Define Measured Ports**.

Click on OK in both open dialogs; now the selected port configuration is active. Since the configuration change might have made the previously selected measured quantities invalid, the measured quantities of all traces are set to a default, which is the reflection coefficient of the port with the lowest logical number in the measured port range. If this port is balanced, the differential reflection S_{ddii} is selected.

In the **MEAS** menu only those quantities can be selected that are defined in the current port configuration.

5 Measurement Examples

In order to become familiar with mixed-mode parameters we first look at a measurement that seems rather trivial when performed in a single-ended environment: All VNA test ports are equipped with male connectors and calibrated using a full 4-port calibration. The following balanced test ports are defined:

Logical Port	Physical Ports
1	1, 3
2	2, 4

Now a very simple DUT is connected. As depicted in Fig. 10, a female / female adapter connects the physical test ports 1 and 2. Another adapter of equal length is inserted between ports 3 and 4.

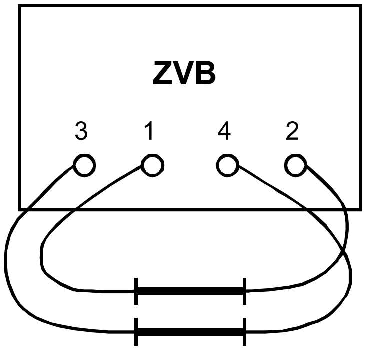


Fig. 10 Measurement of two adapters of equal length

With this symmetrical DUT it is only necessary to consider half of the mixed-mode parameter matrix, that is reflection at logical port 1 and transmission from logical port 1 to 2. Since there are two modes present at each balanced port, a single parameter is not sufficient for the description of reflection or transmission characteristics. Each of them needs 4 parameters to be represented adequately, that is S_{dd11}, S_{cd11}, S_{dc11} and S_{cc11} for reflection, and S_{dd21}, S_{cd21}, S_{dc21} and S_{cc21} for transmission. The generic terms reflection or transmission here do not only mean pure-mode reflection coefficients of the differential and common mode, but also mode-converting coefficients.

The memory traces 5...8 in Fig. 11 show the measured result for the port 1 reflection of our simple DUT. Assuming that the reflection coefficients of the adapters are all equal in magnitude and phase, theory states that the pure-mode reflection coefficients S_{dd11} and S_{cc11} (as well as S_{dd22} and S_{cc22}) are equal to the single-ended reflections S_{11}...S_{44}. The cross-mode reflections S_{dc11} and S_{cd11} arise from slight unsymmetries in the single-ended reflections.

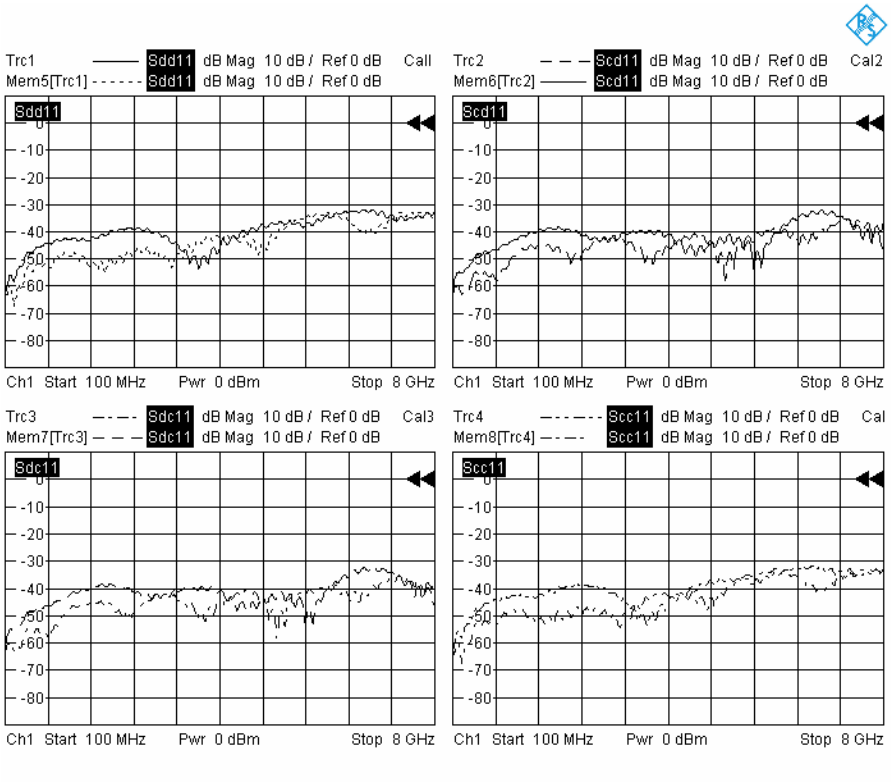


Fig. 11 Mixed-mode reflection parameters of a DUT consisting of two adapters

In the next step, the adapter between physical ports 3 and 4 is replaced by a shorter one, as shown in Fig. 12. Since the two adapters are now different in lenght, there is a phase difference between the two single-ended paths that approaches 180° at 8 GHz.

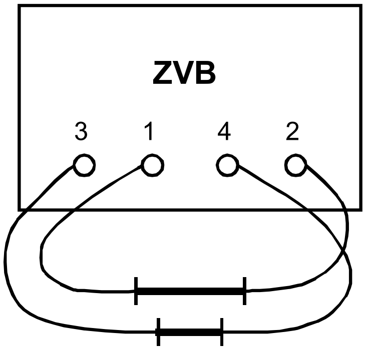


Fig. 12 Measurement of two adapters of unequal length

This measurement gives traces 1...4 in Fig. 11. Swapping the adapter does not change matching conditions significantly, therefore the magnitude of the reflection parameters remains approximately constant.

Fig. 13 comprises the forward transmission parameters of the mixed-mode matrix, which all have the port number index 21 in common. As in Fig. 11, the memory traces refer to the case that the two adapters are equal in length. Note that the traces of S_{dd21} and S_{cc21} coincide with the reference line at 0 dB. Due to symmetry, the mode-conversion parameters S_{cd21} and S_{dc21} are rather small.

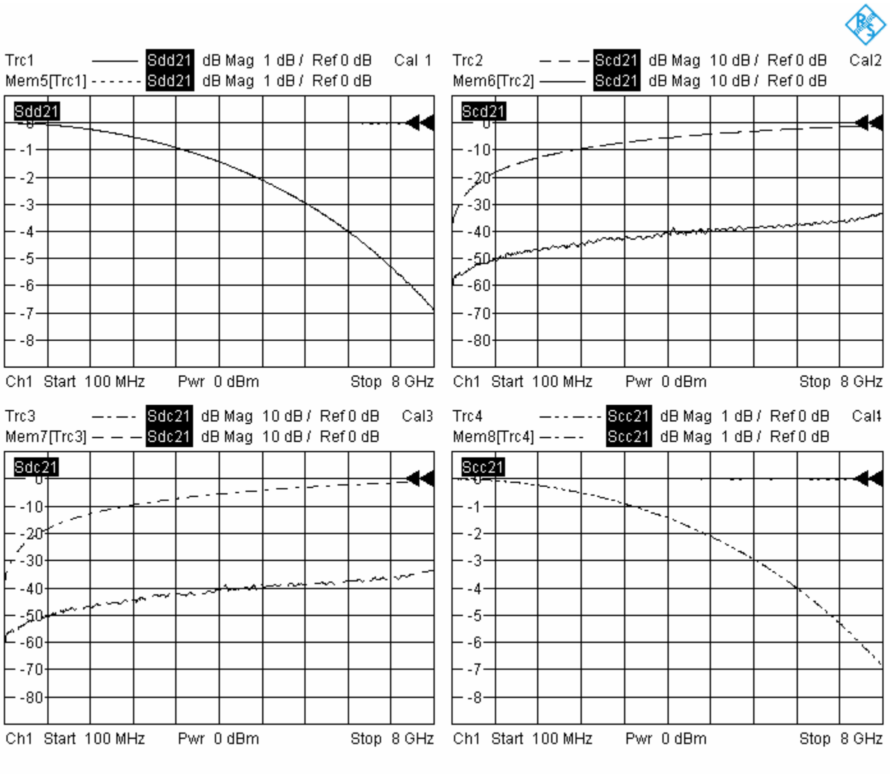


Fig. 13 Mixed-mode transmission parameters of a DUT that consists of two adapters

In contrast to the reflection parameters discussed before, the transmission parameters change significantly after inserting the short adapter. The pure mode transmission factors S_{dd21} and S_{cc21} become smaller with increasing frequency, whereas the mode-conversion transmission factors S_{cd21} and S_{dc21} grow. This is explained as follows: When frequency is swept, the length difference of the two transmission paths makes the phase shift between the single-ended transmission parameters S_{21} and S_{43} increase from 0 degrees towards 180 degrees. Expressing this in mixed-mode parameters means for example that at low frequencies a pure common mode stimulus results in a nearly pure common mode response, but at higher frequencies an increasing part of the energy transported in the common mode is converted to differential mode.

Our next DUT will be more strongly related to practical engineering. Fig. 14 shows the mixed-mode parameters of a SAW filter used in the receiver path of a mobile phone diplexer. Trace 4 is a detailed view of the pass band. From the corresponding trace evaluation field the filter loss, which varies around 2.3 dB, and its ripple can be read. The conversion between single-ended and differential mode on the one hand and common mode on the other hand is below -20 dB. Common mode reflection at port 2 is almost total. This, however, has no significant effect on filter operation, since normally there is not a large common mode signal incident at port 2.

For comparison, Fig. 15 shows the single-ended S-parameters of the same device. These form the base for the calculation of the mixed-mode parameters of Fig. 14. However, they give at best a raw impression of the position of the passband, but no information about loss, match and mode conversion.

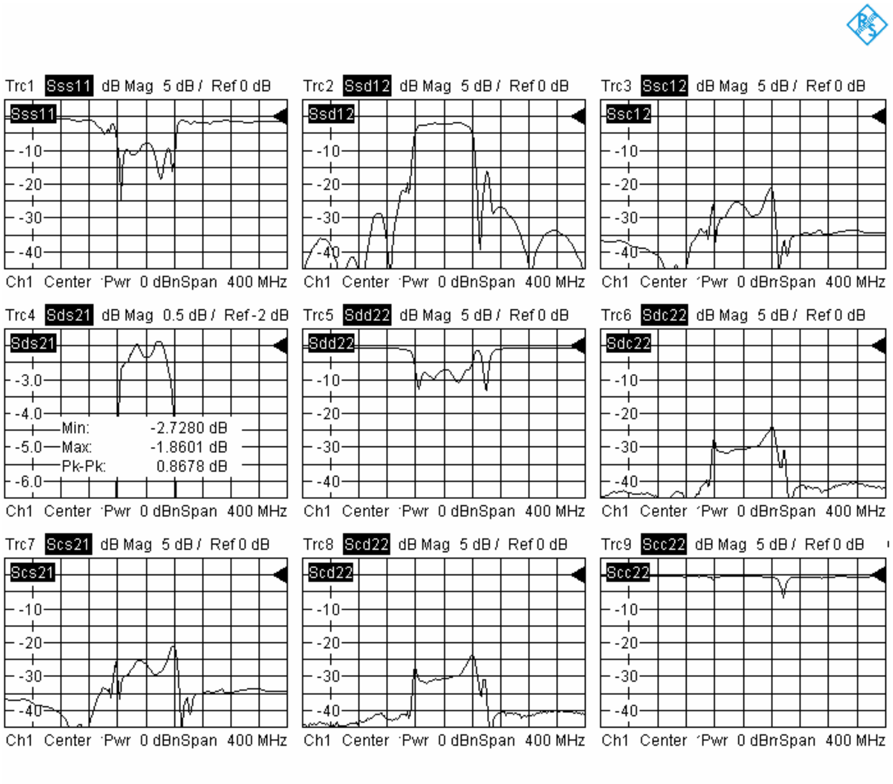


Fig. 14 Mixed-mode-parameters of a diplexer filter

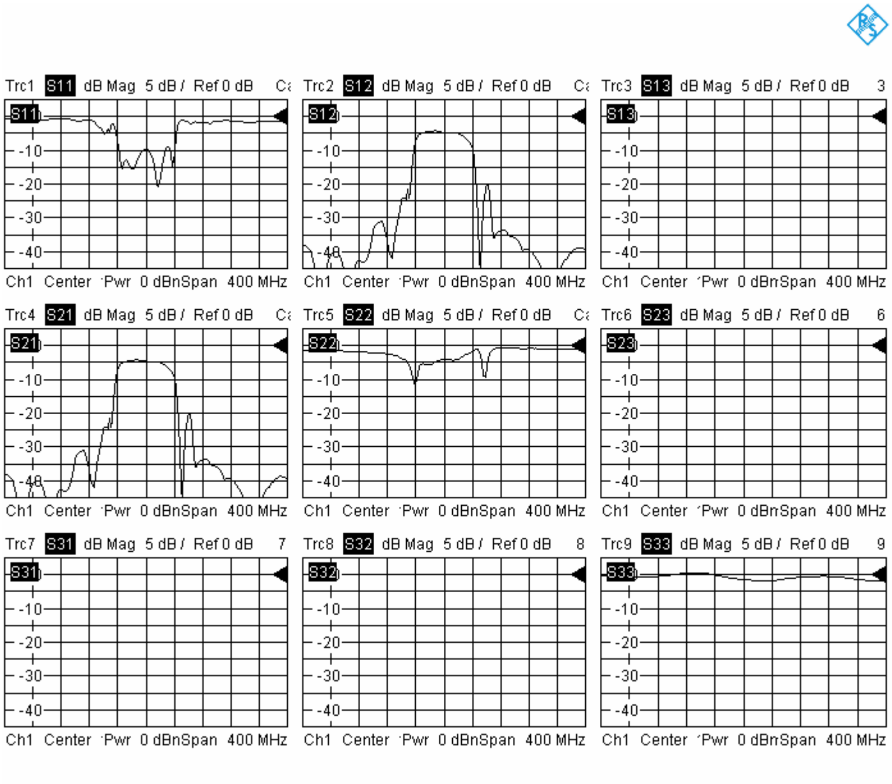


Fig. 15 Single-ended S-parameters of the diplexer filter of Fig. 14

Our last example refers to cable measurement. LAN Ethernet standards such as 10Base-T, 100Base-T or 1000Base-T are based on twisted-pair cables for high-speed data transmission. The 1000Base-T standard defines a data rate of 1 Gbit/s. Depending on the screens and / or shields that enclose single pairs or the complete bundle, cables have designations such as UTP (Unshielded Twisted Pair), FTP (Foil shielded Twisted Pair) S/FTP (Screened Foil shielded Twisted Pair) or S/STP (Screened Shielded Twisted Pair). S/STP provides good isolation between twisted pairs as well as protection against external EMI, since each pair is individually screened and the complete cable is surrounded by a shield.

Fig. 16 shows some mixed-mode parameters of a single pair in a S/STP CAT 7 cable with 4 twisted pairs:

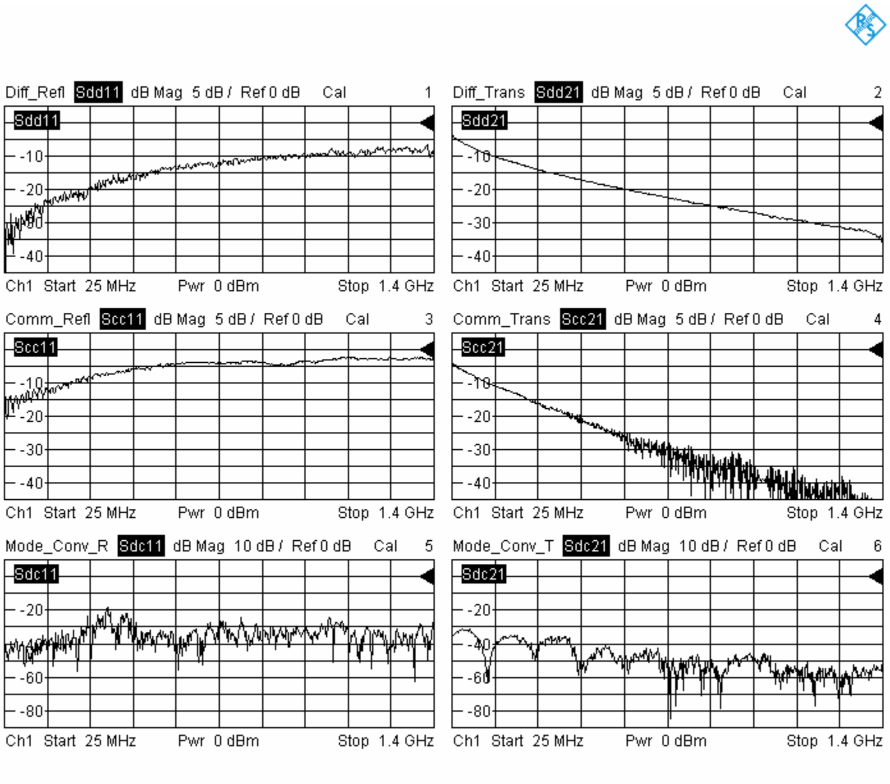


Fig. 16 Mixed-mode-parameters of a conductor pair in a cable

The upper row of diagrams show return loss (left) and attenuation (right) of the differential mode. In the middle row the same parameters are shown for the common mode. The frequency behaviour of the two modes appears to be similar, since for both of them the same physical effects apply. The cable, however, has been optimized for the propagation of the differential mode. For this mode, the reflection coefficient is smaller and the increase in transmission attenuation is slower than for common mode. In the lower row of diagrams in Fig. 16, we can see the conversion loss from common to differential mode for reflection (left) and transmission (right). Due to the symmetry and reciprocity of the cable, the measured parameters for reverse direction and for conversion from differential to common mode are almost equal to those shown.

The quantities in Fig. 16 refer to a single conductor pair. Cable specifications, however, often comprise some characteristic parameters that describe crosstalk and mode conversion between two conductor pairs. Near-End CrossTalk loss (NEXT) is a measure for the differential mode crosstalk from one conductor pair to another at the same end of the cable. It is independent of cable length. For NEXT measurement, the two pairs are terminated with their nominal differential- and common-mode impedances at the far end of the cable. At the near end, the isolation between the pairs is measured:

$$\text{NEXT} = 10 \log_{10} (P_{1N} / P_{2N}) \text{ (dB)}$$

where

- P_{1N} is the input power of the signal-carrying conductor pair – the disturbing pair –
- P_{2N} is the output power of the conductor into which the signal is coupled – the disturbed pair –

The upper diagram in Fig. 17 shows the NEXT for the cable from Fig. 16.

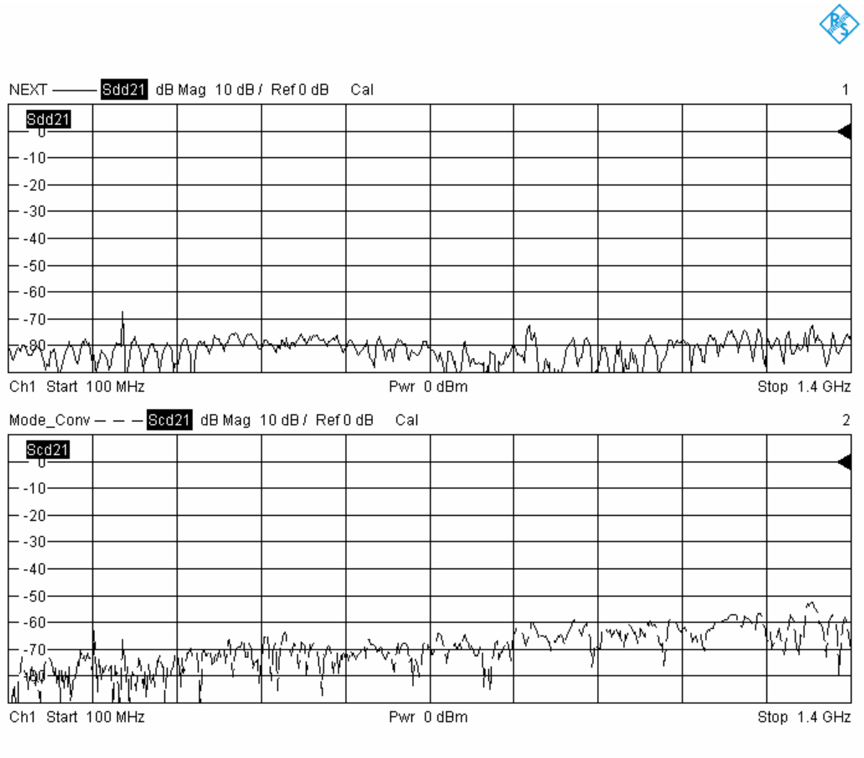


Fig. 17 Crosstalk NEXT and mode conversion TCL between conductor pairs at the near end of a cable

The lower diagram depicts the near-end conversion loss from differential to common mode for the two conductors pairs, measured with the same setup as for NEXT. In some standard specifications this quantity is also referred to as Transverse Conversion Loss (TCL). Due to reciprocity, which can be taken for granted for most cables, TCL is usually equal to the near-end conversion loss from common to differential mode, the Longitudinal Conversion Loss (LCL). Sometimes, one can find the term unbalance attenuation as yet another designation for mode conversion loss in cables.

For crosstalk measurements – especially for NEXT – the connection from the coaxial VNA test cables to the cable conductors must be well designed. It is absolutely necessary to maintain good isolation between the conductor pairs in the area where the screening must be removed to make contact. The original twist of the conductors should not be changed.

For Far-End CrossTalk loss (FEXT) measurement, the differential mode signal is fed into the disturbing pair at one cable end, and crosstalk to the disturbed pair is measured at the other end. Again, the unused ends of the pairs are terminated with their nominal impedances. There are two variants of FEXT. The Input / Output Far-End CrossTalk loss IO FEXT is defined as:

$$\mathrm{IO\ FEXT} = 10 \log_{10} (P_{1N} / P_{2F}) \ \ (\mathrm{dB}) \qquad (3)$$

This quantity varies with cable length, since for a longer cable P_{2F} decreases due to attenuation. In order to get a length-independent measure of far-end crosstalk, the Equal-Level Far-End CrossTalk loss EL FEXT has been defined as:

$$\mathrm{EL\ FEXT} = 10 \log_{10} (P_{1F} / P_{2F}) \ \ (\mathrm{dB}) \qquad (4)$$

In equations (3) and (4),

- P_{1N} is the input power of the disturbing pair at the near cable end
- P_{1F} is the output power of the disturbing pair at the far cable end
- P_{2F} is the output power of the disturbed pair at the far cable end

The transmission loss α is

$$\alpha = 10 \log_{10} (P_{1N} / P_{1F}) \qquad (5)$$

With (3) and (5), (4) can be written as

$$\text{EL FEXT} = \text{IO FEXT} - \alpha \qquad (6)$$

Using (6), EL FEXT can be calculated using the ZVB Trace Mathematics:

1. Measure the differential mode transmission loss, store it to memory
2. Reconfigure the setup for IO FEXT measurement
3. Select **Trace: Trace Funct: Math = Data / Mem**

An EL FEXT measurement performed in this way is shown in Fig. 18:

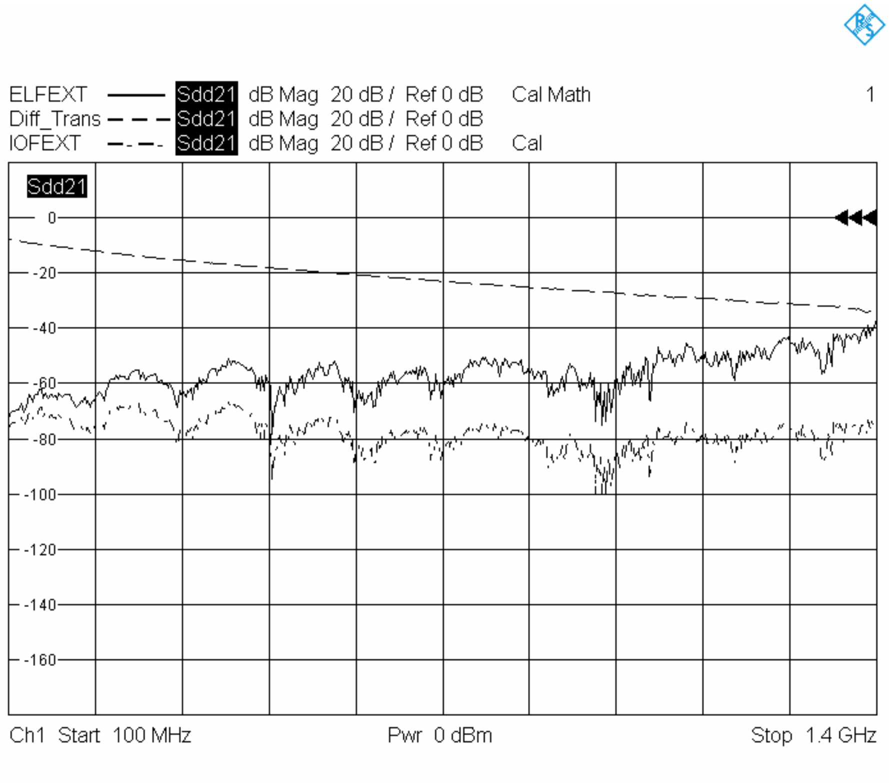


Fig. 18 EL FEXT at the far end of a cable

The dash-dotted IOFEXT is measured directly, as described above. Diff_Trans (dashed trace) is the transmission loss from Fig. 16, which has been stored to memory. Data / Mem results in the solid line trace ELFEXT.

For the sake of completeness, we should also mention the far-end mode conversion parameters of a cable. These are related to TCL and LCL as FEXT is related to NEXT. Transverse Conversion Transfer Loss (TCTL) and Longitudinal Conversion Transfer Loss (LCTL) can be measured directly, whereas Equal-Level Transverse Conversion Transfer Loss (EL TCTL) and Equal-Level Longitudinal Conversion Transfer Loss (EL LCTL) are obtained by applying trace mathematics. The measured quantity must be divided through the corresponding attenuation according to (6).

Literature

[1] D. E. Bockelman and W. R. Eisenstadt: Combined Differential and Common-Mode Scattering Parameters: Theory and Simulation, IEEE Transactions on Microwave Theory and Techniques, Vol. 43, No. 7, July 1995, pp. 1530-1539

6 Ordering information

Vector Network Analyzer		
ZVB	300 kHz ... 8 GHz	1145.1110.10