

Balunless measurement of mixed-mode scattering parameters

Significance of s_{dd21} in HF technology

Increasing data volumes, as well as enormous increases in transfer speeds, place high demands on the signal quality. This is especially evident with the current interface USB 3.0, which is also known as SuperSpeed because of its transfer speed of 5 Gbps. While a common mode inductor was adequate for the previous version USB 2.0 with 480 Mbps to guarantee signal quality, special HF components are now needed for noise suppression. How these differ is shown by the S_{dd21} measurement.

Scattering parameters, or S-parameters, are a measure of how much power or voltage is transferred via a port from the chip to the board. They describe the behavior of linear electrical components by means of wave parameters. S-parameters play an important role in high-frequency technology, as in many cases current and voltage cannot be clearly defined. However, what can be measured is the wave entering a port or being reflected by a port. The advantage of recording the parameter with wave impedances is that undesired impedance transformation at the inputs and outputs of a network are avoided.

The number of S-parameters needed to describe a network depends on the number of ports and is calculated from the square of its port number. A filter element with two inputs and two outputs (Figure 1), a 4-port element, is described with 16 S-parameters (Figure 2).



Figure 1: 4-port filter element with incoming (a) and outgoing (b) guided waves

The scattering matrix represents the connection between the individual ingoing waves a_1, a_2, a_3, a_4 and the reflected waves b_1, b_2, b_3, b_4 .

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{pmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

Figure 2: Scattering matrix of a 4-port filter element

The scattering matrix depends on the reference impedance Z_0 , the characteristic impedance, which in HF technology is usually chosen as 50 Ω . Network analyzers measure the S-parameters as a function of the frequency and show this as a dimensionless complex number that is often converted to decibels and phase. In principle, all devices under test with more than two ports can be measured with a two-gate network analyzer. All gates that are not being measured at a given time must be connected with the reference impedance. To determine all S-parameters, with this nodal method $n(n-1)/2$ complete 2-gate measurements are necessary. On the one hand, this method is very time consuming and cannot be automated because of the manual bonding of the coaxial measuring connection or of on-wafer measurement peaks. Parasitic influences cause a measurement error, on the other.

Physical and mathematical baluns

Baluns allow a two-gate network analyzer to be expanded to four gates. Depending on the design of the balun with 0° or 180° phase difference between the two outputs, it is possible to excite in-phase or out-of-phase. But this method also has two disadvantages: Because of the modal excitation, adapted calibration standards have to be developed and prepared for the modes in order to calibrate the measuring system. The second disadvantage is the frequency response of the power divider. For common mode excitation the power divider can be manufactured from resistors and thus have a large bandwidth. However, adherence to the 180° phase shift is possible only in a limited frequency range. Balun-supported measurement can only be carried out to 1.2 or 1.5 GHz.

If a multigate is to be investigated as regards its behavior with in-phase or out-of-phase excitation, a modal measuring system is needed. However, there is a problem with exciting several ports synchronously. The measuring signal between the two measuring gates has to be maintained across the complete frequency range of a defined phase shift. For excitation with the in-phase wave, this is 0° and for the out-of-phase wave 180° . However, modal excitation can be avoided by calculating the modal behavior from the port-related S-parameters^[1].

Mixed-mode scattering parameters

As opposed to the nodal parameters, modal S-parameters, also known as mixed-mode S-parameters, allow a differential evaluation of the reflection and transmission parameters of any number of 4-ports. To do this, two nodal ports are conceptually aggregated into one differential port in (Figure 3). Compared to traditional balun-supported measurement, mixed-mode S-parameter measurement has the advantage that these mathematical baluns offer ideal symmetry transmission across a wide frequency range and, with measurement ranges of up to several GHz, are especially suitable for the HF range. It is also very easy to measure common mode and differential mode S-parameters and achieve reproducible results.

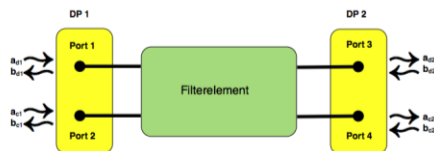


Figure 3: By aggregating two nodal ports into one differential port it is possible to measure a 4-port filter element with a two-gate network analyzer.

The mixed-mode and S-parameter matrices are similarly organized: the columns represent the exciting ports, the rows represent the receiving ports. In the equation, common mode waves are marked analogously to the scattering matrix with the index c, differential mode waves with the index d.

For evaluating filter circuits, the parameters of the in-phase and out-of-phase transmission S_{cc21} and S_{dd21} are significant (Figure 4). The insertion loss S_{dd21} is considered especially when measuring high-frequency differential data signals, as it provides information about whether the coupled differential mode is also present in phase at the output.

$$\begin{bmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{bmatrix} = \begin{pmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd22} & S_{cc21} & S_{cc22} \end{pmatrix} \times \begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix}$$

Figure 4: Mixed-mode scattering matrix of a 4-port filter element: **dd** Differential-mode operation, **cc** Common-mode operation, **dc** Common-mode excitation – Differential-mode response, **cd** Out-of-phase excitation – In-phase response

Out-of-phase interference spreads in the same direction as the useful signal, which is the reason why with differential impulse lines the phases of the two signals have to run synchronously on both conductor tracks. This also means that these lines must have identical properties at any point between the sender and the receiver and must also have almost the same electrical lengths. If this is not the case, the waves reflected at the receiver by the different phase delays of the signals on lines 1 and 2 do not arrive at the node with a phase difference of 180° . Some of the differential mode signals are converted into common mode energy. This causes parasitic interference and additional reflections. The phase difference depends on the frequency. In high-frequency lines the wave resistance is also dependent on the dimensions of the conductor. If the cable is longer than the wavelength, such as is the case in the HF range, this causes line reflections if the impedance relationships within the system are not adapted. For this reason, the suitability of a line filter for a system is examined with the s_{dd21} measurement.

Measurement setup and results

The current-compensated chokes in the WE-CNSW series, the high-frequency variants WE-CNSW HF and components from competitors (table) were investigated. The components were placed on the middle of a test PCB and each was connected to the outer ends of the lines with an SMA connector. A differential signal was then fed into the two signal paths of the choke. The cut-off frequency f_c defined at -3 dB shows the frequency at which fed and reflected differential signals are no longer phase-shifted by 180° , or when the useful signal suffers parasitic interference by the out-of-phase signal and its quality is too severely impaired. A network analyzer calculates the insertion loss s_{dd21} from the nodal scattering parameters.

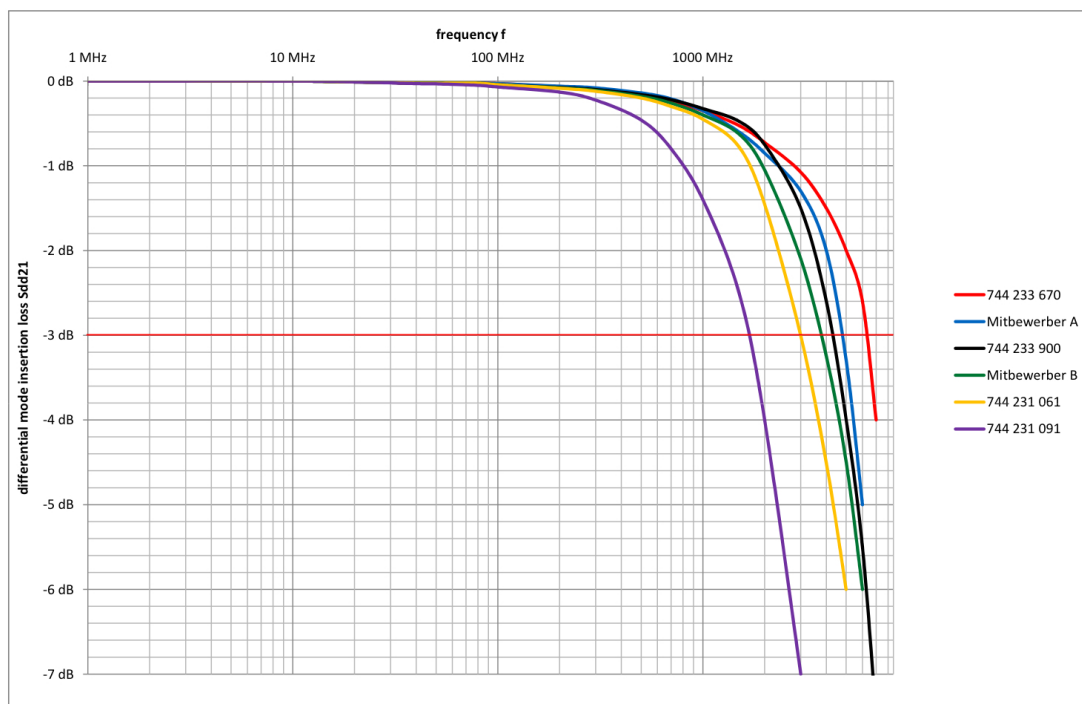


Figure 5: Results of the s_{dd21} measurement. The cut-off frequency f_c at -3 dB is defined as the reference. The line filters from the WE-CNSW HF series achieve a maximum at 6.5 GHz.



Because common-mode chokes for common-mode signals exhibit high impedance and for differential mode signals much lower impedance, these filter elements enable the common-mode rejection of differential transmission systems and, hence, increase interference immunity. Conformity with the EMC Directive is thus ensured.

The difference with filters especially for high-speed data lines, such as for USB 3.0, can best be explained by a direct comparison between the line filter WE-CNSW HF 744233670 with a common mode impedance of $67\ \Omega$ @ 100 MHz and the filter from competitor A with a common mode impedance of $60\ \Omega$ @ 100 MHz. Although both have high common mode attenuation, the cut-off frequency of the HF modules in the WE-CNSW series is about 1 GHz higher at 6.5 GHz. This means that with increasing frequency the influence of asymmetries on differential data signals in the HF modules from Würth Elektronik is lower than with competitors' products. The reasons for this are, on the one hand, the special ferrite material and, on the other, the winding geometry with larger gaps between two windings. Because all of the filters that were investigated have the same design, 0805, a larger gap between the windings also means fewer windings. The fewer windings, the lower the impedance, which, in turn, shifts the resonance point towards higher frequencies. In relation to the S_{dd21} measurement, this means: the lower the common mode impedance, the better the filter properties in differential high-speed data lines.

Conclusion

With the S_{dd21} measurement it could be shown that the HF variants in the WE-CNSW current-compensated data line filter series are suitable for common mode rejection at transmission frequencies up to 6.5 GHz without them affecting differential data signals. Conventional current-compensated filters cannot fulfill this requirement, as demonstrated by the measurement results.

The signal quality in communication via the USB 3.0 interface is guaranteed only with special high-frequency components.

Artikelnummer	Bauform / Baureihe	Grenzfrequenz f_c ($S_{DD21} = -3\text{dB}$)	Impedanz Z (bei 100 MHz)	maximale Betriebsspannung U_R	Gleichstromwiderstand R_{DC}	Nennstrom I_R	Anwendung
744 233 670	WE-CNSW 0805 HF	6,5 GHz	$67\ \Omega$	50 V	240 m Ω	320 mA	USB 3.0
Mitbewerber A	Bauform 0504	5,0 GHz	$60\ \Omega$	50 V	500 m Ω	280 mA	USB 3.0
744 233 900	WE-CNSW 0805 HF	4,5 GHz	$90\ \Omega$	50 V	300 m Ω	280 mA	HDMI
Mitbewerber B	Bauform 0504	3,8 GHz	$90\ \Omega$	50 V	500 m Ω	280 mA	HDMI
744 231 061	WE-CNSW 0805	3,0 GHz	$67\ \Omega$	50 V	250 m Ω	400 mA	
744 231 091	WE-CNSW 0805	1,7 GHz	$90\ \Omega$	50 V	300 m Ω	370 mA	USB 2.0

Table 1: Specifications of the components measured

[1] Dipl.-Ing. Christof Ziegler, 4-gate network analysis and on-wafer measuring technology to determine modal scattering parameters up to 50 GHz