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# Insertion loss
# in terms of four-port network parameters

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*Abstract:* Usually, power filters are characterised by their *insertion loss* (IL). By definition, the IL is applicable to two-port networks, but most filters have a higher number of ports. Single-phase power filters are four-port networks and measurements of their suppression characteristics require one measurement for the *common-mode* (CM) and another for the *differential-mode* (DM) IL. Normally, the measurement apparatus have unbalanced ports and CM measurements are relatively easy to perform. However, the DM measurements require balanced–unbalanced conversion at the input and output of the filter. Wideband transformers (baluns) are used for this conversion. Instead of measuring it directly, the CM or DM IL can be calculated from the four-port parameters of the filter. The equations for IL in terms of four-port network parameters are derived theoretically and verified experimentally. The adoption of four-port parameters in engineering practice would reduce the amount of measurement work and increase the reliability and repeatability of the results because the use of baluns or other changes in the equipment under test are not necessary.

## 1 Introduction

The international CISPR 17 standard [1] prescribes the methods of measurement of *insertion loss* (*IL*) of passive *electromagnetic interference* (EMI) filters and components. The *IL* characterises the suppression capabilities of passive EMI filters and components. Other standards may define the *IL* differently [2] or as a special case of the classical textbook definition, but all *IL* definitions are applicable to two-port networks. Equations expressing the *IL* in terms of two-port network parameters and arbitrary source and load impedance have been known for a long time. In terms of impedance *z*-parameters and chain *c*-parameters, these equations can be found, for example in [3], and in terms of scattering *s*-parameters, for example in [4]. However, most filters and some of their components have higher number of ports. That is why these filters or components have two types of *IL* – one *common-mode* (CM), and depending on the number of phases there can be several *differential-mode* (DM) *IL* characteristics. The CM *IL* ($IL_{CM}$) is measured in the asymmetrical test circuit (Figure 1*a*) and the DM *IL* ($IL_{DM}$) in the symmetrical test circuit (Figure 1*b*) [1].

The *s*-parameters are defined for *n*-port networks and are measured in the unsymmetrical test circuit shown in Figure 1*c*. This paper focuses on passive four-terminal components and filters, that is, four-port networks. Thus the equations proposed in Section 3 are in terms of four-port network parameters.

Among all network parameters, only the *s*-, *y*- and *z*-parameters are defined for networks with more than two ports. The equation for $IL_{CM}$ is shown in terms of four-port *y*-parameters and that for $IL_{DM}$ in terms of *z*-parameters. After that both the $IL_{CM}$ and $IL_{DM}$ are related to the mixed-mode *s*-parameters [5], which can be obtained from the standard four-port *s*-parameters.

The traditional *IL* measurements are affected by the auxiliary circuitry required in the symmetrical and asymmetrical test circuits (Figures 1*a* and 1*b*). *S*-parameter measurements do not require such auxiliary networks and can have higher precision and repeatability. Therefore the proposed indirect *IL* measurement based on four-port network parameters of a suppression device can be more reliable.

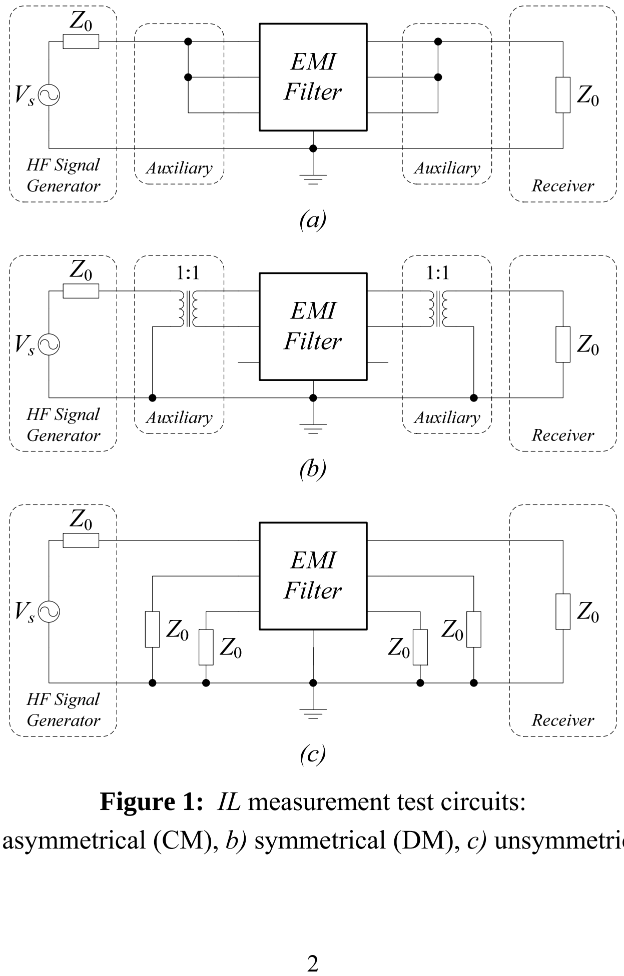


**Figure 1:** *IL* measurement test circuits:
*a)* asymmetrical (CM), *b)* symmetrical (DM), *c)* unsymmetrical

# 2 Insertion loss definitions

The $IL$ is defined in [3] as the ratio, in dB, of two powers in accordance with the following equation:

$$IL = 10 \cdot \lg\left(\frac{P_{20}}{P_2}\right), \text{dB} \tag{1}$$

where $P_{20}$ is the power delivered to the load impedance $Z_L$, which in a measurement set-up is the input impedance of the measurement instrument's receiver, connected to the signal generator as in Figure 2*a*. The $P_2$ is the power delivered to the same impedance by the same generator, but with a filter inserted between them, as shown in Figure 2*b*. In the same figure, $V_1$ and $V_2$ are, respectively, the input and output voltages of the filter. Similarly, $I_1$ and $I_2$ denote the input and output currents. Ideally $V_{10} = V_{20}$ and $I_{10} = -I_{20}$ in the reference measurement (Figure 2*a*).

For the definition of $IL$ the direction of the output current $I_2$ is irrelevant, but it matters in the definitions of network parameters. Sometimes in the literature the direction of $I_2$ is reversed but in the case of *n*-port networks it is better to uniformly define a port current as flowing into the port.

In CISPR 17, the $IL$ is defined as the ratio of voltages appearing across the line immediately beyond the point of insertion, before and after insertion of the filter [1]. Similarly, the oldest textbook definition [6] known to us defines the $IL$ as the *insertion ratio* ($IR$) in dB:

$$IR = \left|\frac{V_{20}}{V_2}\right| = \left|\frac{I_{20}}{I_2}\right| \quad \Rightarrow \quad IL = 20 \cdot \lg\left(IR\right) = 20 \cdot \lg\left|\frac{V_{20}}{V_2}\right| = 20 \cdot \lg\left|\frac{I_{20}}{I_2}\right| \tag{2}$$

It is easy to show that definitions (1) and (2) are equivalent:

$$IL = 10 \cdot \lg\left(\frac{P_{20}}{P_2}\right) = 10 \cdot \lg\frac{V_{20}^2 \operatorname{Re}\{Y_L\}}{V_2^2 \operatorname{Re}\{Y_L\}} = 20 \cdot \lg\left|\frac{V_{20}}{V_2}\right| \tag{3}$$

and similarly:

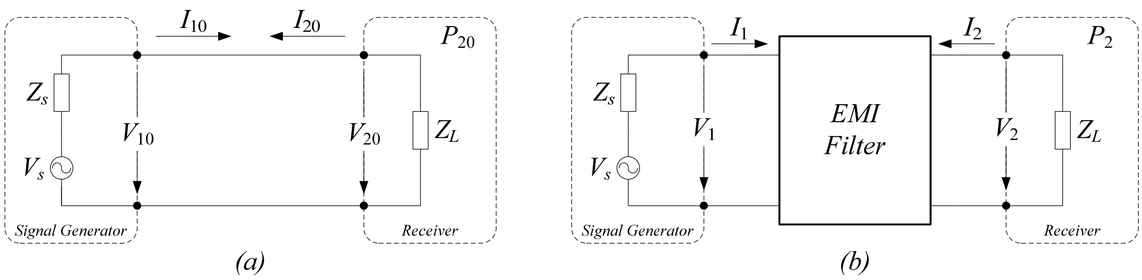


**Figure 2:** $IL$ definition:
*a)* reference measurement (filter replaced by short circuit), *b)* measurement with the filter inserted

$$IL = 10 \cdot \lg\left(\frac{P_{20}}{P_2}\right) = 10 \cdot \lg\frac{I_{20}^2 \operatorname{Re}\{Z_L\}}{I_2^2 \operatorname{Re}\{Z_L\}} = 20 \cdot \lg\left|\frac{I_{20}}{I_2}\right| \tag{4}$$

It is worth noting that the requirement in the above definition of *IL* is that the source and load impedances ($Z_s$ and $Z_L$) are same in both measurements – with and without filter. $Z_s$ and $Z_L$ do not have to be resistive, equal to each other, or constant.

CISPR 17 specifies that in the standard *IL* measurements the input and output of the filter must be terminated in equal and fixed resistances – normally 50 to 75 Ω [1]. When $Z_s = Z_L$ the load voltage $V_{20} = V_s/2$ and (3) becomes

$$IL' = 20 \cdot \lg\left|\frac{V_s}{2V_2}\right| \tag{5}$$

Obviously, (5) is a special case but not equivalent to the classical *IL* definition given by (1)–(4). There may be other definitions of *IL* [2] but they are not considered in this paper.

# 3 IL in terms of four-port network parameters

Single-phase filters have two pairs of terminals – one pair at their input and another at the output. There is also the ground terminal that is common for both the input and output of the filter. By definition, a port is a pair of circuit terminals carrying the same current, i.e. the same current must enter and leave the port. Owing to the CM current component, the currents through the input terminals are different. The same is true also for the output. Therefore the input and output pairs of terminals are not ports, but together with the ground terminal, each of the four terminals constitutes a port. Thus single-phase filters are four-port networks.

## 3.1 Common-mode insertion loss

According to [1], the $IL_{CM}$ is measured in the asymmetrical test circuit shown in Figure 1*a*. In the case of four-port networks, or single-phase filters, the CM equivalent circuit with arbitrary source and load impedances is shown in Figure 3*a*.

The admittance *y*-parameters of a four-port network are

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & y_{13} & y_{14} \\ y_{21} & y_{22} & y_{23} & y_{24} \\ y_{31} & y_{32} & y_{33} & y_{34} \\ y_{41} & y_{42} & y_{43} & y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \tag{6}$$

Noting that

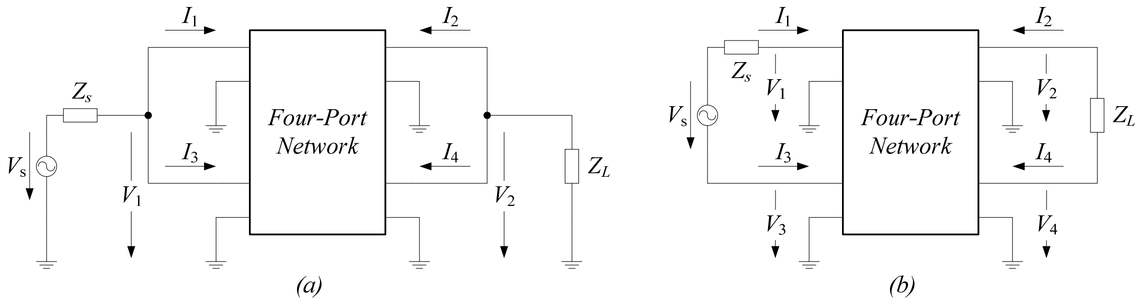


**Figure 3:** Set up for measuring *IL*: *a)* common-mode *IL*, *b)* differential-mode *IL*

$$V_1 = V_3 = V_s - Z_s\left(I_1 + I_3\right) \quad \text{and} \quad V_2 = V_4 = -Z_L\left(I_2 + I_4\right) \tag{7}$$

Solving the system (6) and (7) for $V_2$ yields

$$V_2 = \frac{\frac{1}{Z_s}V_s}{y_{12} + y_{14} + y_{32} + y_{34} - \frac{\left(y_{11} + y_{13} + y_{31} + y_{33} + \frac{1}{Z_s}\right)\left(y_{22} + y_{24} + y_{42} + y_{44} + \frac{1}{Z_L}\right)}{y_{21} + y_{23} + y_{41} + y_{43}}} \tag{8}$$

The voltage across $Z_L$, without the four-port network, i.e. without the filter (Figure 2*a*), is

$$V_{20} = \frac{Z_L}{Z_s + Z_L}V_s \tag{9}$$

Then the $IL_{CM}$ in terms of four-port *y*-parameters is obtained by inserting (8) and (9) in (3):

$$IL_{CM} = 20 \cdot \lg\left|\frac{Z_s Z_L}{Z_s + Z_L}\left[y_{12} + y_{14} + y_{32} + y_{34} - \frac{\left(y_{11} + y_{13} + y_{31} + y_{33} + \frac{1}{Z_s}\right)\left(y_{22} + y_{24} + y_{42} + y_{44} + \frac{1}{Z_L}\right)}{\left(y_{21} + y_{23} + y_{41} + y_{43}\right)}\right]\right| \tag{10}$$

For the special case when $Z_s = Z_L = Z_0$ the $IL_{CM}$ is

$$IL'_{CM} = 20 \cdot \lg\left|\frac{Z_0}{2}\left[y_{12} + y_{14} + y_{32} + y_{34} - \frac{\left(y_{11} + y_{13} + y_{31} + y_{33} + \frac{1}{Z_0}\right)\left(y_{22} + y_{24} + y_{42} + y_{44} + \frac{1}{Z_0}\right)}{\left(y_{21} + y_{23} + y_{41} + y_{43}\right)}\right]\right| \tag{11}$$

It is possible to express the $IL_{CM}$ also in terms of *z*-parameters, but that would lead to more cumbersome equation. Noting that the *z*- and *y*-parameter matrices are inverses of each other, it is not difficult to express the $IL_{CM}$ in terms of *z*-parameters, if anyone would need it.

## 3.2 Differential-mode insertion loss

The equation for the $IL_{DM}$ can also be derived in terms of $y$-parameters, but it is more compact in terms of $z$-parameters, which for four-port network are defined as follows:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{21} & z_{22} & z_{23} & z_{24} \\ z_{31} & z_{32} & z_{33} & z_{34} \\ z_{41} & z_{42} & z_{43} & z_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{12}$$

According to [1], the $IL_{DM}$ is measured in the symmetrical test circuit shown in Figure 1*b*. If measurement apparatus with balanced ports would have been available, the set-up for $IL_{DM}$ measurement of a four-port network, or a single-phase filter, would be as shown in Figure 3*b*. However, most of today's measurement equipment – like EMI test receivers and *vector network analyzers* (VNAs) have unbalanced ports, i.e. one of the port terminals is always grounded. This is the reason for using the two wideband transformers, connected at the input and output ports of the filter in Figure 1*b*. They are called baluns because they transform the unbalanced signals from/to the ports of the measurement instrument to balanced signals at the I/O of the filter. Unfortunately, the inclusion of baluns significantly changes the circuit under test. Therefore, DM measurement cannot be reliable across wide frequency range.

From Figure 3*b* and Kirchhoff's current law

$$I_3 = -I_1 \quad I_4 = -I_2 \tag{13}$$

From Kirchhoff's voltage law

$$\begin{gathered} V_1 = V_3 + V_s - Z_s I_1 \\ V_2 = V_4 - Z_L I_2 \end{gathered} \tag{14}$$

Solving (12), (13) and (14) for $I_2$ yields

$$I_2 = \frac{V_s}{z_{12} - z_{14} - z_{32} + z_{34} + \dfrac{(Z_s + z_{11} - z_{13} - z_{31} + z_{33})(z_{24} - z_{22} + z_{42} - z_{44} - Z_L)}{z_{21} - z_{23} - z_{41} + z_{43}}} \tag{15}$$

The load current without filter (Figure 2*a*) is

$$I_{20} = -\frac{V_s}{Z_s + Z_L} \tag{16}$$

The $IL_{DM}$ in terms of four-port $z$-parameters is obtained by inserting (15) and (16) in (4):

$$IL_{DM} = 20 \cdot \lg \left| \frac{z_{12} - z_{14} - z_{32} + z_{34} + \dfrac{(z_{11} - z_{13} - z_{31} + z_{33} + Z_s)(z_{24} - z_{22} + z_{42} - z_{44} - Z_L)}{z_{21} - z_{23} - z_{41} + z_{43}}}{Z_s + Z_L} \right| \tag{17}$$

For the special case when $Z_s = Z_L = Z_0$

$$IL'_{DM} = 20 \cdot \lg \left| \frac{z_{12} - z_{14} - z_{32} + z_{34} + \dfrac{\left(z_{11} - z_{13} - z_{31} + z_{33} + Z_0\right)\left(z_{24} - z_{22} + z_{42} - z_{44} - Z_0\right)}{z_{21} - z_{23} - z_{41} + z_{43}}}{2Z_0} \right| \tag{18}$$

## 3.3 CM and DM insertion loss in terms of s-parameters

The scattering *s*-parameters [7] are measured with VNAs [8], which have unbalanced (single-ended) ports. For an *n*-port network there are $n^2$ *s*-parameters arranged in an $n \times n$ matrix. However, as mentioned earlier the *IL* is applicable to two-port networks, which have 2×2 s-matrices. The equation for *IL* in terms of two-port *s*-parameters [4] is

$$IL = 20 \cdot \lg \left| \frac{\left(1 - \rho_s s_{11}\right)\left(1 - \rho_L s_{22}\right) - \rho_s \rho_L s_{12} s_{21}}{\left(1 - \rho_s \rho_L\right) s_{21}} \right| \tag{19}$$

where $\rho_s$ and $\rho_L$ are the source and load reflection coefficients, defined as

$$\rho_s = \frac{Z_s - Z_0}{Z_s + Z_0} \quad \text{and} \quad \rho_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{20}$$

The current practice is to measure the *IL* in the asymmetrical (Figure 1*a*) and symmetrical (Figure 1*b*) test circuits that transform the multi-port filter circuits into two-port circuits. The measurement in the asymmetrical test circuit yields one set of CM *s*-parameters – that is four complex-valued parameters in a 2×2 matrix. If the *s*-parameters in (19) are the CM ones, the result would be the $IL_{CM}$ of the filter. The measurement(s) in the symmetrical test circuit yield one or more set(s) of DM *s*-parameters, depending on how many lines the filter has. For a single-phase filter, there will be only one set of DM *s*-parameters – again a 2×2 matrix of complex-valued parameters, which can be inserted in (19) to obtain the $IL_{DM}$.

When *s*-parameters are measured with VNA, whether they are the CM or DM, the source and load impedances are equal to the reference impedance $Z_0$. Therefore, for the special case when $Z_s = Z_L = Z_0$, the $\rho_s = \rho_L = 0$ and (19) becomes

$$IL' = -20 \cdot \lg \left| s_{21} \right| \tag{21}$$

The main disadvantage of the current practice is the need of auxiliary wiring, which alters the filter circuit and inevitably reduces the accuracy of the measurements. In the asymmetrical test circuit the changes to the circuit and the consequent measurement errors can be insignificant. However, in the symmetrical test circuit, the errors can be large – they depend on the characteristics of the baluns and additional wiring. The repeatability of the DM measurements is also compromised because of the differences and tolerances in the characteristics of the baluns, which are not specified in CISPR 17.

An alternative approach is to use the standard single-ended *s*-parameters, which are measured in the unsymmetrical test circuit, shown in Figure 1*c*. Four-port networks have 16 *s*-parameters, arranged in a 4×4 matrix. Such an example is shown in Figure 4. Unfortunately, the standard *s*-parameters do not reveal how the *equipment under test* (EUT) suppresses the CM and DM noise components. However, the single-ended *s*-parameters can be converted to mixed-mode *s*-parameters [5], which overcome this disadvantage:

$$\mathbf{S}_{mm} = \begin{bmatrix} \mathbf{S}_{cc} & \mathbf{S}_{cd} \\ \mathbf{S}_{dc} & \mathbf{S}_{dd} \end{bmatrix} \tag{22}$$

where $\mathbf{S}_{mm}$ is the mixed-mode s-matrix - a 4×4 matrix, consisting of four 2×2 sub-matrices. The $\mathbf{S}_{cc}$ sub-matrix contains the CM *s*-parameters, which relate to the elements of the standard s-matrix as follows:

$$\mathbf{S}_{cc} = \begin{bmatrix} s_{cc11} & s_{cc12} \\ s_{cc21} & s_{cc22} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} s_{11}+s_{13}+s_{31}+s_{33} & s_{12}+s_{14}+s_{32}+s_{34} \\ s_{21}+s_{23}+s_{41}+s_{43} & s_{22}+s_{24}+s_{42}+s_{44} \end{bmatrix} \tag{23}$$

The $\mathbf{S}_{dd}$ sub-matrix in (22) contains the DM *s*-parameters, which are related to the single-ended *s*-parameters as follows:

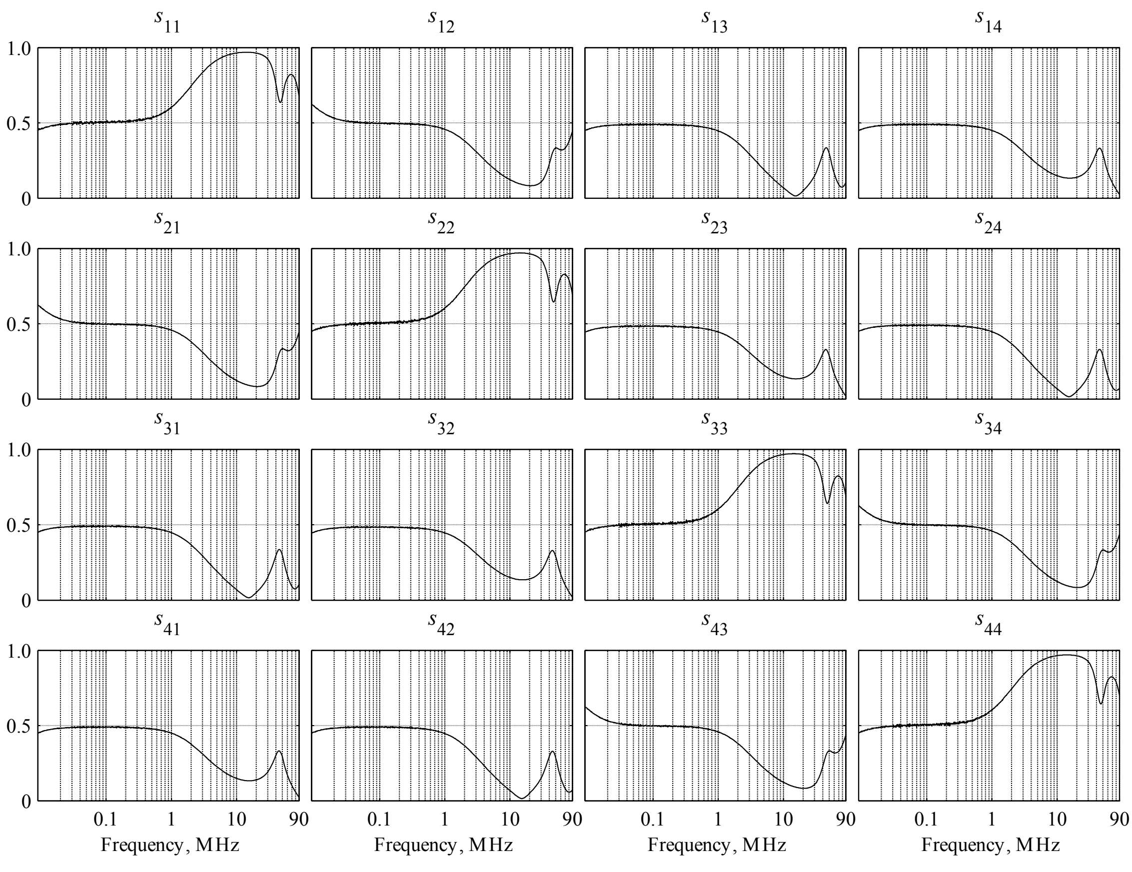


**Figure 4:** Measured single-ended s-parameters of the EUT

$$\mathbf{S}_{dd} = \begin{bmatrix} s_{dd11} & s_{dd12} \\ s_{dd21} & s_{dd22} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} s_{11} - s_{13} - s_{31} + s_{33} & s_{12} - s_{14} - s_{32} + s_{34} \\ s_{21} - s_{23} - s_{41} + s_{43} & s_{22} - s_{24} - s_{42} + s_{44} \end{bmatrix} \quad (24)$$

The remaining two sub-matrices $\mathbf{S}_{cd}$ and $\mathbf{S}_{dc}$ in (22) represent the cross-mode *s*-parameters. They are also 2×2 matrices and in theory should be zero – that would be the case if there is a perfect balance between the two sides of the device, which is impossible in practice. This is clearly seen in Figure 5, which shows the mixed-mode *s*-parameters obtained from the single-ended *s*-parameters in Figure 4. The cross-mode *s*-parameters are relatively small but are not zero.

It should be noted that the reference impedance for the CM *s*-parameter matrix $\mathbf{S}_{cc}$ is half of the reference impedance of the single ended four-port *s*-parameters. Usually the reference impedance for the measured single-ended *s*-parameters is $Z_0 = 50\ \Omega$. Therefore the reference impedance for $\mathbf{S}_{cc}$ is 25 Ω and the $IL_{CM}$ for arbitrary termination is:

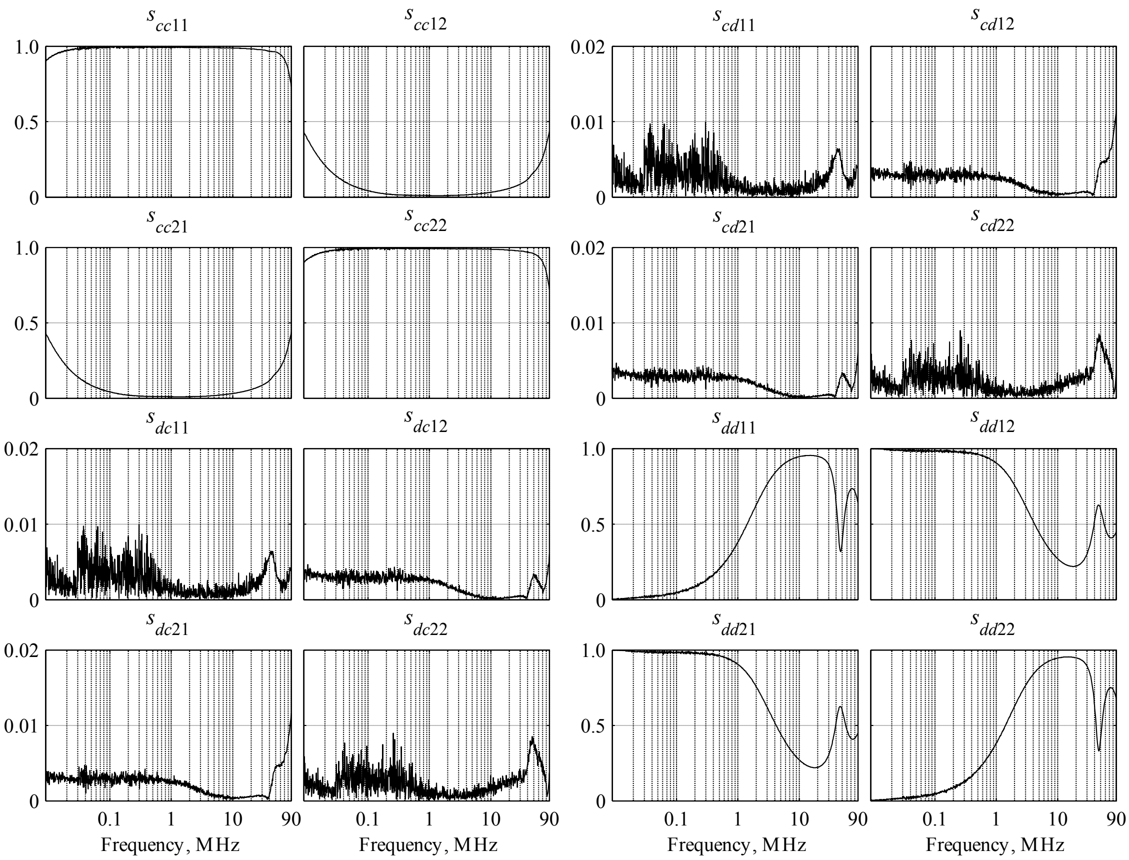


**Figure 5:** Mixed-mode s-parameters obtained from the single-ended s-parameters in **Figure 4**

$$\rho_s = \frac{Z_s - Z_0/2}{Z_s + Z_0/2} \quad \rho_L = \frac{Z_L - Z_0/2}{Z_L + Z_0/2}$$
$$IL_{CM} = 20 \cdot \lg \left| \frac{(1-\rho_s s_{cc11})(1-\rho_L s_{cc22}) - \rho_s \rho_L s_{cc12} s_{cc21}}{(1-\rho_s \rho_L) s_{cc21}} \right| \tag{25}$$

The $IL$ data, that are usually published nowadays, are for matched source and load, that is when $Z_s = Z_L = Z_0$. In such a case

$$\rho_s = \rho_L = \frac{1}{3} \quad \Rightarrow \quad IL'_{CM} = 20 \cdot \lg \left| \frac{(3 - s_{cc11})(3 - s_{cc22}) - s_{cc12} s_{cc21}}{8 s_{cc21}} \right| \tag{26}$$

The conversion to mixed-mode parameters affects also the reference impedance for the DM s-matrix $\mathbf{S}_{dd}$, but in a different way – it is twice the reference impedance of the source matrix. Therefore in the standard case, when the reference impedance for the measured single-ended four-port *s*-parameters is $Z_0 = 50\ \Omega$, the reference impedance for $\mathbf{S}_{dd}$ is $100\ \Omega$. Then for arbitrary source and load impedances, the $IL_{DM}$ in terms of mixed-mode *s*-parameters is

$$\rho_s = \frac{Z_s - 2Z_0}{Z_s + 2Z_0} \quad \rho_L = \frac{Z_L - 2Z_0}{Z_L + 2Z_0}$$
$$IL_{DM} = 20 \cdot \lg \left| \frac{(1-\rho_s s_{dd11})(1-\rho_L s_{dd22}) - \rho_s \rho_L s_{dd12} s_{dd21}}{(1-\rho_s \rho_L) s_{dd21}} \right| \tag{27}$$

Finally, in the special case when $Z_s = Z_L = Z_0$, the $IL_{DM}$ is

$$\rho_s = \rho_L = -\frac{1}{3} \quad \Rightarrow \quad IL'_{DM} = 20 \cdot \lg \left| \frac{(3 + s_{dd11})(3 + s_{dd22}) - s_{dd12} s_{dd21}}{8 s_{dd21}} \right| \tag{28}$$

## 3.4 Verification

To verify (10)-(11), (17)-(18) and (25)–(28) we used a commercially available CM choke coil RN143-6-02 [9] – a typical four-port filter component. All test circuits were implemented on *printed circuit boards* (PCBs) with *Bayonet Neill Concelman* (BNC) type coaxial connectors. The four-port *y*- and *z*-parameters, as well as the mixed-mode *s*-parameters, are obtained by conversion from the standard four-port *s*-parameters (Figure 4), which were measured with a VNA [10]. The instrument was calibrated with the coaxial cables attached to it, using *trough-open-short-match* (TOSM) calibration [10]. Thus the reference plane in the measurements was at the BNC connectors on the test boards, i.e. the measured four-port *s*-parameters, as well as the measured *IL* in the two-port test circuits for CM and DM include the CM choke, the BNC connectors, the auxiliary networks, and the PCB traces.

The $IL_{CM}$ measured in the traditional way, i.e. in the asymmetrical test circuit (Figure 1*a*) with $Z_0 = 50\ \Omega$, is shown in Figure 6*a*. The auxiliary wiring in this

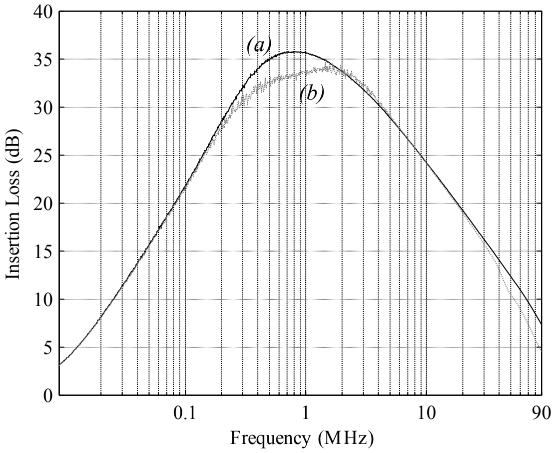


**Figure 6:** *a)* $IL_{CM}$ measured in the asymmetrical test circuit in Figure 1*a, b)* $IL_{CM}$ calculated from the four-port network parameters, measured in the unsymmetrical test circuit in Fig. 1*c*

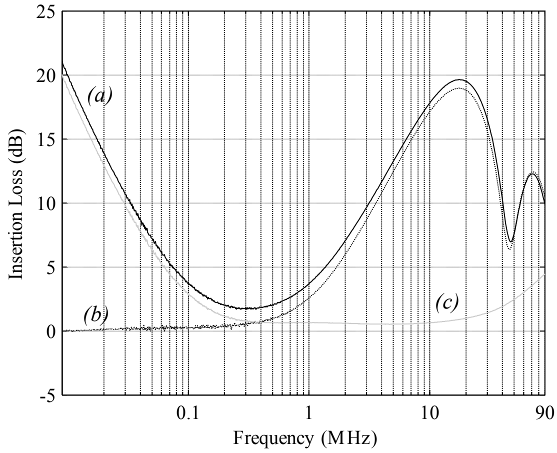


**Figure 7**: *a)* $IL_{DM}$ measured in the symmetrical test circuit in Figure 1*b*, *b)* $IL_{DM}$ calculated from the four-port network parameters, measured in the unsymmetrical test circuit in Figure 1*c*, *c) IL* of the baluns without filter

measurement is minimal – only to short-circuit the input and output lines. To minimize its impact on the measured $IL_{CM}$ , the auxiliary wiring should be as short as possible. In the presented measurement, it was 2-3 cm long PCB tracks between the CM choke and connectors.

The $IL_{CM}$ calculated according to (10) with $Z_s = Z_L = Z_0 = 50\ \Omega$, which makes it equivalent to (11), is shown in Figure 6*b*. The same curve overlaps the $IL_{CM}$, calculated from (25) and (26), because the *y*-parameters and mixed-mode *s*-parameters were obtained from the same source – the single-ended four-port *s*-parameters in Figure 4. A discrepancy would mean either that (10) and (11) are not equivalent to (25) and (26), or that the conversion from standard *s*-parameters to *y*- or mixed-mode *s*-parameters was wrong.

The $IL_{DM}$ measured in the traditional way, i.e. in the symmetrical test circuit (Figure 1*b*) with $Z_0 = 50\ \Omega$, is shown in Figure 7*a*. The $IL_{DM}$ calculated according to (17) with $Z_s = Z_L = Z_0 = 50\ \Omega$, which is same as that calculated from (18), is shown in Figure 7*b*. This curve also overlaps the $IL_{DM}$ calculated from (27) and (28) because the *z*-parameters and the mixed-mode *s*-parameters have the same source – the single-ended four-port *s*-parameters.

The difference between Figures 7*a* and 7*b* is due to the baluns used in the symmetrical test circuit. To demonstrate this fact the *IL* of the two cascade-connected baluns without the EUT is plotted in Figure 7*c*, which shows that the difference between the directly measured (Figure 7*a*) and indirectly measured $IL_{DM}$ (Figure 7*b*) is approximately equal to the *IL* of the baluns (Figure 7*c*).

# 4 Discussion

Admittance and impedance parameters can be obtained from the measured port voltages and currents, while the ports are kept open- or short-circuited. The main problem with this method is that due to the parasitic impedances between the terminals of each port, it is impossible to have truly open- or short-circuit and that leads to erroneous results at higher frequencies. The scattering *s*-parameters overcome this problem because they are measured with specified port termination impedance (usually 50 Ω). After careful calibration, the systematic errors can be removed and the *s*-parameter measurements can be accurate even in the GHz-range. Because measurements with VNA are easy, repeatable, and accurate over a wide frequency range, the *s*-parameters have become the most widely used network parameters. They can be converted to *y*- or *z*-parameters if necessary [7], [11].

The accuracy of the proposed indirect *IL* measurements depends only on the accuracy of the four-port network parameter measurements. All indirect *IL* measurements (Figures 6*b* and 7*b*), for a given conduction mode (CM or DM), overlap each other because of the following reasons:

- The four-port *z*-, *y*-, and mixed-mode *s*-parameters have been calculated from the same source – the measured single-ended four-port *s*-parameters in Figure 4.
- The equations for *IL* in terms of *y*- or *z*-parameters are equivalent to the equations in terms of mixed-mode *s*-parameters.
- The *IL* plots obtained from the equations for arbitrary source and load impedance (10), (17), (25), and (27) overlap the plots obtained from the special case equations (11), (18), (26) and (28), because the source and load impedances were both equal to $Z_0 = 50\ \Omega$.

There can be an argument that the presented measurements do not confirm (10), (17), (25), and (27) for *IL* with arbitrary source and load impedance. In response, it is not difficult to calculate the $IL_{CM}$ and $IL_{DM}$ based on these equations with different $Z_s$ and $Z_L$, but without reference measurements for comparison, the equations would not have been proven. The reason we do not present *IL* measurements with $Z_s$ and $Z_L$, other than 50 Ω is that such measurements are more complicated [3, 12], and their results are unreliable [12] because they depend strongly on the characteristics of the impedance changing transformers. Not surprisingly, CISPR 17 considers such measurements only in a narrow frequency range from 1 to 300 kHz, and they are not mandatory [1].

Although the indirect *IL* measurements overlap each other, they do differ from the traditional, directly measured *IL*. Apart from the inevitable random measurement errors, there are the following reasons for these differences:

- The traditional *IL* measurements are actually the *IL* of the filter with the auxiliary wiring necessary to realize the test circuits in Figures 1*a* and 1*b*. The indirect *IL* measurements, on the other hand, do not require any auxiliary networks, because they are calculated from the four-port network parameters, which are measured in the unsymmetrical test circuit in Figure 1*c*.
- The conversion from single-ended to mixed-mode *s*-parameters is not error-free either [13]. In particular, when two of the single-ended parameters are large and the other two are small, the conversion error can be significant.

There are several advantages in favor of the four-port network parameters: first, they provide sufficient information to calculate the $IL_{CM}$ and $IL_{DM}$ for any termination impedance, whether it is the standard 50 Ω, or any other value. Second, they allow calculating the input, output, or transfer impedances of the four-port device. Third, network parameter measurements do not need the auxiliary wiring required in the traditional CM and DM two-port *IL* measurements, and when measured with VNA, the errors associated with open- and short-circuit terminations are avoided. Finally, simulation models of the device can be built based on its network parameters.

Possible disadvantage of the four-port network parameters include: In the case of *z*- and *y*-parameters, their measurement accuracy might be questionable at higher frequencies, but that is only if they were not measured with VNA. In the case when the data originate from the measured four-port *s*-parameters, the only disadvantage is the conversion error. However, this error does not depend on when and where the conversion is performed. Therefore, the *IL* obtained from network parameters will have higher repeatability than the direct *IL* measurements.

# 5 Conclusions

The current practice for measuring *IL* requires auxiliary networks, which can compromise the accuracy of the measurement. Measuring *IL* at different source and load impedances is even less accurate because it requires more complicated auxiliary networks.

The equations for $IL_{CM}$ and $IL_{DM}$ in terms of four-port network parameters were derived and verified by measurements. A major advantage of the proposed methods to obtain the *IL* is that they make the auxiliary networks unnecessary and eliminate the errors associated with these networks. Furthermore, the CM and DM *IL* from four-port network parameters are not restricted to matched source and load impedances. Therefore, the proposed equations offer a fast, accurate, and repeatable way to obtain the $IL_{CM}$ and $IL_{DM}$ of single-phase passive filters for arbitrary source and load impedances. This would benefit the design and selection of power filters.

Four-port network parameters allow complete characterization of single-phase filters. Not only the *IL*, which was the focus of this paper, but also simulation models as well as the input, output, and transfer impedance of the filter at CM and DM can be obtained, if any set of network parameters is available.

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