Constructed fixture for RF measurement of reflection coefficient S_{11}

S. Dobák[1]

[1] *Institute of Physics, Faculty of Science, P. J. Šafárik University in Košice, 04154 Košice, Slovakia*

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As part of the project, a radio-frequency (RF) shorted coaxial measurement cell was designed, developed, and tested for the characterization of soft magnetic materials via reflection coefficient S_{11} measurements using the transmission line technique. This setup enables material characterization up to 1.5 GHz through the use of a vector network analyzer (VNA). The developed measurement apparatus is shown in Figs. 1, 2, and 3.

To overcome the typical upper frequency limitation of fluxmetric measurements (on the order of several MHz), the impedance characterization method was adopted. This technique, extending to several GHz, is implemented through measurement of the complex scattering parameter S_{11} using a vector network analyzer. To understand the principles underlying this high-frequency technique, selected properties of electrical networks are introduced.

A key descriptor of a general two-port network, illustrated in Fig. 4, is its scattering matrix $[S]$, which relates the incident and reflected signals at each port. Let a_1 and a_2 denote the incident signals at ports 1 and 2, respectively, and b_1 and b_2 the corresponding outgoing signals. The scattering relation is defined as:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \tag{1}$$

where the scattering parameters $S_{ij} = S'_{ij} + jS''_{ij}$ $(i,\, j = 1,\, 2)$ are complex quantities with real parts S'_{ij} and imaginary parts S''_{ij}. They are defined as follows: the reflection coefficient at port 1 is $S_{11} = (b_1/a_1)|_{a_2=0}$, the forward transmission coefficient is $S_{21} = (b_2/a_1)|_{a_2=0}$, the reflection coefficient at port 2 is $S_{22} = (b_2/a_2)|_{a_1=0}$, and the reverse transmission coefficient is $S_{12} = (b_1/a_2)|_{a_1=0}$.

In this work, electrical impedance measurements were conducted on ring-shaped samples inserted into a shorted brass coaxial cell terminated with an N-type 50 Ω connector and connected via coaxial cable to port 1 of a vector network analyzer. A cross-sectional view of the cell containing the sample is presented in Figs. 5 and 6.

The coaxial cell is considered a one-port network, and its input impedance is calculated from the measured reflection coefficient S_{11} as:

$$Z_{\mathrm{in,sh}} = Z_0 \frac{1+S_{11}}{1-S_{11}}, \tag{2}$$

where Z_0 is the characteristic impedance of the transmission line. Measurement of the complex reflection coefficient S_{11} by the VNA at a fixed power level (typically up to 10 mW) yields the input impedance at the sample location through Eq. (2). In the present work, S_{11} measurements were performed using Siglent SVA1015X spectrum & vector network analyzer.

The ring sample is positioned at the bottom of the shorted coaxial line (see Fig. 5), where the electric field is minimal (node) and the magnetic field is maximal (anti-node). This configuration allows the dielectric effects to be neglected, provided that the sample thickness h is much smaller than a quarter wavelength, i.e., $h \ll \lambda/4$. Under this condition, the input impedance of the shorted coaxial line of length h is:

$$Z_{\mathrm{in,sh}} = jZ_0 \tan(\beta h) \simeq jZ_0 \beta h, \tag{3}$$

where $\beta = \omega\sqrt{LC}$ is the propagation constant and $Z_0 = \sqrt{L/C}$ is the characteristic impedance of the line. Hence, the input impedance simplifies to:

$$Z_{\mathrm{in,sh}} = j\omega hL.$$

For an air-filled, lossless coaxial line with outer radius R and inner radius r, the inductance per unit length leads to an impedance of:

$$Z_{\mathrm{in,sh}} = j\omega \frac{\mu_0}{2\pi} h \ln\left(\frac{R}{r}\right). \tag{4}$$

When a magnetic sample is inserted, dissipation must be taken into account via the complex permeability $\mu = \mu_0\mu'_{\mathrm{r}} - j\mu_0\mu''_{\mathrm{r}}$. The corresponding input impedance becomes:

$$Z_{\mathrm{in,sh}} = j\omega \frac{\mu_0}{2\pi} h(\mu'_{\mathrm{r}} - j\mu''_{\mathrm{r}}) \ln\left(\frac{R}{r}\right), \tag{5}$$

where the real part of the impedance reflects magnetic losses. Equation (5) assumes the sample completely fills the coaxial region. If the sample has outer and inner radii $R_{\mathrm{m}} \le R$ and $r_{\mathrm{m}} \ge r$, respectively, the input impedance consists of two additive components: one corresponding to the region filled by the sample (using Eq. (5) with $R = R_{\mathrm{m}}$ and $r = r_{\mathrm{m}}$), and another due to the air-filled remainder of the line. In this case, concentric placement of the ring sample is essential to avoid demagnetization effects.

By performing two measurements—one without and one with the sample—the differential input impedance $\Delta Z_{\mathrm{in,sh}}$ is defined. Its real and imaginary parts:

$$\Delta Z_{\mathrm{in,sh}} = (\Delta Z_{\mathrm{in,sh}}) + j\,(\Delta Z_{\mathrm{in,sh}}) \tag{6}$$

are used to calculate the real and imaginary components of the sample's relative permeability:

$$\mu'_{\mathrm{r}} = 1 + \frac{(\Delta Z_{\mathrm{in,sh}})}{\mu_0 f h \ln(R_{\mathrm{m}}/r_{\mathrm{m}})}, \tag{7a}$$

FIG. 1. RF shorted coaxial cell developed within the project.

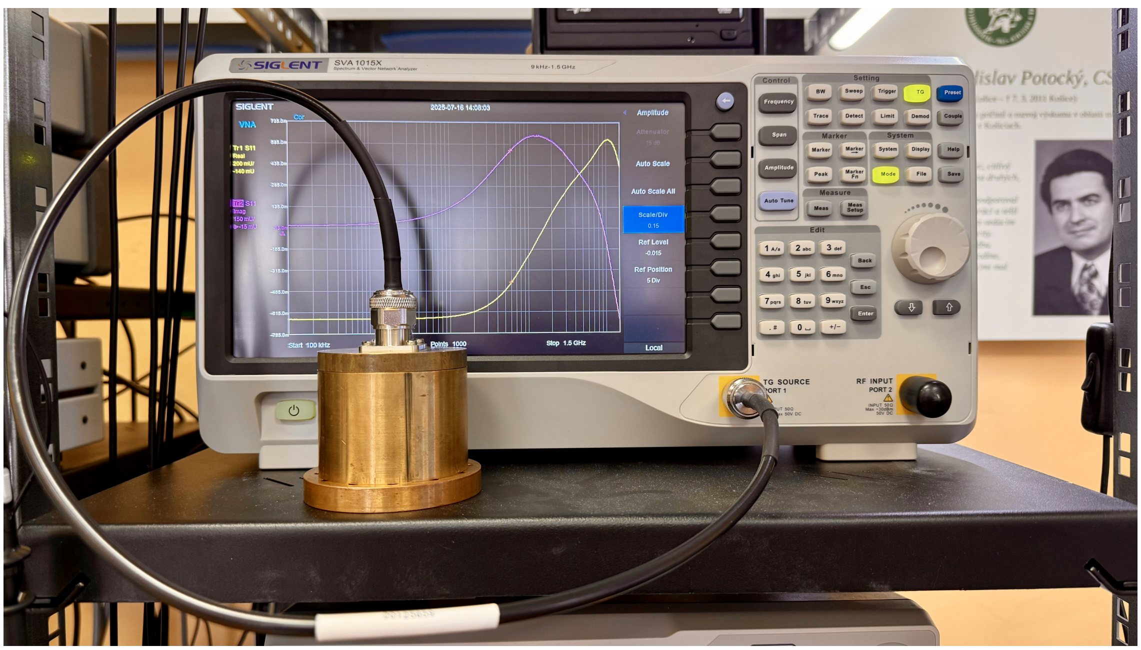

FIG. 2. The RF shorted coaxial cell connected to the vector network analyzer.

$$\mu_r'' = \frac{(\Delta Z_{\mathrm{in,sh}})}{\mu_0 f h \ln\left(R_m/r_m\right)}. \tag{7b}$$

This method is, in principle, valid up to several gigahertz. However, at higher frequencies, the excitation of resonant modes within the measurement cell and the onset of dielectric effects—particularly when the condition $h \ll \lambda/4$ is no longer met—can introduce measurement uncertainties.

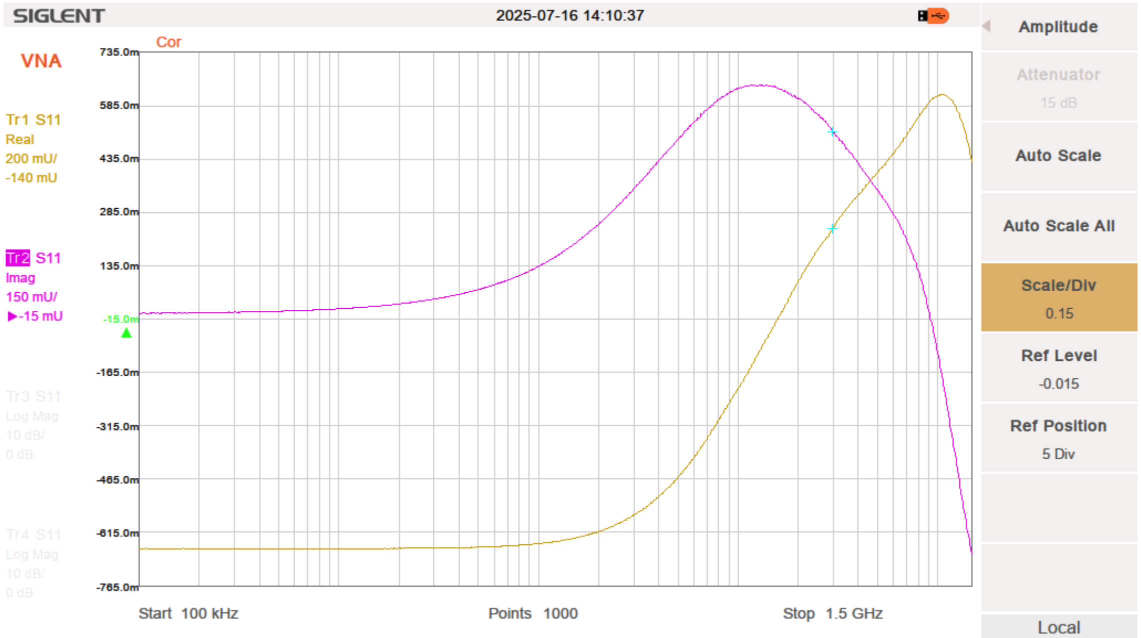

FIG. 3. Example of a vector network analyzer screen showing real and imaginary components of the reflection coefficient S_{11} measured on a soft magnetic material sample.

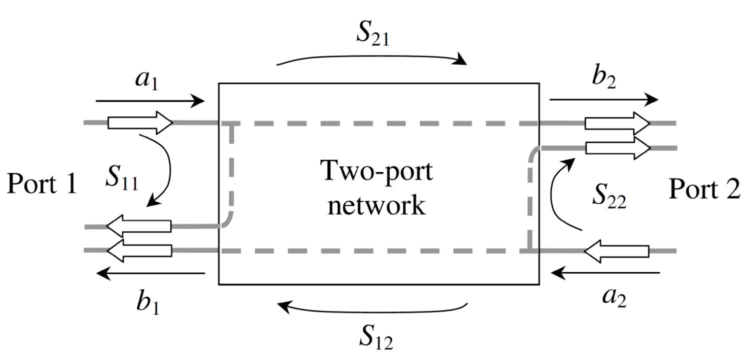

FIG. 4. General representation of a two-port electrical network.

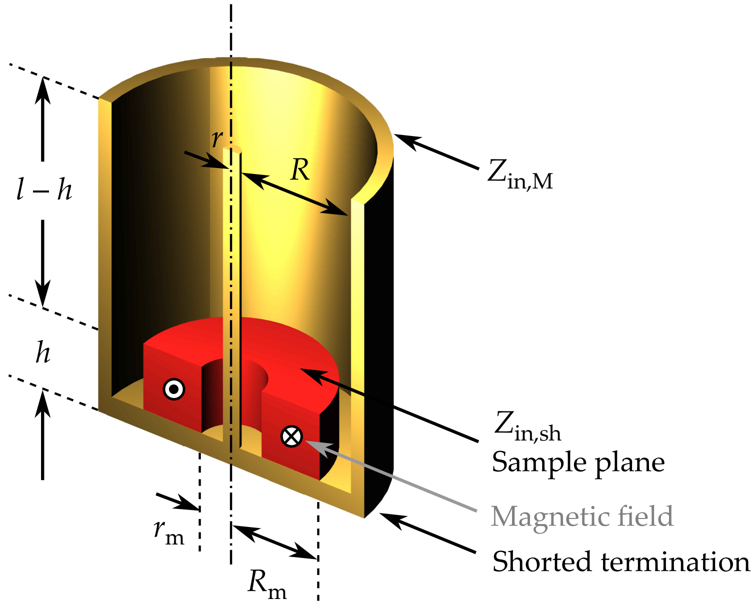

FIG. 5. Cross-section of the shorted brass coaxial cell with a ring-shaped sample placed at the bottom. The upper end is terminated with a 50 Ω N-type connector for interfacing with the vector network analyzer.

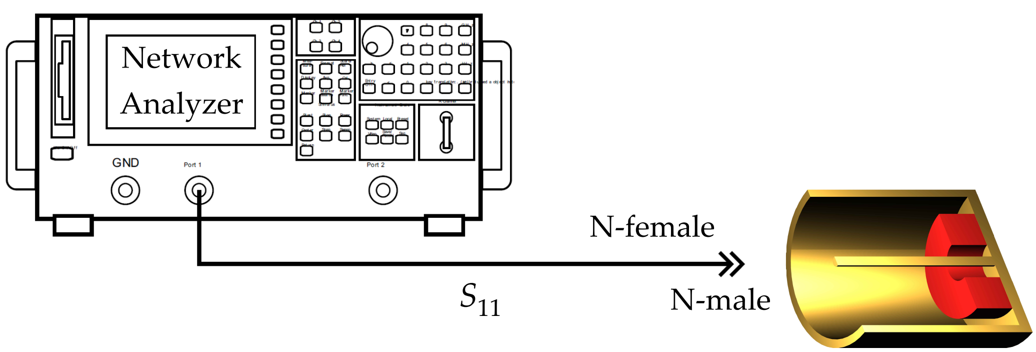

FIG. 6. Schematic representation of the measurement of the complex reflection coefficient S_{11} and the derived input impedance at the ring sample plane using a coaxial cell connected to port 1 of the vector network analyzer.