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Calculation of scattering parameters in multiple-interface transmission-line transducers

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ABSTRACT

Transmission-line scattering parameters becomes unpractical to calculate as one includes more interfaces. Thus, to get an analytical expression, approximations are required. In this paper, an approximation methodology for the calculation of scattering parameters of transmission-line transducers is presented. The transducer cell is partitioned at each interface and the partial scattering equations are calculated, considering two interfaces at a time. Next, standard techniques are applied to solve the signal-flow diagrams to obtain the full scattering equations. Transmission-line transducers are used for the measurement of power absorption and reflection of different materials, such as: liquids, granular medium, and ground, in the RF/microwave range. Such measurements are used to extract materials properties. The proposed methodology has been applied to a coaxial transducer cell filled with different low-loss liquids. The results have been validated with computer simulations and experimental measurements. Measurements and simulations were carried out in the 300 kHz to 3 GHz frequency range.

1. Introduction

Multiple-interface transmission-line transducer cells are very much used to extract physical properties of different materials, both liquids and solids. By measuring the transmitted and reflected power, as provided by the *S*-parameters, one can extract the complex permeability and permittivity by applying the NRW algorithm [1–8]. However, impedance mismatch at the interfaces results in partial multiple reflections and transmissions at each interface. Besides, wall surface absorption, possible non-linearity with increased power, and evanescent modes adds to the difficulty. Thus, the goal of obtaining theoretical expressions for the complete device is daunting task, as the signal-flow diagram becomes quite complex. The resulting expressions are hard to analyze and the contributions of a particular interface is difficult to isolate. Although, computer programs can be used to simulate transmission and reflection for the complete device, analytical expressions are more useful to give further insight into the transducer design.

In this paper, a useful approach to make this calculation feasible is presented, and an example is worked out in detail. For this example the coaxial transducer cell has four interfaces. The resulting expressions are compared to measurement data and simulation. The measurement is carried out with a vector network analyzer. The simulation was performed with COMSOL Multiphysics$^{®}$ 4.1a, a finite element package [9]. The *S*-parameters are obtained in the 300 kHz to 3 GHz frequency range.

This paper is divided into four sections. This introduction is the first. Next, the coaxial transducer cell design is presented, the solution of the proposed signal flow diagram, the computation model, and low- and high-frequency measurements are described. In Section 3, the results and analysis are presented. Finally, the conclusions.

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2. Methodology

2.1. Coaxial transducer cell design

To validate the methodology, a two-port coaxial transducer cell with four interfaces is used. The designed and machined coaxial line is presented in Fig. 1 [5]. Five sections and four interfaces are identified, as shown in Fig. 2. The center section can be filled with a liquid to modify the permittivity. The connectors at both ends are 703-model SMA-connector [10], and can be modeled as two-section elements, of lengths: d_1 and d_2. The first section with length d_1 = 6.6 mm is a coaxial element filled with Teflon. It is a transition region connected to the cable from the network analyzer. The second section has the same dielectric as the transmission line itself. This region has a length d_2 = 5.6 mm, and a diameter $2b_1$ = 3.7 mm. The center section of the coaxial cell has a length L = 92.6 mm, and the central wire has a diameter, $2a$ = 1.35 mm, which is the same in the connectors and in the cell. The coaxial cell has an internal diameter $2b_2$ = 11.2 mm.

The first section of the connector, filled with Teflon, is assumed to have an impedance Z_T = 50 Ω. The impedance of the second section is given by Eq. (1).

$$Z_{CS} = 60\sqrt{\frac{\mu_r}{\epsilon_r}}\ln\left(\frac{b_1}{a}\right) \tag{1}$$

where $\epsilon_r = \epsilon_r' - j\epsilon_r''$ and $\mu_r = \mu_r' - j\mu_r''$ are respectively the relative complex permittivity and complex permeability of the sample.

The third section corresponds to the transducer cell. It is a transmission line with impedance given by the following equation:

$$Z_S = 60\sqrt{\frac{\mu_r}{\epsilon_r}}\ln\left(\frac{b_2}{a}\right) \tag{2}$$

For the designed passive device, when the coaxial line is filled with air the characteristic impedance is Z_S = 127 Ω. The fourth and fifth sections are equal to the first two in reverse order.

The first half of the connector is the region named TFL; the second half is the region named CON-CTL. The transducer cell section is named CTL. The first and last regions are assumed to be matched to the cables, and are modeled as a phase displacement. The other three sections are modeled with a signal flow diagram, as presented in Fig. 2(a).

2.2. Solving the signal-flow diagram

To solve the signal-flow diagram for the complete cell is a dauting task. Depending on the level of mismatch, there will be infinite reflections in all interfaces. The simplification proposed in this paper is to consider two interfaces at a time. As the test transducer cell can be divided into five regions, there will be three two-interface blocks.

- Block 1: TFL/CON-CTL/CTL.
- Block 2: CON-CTL/CTL/CON-CTL.
- Block 3: CTL/CON-CTL/TFL.

The coaxial structure supports the *TEM* mode. Neglecting evanescent waves at the region boundaries and assuming perfect conductivity at the metal surfaces, the *TEM* mode propagation can be calculated with conventional circuit analysis [11]. The transmission/reflection analysis is carried out for each block.

Considering the first block, Γ_1 is the reflection coefficient at the interface TFL/CON-CTL. The transmission coefficient at this interface is given by $1 + \Gamma_1$. This is the complex transmitted voltage, not the measured power, as Γ_1 by definition is the reflected to incident voltage ratio. Hence, there is no energy conservation issue, as this is a inner part of the flow model. As the wave travels in the dielectric inside the region CON-CTL, some energy is absorbed. To account for such absorption, a transmission coefficient T_1 is introduced [12,13]. As the transmitted signal reaches the interface CON-CTL/CTL a new reflection, with coefficient Γ_2, and a new transmission, with coefficient $1 + \Gamma_2$, occurs. The reflected signal in the region CON-CTL reaches the interface TFL/CON-CTL and the same behavior is observed, but now the reflection coefficient is

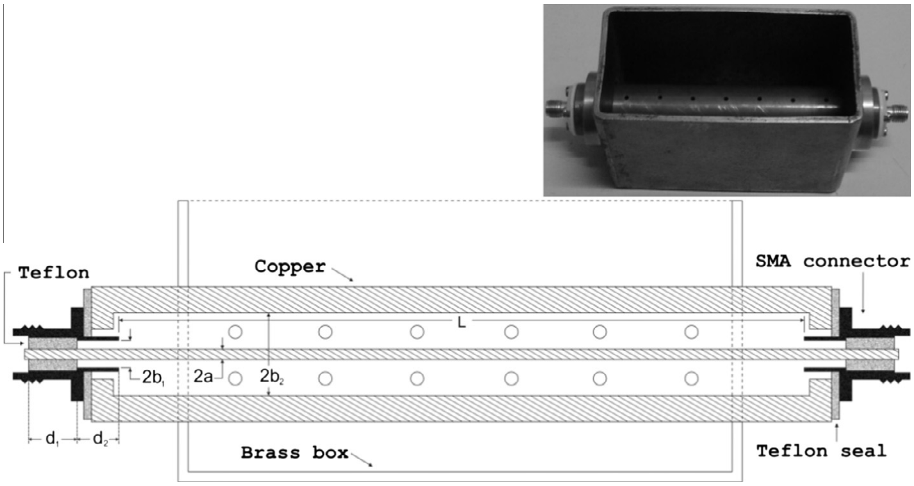

Fig. 1. Transducer cell to demonstrate the proposed methodology.