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Electric and Magnetic Characterization of Materials

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1. Introduction

The knowledge of the electric and magnetic properties of materials over a broadband frequency range is an essential requirement for accurate modelling and design in several engineering applications. Such applications span printed circuit board design, electromagnetic shielding, biomedical research and determination of EM radiation hazards (Deshpande et al. (1997); Li et al. (2011); Murata et al. (2005)). The electric and magnetic properties of materials usually depend on several factors: frequency, temperature, linearity, isotropy, homogeneity, and so on. The dispersive behaviour exhibited by these materials can be represented by a complex relative permittivity and magnetic permeability which depend on frequency as

$$\hat{\epsilon}(\omega) = \epsilon'(\omega) - j\epsilon''(\omega) \quad (1)$$

$$\hat{\mu}(\omega) = \mu'(\omega) - j\mu''(\omega) \quad (2)$$

being ω the angular frequency, ϵ' , μ' the real parts and ϵ'' , μ'' the imaginary parts of the complex relative permittivity and magnetic permeability, respectively. The real part takes the ability of the medium to store electrical (or magnetic) energy into account, the imaginary part the dielectric (or magnetic) energy losses. The interaction of incident electromagnetic fields with a material can be successfully investigated only when accurate information on the complex permittivity and magnetic permeability is attained. For example, from the knowledge of the frequency dependence of the complex relative permittivity and magnetic permeability of a material, the shielding effectiveness of a structure made of that material can be predicted; similarly, signal interconnects can be accurately designed when the frequency dependence of the dielectric substrate is known; from dielectric property information of tissues the spatial distribution of an incident electromagnetic field and the absorbed power can be accurately determined. Although the complex relative permittivity and magnetic permeability are quantities not directly measurable, they are reconstructed from the measurement of a sensor reflection coefficient or scattering parameters, which can be obtained with a number of different techniques proposed and developed over the last decades (Afsar et al. (1986); Baker-Jarvis et al. (1995); Faircloth et al. (2006); Ghodgaonkar et al. (1990); Queffelec et al. (1994)). Some of these techniques are: open-ended coaxial probe, free-space measurement, cavity resonator, parallel plate capacitor, transmission-line techniques (microstrip, waveguide, etc.); they may be in time domain or frequency domain and make use of probes with one or two ports. No technique is all-embracing as each

is limited by its own constraint to specific frequencies, materials (e.g., liquid, malleable or solid material; isotropic or anisotropic) and applications. Regardless of the technique used for the measurement, the common challenge is the extraction of the complex relative permittivity and/or magnetic permeability from measured data by expressing the measured quantities as a function of these parameters. The inversion problem to be solved is thus affected by the mathematical model, i.e., the theoretical expressions that relate the electrical and/or magnetic parameters to the measured quantities. The inversion problem can be solved with deterministic or stochastic methods. The complex relative permittivity and magnetic permeability can be determined over the whole frequency range of interest or on a point-by-point basis (at individual frequency points). It is assumed that the materials considered in the analysis present a negligible ohmic conductivity ($\sigma = 0$). The chapter is organized as follows. Section 2 of the chapter will briefly cover the most common experimental methods used in the electric and magnetic characterization of materials. The problem formulation is presented in Section 3 and the outline of a proposed procedure for parameter extraction is given in Section 4. Finally, results obtained with the proposed approach are shown and commented in Section 5.

2. Techniques of measurement

There exist a large number of techniques developed for the measurement of the electric and magnetic properties of materials. The most common and widespread one- and two-port techniques are transmission-line techniques (open-ended coaxial probe (Misra et al. (1990); Xu et al. (1991)), rectangular (Deshpande et al. (1997); Faircloth et al. (2006); Jarem et al. (1995)) or cylindrical (Ligthart (1983)) waveguide, microstrip or stripline (Barry (1986); Queffelec et al. (1994))), free-space measurement (Galek et al. (2010); Ghodgaonkar et al. (1990)) and cavity resonator (Yoshikawa and Nakayama (2008)). These techniques are different for accuracy and frequency bandwidth of measurement; some are nondestructive and noncontacting and may require sample preparation. Measurement results can also be different because of the field orientation with respect to the material interface, being the measurement more accurate when the fields are tangential to the interface. Although resonator techniques are recognized as more accurate than transmission-line techniques, they can be applied in a narrow frequency band only. In the next sections an overview of the most common broadband techniques of measurement is given.

2.1 One-port techniques

2.1.1 Open-ended coaxial probe

Open-ended coaxial probes have been used extensively by a number of authors mainly for measuring the complex permittivity of dispersive materials (Misra et al. (1990); Stuchly et al. (Febr. 1994); Xu et al. (1991)). For instance, they have been used to measure the electric properties of biological tissues, soils, food, chemicals. The open end of the probe is put in contact with a specimen of the material and the complex reflection coefficient at the aperture is measured with a vector network analyzer (VNA). The technique is particularly suitable for liquids or malleable solids that make a good contact with the probe face. The measurement of solid materials may be affected by a significant error if there are air gaps between the face of the probe and the sample due to surface roughness of the sample. In fact, the electric field at the probe aperture has both the radial and axial components. Models which keep the lift-off of the probe into account have also been proposed (Baker-Jarvis et al. (1994)). Basically, the technique consists in retrieving the complex permittivity from the measurement by relating

it to the coaxial probe aperture admittance which, in turn, is obtained from the measured reflection coefficient. The probe is designed in order to have only the TEM mode propagating along the coaxial line, therefore the upper limit of the frequency range in which this fixture can be employed is determined by the frequency cutoff of the higher order modes created at the discontinuity introduced by the material under test. This cutoff frequency depends on the inner and outer diameters of the probe. Moreover, the cell must be long enough to make the evanescent modes decay appreciably far from the open end of the probe. Another issue of this technique concerns the probe calibration, which is usually carried out in three steps with factory-standard calibration loads (short, open and load terminations) (Blackham and Pollard (1997)). In order to improve the accuracy of the measurement, reference loads with liquids of known permittivity (Marsland and Evans (1987)) or short-cavity terminations (Otto and Chew (1991)) have been proposed.

2.2 Two-port techniques

2.2.1 Waveguide

The technique consists in filling completely or in part the cross-section of a waveguide (or TEM transmission line) with a material sample and in measuring the scattering parameters by means of a VNA in a broadband frequency range. The electric and magnetic parameters of the material are found through the discontinuity introduced by the sample inside the waveguide as the scattering parameters are related to the permittivity and magnetic permeability of the material with the scattering equations (Nicolson and Ross (1970)). Although preparation is simple, the sample needs to be machined to be fit into the fixture. The most common geometry for the waveguides is the rectangular one; in particular, the waveguide is designed to have only the dominant mode TE_{10} in order to avoid exciting higher order modes.

2.2.2 Free-space measurement

The technique consists in measuring the insertion loss and phase change of a material sample by means of a couple of antennas. The measurement is carried out in free space in a wide broadband frequency range, which extends from a few tens of MHz to tens of GHz according to the available instrumentation. As the technique is contactless and nondestructing, it can be suitable to high-temperature measurements (Ghodgaonkar et al. (1990)). The two antennas are connected to the two ports of a VNA and the scattering parameters related to transmitted and reflected fields are measured. The permittivity and magnetic permeability of the material are then calculated through the scattering equations.

3. Problem formulation

The extraction of the electric and/or magnetic parameters of materials from measurement is a two-step process. The first step of this inversion problem is to find a mathematical model that relates the electrical and/or magnetic parameters of the material under test to the measured quantities.

3.1 Open-ended coaxial probe formulation

For the open-ended coaxial probe measurement technique the complex relative permittivity is determined by inverting the expression of $\hat{Y}(\hat{\epsilon})$, where \hat{Y} is the aperture admittance of the probe (Stuchly et al. (Febr. 1994))

$$\hat{Y} = Y_0 \frac{1 - \hat{\Gamma}}{1 + \hat{\Gamma}} \quad (3)$$

where Y_0 is the characteristic admittance of the coaxial line and $\hat{\Gamma}$ is the reflection coefficient at the aperture. There are several analytical expressions for the aperture admittance of open-ended coaxial probes (De Langhe et al. (1993); Misra et al. (1990); Xu et al. (1987; 1991)) which contain the complex permittivity explicitly and that can be compared to the measured admittance. Some are very heavy from the computational point of view and may result in convergence problems when numerically solved, because of the presence of multiple integrals, Bessel functions and sine integrals. The expression for the aperture admittance given by (Marcuvitz (1951)), found by matching the electromagnetic field around the probe aperture, can be adopted

$$\hat{Y} = \frac{\sqrt{\hat{\epsilon}}Y_0}{\sqrt{\epsilon_{cl}}\ln(b/a)} \left\{ \int_0^{\pi/2} \left[J_0(\gamma_0 a \sqrt{\hat{\epsilon}} \sin \theta) - J_0(\gamma_0 b \sqrt{\hat{\epsilon}} \sin \theta) \right]^2 \frac{d\theta}{\sin \theta} \right. \\ \left. + \frac{j}{\pi} \int_0^{\pi} \left[2Si \left(\gamma_0 a \sqrt{\hat{\epsilon}} \sqrt{1 + \frac{b^2}{a^2} - 2\frac{b}{a} \cos \theta} \right) - Si \left(2\gamma_0 a \sqrt{\hat{\epsilon}} \sin \frac{\theta}{2} \right) - Si \left(2\gamma_0 b \sqrt{\hat{\epsilon}} \sin \frac{\theta}{2} \right) \right] d\theta \right\} \quad (4)$$

where: $\hat{\epsilon}$ is the complex relative permittivity of the material under test, ϵ_{cl} is the relative permittivity of the coaxial line, a and b are the inner and outer radii of the coaxial line, respectively, γ_0 is the absolute value of the propagation constant in free space (see (16)), Si and J_0 are the sine integral and the Bessel function of zero order, respectively. This integral expression can be evaluated numerically by means either of series expansion as in (Misra et al. (1990); Xu et al. (1987)) or numerical integration.

3.2 Two-port formulation

In a similar manner, for two-port techniques the theoretical expressions of the scattering parameters as functions of the complex relative permittivity (1) and magnetic permeability (2) have to be found. This can be easily achieved expressing the scattering parameters $\hat{S}_{11}(\omega)$ and $\hat{S}_{21}(\omega)$, which can be measured with a VNA and with a two-port fixture, as a function of the reflection coefficient of the air-sample interface and transmission coefficient, $\hat{\Gamma}$ and \hat{T} , respectively. For the TEM propagation mode (free-space measurement system and TEM transmission line) and for waveguides with only the TE_{10} propagation mode these expressions for S_{11} and S_{21} are (Barroso and De Paula (2010); Boughriet et al. (1997); Ghodgaonkar et al. (1990); Ligthart (1983))

$$\hat{S}_{11} = \frac{\hat{\Gamma}(1 - \hat{T}^2)}{1 - \hat{\Gamma}^2 \hat{T}^2}, \quad (5)$$

$$\hat{S}_{21} = \frac{\hat{T}(1 - \hat{\Gamma}^2)}{1 - \hat{\Gamma}^2 \hat{T}^2} \quad (6)$$

being

$$\hat{\Gamma} = \frac{\hat{Z} - Z_0}{\hat{Z} + Z_0}, \quad (7)$$

$$\hat{T} = e^{-\hat{\gamma}d} \quad (8)$$

and for a rectangular waveguide (Inan and Inan (2000); Kraus and Fleisch (1999); Sadiku (2007))

$$\hat{Z} = j \frac{\omega \mu_0 \hat{\mu}}{\hat{\gamma}}, \quad (9)$$

$$Z_0 = j \frac{\omega \mu_0}{\hat{\gamma}_0}, \quad (10)$$

$$\hat{\gamma} = j \frac{2\pi}{\lambda_0} \sqrt{\hat{\epsilon} \hat{\mu} - \left(\frac{\lambda_0}{\lambda_{0c}} \right)^2}, \quad (11)$$

$$\hat{\gamma}_0 = j \frac{2\pi}{\lambda_0} \sqrt{1 - \left(\frac{\lambda_0}{\lambda_{0c}} \right)^2} \quad (12)$$

where \hat{Z} and $\hat{\gamma}$ are the intrinsic impedance and propagation constant of the filled waveguide, respectively, Z_0 and $\hat{\gamma}_0$ are the intrinsic impedance and propagation constant of the empty waveguide, respectively, and d is the thickness of the sample. The propagation constants depend on the wavelength in free space λ_0 and the cutoff wavelength in the waveguide λ_{0c} (i.e., the wavelength in free space at the cutoff frequency in the empty waveguide (Kraus and Fleisch (1999))). For a rectangular waveguide $\lambda_{0c} = 2a$, where the width of the waveguide a is chosen to be twice the height of the waveguide in order to have only the TE_{10} propagation mode impinging on the material sample in the frequency range of interest.

For free space-measurement, (9)-(12) become (Galek et al. (2010); Ghodgaonkar et al. (1990))

$$\hat{Z} = Z_0 \sqrt{\frac{\hat{\mu}}{\hat{\epsilon}}}, \quad (13)$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}, \quad (14)$$

$$\hat{\gamma} = \hat{\gamma}_0 \sqrt{\hat{\epsilon} \hat{\mu}}, \quad (15)$$

$$\hat{\gamma}_0 = j \frac{2\pi}{\lambda_0} \quad (16)$$

where \hat{Z} and Z_0 are the intrinsic impedances of the material under test and free space, respectively.

Once the scattering parameters (5) and (6) are expressed as functions of $\hat{\epsilon}$ and $\hat{\mu}$, they must be inverted to yield the complex relative permittivity and magnetic permeability.

4. Procedure for the extraction

The second step of the inversion problem is the extraction of the material parameters from the measured quantities.

4.1 Nicolson-Ross-Weir procedure

In the standard Nicolson-Ross-Weir procedure (Nicolson and Ross (1970); Weir (1974)), the relative complex permittivity and magnetic permeability are obtained explicitly for a rectangular waveguide from (7) to (12) on a point-by-point basis as

$$\hat{\mu} = \frac{\lambda_{0g}}{\hat{\Lambda}} \left(\frac{1 + \hat{\Gamma}}{1 - \hat{\Gamma}} \right), \quad (17)$$

$$\hat{\varepsilon} = \frac{\lambda_0^2}{\hat{\mu}} \left(\frac{1}{\hat{\Lambda}^2} + \frac{1}{\lambda_{0c}^2} \right) \quad (18)$$

where λ_{0g} is the wavelength in the empty waveguide

$$\lambda_{0g} = \frac{\lambda_0}{\sqrt{1 - (\lambda_0/\lambda_{0c})^2}} \quad (19)$$

and

$$\frac{1}{\hat{\Lambda}^2} = - \left(\frac{1}{2\pi d} \ln \frac{1}{\hat{T}} \right)^2. \quad (20)$$

This requires to express $\hat{\Gamma}$ and \hat{T} from the measured scattering parameters \hat{S}_{11} and \hat{S}_{21} : from (5) and (6) one can write

$$\hat{K} = \frac{\hat{S}_{11}^2 - \hat{S}_{21}^2 + 1}{2\hat{S}_{11}} \quad (21)$$

$$\hat{\Gamma} = \hat{K} \pm \sqrt{\hat{K}^2 - 1} \quad (22)$$

$$\hat{T} = \frac{\hat{S}_{11} + \hat{S}_{21} - \hat{\Gamma}}{1 - (\hat{S}_{11} + \hat{S}_{21}) \hat{\Gamma}}. \quad (23)$$

However, this procedure presents phase ambiguity and suffers instability at frequencies where the sample length is a multiple of one-half wavelength in low-loss materials. To overcome this problem, in (Baker-Jarvis et al. (1990)) an iterative procedure has been proposed, which gives stable solutions over the frequency range. This technique requires setting the relative magnetic permeability to 1 and a good initial guess for the permittivity (usually a solution of the Nicolson-Ross equations).

4.2 Fitting procedure

A different procedure for the extraction of material parameters involves minimizing the distance between the calculated aperture admittance (4) or scattering parameters (5) and (6) and the corresponding measured quantities through fitting algorithms, which may be based either on deterministic or stochastic optimization procedures. The minimization can be carried out over the whole frequency range or on a point-by-point basis (i.e., at individual frequency points).

The former approach, followed by a number of authors, consists in modelling the complex relative permittivity and magnetic permeability with a prespecified functional form whose parameters needs to be determined with an optimization procedure. Laurent series can be used for complex relative permittivity and magnetic permeability models (Domich et al. (1991)), as well as dispersive laws, such as Havriliak-Negami and its special cases Cole-Cole and Debye to model dielectric relaxation (Kelley et al. (2007)), or the Lorentz model for both dielectric and magnetic dispersion (Koledintseva et al. (2002)). The Havriliak-Negami model is an empirical modification of the single-pole Debye relaxation model

$$\hat{\varepsilon}(\omega) = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{[1 + (j\omega\tau)^{1-\alpha}]^{\beta}} \quad (24)$$

where ε_s and ε_{∞} are the values of the real part of the complex relative permittivity at low and high frequency, respectively, τ is the relaxation time, and α and β are positive real constants

($0 \leq \alpha, \beta \leq 1$). From this model, the Cole-Cole equation can be derived setting $\beta = 1$; the Debye equation is obtained with $\alpha = 0$ and $\beta = 1$. This empirical model has the ability to give a better fit to the behaviour of dispersive materials over a wide frequency range. When multiple relaxation times are needed, the complex relative permittivity can be modelled with a Debye function expansion

$$\hat{\epsilon}(\omega) = \epsilon_{\infty} + \sum_{n=1}^N \frac{\Delta\epsilon_n}{1 + j\omega\tau_n} \quad (25)$$

being $\Delta\epsilon_n$ and τ_n for $n = 1, 2, \dots, N$ the strengths and relaxation times of the Debye dispersion, respectively. Modelling the complex relative permittivity with the Lorentz model yields

$$\hat{\epsilon}(\omega) = \epsilon_{\infty} + \frac{(\epsilon_s - \epsilon_{\infty})\omega_0^2}{\omega_0^2 + j\omega\delta - \omega^2} \quad (26)$$

where ω_0 is the resonance frequency and δ is the damping factor. For instance, for open-ended coaxial probe measurements of complex relative permittivity, introducing (24) into (4) we obtain an aperture admittance which depends then on five parameters

$$\hat{Y}(\epsilon_s, \epsilon_{\infty}, \tau, \alpha, \beta) \quad (27)$$

which reduce to four in the case of the Cole-Cole model

$$\hat{Y}(\epsilon_s, \epsilon_{\infty}, \tau, \alpha) \quad (28)$$

and to three for the Debye model

$$\hat{Y}(\epsilon_s, \epsilon_{\infty}, \tau). \quad (29)$$

For the Debye function expansion, the aperture admittance depends on $2N + 1$ parameters

$$\hat{Y}(\Delta\epsilon_1, \dots, \Delta\epsilon_N, \epsilon_{\infty}, \tau_1, \dots, \tau_N). \quad (30)$$

Eventually, for the Lorentz model, the aperture admittance is

$$\hat{Y}(\epsilon_s, \epsilon_{\infty}, \omega_0, \delta). \quad (31)$$

With reference to the above listed models (24)-(26) for the dispersion law, this approach is summarized in Fig. 1. The unknown parameters are then extracted by fitting the expressions from (27) to (31) to the measured characteristic data.

It can be observed that this approach can also be applied to measurement techniques of the complex permittivity other than open-ended coaxial probes, provided that the analytical relation between a measurable quantity and the complex permittivity is known. In a similar manner, it can be applied to the simultaneous extraction of the complex permittivity and magnetic permeability of a material by comparing the analytical reflection (\hat{S}_{11}) and transmission (\hat{S}_{21}) coefficients to the measurements carried out with a VNA in the standard transmission-line or free-space techniques.

The success of the extraction of the model parameters relies on a proper choice of the dispersive laws for the material under test; conversely, the fitting algorithms may experience nonconvergence issues or the parameters of the models may be determined with excessive errors. Especially for newly developed materials, individuating the proper dispersion laws may result in a difficult task. Moreover, the complexity of the models affects also the choice of the fitting algorithm for the parameter extraction.

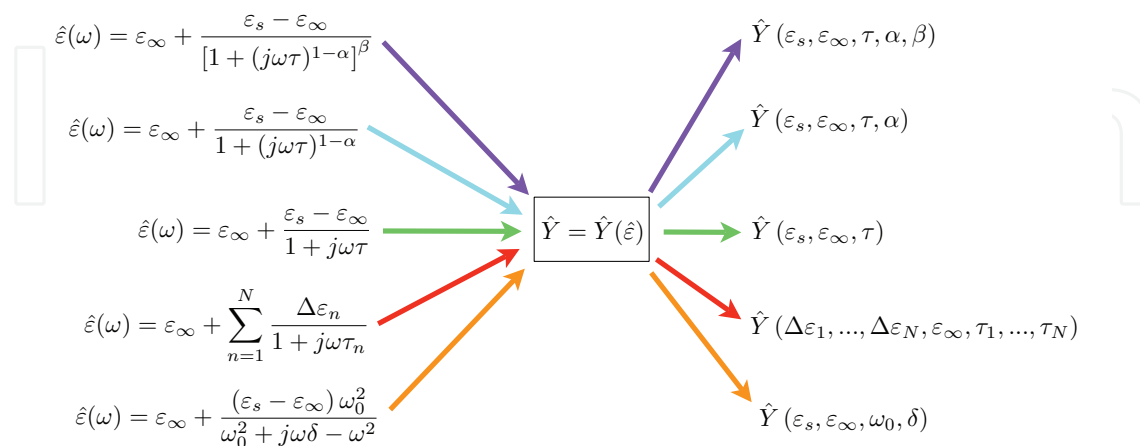


Fig. 1. Aperture admittance of an open-ended coaxial probe as a function of dispersion law parameters.

For these reasons, the latter approach can be followed, which consists in not making any assumption on the dispersive laws and in determining the real and imaginary parts of the material complex parameters at each measurement frequency (on a point-by-point basis). Once the complex relative permittivity and magnetic permeability as a function of frequency are known, proper models can be chosen to represent the material properties over the entire frequency range of measurement. For example, for isotropic materials which exhibit electric and magnetic properties, the inversion process involves the minimization of an objective function φ of the kind

$$\begin{aligned} \varphi(f_i, \epsilon', \epsilon'', \mu', \mu'') = & \sum_{i=1}^N \left[(\hat{S}_{11\text{measured}}(f_i) - \hat{S}_{11\text{calculated}}(f_i, \epsilon', \epsilon'', \mu', \mu''))^2 \right. \\ & \left. + (\hat{S}_{21\text{measured}}(f_i) - \hat{S}_{21\text{calculated}}(f_i, \epsilon', \epsilon'', \mu', \mu''))^2 \right] \end{aligned} \quad (32)$$

where f_i is the generic frequency of the N frequencies of the measurement data set. The reflection and transmission coefficients \hat{S}_{11} and \hat{S}_{21} are those of a two-port technique of Sec. 2. Similarly, when the open-ended coaxial probe is used, the determination of the complex permittivity requires to minimize an objective function ψ at each frequency of the measurement data set

$$\psi(f_i, \epsilon', \epsilon'') = \sum_{i=1}^N (\hat{Y}_{\text{measured}}(f_i) - \hat{Y}_{\text{calculated}}(f_i, \epsilon', \epsilon''))^2. \quad (33)$$

This approach is handled with the proposed procedure, where a number of optimization algorithms are used to search the minimum values and to overcome possible convergence issues or local minima stalemates. They can be deterministic (e.g., Newton, Interior Point, Quasi-Newton, Levenberg-Marquardt, Gradient, Nonlinear Conjugate Gradient, Principal Axis, Nelder-Mead) or stochastic (e.g., Differential Evolution, Simulated Annealing, Random Search, Particle Swarm). This choice is also motivated as different optimization methods may result in being more appropriate to extract the complex relative permittivity and/or magnetic permeability of the same material at different measurement frequencies. For each measurement frequency, the optimization methods are applied according to a user defined sequence. In case an optimization method does not reach convergence or the desired accuracy within the maximum number of iterations, the minimum search is repeated with the next optimization method in the sequence. The proposed procedure, summarized in the flow-chart of Fig. 2, was implemented in Mathematica (Wolfram Research, Inc. (2008)), a powerful and complex programming environment with the capability of performing both numerical and symbolic calculations. This computational language can be easily extended developing custom algorithms. The optimization methods employed in the parameter extraction procedure are listed in Table 1; of course, other optimization algorithms may be added to this sequence, thus increasing the chances of determining the complex relative permittivity with the requested accuracy. The worst result is given by the failure of all optimization methods.

The interesting aspect of this approach is that the determination of the complex relative permittivity and magnetic permeability may be enhanced with subsequent refinements; more experimental points measured at different frequencies can be added to the first set of measurement data. The procedure can then be run on this additional data set only, extracting the complex relative permittivity at these additional frequencies. Parallelization is another interesting feature of the proposed procedure: in fact, the minimization of the objective function is carried out at each single frequency, and each minimization process is independent from the others. The procedure can then be quite easily implemented on a grid computing system to speed up the extraction process.

5. Results

In order to show the application of the procedure, the complex relative permittivity of methanol was extracted over the frequency range 1–15 GHz. For this nonmagnetic material, the reflection coefficient is sufficient for the complex permittivity determination and thus a single objective function in terms of $\hat{\epsilon}$ was used. In particular, the complex relative permittivity was obtained from the aperture admittance of an open-ended coaxial probe, that can be related to the reflection coefficient. With reference to (4), the inner and outer radii of the open-ended coaxial probe are $a = 0.04\text{ cm}$ and $b = 0.114\text{ cm}$, respectively, and the dielectric between the inner and outer conductors has a relative permittivity $\epsilon_{cl} = 1.58$ (Misra et al. (1990)). With the former approach outlined in Sec. 4.2, solving the inverse problem yields a vector of the unknown parameters. The dispersion models considered in the extraction are the Havriliak-Negami, the Cole-Cole, the Debye and Debye function expansion models. As some of the algorithms are stochastic with initial values chosen randomly within a search range, different runs of the procedure may give spread solutions which are averaged out. The dispersion of the parameter values of these models (Havriliak-Negami, Cole-Cole, and Debye) can be compared graphically, as shown in Fig. 3, by normalizing each parameter value over its own search range. It can be noticed that the fewer the parameters, the less they are spread

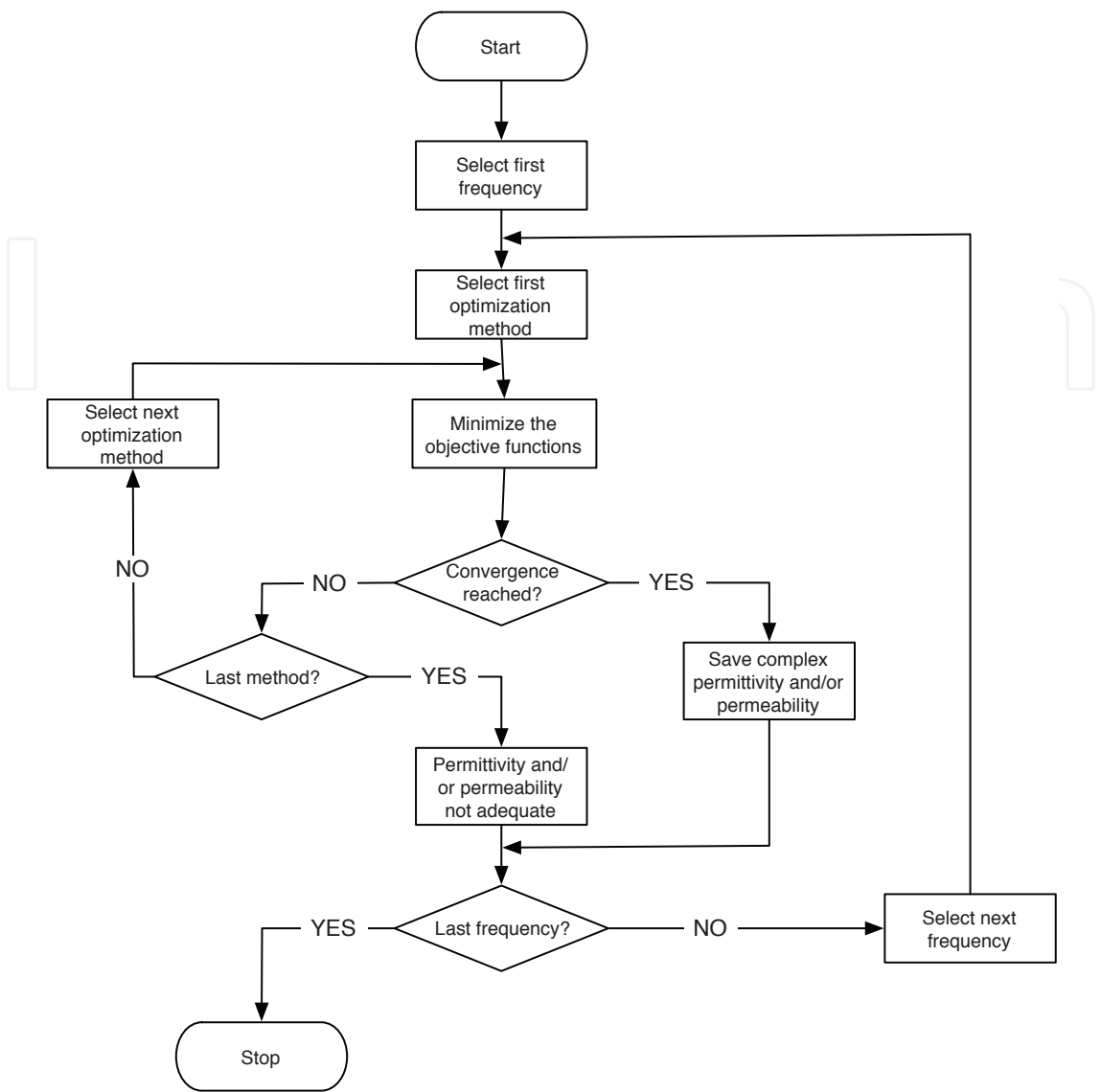


Fig. 2. Flow-chart of the extraction procedure of the complex relative permittivity and/or magnetic permeability.

over the search range: the parameters of the Debye model are less dispersed than those of Havriliak-Negami or Cole-Cole models. Conversely, when the latter approach in Sec. 4.2 is adopted, the complex permittivity is extracted on a point-by-point basis at each frequency of the measurement range. The real and imaginary parts of the complex relative permittivity extracted with both approaches are shown in Figs. 4 and 5, respectively, together with the permittivity values as calculated in (Misra et al. (1990)). The curves in the plots are labelled accordingly. From the two plots it can be noticed that the behaviour versus frequency of the complex relative permittivity extracted at individual frequencies (labelled “No model” in the graphics) is in good agreement with that related to the Havriliak-Negami and Debye function expansion dielectric relaxation models. The agreement is less good with both the Debye and Cole-Cole dispersive models, which give similar values for the permittivity over the frequency range.

The validation of the extraction procedure consists in calculating the aperture admittance of the coaxial probe using (4) and the complex relative permittivity extracted and comparing

	Method
Deterministic	Newton
	Interior Point
	Quasi-Newton
	Levenberg–Marquardt
	Gradient
	Nonlinear Conjugate Gradient
	Principal Axis
	Nelder–Mead
Stochastic	Differential Evolution
	Simulated Annealing
	Random Search
	Particle Swarm

Table 1. Optimization methods employed in the parameter extraction procedure.

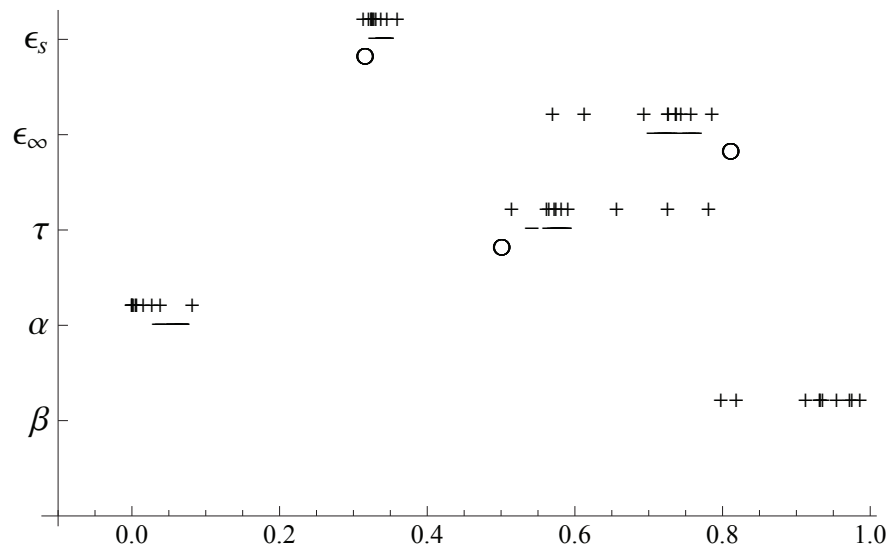


Fig. 3. Normalized parameter values obtained with the Havriliak-Negami (+), Cole-Cole (-) and Debye (o) models.

it to the measured one. The comparison is shown in Figs. 6 and 7 for the real and imaginary parts of the aperture admittance, respectively. The plots show that the aperture admittance calculated with the complex permittivity extracted on a point-by-point basis and that obtained with the Havriliak-Negami and Debye function expansion models are in a very good agreement with the measurement. Differently, the aperture admittance calculated with the permittivity modelled with the Debye and Cole-Cole models differs from the measured one especially at higher frequencies. The complex permittivity extracted on a point-by-point basis shows the best overall result.

6. Conclusion

The chapter outlines possible procedures for the extraction of electric and magnetic parameters of dispersive materials. The complex relative permittivity and magnetic permeability can be modelled with either dispersive laws or on a point-by-point basis (at individual frequencies). The latter approach was implemented in a procedure proposed in

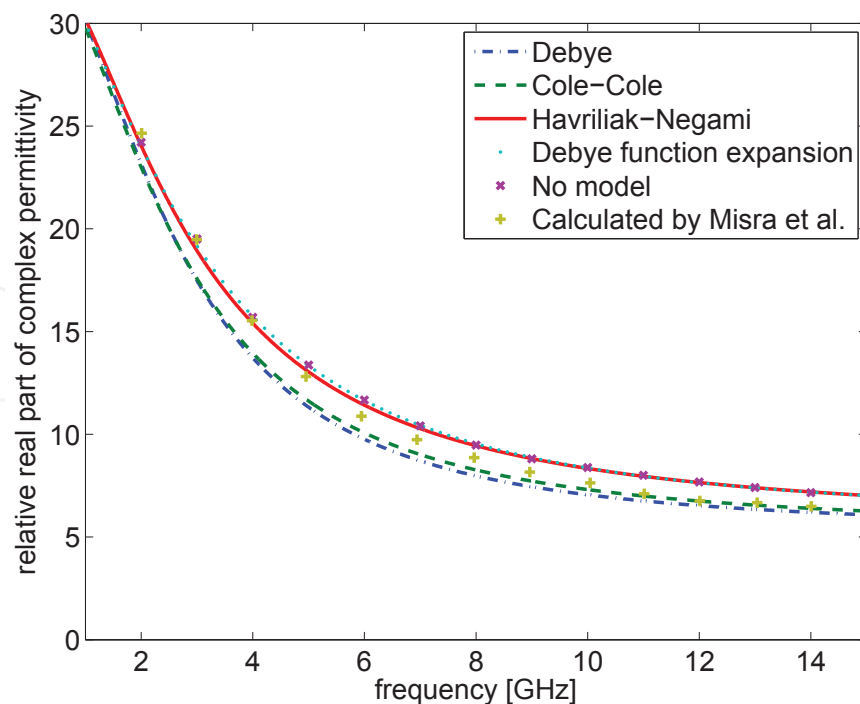


Fig. 4. Comparison of the real part of the complex relative permittivity versus frequency extracted with the Havriliak-Negami, Cole-Cole, Debye and Debye function expansion models and without assuming a dispersive model with that calculated according to the procedure in (Misra et al. (1990)).

this chapter, where a number of optimization algorithms are cycled to extract the complex relative permittivity and to overcome possible convergence issues or local minima stalemates. The assessment and validation of the procedure were carried out against the experimental data for the aperture admittance of an open-ended coaxial probe immersed in methanol. It is found that the frequency behaviour of the complex relative permittivity extracted with the procedure is in a very good agreement with that modelled according to two classic dielectric relaxation models (Havriliak-Negami, and Debye function expansion models), commonly adopted in literature to represent dispersive materials. Furthermore, the calculated aperture admittance was compared with the measured one. The comparison shows that the best level of agreement between the calculated and measured aperture admittance is obtained with the complex relative permittivity extracted with the proposed procedure. This approach is particularly advantageous when applied to new developed materials or materials whose frequency behaviour is not known (materials which cannot be modelled *a priori* with a dielectric relaxation model). In any case, once the complex relative permittivity is known, a proper dielectric relaxation model can be adopted to represent the permittivity over the whole frequency range of measurement. Its parameters can be quickly determined with standard interpolation routines of the complex relative permittivity values previously extracted. Interesting features of the proposed procedure are the possibility of further refining the complex relative permittivity extraction by adding more experimental data points at later times, and its intrinsic parallel nature, being each minimization process carried out at every single frequency independent from the others.

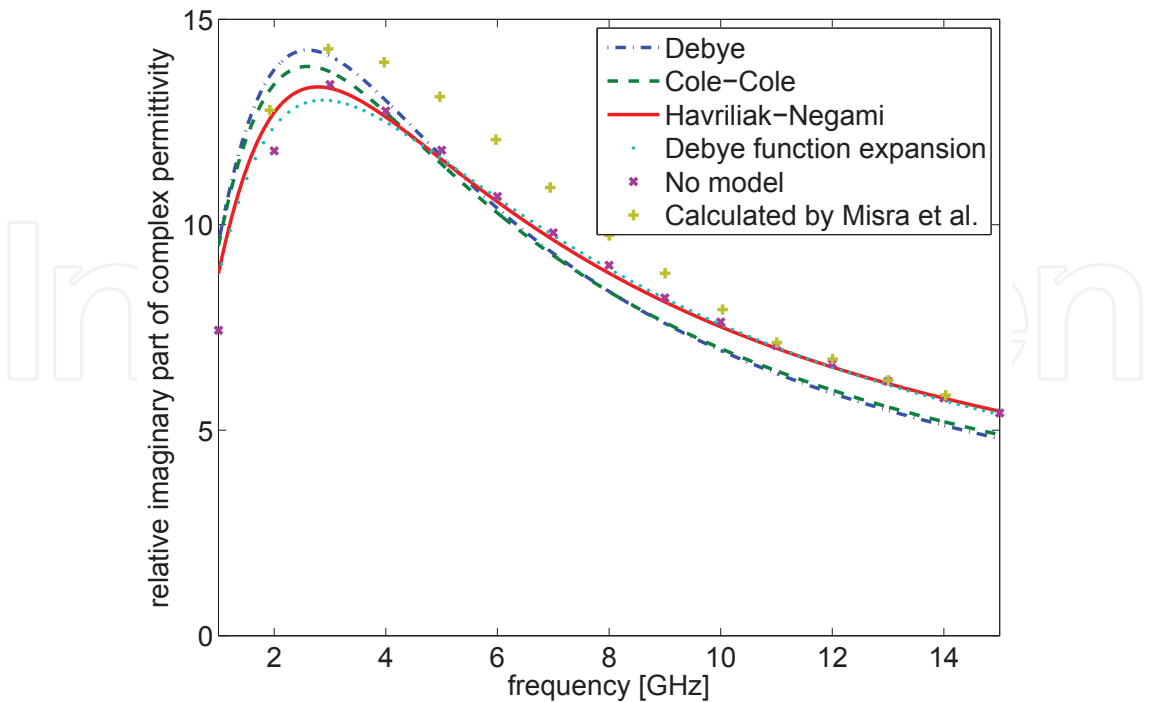


Fig. 5. Comparison of the imaginary part of the complex relative permittivity versus frequency extracted with the Havriliak-Negami, Cole-Cole, Debye and Debye function expansion models and without assuming a dispersive model with that calculated according to the procedure in (Misra et al. (1990)).

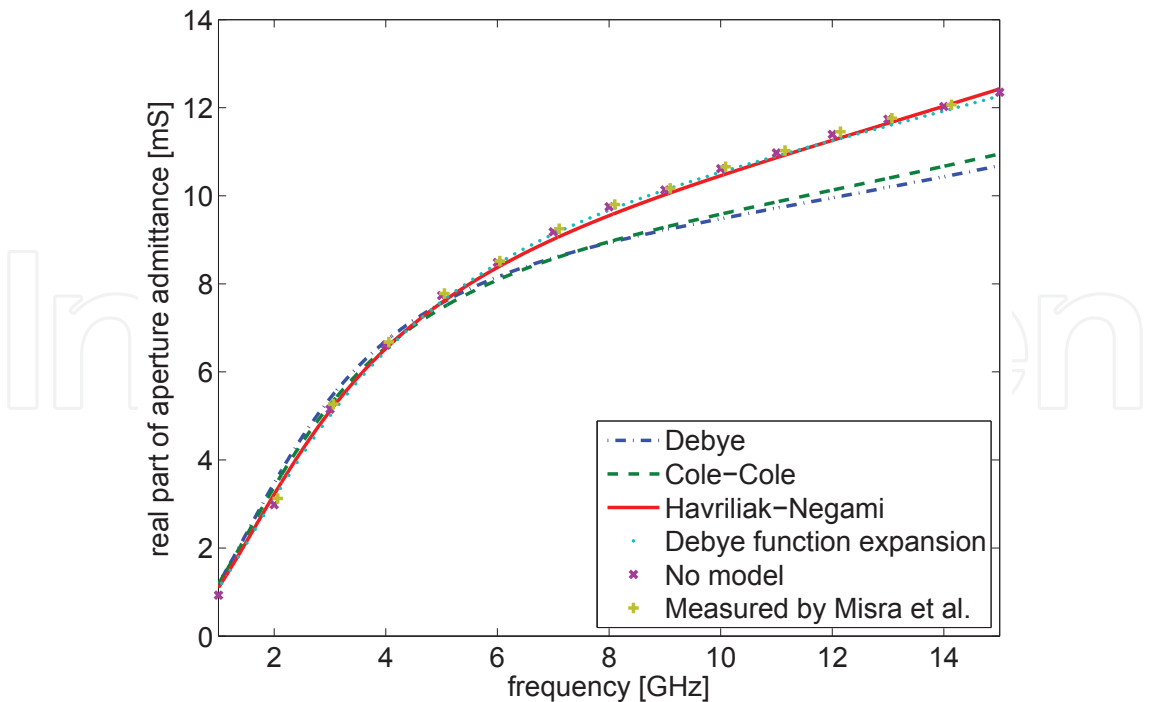


Fig. 6. Comparison of the real part of the calculated and measured (Misra et al. (1990)) aperture admittance versus frequency.

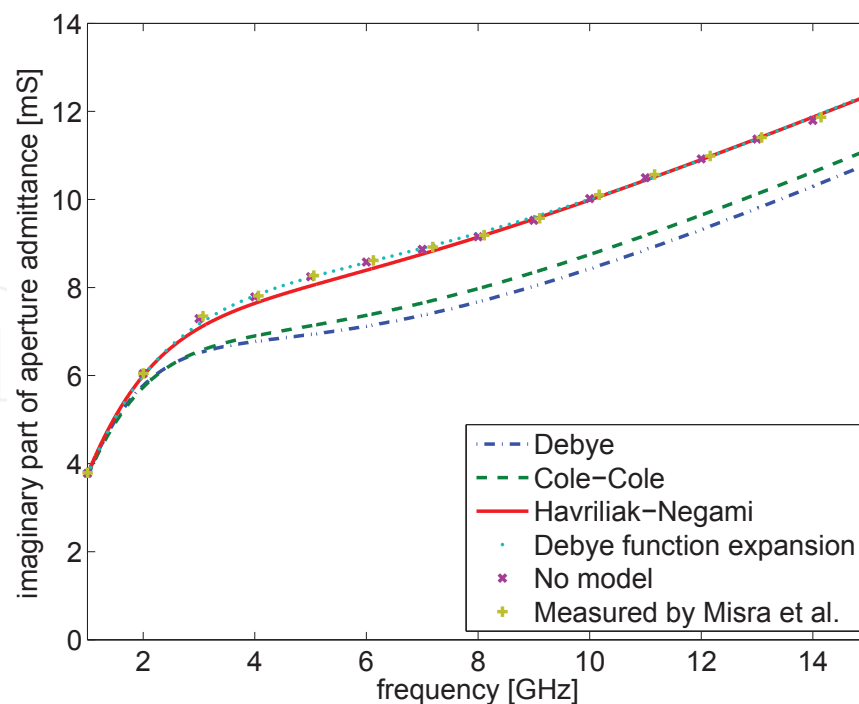


Fig. 7. Comparison of the imaginary part of the calculated and measured (Misra et al. (1990)) aperture admittance versus frequency.

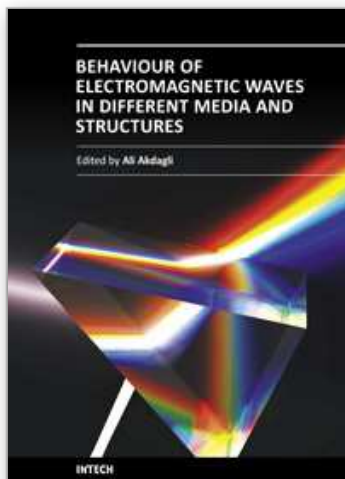
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