Note: Coaxial apparatus to measure the permittivities of chemical solutions at microwave frequencies

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Citation: Review of Scientific Instruments **88**, 046102 (2017); doi: 10.1063/1.4979074
View online: http://dx.doi.org/10.1063/1.4979074
View Table of Contents: http://aip.scitation.org/toc/rsi/88/4
Published by the American Institute of Physics

REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 046102 (2017)

Note: Coaxial apparatus to measure the permittivities of chemical solutions at microwave frequencies

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(Received 26 February 2016; accepted 12 March 2017; published online 10 April 2017)

Traditional permittivity measurements in microwave chemistry have some limitations on bandwidth and probe erosion. To resolve these problems, in this note, an apparatus that realizes a real-time wide-band non-contact measurement is proposed. Scattering parameters are obtained from measurements made using the proposed coaxial apparatus. These parameters are used to reconstruct the permittivities of several solutions using artificial neural networks. The maximum deviations in measured permittivity at 2.45 and 5.8 GHz are within 5% of results from the literature, showing the obvious advantages of coaxial apparatus with artificial neural network reconstruction over conventional apparatus. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4979074]

Permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) plays a very important role in materials for industrial, scientific, and medical applications.[1–3] The permittivity of materials and the absorption and reflection on microwave energy are desired, especially in microwave chemistry. Hence, the measurement of permittivity of a reaction in microwave chemistry is very important. Moreover, to optimize the performance of a chemical reaction, it is necessary to understand its permittivity. In the laboratory, permittivities have been measured by different methods.[4] These methods can roughly be divided into resonant and non-resonant methods.[5–7] Resonator-based approaches are an attractive choice due to their high sensitivity such as planar resonators, resonant frequency-selective filters, and whispering gallery mode dielectric resonators.[8,9] Nevertheless, these sensors are limited in broadband frequency capabilities. For broadband sensors, such as transmission lines and tunable RF resonators, their sensitivities are limited.[10,11] A traditional broadband sensor, such as an open-ended coaxial probe, usually contacts with and is corroded by chemical solutions in permittivity measurements.[12] Therefore, in this note, a coaxial apparatus that realizes a non-contact and wide-band chemical solution measurement is proposed.

We proposed and demonstrated a measurement apparatus to simultaneously apply corrosion resistance and broadband frequency capability. The permittivity of reaction has been reconstructed using a modern optimization algorithm and the validity of the proposed apparatus has been examined. First, the measurement apparatus is suitable for measuring the permittivities of solutions and powders. Second, to realize real-time measurements, back-propagation (BP) neural network techniques, commonly used for training artificial neural networks (ANNs), were applied to reconstruct the permittivity of materials. Third, the apparatus was constructed. Test results which were acquired by the apparatus for several organic solvents and for saline with varying degrees of salinity agree well with results from the literature.

We designed the apparatus based on a tapered coaxial line structure, which realizes wide-band non-contact chemical solution measurement. We proposed a new tapered coaxial line based on the transmission/reflection (T/R) method, with a disconnected inner conductor in the test section, to measure the permittivity of materials. The sample is poured into a glass tube, which is then plugged into the coaxial apparatus for measurement. The material in the test section of the apparatus does not come into contact with the coaxial apparatus directly, so the apparatus cannot be corroded by the tested material. The scattering parameters of the coaxial apparatus with sample are measured and recorded. The complex permittivity is retrieved by these scattering parameters accordingly for measurements. The permittivity measurement system described in this note includes a network analyzer for determining properties, coaxial apparatus, and a coaxial cable. The proposed coaxial apparatus includes the coaxial test section for receiving the sample and two coaxial connectors. Each connector has a smaller-diameter end for coupling with the analyzer and a larger-diameter end for communicating with the coaxial test section.

We simulated the proposed coaxial apparatus with different samples using full-wave simulations at different frequencies ranging from 500 MHz to 6 GHz. The simulated electric field on the longitudinal section of the test section under 1 W input power at 5.8 GHz is shown in Fig. 1. The inner conductor of the test section has a disconnection in the middle of the apparatus. The tested material is inserted into this gap in the inner conductor. The simulation results show that the electric field near the tested material is very intensive. It changes the S-parameter significantly when different materials are tested, since the sample is situated at the maximum region of the electric field. The scattering parameters are sensitive to the permittivity of the sample and are thus used to accurately extract the properties of the material under test.

We used four scattering parameters ($|S_{11}|$, $|S_{21}|$, $\varphi_{S_{11}}$, and $\varphi_{S_{21}}$) simultaneously. The four scattering parameters provide enough information to improve the accuracy and reliability of the reconstruction of the permittivities.

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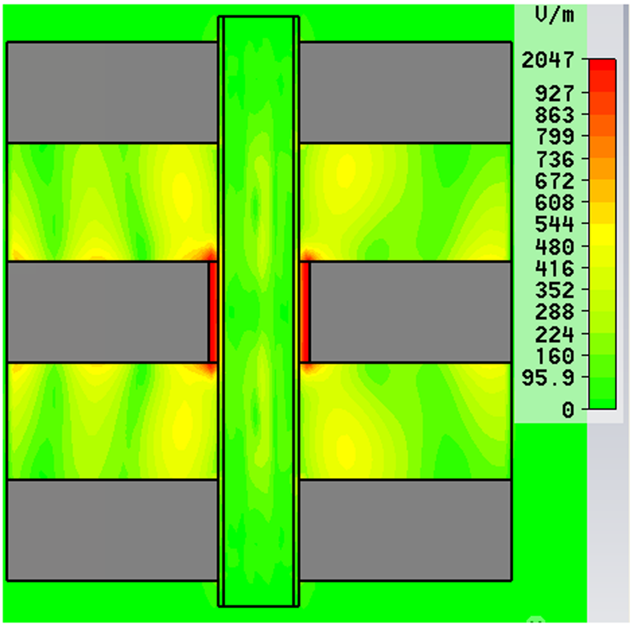
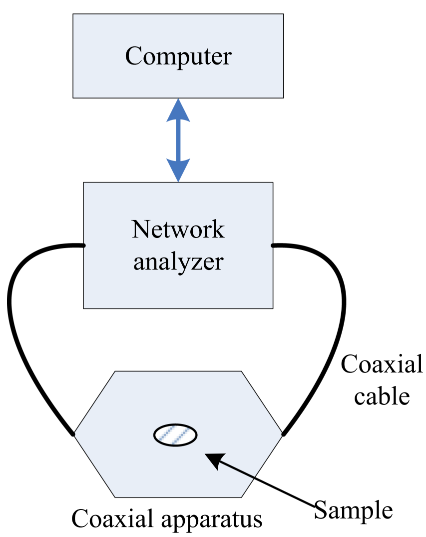
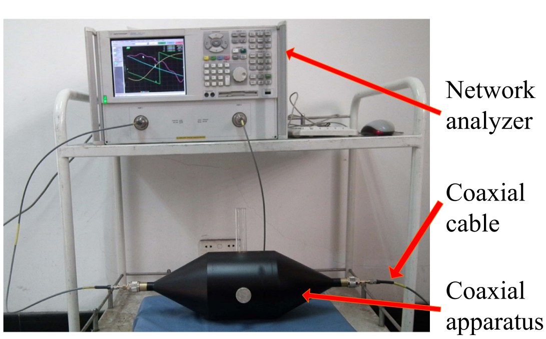


FIG. 1. Simulated electric field on the longitudinal section of the test section at 5.8 GHz.



(a) Diagram of the system;



(b) Photo of the system.

FIG. 2. Experimental system.

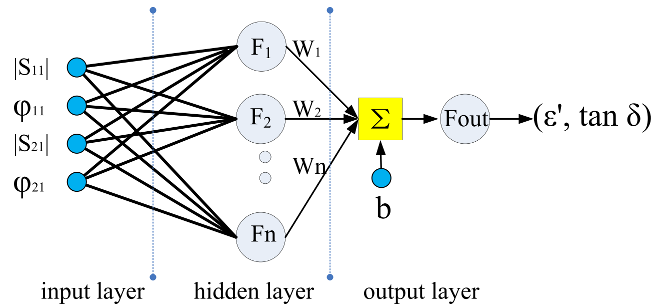


FIG. 3. Structure of the BP.

The proposed permittivity measurement system (Fig. 2) has three parts: a network analyzer, a coaxial apparatus, and two coaxial cables. A network analyzer N5230 is used to measure the scattering parameters when the sample is plugged into the coaxial apparatus. The scattering parameters $|S_{11}|$ and $|S_{21}|$ are recorded as amplitudes (in dB). φ_{S11} and φ_{S21} are recorded as phases (in degrees).

We used a BP neural network (Fig. 3) to reconstruct the complex permittivity of the material measured by the scattering parameters ($|S_{11}|$, $|S_{21}|$, φ_{S11}, and φ_{S21}).

Results are gained very quickly once the network has been trained. We obtained sample data for training the neural network by measuring a large number of experimental data. Using the measurement results ($|S_{11}|$, $|S_{21}|$, φ_{S11}, and φ_{S21}) as BP training sample data can avoid errors owing to the difference between the simulation model and the experimental system. The permittivity of methanol–water mixtures for the entire concentration range in the frequency range from 500 MHz to 25 GHz is known.[13] We measured methanol–water mixtures with different X (molar fraction of methanol) and the scattering parameters were recorded when the mixtures were put into the experimental system. The measured scattering parameters and permittivities of the methanol–water mixtures constitute the input and output of the BP network. When the measured scattering parameters have been input into the trained BP network, the scattering parameter can be used to calculate the complex permittivity of the materials in real-time.

The reconstructed results for several organic solvents have errors of less than 5% compared with the permittivity measured

TABLE I. Effective permittivities of materials at 2.45 GHz.

	Real part of complex permittivity		
Solution name	Measurement	Reference 14	Relative error (%)
DI water	75.10	78.00	−3.7
Formaldehyde	48.39	50.20	−3.6
Methanol	26.10	24.97	4.5
	Loss tangent		
Solution name	Measurement	Reference	Relative error (%)
DI water	0.131	0.127	3.1
Formaldehyde	0.386	0.4	−3.5
Methanol	0.556	0.582	−4.5

TABLE II. Effective permittivities of saline solutions with different concentrations at 5.8 GHz. ω^a is the amount of salt found in 1000 g of water.

	Real part of complex permittivity		
ω^a(NaCl)/(‰)	Measurement	Reference 15	Relative error (%)
5	67.73	70.92	−4.5
20	64.51	66.60	−3.1
	Loss tangent		
ω^a(NaCl)/(‰)	Measurement	Reference	Relative error (%)
5	0.325	0.310	4.8
20	0.412	0.430	−4.2

by the cavity-perturbation method.[14] This validates the accuracy and applicability of this measurement apparatus. Table I shows the reconstructed results of several organic solvents at 2.45 GHz at 17 °C. Table II shows the reconstructed results of the saline solution at 5.8 GHz at 25 °C. The permittivities measured by the proposed apparatus agree well with reference permittivities of saline solutions, and the relative errors between them are less than 5%. The errors in the calculations are caused by training errors in the BP and measurement errors. The results show that the measurement apparatus may be applied for broadband measurements.

We designed a real-time corrosion-resistant coaxial apparatus for calculating material permittivities with a wide frequency band. The new coaxial apparatus was designed to measure the scattering parameters. BP neural network techniques were applied to reconstruct the permittivity. The measured results show that BP neural networks can be used to measure material permittivities. Moreover, the real-time measurement apparatus can be used to measure the permittivity of liquid, solid, or powder materials and even to measure the permittivity in a chemical reaction as it varies with time and temperature.

This work was supported in part by the 973 Program No. 2013CB328902 and NSFC under Grant No. 61271074.

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