Refinements to the microwave waveguide material parameters measurements. Case study

K.M. Zeyde[1], V.V. Sharov[1], A.I. Malkin[1]

[1]Ural Federal University, Mira str. 32, Ekaterinburg, Russia, 620002

Abstract. This work presents the results of experimental measurements of permittivity and permeability of materials (dried pine, paraffin, acrylic resin, bitumen, polypropylene and texolite) that has a comparative values. The laboratory installation compile from waveguides 23x10 mm that provides the frequency range 8 – 12 GHz. The results processing lay not only in comparison with the existing data, but also in investigation of physical conditions that should be taken into account for waveguide experiment setup. The main aim is to establish the variation of electro physical parameters of the material measured in waveguides and in free space. Selection of reference material samples is the main part of this work.

1. Introduction

The number of open literature offers materials parameters (permittivity and permeability as well) in the form of constant value, for example in [1]. This form describes the frequency independent materials, but specific frequency dependence with material polarization density must be taken into account. For some dielectrics this behavior determined by Debye characteristic [2]. Such dependences can be generalized to the completed form: Cole – Cole, Havrillak – Negami, Djordevic-Sarkar [3]. But even if material demonstrated the weak frequency dependence in the case of permittivity this situation saved in appropriative diapason [4].

Next problem connected with waveguides measurement physical condition itself. Changing the structure of the field, dispersion and parasitic effects can give a significant discrepancy for the material parameters measured in free space. The method alone has certain limitations. Posing such a question has a description in [4].

Physical features not determined by the measurement errors. This errors could be considered and established at the experiment stand calibration stage to forming the confidence interval of transmission line. Whatever the circuit was formed (though, match, short) such estimation can be carried out (for example in [5]). The account of physical ambiguities is possible only for simple materials that have the comparative values.

An alternative approach to measuring the parameters of materials is based on the half-waveguide method. Its description, as well as the validation of the results, which can also be applied to the present work, is presented in [6].

2. Experiment setup

On Fig. 1 the structural scheme of laboratory stand presented. The material samples are (t – thickness): dried pine (DUT1, t= 8.5 mm), paraffin (DUT2, t= 9 mm), acrylic resin (DUT3, t= 3.2 mm), bitumen

(DUT4, $t= 9$ mm), polypropylene (DUT5, $t= 4.3$ mm) and textolite (DUT6, $t= 8.1$ mm). The experimental objects presented on fig. 2. The initial data collected in tab. 1.

Table 1. Initial data.

DUT	Comment	Material parameter	
		ε_r [1]	ε_r [7]
1	$\mu_r = 1$. No frequency dependence.	$3 - 4$	$2 - 6$
2	$\mu_r = 1$. No frequency dependence.	$2 - 2.3$	$1.9 - 2.5$
3	$\mu_r = 1$. No frequency dependence.	3.2	$2.7 - 4.5$
4	Close to the oil at the temperature 20°C. Permeability strongly depends on impurity. Frequency dependence.	$2.5 - 3$	$2.6 - 3.3$
5	$\mu_r = 1$. No frequency dependence.	$2.2 - 2.4$	1.5
6	Clarifications requires.	7	3.67

The experimental procedure corresponds to [8]. R&S ZVA 24 used as the vector circuit analyzer. The recalculation algorithm form S-parameters to electro physical condition – Nicolson – Ross – Weir [9]. Two port calibration method was used, with TRL devices algorithm. The maximum error of measurements not exceeds 10%.

On fig. 3 presented the experimental results for $\varepsilon_r(f)$. The necessary analysis was made. In fact, DUT1, DUT3 and DUT5 confirm the absence of frequency dependence in the experiment confident interval of measurement. Comparison with initial data (tab. 1) gives that: for dried pine significant diapason of referent values explained only by a wood species, therefore, this result can be considered verified. Experimental acrylic resin, also close to open literature values. Results for polypropylene strictly compare. Apply this materials as the reference for future study in free space.

DUT2 demonstrated stable correlate to a certain resonance frequency ($f_{abn} \approx 10.6$ GHz). This region should be deleted from the analysis, by the reason of incorrect sample thickness, that provides uncertainty in calculations ($t << \lambda_m/2$, where λ_m – wavelength in material). This formulation is a physical feature of the waveguide method (especially for Nicolson – Ross – Weir algorithm). After the exclusion of this points it can be argued that results compare with tab. 1, but with huge error if whole frequency band. Formulation of sample thickness has an unsolvable problem. Due to the fact, that permittivity of object is unknown value it is impossible to find λ_m in material, hence optimal sample thickness fundamentally not determinable. This feature of waveguide method, however, can be used in abnormal analysis of characteristic behavior (is only applicable in such a case).
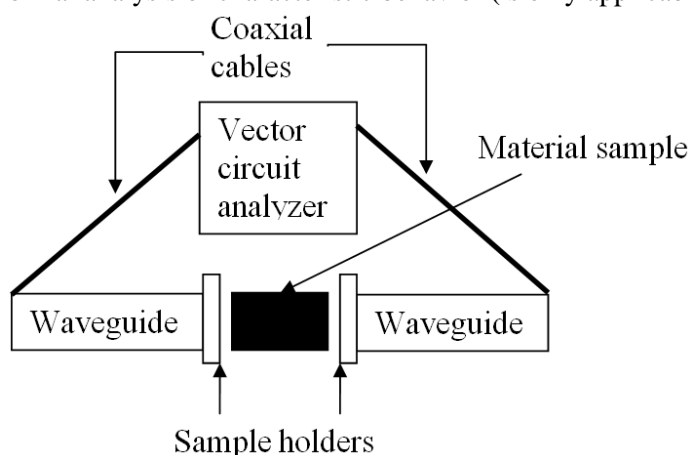

Figure 1. Laboratory stand.

Figure 2. Material samples under test.

$$\varepsilon_r^{abn}\Big|_{\mu_r=1} \approx \left(\frac{c}{2tf_{abn}} \right)^2 ,$$

(1)

where $\varepsilon_r^{abn}\big|_{\mu_r=1}$ – real part of material permittivity at resonance frequency (f_{abn}) for non magnetic objects ($\mu_r = 1$). Following to (1) value $\varepsilon_r^{abn} \approx 2.47$.
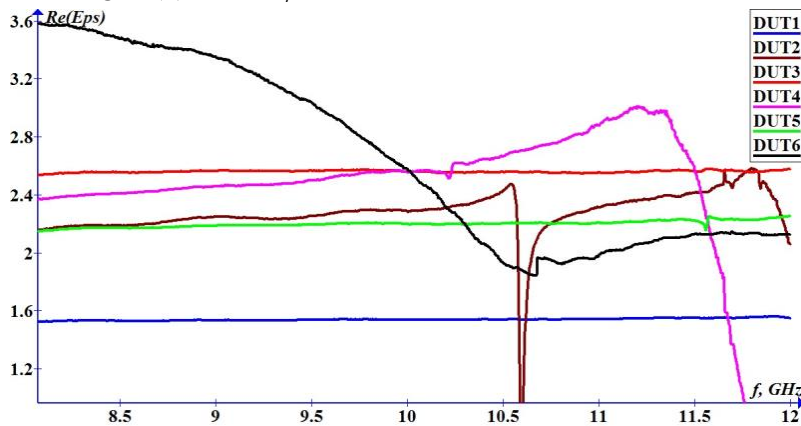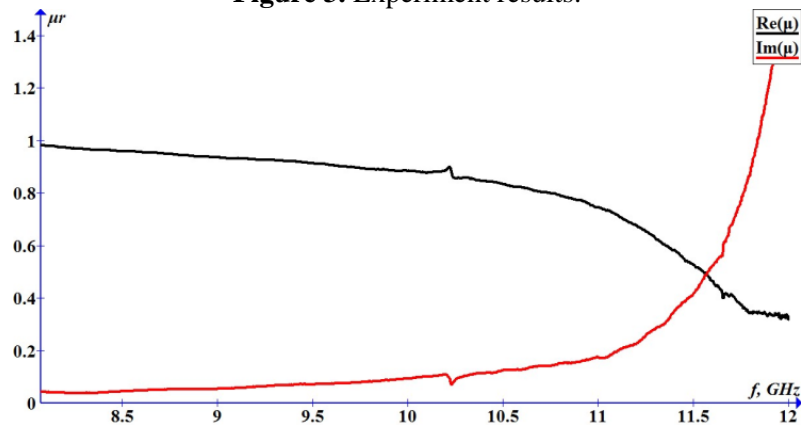
Figure 3. Experiment results.

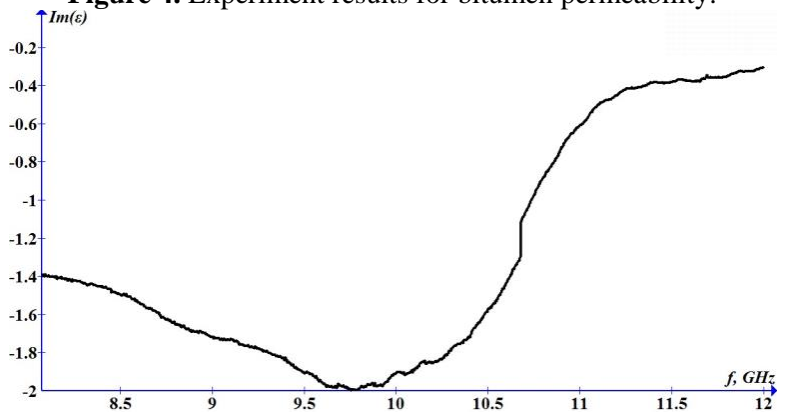**Figure 4.** Experiment results for bitumen permeability.

Figure 5. Experiment results for textolite dielectric losses.

DUT4 demonstrated the same situation, for the same reasons. The displacement of resonance frequency explained by the electro physical parameters of bitumen. Anyway, after the exclusion of uncertainty, results should be clarified. At low frequencies ε_r compare with initial data. However, the statement of frequency independent does not correspond to real situation. Such a increasing of permittivity can be explained only in the case of magnetic properties of material. The obvious assumption is that $\mu_r \neq 1$ (for this reason formula (1) is not applicable). Fig. 4 presents the experimental permeability of bitumen. Object expectedly shows diamagnetic properties in microwave diapason. For most paramagnetics permeability effects on this frequency disappearing (due to a slow relaxations processes) [10]. Magnetic losses increasing precipitously. This material should be

measured in free space, priority. The absence of magnetic effects on start frequency may indicate the influence of waveguide itself on the permeability results.
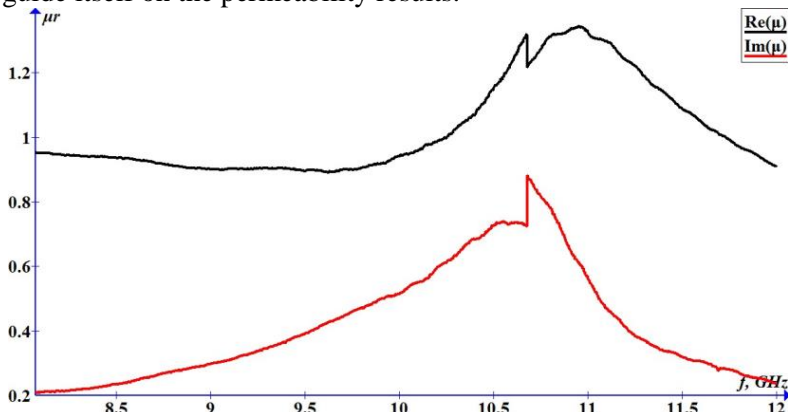

Figure 6. Experiment results for textolite permeability.
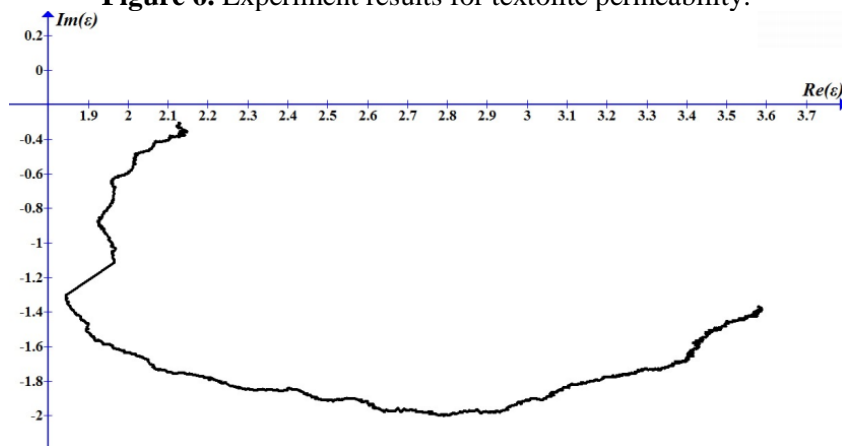

Figure 7. Experimental texalite Cole – Cole diagramm.

At last, DUT6 shows the Debye relaxation characteristic. This is of particular interest for free space measurements. In this case the imagery part of permittivity should be considered. Fig. 5 clearly shows full compliance with expectancy theory [2,3,11]. Maximum of absolute value of $Im(\varepsilon_r)$ observed at 9.77 GHz, that complies with final section of decreasing of real part of value. In this regard, it can be argued about the success of the measurements. In addition, fig. 6 shows magnetic parameters of material. Abnormal function jump explained by the samples thickness again. Cole – Cole diagram (fig. 7) confirmed by the theory. A detailed analysis of this material gives reason to believe that it can be used as referent to free space experiment.

In this regard, particularly important the formulation that Debye relaxation frequency for material may be investigated with required accuracy with waveguide method.

3. Results and discussion

In tab. 2 the experimental results are collected. It has no sense to estimate the relative error, because measurement condition for data in fig. 1 is not available. However, the results are verified.

During the experiment three different types of materials was investigated: frequency independent, abnormal magnetic, Debye characteristics. Free space refinements requires only for DUT4 that demonstrate the sharp increasing of permittivity with frequency increasing. Other samples (with the exception of DUT2) may be used as the reference.

All measured samples are of interest for further study. Further to the existing, materials data with exactly specified measurement condition can serve as the addition information for quality of free space experiment.

Table 2. Experimental data.

DUT	Comment	Material parameter	
		$Re(\varepsilon_r)$ $Im(\varepsilon_r)$	$Re(\mu_r)$ $Im(\mu_r)$
1	Free space reference material.	1.52 – 1.55 0.10	1 0
2	f [8-10]GHz.	2.14 – 2.30 0.24 – 0.47	1 – 0.90 0 – 0.15
3	Free space reference material.	2.53 – 2.57 0	1 0
4	f [8-11.2]GHz.	2.36 – 3.00 0.14 – 1.10	1 – 0.67 0 – 0.22
5	Free space reference material.	2.14 – 2.25 0	1 0
6	Debye characteristic behavior ($f_{rel} = 9.77$ GHz); free space reference material.	3.57 – 2.12 1.39 – 0.30 (max 2.00 on f_{rel})	0.90 0.20 – 0.23

4. Conclusion

Numbers of further refinements to the waveguides method of materials parameters measurements was made. Frequency independent materials can serve as free space reference. If free space experiment gives the same or comparable results it would mean that physical conditions of wave propagation no any impact to parameters of this materials. Resonance abnormal function behavior for samples with t ≈ $\lambda_m/2$ can not be predicted as well, but for non magnetic materials can be overcome by using (1) ratio. The increasing of frequency dependence of real part of permittivity can be explained by the magnetic properties of material. Since that the majority of materials demonstrated $\mu_r = 1$ on microwave range, such a behavior corresponds to diamagnetics. Debye characteristic obtaining well with theory matching. If free space experiment gives the same or comparable results it would mean that physical conditions of wave propagation no any impact to parameters of this materials again.

5. References

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