Experimental Verification of Resonant Reflection Notch Method for Quasi-Optical MM-Wave Dielectric Parameters Measurements

Vladimir Yurchenko, Mehmet Ciydem, Marcin Gradziel*, Anthony Murphy*
Engitek Engineering Technologies Ltd
Ceyhun Atif Kansu Cad. 197 / 16
Ankara, Turkey
v.yurchenko@nuim.ie, mehmet.ciydem@engitek.com.tr

*Maynooth University (NUIM)
Maynooth, Ireland
marcin.gradziel@nuim.ie, anthony.murphy@nuim.ie

Özet: *Büyük dielektrik kayıplı malzemelerin quazi-optik mm-dalga karakterizasyonu için rezonans dip yansıma yönteminin deneysel doğrulanması sunulmaktadır. Yöntem, test edilen malzemeyi içeren kusur–katman saplamalı açık dielektrik Bragg rezonatör kullanmaktadır. Önerilen yapı ölçülen dielektrik parametrelere çok aşırı duyarlı belirli frekanslarda, çok dar dip rezonans yansıma yapmaya göre ayarlanmıştır. Bu yöntem, "dalga kılavuzunda kılcal" tekniğine benzemekle beraber, transmisyon yerine yansımaya dayalı daha basit (düzlemsel) tek boyutlu bir sistem uygulaması sağlamaktadır. Bu bildiride, 75-110Ghz mm-dalga bandında, su çözeltisinin dielektrik karakterizasyonu için önerilen yöntemin uygulaması ve doğrulanması sunulmaktadır.*

Abstract: *We present experimental verification of resonant reflection notch method for quasi-optical mm-wave characterisation of dielectric materials, particularly, those with large dielectric losses. The method utilises an open dielectric Bragg resonator with a "defect-layer" insertion that contains the material under test. The structure is tuned to show narrow reflection notches at certain frequencies which are exceptionally sensitive to the measured dielectric quantities. The method is analogous to the "capillary-in-a-waveguide" technique, though implemented in a simpler (planar) one-dimensional system and in reflection rather than in transmission mode. Here we present experimental implementation and verification of the method as applied to the dielectric characterization of water solutions in the millimetre-wave frequency band of 75-110 GHz.*

1. Introduction

A challenging problem in the electromagnetic characterization of dielectric materials is the measurement of real (ε_r) and imaginary (ε_i) parts of dielectric constant of materials with large dielectric losses. The problem is particularly complicated when dealing with liquid materials since they have to be placed in a certain container that also affects the measurements. A typical example is the water and water-based solutions in the millimetre-wave (mm-wave) frequency band where ε_r and ε_i may vary in the range of about 4 to 40. Measuring high-frequency (mm-wave) dielectric parameters of water solutions could be an efficient way of detection and characterization of those solutions and substances they may contain. This could have numerous applications in chemical, biochemical, pharmaceutical, and similar industries. We present experimental verification of a method proposed recently for this kind of problem [1] as applied to the dielectric characterization of water solutions in the frequency band of 75-110 GHz.

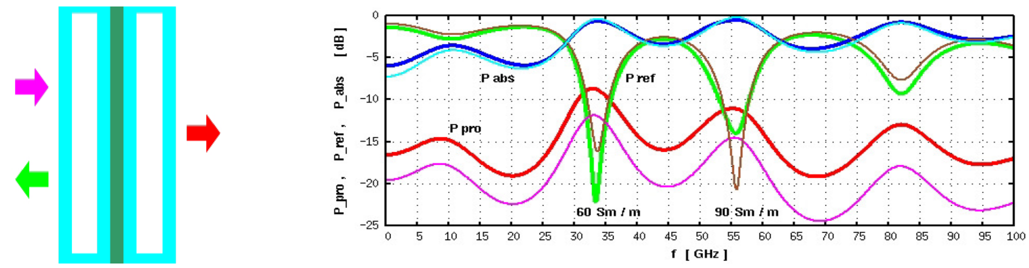
There are numerous approaches developed for the measurement of dielectric parameters of materials which, generally, fall into two categories of being either the broadband transmission wave methods or, alternatively, the resonance-kind techniques [2, 3]. Each method has its own advantages, areas of application, and specific limitations. Of basic approaches, the resonant methods are, generally, more sensitive and precise [4-6] whereas broadband transmission methods are more straightforward and universal. None of the methods is, though, particularly suited for the materials with large dielectric losses since the latter, generally, prevent the appearance of either the high-quality (high-Q) resonances or the wave propagation for essential distances.

A special method suited for this particular problem was found years ago [7, 8]. It operates as a high-Q resonance technique despite the measurement of lossy material. The method is known as a "capillary-in-a-waveguide" technique that recently got new development [9]. It is based on a fine tuning of scattering and absorption of partial waves in a waveguide with a capillary insertion that makes the wave transmission to form a narrow peak as a function of frequency depending on the balance of real and imaginary parts of dielectric constant of the insertion material. A method proposed in [1] is one of a similar kind, though implemented in a simpler (planar) one-dimensional structure and in the reflection rather than in transmission mode. As an alternative method, it should have different benefits and pitfalls as compared to other techniques, thus, providing a complementary approach to solving the problem.

2. Theoretical Background

The idea of the resonant reflection notch method is explained and numerically studied in [1]. The approach is conceptually similar to the "capillary-in-a-waveguide" technique. The method utilises an open dielectric Bragg resonator with a "defect-layer" insertion structure that contains a lossy material under investigation (e.g., a layer of liquid solution). The structure is tuned to show narrow reflection notches at certain frequencies, whose depth, width, and spectral positions are exceptionally sensitive to the measured dielectric quantities in the given range of their expected values.

Simulations for different Bragg structures made of either fused quartz, or sapphire, or polycarbonate layers, and using water dielectric parameters available for the mm-wave range [10] allowed us to find the structures best suited for the experimental implementation of the technique. Fig. 1 shows schematics of a typical structure (a dark strip represents a layer of liquid confined between, e.g., two quartz wafers) and an example of mm-wave reflection and transmission spectra (S11 and S21 signals, respectively) simulated for certain structures (e.g., those designated as "qaqwq" that means a sequence of quartz-air-quartz-water-quartz layers in the assembly). It is the sharp resonant notch (deep minimum) in the reflection spectrum S11 that is sensitive to the water dielectric parameters and used for the accurate evaluation of permittivity and dielectric losses of water at the given frequency. It appears that, when making the air slot of the optimal size, we obtain a possibility of more accurate and sensitive measurements of dielectric parameters of various water solutions.



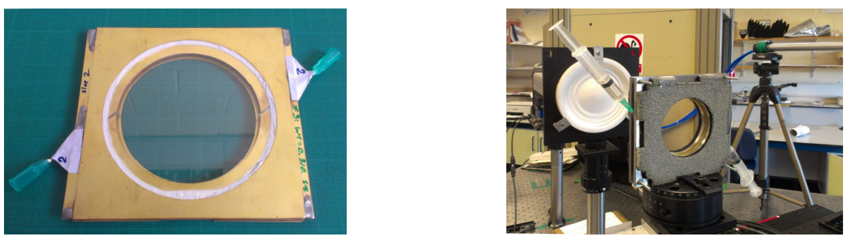
(a) (b)

Figure 1. (a) Schematics of a typical structure and (b) examples of simulated reflection and transmission spectra.

3. Experimental Results

For experimental verification of the method, we used the measurement cell as a "qaqwq" structure assembled of the fused quartz wafers of thickness $q = 0.52$ mm and diameter $D = 75$ mm with dielectric constant, as measured in other experiments, $\varepsilon_r = 3.83$ and the loss tangent $\tan\delta = 0.001$. The air slot was made to be $a = 1.66$ mm and the water layer thickness $w = 1.14$ mm (Fig. 2).

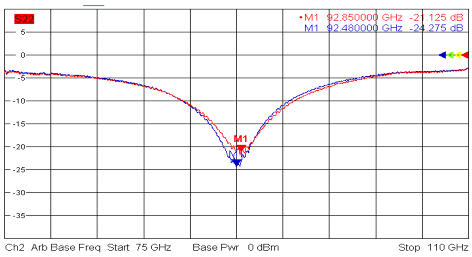
Reflection and transmission spectra were measured in the band of 75 GHz to 110 GHz for three cases when the cell was (a) empty, (b) filled with distilled water, and (c) filled with 5mol NaCl water solution. Cases (a) and (b) were used for calibration and verification of data against the known water parameters [10] whereas the case (c) was used for testing the sensitivity of the method taking into account that the NaCl water solutions, despite their increased conductivity, are hard to distinguish from pure water by the RF methods in the mm-wave band.



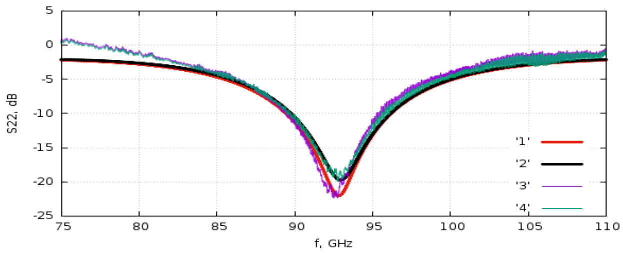
(a) (b)

Figure 2. (a) A part of the measurement cell and (b) the entire setup on the mm-wave quasi-optical bench.

Some measurement results for (b) and (c) cases and their comparison with simulations are shown in Fig. 3. The results confirm the emergence of a resonant reflection notch in a structure with a layer of highly absorbing material. The effect allows one to distinguish the cases of distilled water and NaCl solutions which are hard to identify by alternative mm-wave methods. Yet, at present, we observe a certain discrepancy (<10%) between the measured (curves 3, 4) and simulated data since, due to some systematic errors, the best fit is obtained if using quartz parameters $q = 0.56$ mm, $\varepsilon_r = 3.95$ (curves 1, 2) instead of the values specified above. The errors could arise due to bending of wafers under the water pressure, uneven thickness of spacers controlling the air slots between wafers, insufficient accuracy of measurements of wafer parameters q and ε_r , and so on.



(a)



(b)

Figure 3. (a) Raw measurement data and (b) comparison with simulations after the account of reference signal.

4. Conclusions

Experimental research confirmed theoretical predictions concerning the emergence of a resonant reflection notch in Bragg structures with a layer of highly absorbing material that shows enhanced sensitivity to the real and imaginary parts of dielectric constant of the material. In the same time, the initial results indicate the presence of some uncertainties and systematic errors which have to be eliminated for enhancing the accuracy and reliability of measurements of dielectric parameters of materials with this kind of quasi-optical mm-wave technique.

5. Acknowledgments

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