Vector Network Analysis of Dielectric and Magnetic Materials in the Millimetre Wave Band

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Abstract. A well-designed, quasi-optical spectrometer (transmissometer and reflectometer) driven by a HP N5244A Vector Network Analyzer is introduced for characterization of solid condensed materials such as silicon, Perspex and hexaferrite in the millimetre wave band. A brief note is made on quasi-optical transmissometry being adapted for study of soft condensed phase (biological) systems.

1. Introduction
High quality measurement systems in millimetre and sub-millimetre wave bands have critical design requirements in a number of major research fields. One of these fields is spectrometric characterization of materials, metamaterials and biomaterials. In this paper, a well-designed, quasi-optical spectrometer (transmissometer and reflectometer) driven by a HP N5244A Vector Network Analyzer (QO+VNA) is introduced for characterization of the solid condensed materials such as silicon, Perspex and hexaferrite. Sample vessels prototyped for handling soft condensed material such as liquids and proteins have also been characterized for the calibration (or reference) condition of empty-vessel.

2. Measurement System
Vector Network Analysis has been extensively used in microwave measurement systems. It is a heterodyne receiver that is capable of measuring the amplitude and phase-difference between a test and reference path to very high accuracy and phase-stability. Ongoing advances in microwave electronics has extended operation of the VNA beyond low millimetre wave bands upto 1 THz. Vector Network Analysis has distinct advantages over Time Domain Spectroscopy (TDS) and Fourier transform Infrared spectroscopy (FTIR). These are superior spectral resolution (down to 1MHz), a huge dynamic range (100 to 140 dB at low sub-THz band to 50-80 dB near 1THz) and, a rapid sweeping efficiency (spot rate less than picoseconds) [1]. A well-designed, quasi-optical spectrometer (transmissometer and reflectometer) [2] delivers a very pure collimated plane-wave, and in this case is established at the geometric centre of the measurement bench. It is here that sample-location is set. A large sample-plate (width 100 mm) is used to ensure negligible diffraction at the edges of the plate, even though the horns deliver a beam with high taper. It is quite strait forward to extend the
spectrometer to THz energies by using the same quasi-optical circuit, by replacing only the corrugated feed-horns with a higher frequency band pair.

3. Theory
The transmittance and reflectance of the plate, \( t(\omega, d) \) and \( r(\omega, d) \) respectively [3] are given by

\[
t(\omega, d) = \frac{(1 - r_\omega^2(\omega, d)) \cdot \exp i\phi(\omega, d)}{1 - r_\omega^2(\omega, d) \cdot \exp 2i\phi(\omega, d)},
\]

\[
r(\omega, d) = \frac{r_\omega(\omega, d) \cdot (1 - \exp 2i\phi(\omega, d))}{1 - r_\omega^2(\omega, d) \cdot \exp 2i\phi(\omega, d)}.
\]

\( d \) is the sample’s thickness and \( c \) is speed of light in vacuum; \( \phi_\omega(\omega, d) \) is the complex angle \( \omega n(\omega, d) / c \) and \( n \) is the refractive index; \( r_\omega(\omega, d) \) is the single-surface reflectance which is related to the reduced wave-impedance, \( r_\epsilon = (z - 1)/(z + 1) \).

For a layered structure such as biological liquid sandwiched by two dielectric layers, ABCD matrix methods can be used to set up the transmittance and reflection equations. In this paper, the regression analysis fitting is used to characterize the materials’ constants.

4. Results and Discussion
The measured transmittances and reflections of silicon and Perspex are presented in Fig.1. The best fitted permittivity of silicon is 11.65 ± 0.02, and of Perspex is 2.59 ± 0.01. These are very close to those reported from high-precision measurements on high-purity silicon [4] and Perspex [5].

The inherent optical properties of hexaferrite materials support circularly-polarized propagating waves, i.e. \( t_\pm(\omega, d) \) and \( r_\pm(\omega, d) \), rather than linearly-polarized waves, where the ‘+’ indicates clockwise rotation of the electric vector in the direction of propagation and ‘-‘ anti-clockwise rotation. It is, however, very time consuming to directly measure material properties using circularly-polarized waves [6]. Instead, in this spectrometer, the plate’s linear-polarisation transmittance and reflectance, both co- and cross-polar, respectively, are first measured and the results then transformed into circularly-polarised transmittance and reflectance. The results for each sense are illustrated in Fig.2. The detailed experimental and analysis methods are published elsewhere [2].

Vector network analysis of biological liquid samples is another interesting application of the measurement system. Our work has therefore developed a new bespoke cuvette system enabling analysis of bio-liquids. The first cuvette consisted of two 1.1 mm thick boron glass plates (a material generally transparent over millimeter and sub-millimeter wavelengths) having a 0.28 mm separation (established by four metallic corner-located pads). Inlet and outlet valves are placed at opposite ends of the plates to allow for flushing without the need to dismantle the cuvette. Its performance is presented in Fig. 3(left) and shows that the loss is very low when the wave propagates through the empty cuvette. The theoretical 3-layer ABCD model yield a high quality fit to the experimental results. The second design of cuvette incorporates a vacuum layer made of a Perspex vessel. The sample can be located in the middle of the container. The vacuum establishes an adiabatic environment to ensure internal thermal stability for stable and controllable test conditions. This is particularly important for biological samples. In Fig.3 (right), a 5.74 mm thick Perspex plate is put in the sample-position for the test. Theoretical calculations are very close to the measured transmittance of the 5-layer structure.
Fig. 1: (left) measured complex transmittances (line) and reflections (dashed line) of 1.98 mm thick silicon; (right) measured complex transmittance (line) and reflection (dashed line) of 5.74 mm thick plastic. Upper plots, left and right, are of amplitude and the lower plots are of phase.

Fig. 2: Complex circularly-polarised transmittances (lines) and reflections (dashed lines) (upper for the amplitudes, lower is for the phases) of hexaferrite sample; the plots on the left are for positive circular-polarisation and the plots on the right for negative.
Fig. 3: Comparison of theoretical transmittance (circles) with measured data (lines); upper plots are for the amplitudes, lower for phase: (left-plots) boron glass | air | boron glass 3 layer structure. Constituent thicknesses (mm) are 1.1 | 0.28 | 1.1; (right-plots) Perspex | air | Perspex | air | Perspex. Constituent thicknesses (mm) are 19.05 | 40.10 | 5.74 | 40.10 | 18.89.

5. Conclusions

Complex transmission and reflection spectra from a well-designed, quasi-optical spectrometer (transmissometer and reflectometer), driven by a HP N5244A Vector Network Analyzer (QO+VNA), have been presented on calibration materials (high-purity silicon and Perspex) and to further materials supporting biological fluid measurements. The sample holders developed for coming biological sample studies display the required low-loss and environmental stability.

References

[1] Manual of HP N5244A Vector Network Analyzer.
[2] B.Yang, R.J.Wylde, D.H.Martin, P.Goy, R.S.Donnan and S.Caroopen, IEEE Trans Microw. Theory. Tech, DOI: 10.1109/TMTT.2010.2086290.
[3] D.M.Pozar, Microwave Engineering, 3rd edition, Wiley.
[4] M.N.Afsar and H.Chi, Int J.Infr.Millimeter waves, vol.15, no.7, 1994.
[5] J.W.Lamb, Int J.Infr.Millimeter waves, vol.17, no.12, 1996.
[6] G.M.Smith, C.P.Unsworth, M.R.Webb and J.C.G.Lesurf, Microwave symposium digest, 1994, IEEE MTT-S International vol.1.pp.293-296.