Highly Sensitive Measurements With a Lens-Focused Reflectometer

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Abstract—**A lens-focused microwave reflectometer is described which offers exceptional sensitivity and very wide bandwidth. The system produces a well confined spot focus and, with the prescribed calibration procedure, gives effective directivity approaching 70 dB. Applications include dielectric constant measurements and scanned imaging of bodies. Precision of ± 1 dB is demonstrated for measurements, in X-band, at the -50 dB level.**

Introduction

In THIS paper, a technique is described for measuring very small reflections from a scattering body in free space. The sensitivity which is achieved far exceeds the sensitivity which is normally obtained in a vector measurement employing a microwave network analyzer. The focusing lens can provide very tight beam confinement to separately resolve closely spaced scatterers. Applications include measurement of material properties and scanned imaging of weakly scattering objects. The design of the lens is frequency independent making it useful over a wide range of frequencies. Lenses can be fabricated from a suitable low-loss dielectric such as teflon or rexolite and the design of the lenses is straightforward [1].

For a lens aperture which is much larger than the wavelength, the radiated field can be described quite accurately as a single, fundamental Gaussian mode. At the focal distance, the beam has a plane wavefront and, for the axially symmetrical case, produces a field strength function given by

$$E(r) = E(o) \exp\left[\frac{-r^2}{w_o^2}\right] \tag{1}$$

where r is the radial distance from the axis of the beam and w_o is the beam waist radius at which the field strength falls to e^{-1} of its on-axis value. The focusing lens which was used for the measurements had a circular aperture with a diameter of 12 inches and a focal length of 18 inches, producing a beam waist radius of about 2 inches at 10 GHz. Because the calibration and measurements are performed in or very near the focal plane of the lens, good accuracy can be obtained with the assumption of TEM propagation and the analysis of the measurement system can be treated as a transmission line problem. A detailed description of Gaussian beam propagation is, therefore, not essential to the analysis and can be found elsewhere [2], [3].

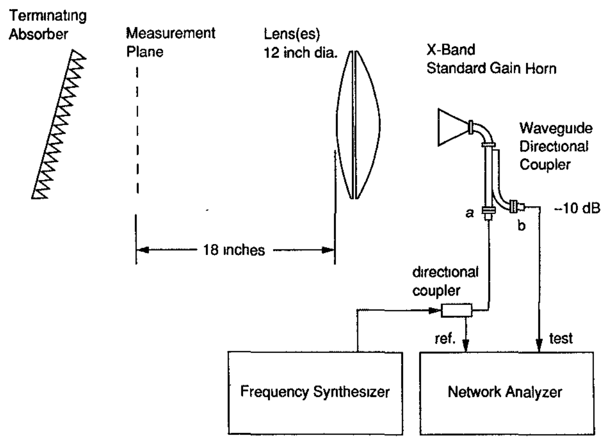

Fig. 1. Diagram of the X-band, lens-focused reflectometer setup.

For the apparatus described in this paper and shown in Fig. 1, a bi-convex lens was assembled from two plano-convex dielectric lenses placed back-to-back. One lens surface forms a plane wavefront from a spherical wave at the feedpoint and the second lens surface refocuses the plane wave at the beam waist which determines the measurement plane 18 inches from the front surface of the lens. Lenses were machined from cast acrylic (PMMA). The phase center of a small standard gain horn is placed at the focal point, 12 inches from the rear surface of the lens to serve as the feed. The measurements described in this paper were made using an HP 8510B network analyzer with an 8340B synthesizer, operated under the control of an HP 9000 computer. As shown in Fig. 1, a 10 dB directional coupler was used to pick up the reflected signal but, with an S-parameter test set, an S_{11} measurement can be made directly at the lens feed without the external couplers.

Calibration Procedure

The accuracy of calibration depends on the stability of the frequency source, the repeatability of device interconnections and the quality of the calibration standards. The

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frequency synthesizer which was used for the measurements has a specification for residual FM of less than 120 Hz RMS in X-band, giving a fractional frequency stability of about 1 part in 10^8. Unlike a typical transmission line system, the calibration standards and the "device under test" are all measured with the same device connectivity. This eliminates the variable discontinuities which are introduced by connectors and which typically limit the effective directivity of network analyzer measurements to not much more than about 40 dB.

By the use of a vector network analyzer, the output of the reflectometer is referenced to the input, which accounts for variation of power output from the generator due to mismatch between the generator and the input of the reflectometer. The measurement system can then be accurately represented as a two-port connected to an unknown termination. The measured reflection coefficient, Γ, is thereby given, in terms of the unknown terminating reflection coefficient, R, by the following relation:

$$\Gamma = \frac{b}{a} = \frac{S_{11}(1 - S_{22}\,\mathrm{Re}^{-j2\phi}) + S_{21}S_{12}\,\mathrm{Re}^{-j2\phi}}{1 - S_{22}\,\mathrm{Re}^{-j2\phi}}. \tag{2}$$

For economy of notation, relabel the parameters from (1) according to

$$A = S_{11}, \qquad B = S_{21}S_{12}e^{-j2\phi}, \qquad C = S_{22}e^{-j2\phi},$$

to give the following, simplified expression of (1):

$$\Gamma = \frac{A(1 - CR) + BR}{1 - CR}. \tag{3}$$

The unknown calibration coefficients A, B, and C, are determined from measurements made with a short-circuit, an offset short-circuit and a matched load. The calibration coefficients thus obtained are given by

$$A = \Gamma_L \tag{4}$$

$$B = \frac{(\Gamma_L - \Gamma_o)(\Gamma_L - \Gamma_1)(1 - e^{-j2\delta})}{\Gamma_o - \Gamma_1} \tag{5}$$

$$C = \frac{(\Gamma_L - \Gamma_o) - (\Gamma_L - \Gamma_1)e^{-j2\delta}}{\Gamma_o - \Gamma_1} \tag{6}$$

where Γ_o is measured (complex) reflection coefficient of the reference short, Γ_1 is the measured reflection from a short offset a distance δ from the reference plane toward the generator, and Γ_L is the measured reflection with a matched termination.

Inverting (2) gives the actual value of the reflection coefficient of the device under test in terms of the measured reflection and the calibration coefficients:

$$R = \frac{\Gamma - A}{C\Gamma - AC + B}. \tag{7}$$

The short-circuit calibration is performed by use of a metal plate placed normal to the microwave beam at the beam waist or the focal distance of the lens. The short-circuit calibration is performed by use of a rigid metal plate placed normal to the microwave beam at the beam waist or the focal distance of the lens. In order to align the system for true normal incidence of the beam upon the metal plate, the lens feed horn was carefully positioned by moving it in a plane parallel to the calibration plate to give maximum return from the plate. The offset short measurement was obtained using the same metal plate as for the reference short, displaced from the reference plane about a quarter of a wavelength at mid-band by machined metal spacers. For the matched load calibration, a two-foot square of two-inch wedged absorbing material was placed several inches beyond the measurement plane. Subsequent measurements of a test object are made with the terminating absorber at the same position as for the calibration.

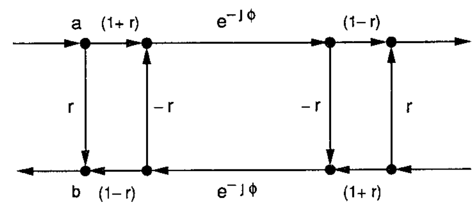


Fig. 2. Signal flow graph representation of transmission and reflection for normal incidence on a uniform sheet of dielectric material.

For ordinary swept-frequency measurements employing an automated network analyzer, such as the Hewlett Packard model 8510, it is not necessary to program the equations which have been presented here. All that is required is specification of the calibration standards, which are represented as an ideal (50 Ω) load, a short-circuit with zero delay for the reference short, and a short-circuit with the correct delay for the offset short. However, in real-time measurements or in scanned measurements of an object, for which the background termination is not fixed, it is necessary to acquire appropriately parameterized calibration data.

Measured Results

As an example of the type of measurement which can be made with the reflectometer, measurements were made of the reflection coefficient, at normal incidence, of 3M Corp. type 6700 bonding film. According to the manufacturer's specifications, the material has a relative dielectric constant of 2.35 ± 0.10. The measured average thickness of the sample was 0.0014 inches. A signal flow graph, shown in Fig. 2, was used to represent the film sample for the purpose of calculating the theoretical reflectivity of the film. The two surfaces of the film are represented as a pair of two-ports separated by a transmission line which represents the bulk of the film sample. By application of the non-touching loop rule [4] to the signal flow graph, the complex voltage reflection coefficient of the film for

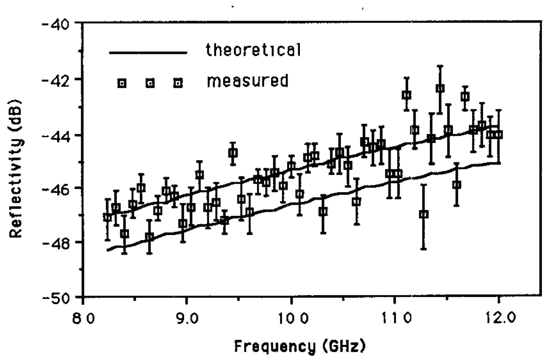


Fig. 3. Plot of measured and calculated reflectivity of 3M Corp. type 6700 bonding film. Solid lines give upper and lower limits of calculated theoretical reflectivity within specified tolerance of the dielectric constant.

an incident plane wave is given exactly by the following relation:

$$R = r - \frac{r(1-r^2)\cos 2\phi - r^3 + r^5}{1-2r^2\cos 2\phi + r^4} + j\frac{r(1-r^2)\sin 2\phi}{1-2r^2\cos 2\phi + r^4}. \quad (8)$$

At normal incidence, the reflection coefficient of the film/air interface is given by

$$r = \frac{[\epsilon_r(1-j\tan\delta)]^{1/2}-1}{[\epsilon_r(1-j\tan\delta)]^{1/2}+1} \quad (9)$$

where ϵ_r is the relative dielectric constant and $\tan\delta$ is the "loss tangent" of the film. The quantity ϕ, in equation (8), is the electrical thickness of the sample which, for normal incidence, is given by

$$\phi = \frac{2\pi t[\epsilon_r(1-j\tan\delta)]}{\lambda_0} \quad (10)$$

where t is the lineal thickness of the film and λ_0 is the measurement wavelength in free space.

Fig. 3 displays the results obtained for the measurements and the theoretical calculated reflectivity of the film sample for normal incidence. Each data point gives the reflectivity of the film sample obtained from the mean of the measured amplitude and phase of the reflection at each frequency. The error bars represent the range of the reflectivity which falls within the limits of one standard deviation of the measured amplitude and phase of the raw film data. These error bars extend over a range of less than ± 1 dB for almost all of the results. The solid lines which are plotted on Fig. 3 give the upper and lower values of the reflectivity of the film sample which were calculated using the upper and lower limits of the dielectric constant specified by the manufacturer. For calculating the reflectivity of the film sample, losses were ignored and $\tan\delta$ was set to zero. The calculated phase of the reflection coefficient was 90° at each frequency and the measured phase, averaged over frequency was, 92.8° with a standard deviation of 6.4°.

For frequencies below 8.2 GHz, the lens aperture is apparently too small to support the fundamental Gaussian mode at the longer wavelengths. The loss of accuracy at frequencies near 11.5 GHz is due to a measurement "fade" caused by interference between various reflections in the system which reduce the measurable effect of the reflection from the sample. This problem could be remedied by repositioning the feed slightly or by moving the reference plane of the measurement.

These procedures can be applied to measurement of the dielectric constants of materials by performing numerical iteration to obtain the dielectric constant which gives the measured reflection according to (8). The lens-focused, free-space measurement of dielectric constants [5]–[7] offers a number of advantages over cavity and transmission-line techniques, particularly in terms of simplicity and ease of sample preparation. It should be noted that the signal flow graph of Fig. 2 does not accurately represent the case of oblique incidence on a dielectric sample of appreciable thickness because it cannot account for the fact that multiple reflections *within* the sample produce multiple reflected and transmitted beams which do not add like plane waves. For transmission or reflection measurement employing a lens-focused beam, this effect limits the accuracy of the plane-wave representation when applied to the case of oblique incidence on a dielectric slab.

Conclusion

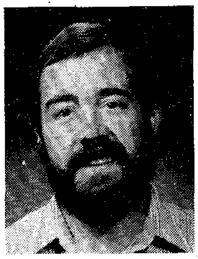
The use of a focusing lens in a microwave reflectometer is found to significantly enhance the sensitivity of reflection measurements in free-space. The high directivity combined with very small space loss, obtained with the lens, gives excellent measurement gain. Because the calibration standards and the "device under test" are all measured with the same device connectivity, the calibration errors which normally arise from connecting and reconnecting transmission lines are eliminated. The small reflections from a microwave absorber, which is placed some distance beyond the lens focal plane, are poorly coupled to the Gaussian mode of the lens antenna, giving a nearly ideal termination. This high-quality termination provides for a particularly simple and accurate calibration procedure for measurements performed using a vector network analyzer.

References

[1] H. Jasik, *Antenna Engineering Handbook*. New York: McGraw-Hill, 1961.
[2] H. Kogelnik and T. Li, "Laser beams and resonators," *Proc. IEEE*, vol. 54, pp. 1322–1329, 1966.
[3] A. Yariv, *Quantum Electronics*, 2nd ed., New York: Wiley, 1975.
[4] J. K. Hunton, "Analysis of microwave measurement techniques by means of signal flow graphs," *IRE Trans. MTT*, vol. 8, pp. 206–212, 1960.
[5] D. R. Gagnon, D. J. White, G. E. Everett, and D. J. Banks, "Techniques for microwave dielectric measurements," Final Rep. NWC TP 6643, Naval Weapons Center, China Lake, CA, pp. 39–50, 1986.
[6] D. K. Ghodgaonkar, V. V. Varadan, and V. K. Varadan, "A free-space method for measurement of dielectric constants and loss

tangents at microwave frequencies," *IEEE Trans. Instrum. Meas.*, vol. 38, pp. 789–793, 1989.

[7] ____, "Free-space measurement of complex permittivity and complex permeability of magnetic materials at microwave frequencies," *IEEE Trans. Instrum. Meas.*, vol. 39, pp. 387–394, 1990.



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