Electric Probe Measurements on Dielectric Image Lines in the Frequency Range of 26-90 GHz

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Abstract—**Electric-field probes, using miniature semirigid coaxial cable in connection with standard metal waveguide detectors, are described and shown to be well-suited for direct standing wave measurements on dielectric image lines. Experiments in the frequency range of 26–90 GHz for the determination of phase and attenuation constants of image lines as well as experiments for the determination of very small reflections from matched dielectric image-line terminations and the scattering coefficients of dielectric image-line discontinuities are described.**

I. Introduction

SINCE THE introduction of the dielectric image line as a guiding structure in the centimeter- and millimeter-wave range, several authors have described techniques for the measurement of the properties of the dielectric image line. King and Schlesinger [1]–[3] utilized metal waveguide mode launchers to launch and decouple the waves on the dielectric image line. The measurements of the wave amplitudes on the dielectric lines were made on the metal waveguide part of their measuring setup. The same is true for the more recently published measurements of the field distributions of inverted strip dielectric waveguides by Itoh [4].

Since movable electric-field probes successfully had been utilized to probe guided and leaky waves on dielectric loaded through guides in the microwave range [5] and have been employed in the investigation of the field distributions of single- and coupled-microstriplines in the microwave range [6], electric-field probes were applied to the measurement of the guided wavelength and the field distribution of waves on rectangular dielectric image lines in the X band [7] and in the R band [8]. The results from measurements of the guided wavelength and the field distributions of waves on dielectric image lines have proven the movable electric-field probe to be a simple and reliable measuring technique for dielectric image lines.

Using the field probes described in this paper, measurements of the field distributions and the guided wavelengths of waves on dielectric image lines were carried out up to 90 GHz. Furthermore, the use of the electric-field probe was extended to the measurement of the VSWR on dielectric image lines in order to investigate the attenuation constants of the dielectric image lines and to determine the effects of line discontinuities in the image lines, expecially those required in the implementation of active devices into the lines.

II. The Probes

To cover both the R (26–40 GHz) and the E (60–90 GHz) band, two probes were built using RG-(90/U) and RG-(96/U) metal waveguide. Sections of miniature 50-Ω coaxial cable[1] with partially removed outer conductors were inserted and soldered into holes in the broad walls of the metal waveguide sections, as shown in Fig. 1. The open ends of the metal waveguides were cut to about $\lambda_g/4$ at the midfrequencies of the R and the E band, respectively, and were shorted by copper plates, which were soldered to the open waveguides. The sensitivity of the probes could be enhanced by means of a movable short circuit (tunable probe).

The high-attenuation constant of the coaxial cable in the frequency range, considered here, can be neglected since sections of only a few centimeters were employed (the total losses of the completed probes were estimated to be less than 10 dB in the E band). The open waveguide ends of the probes were flanged to metal waveguide tunable detectors, and the completed probes were mounted on a three-axes vernier mechanism.

III. The Experiments

In the experiments described below, the dielectric image lines were made of paraffin wax, but other experiments have been carried out on Stycast-resin-35-DA[2] and Epsilam-10[3] lines, too. The paraffin-wax lines and the Stycast-resin lines were produced employing a die-cast technique described elsewhere [8].

To illustrate the usefulness of the field probes, two example applications shall be given.

1) To measure the phase and attenuation constant of dielectric image lines, avoiding the use of resonators and very long line sections, the experimental setup of Fig. 2 was used.

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[1]SR06 standard semirigid cable produced by Suhner GmbH (Switzerland).
[2]Emerson–Cumings.
[3]3M-Company.

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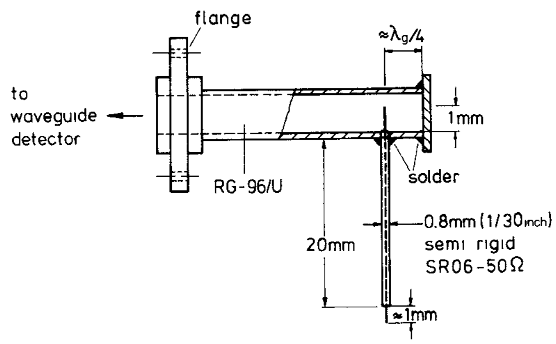


Fig. 1. Sketch of the electric-field probe for the frequency range of 60–90 GHz.

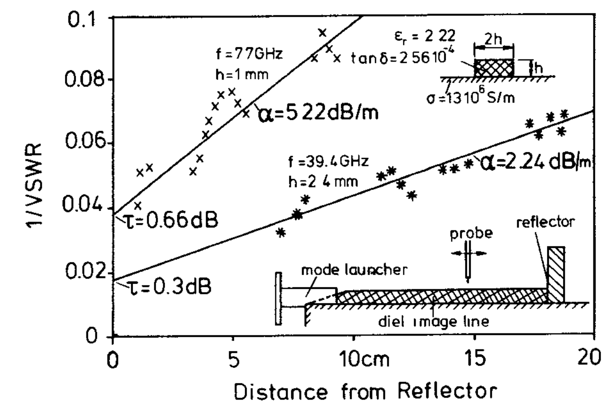


Fig. 2. Measurement of the voltage standing wave ratio on two short-circuited dielectric image lines and evaluation of the measurement points for the attenuation constants of the lines and the termination losses of the reflector walls.

A CW signal is supplied to the mode launcher through a metal waveguide. The incident surface wave propagating along the dielectric image line is reflected and attenuated by the metallic reflector wall, and the reflected wave leaves through the launcher. In order to reduce the reflections of the waves on the dielectric image lines the mode launchers have to be loaded by absorbing material. If this is not done, a part of the wave returning from the reflector wall is reflected by the mode launchers. The additional incident wave, produced in this manner, superimposes with the original incident wave causing a strong ripple of the VSWR distribution. The resultant standing wave pattern is probed as a function of the distance from the reflector wall.

The guide wavelength is determined very accurately by running the probe several wavelengths and by dividing the distance by one half of the counted number of minima or maxima [7]. The standing wave ratio on the line is measured accurately employing a calibrated variable attenuator in the incident power path for the determination of the probe-voltage ratio at adjacent minima and maxima. The VSWR is a maximum at the reflector plane and decreases with increasing distance from the reflector. Typical reflection losses of the reflector walls used in these experiments ranged between 0.25 and 0.7 dB resulting in VSWR values of up to 40 dB, to be measured on the dielectric image lines.

The experimental VSWR values are approximated numerically by the analytical expression for the VSWR on a short-circuited line:

$$\mathrm{VSWR} = \frac{1 + e^{-\tau} e^{-2\alpha z}}{1 - e^{-\tau} e^{-2\alpha z}} \tag{1}$$

where τ is the reflector loss of the termination wall, α is the line attenuation constant, and z is the distance from the reflector wall. As shown in the Appendix, for large values of VSWR, (1) can be approximated by

$$1/\mathrm{VSWR} \approx \frac{\tau}{2} + \alpha z. \tag{2}$$

To evaluate the measured VSWR values, a least-squares-fit algorithm was worked out, yielding the two unknown quantities τ and α. Due to the high losses of the Stycast-35-DA and the Epsilam-10 dielectric image lines (the attenuation constants measured in the R band ranged between 10 and 40 dB/m which are not shown in this paper) the fit had to be based on the exponential dependence (1) leading to a system of two nonlinear equations of the two unknown quantities τ and α. The low losses of the paraffin-wax dielectric image lines allowed the fit to be based on the linear dependence (2); the approximating line for the experimental VSWR points in this case is a straight line, as shown in Fig. 2. In Fig. 2, two typical plots of the measured 1/VSWR versus the distance from the reflector wall are shown together with the approximating lines. By evaluating a large number of experimental points, a high degree of confidence can be gained in the results.

Due to the fact that the fields of the guided waves of the dielectric image lines decay exponentially with the distance from the lines, the measured voltage of the field probes decreases with increasing distance from the lines. Likewise, the perturbation of the guided waves due to the probes decreases. Although, generally, a fair compromise between high-probe voltage and low-field perturbation was achieved (with the probes causing reflections of up to a few percent) at places of very high VSWR on the lines, the probes had to be adjusted very close to the dielectric image lines, so that the limited output power of the RF source allowed the measurement of the very low-field-strength minima. As a consequence, the measurement of the field-strength maxima was degraded because of the very tight coupling of the probes. This drawback can be avoided by degrading the VSWR of the reflector walls by means of absorbing material.

In the frequency range of 26–40 GHz, the results obtained by this method were compared with the results based on the loaded Q-factor method of variable length resonators, first applied to dielectric image lines by King and Schlesinger [2]. The measurement results for the attenuation of the dielectric image lines (α in the range of 1.5–2.4 dB/m) of both methods agree within an average of 10 percent.

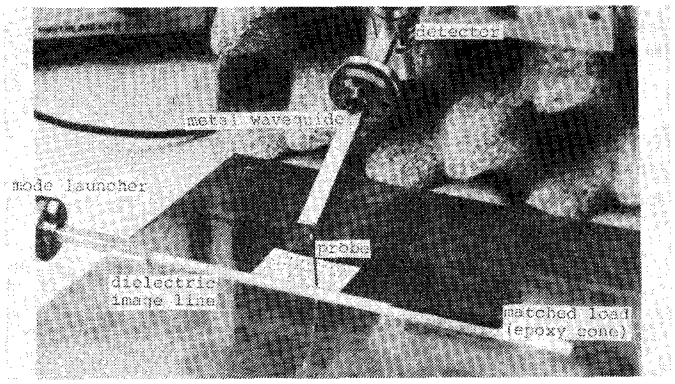
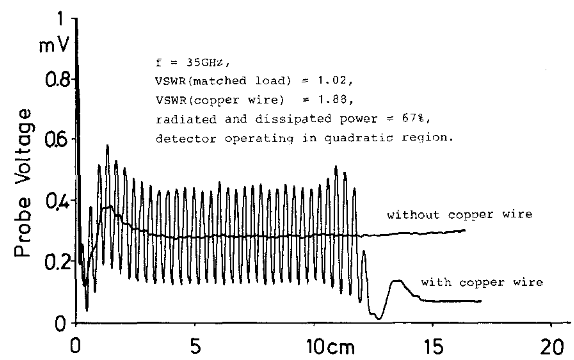
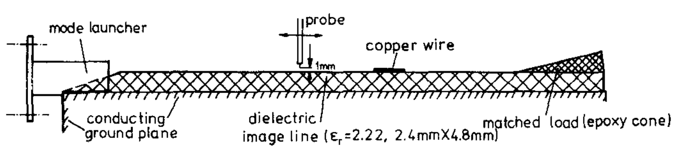


Fig. 3. Measurement setup used for the determination of the reflections from matched loads of the dielectric image line in the frequency range of 60–90 GHz.



(a)



(b)

Fig. 4. (a) The measurement of the scattering coefficients of a line discontinuity (dielectric image line with copper wire placed on top). (b) The measurement of the reflection coefficient of the matched load (epoxy cone placed on top of the dielectric image line).

2) To measure the reflections from attenuators, matched loads, or metal waveguide dielectric image-line transitions, an experimental setup was used as shown in Fig. 3. The CW-wave incident from the launcher propagates along the dielectric image line and is dissipated at the matched termination or is terminated by a second metal waveguide transition in place of the matched load. In either case, the wave is reflected partially at the termination, and the resultant standing wave pattern on the dielectric image line can be observed by means of the electric-field probe. The matched loads used in both the R and E band were "Ferrosorb"-epoxy cones[4] (originally designed for metal waveguide applications) of length 50 mm and 35 mm, respectively. They were placed on top of the dielectric image lines.

[4]Produced by Microwave Filter Company.

The reflection coefficients of the transitions used in the experiments were measured to be in the range of 0.06–0.1. The measurement of a reflection coefficient of a matched load on a dielectric image line as low as 0.01 (see Fig. 4, the probe voltage labeled "without copper wire") thus would be difficult to achieve within the metal waveguide.

The experimental setup was used to measure the complex scattering coefficients of dielectric image-line discontinuities too. As a simple example, in Fig. 4 the incident wave is scattered at a short section of copper wire (diameter 1 mm, length 15 mm) placed on top of the dielectric image line. One part of the incident guided wave is reflected in the form of a guided wave—resulting in the standing wave pattern between the mode launcher and the wire; another part of the wave is radiated at the wire—resulting in the nonuniformity of the field pattern near the wire. A third part of the wave is transmitted to the matched load at the end of the image line.

Both the absolute value and the phase of the input reflection coefficient of the line section loaded by the wire can be evaluated by means of the magnitude of the measured VSWR and the position of either the minima or the maxima of the standing wave pattern. The absolute value of the transmission coefficient of the discontinuity can be determined by comparing the amplitudes of the incident wave (recorded when the copper wire was absent) and the transmitted wave far enough behind the radiating discontinuity region.

In the experiments difficulties arise from a) nonuniformities of the dielectric image lines and from b) the radiation field due to the mode launcher.

a) If dielectric image lines are not fixed to the ground plane in a totally uniform manner, e.g., due to a nonuniform bonding film, these nonuniformities act as additional line discontinuities, and distinct standing wave patterns can be observed on the lines in spite of the nearly ideal termination loads used. This problem does not occur in the case of die-casted dielectric image lines since adhesion is achieved without a bonding film. Since the output of the field probes depends on the height of the probes above the lines, severe disturbances of the measured field-strength characteristics have been noticed due to nonuniformities of the height of the dielectric image lines, e.g., in Fig. 4 the probed field strength should decay with the distance from the mode launcher towards the end of the line (about 2 dB/m), but, due to a very small increase in the height of the dielectric image line near the end of the line, the probe voltage slightly rises at the end of the line.

b) Due to the mode launcher, leaky waves are generated. They superimpose with the fields of the guided waves of the dielectric image line producing severe deviations of the probe output from the ideal case near the source of the leaky waves (this phenomenon has been reported by Cassedy and Cohn [5] for line-source mode launchers for the grounded dielectric slab guide and the dielectric through guide).

As a consequence, in all measurements the distance from the mode launcher has to be carefully chosen with respect to the height of the probe above the dielectric image line, e.g., in Fig. 4, with the probe only about 1 mm above the top of the line, the first 5 cm of the probe voltage recorded versus the distance from the mode launcher have to be disregarded if the VSWR of the line discontinuity is to be measured.

IV. Conclusion

The experimental method described here is a simple and straightforward method for the investigation of the properties of the dielectric image lines and for the investigation of arbitrary line discontinuities. It is assumed that for several other types of open millimeter waveguides, such as the insular or the inverted strip dielectric lines, the use of the described techniques could be advantageous.

V. Appendix
The Derivation of (1) and (2)

Let the magnitude of the reflection coefficient of a short-circuited line section at the distance z from the short circuit (reflecting termination wall) be

$$|r| = e^{-\tau} e^{-2\alpha z} \qquad \text{(A-1)}$$

where τ is the reflection loss and α is the line attenuation constant. Then the VSWR as a function of the distance from the short circuit can be expressed as

$$\mathrm{VSWR} = \frac{1+|r|}{1-|r|} = \frac{1+e^{-\tau}e^{-2\alpha z}}{1-e^{-\tau}e^{-2\alpha z}}. \qquad \text{(A-2)}$$

The Maclaurin's series expression for e^{-x} is given by

$$e^{-x} = 1 - x + \frac{x^2}{2!} - \frac{x^3}{3!} + \cdots + \frac{(-x)^{n-1}}{(n-1)!} + \cdots \qquad \text{(A-3)}$$

where $x^2 < \infty$. For values of x close to zero, (A-3) becomes

$$e^{-x} \approx 1 - x. \qquad \text{(A-4)}$$

Now when the VSWR is very large, $|r|$ is very close to 1, and $-(\tau + 2\alpha z)$ is close to zero; therefore, (A-2) with the help of (A-4) becomes

$$\mathrm{VSWR} = \frac{1+e^{-(\tau+2\alpha z)}}{1-e^{-(\tau+2\alpha z)}} \approx \frac{2}{\tau + 2\alpha z} \qquad \text{(A-5)}$$

or

$$1/\mathrm{VSWR} \approx \frac{\tau}{2} + \alpha z. \qquad \text{(A-6)}$$

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