The Measurement of the Radiation Losses in Dielectric Image Line Bends and the Calculation of a Minimum Acceptable Curvature Radius

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***Abstract*—Measurements of the insertion loss due to radiation in curved dielectric image lines of rectangular cross section are described for the frequency range from 26 to 90 GHz. A minimum acceptable curvature radius as a function of the frequency is calculated employing the field distributions of straight dielectric image lines and is compared with measurements.**

I. Introduction

During the last decade several authors have presented approximate theoretical calculations and measurements of the radiation in curved dielectric lines [1]–[7], but no measurements in the millimeter-wave range have been reported yet. In the following, the radiation losses in curved dielectric image lines in the R band (26–40 GHz) and in the E band (60–90 GHz) are presented. Additionally, an estimate for the minimum acceptable curvature radius, using a formula originally proposed by Miller [1], is calculated and compared with measurements.

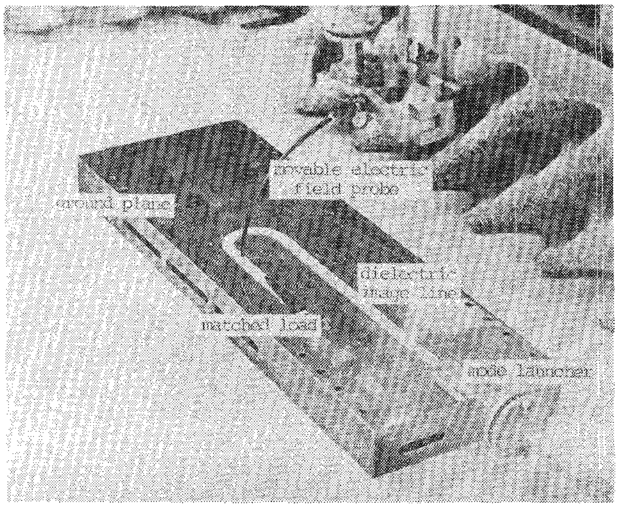

Fig. 1. The measurement setup for the determination of the radiation losses of curved dielectric image line sections. The dielectric image line shown is made from Epsilam 10 laminate.

II. The Measurements

In Fig. 1 the measurement setup for the determination of the attenuation due to radiation in a curved dielectric image line section is shown. The wave incident from the mode launcher propagates along the straight line section to the curved line section and is terminated by a matched load. In the experiments paraffin wax lines and Epsilam 10 lines were investigated. The paraffin wax lines were fabricated by a die-casting technique [8], whereas the Epsilam 10 lines were cut from a laminate and were bonded to the ground plane by means of an adhesive.

The insertion loss of the curved line section is determined by means of an electric field probe [9] measuring the amplitudes of the wave incident to the bend and the wave emerging from the bend. The insertion loss of the curved line section consists of the line losses (dielectric and conductor losses) and the radiation losses. Losses due to reflections of the incident wave have been measured to be neglegibly small in all cases. Mode coupling did not occur since the lines were designed to support the fundamental EH_{11} mode only. The dielectric and conductor losses in the curved line section are approximately identical to the losses in the straight line section which are measured seperately employing the VSWR method [9].

In the case of very high insertion loss of the curved section, a shielding wall has to be inserted between the mode launcher and the output terminal of the curved line section to prevent a superposition of the guided wave emerging from the curved line section and the radiation field due to the mode launcher.

In Figs. 2–4 the results of the measurements are plotted for low-permittivity and high-permittivity dielectric image lines using various normalized curvature radii R/w, where R is the curvature radius and $2w$ is the width of the guide in the plane of the bend.

It can be concluded that the radiation attenuation decreases with increasing frequency (high-pass characteristic) and with increasing curvature radius. Furthermore, comparing Figs. 2 and 3, it can be concluded that the radiation attenuation increases with frequency, if the cross-sectional dimensions of the guides are decreased with increasing frequency to allow single-mode operation.

Manuscript received May 26, 1978; revised August 10, 1978. This work was supported by the German Research Society (DFG) under Contract Wo 137/4.

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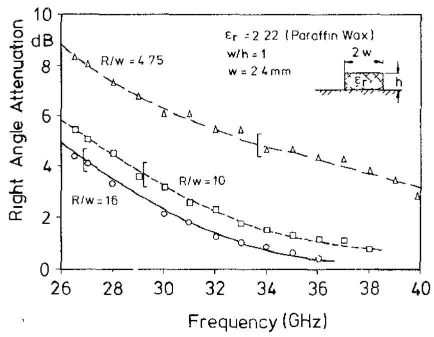

Fig. 2. The measured radiation losses of 90° bends in curved dielectric image lines versus the frequency for low-permittivity lines in the R band, indicating the theoretical minimum acceptable frequency.

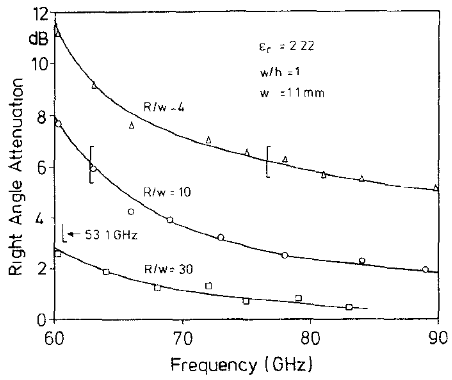

Fig. 3. The measured radiation losses of 90° bends in curved dielectric image lines versus the frequency for low-permittivity lines in the E band, indicating the theoretical minimum acceptable frequency.

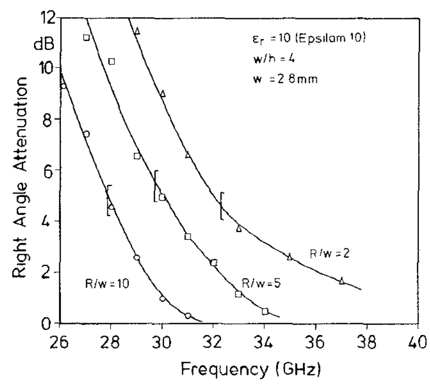

Fig. 4. The measured radiation losses of 90° bends in curved dielectric image lines versus the frequency for high-permittivity lines in the R band, indicating the theoretical minimum acceptable frequency.

Comparing Figs. 2 and 4 it can be concluded that the bends of the high-permittivity lines exhibit a more abrupt transition from the strongly radiating condition to the weakly radiating condition than the bends of low-permittivity lines. The transition from the strongly radiating condition to the weakly radiating condition occurs near the frequencies where the transition from the loosely binding condition of the waves to the tightly binding condition occurs, compare [10].

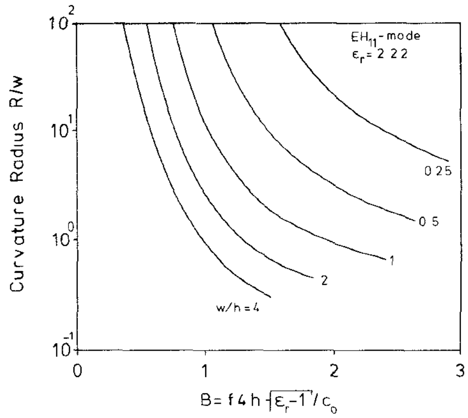

Fig. 5. The calculated normalized minimum curvature radius versus the normalized frequency for low-permittivity lines of various aspect ratios.

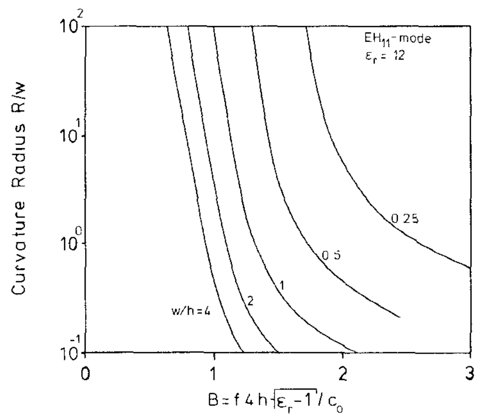

Fig. 6. The calculated normalized minimum curvature radius versus the normalized frequency for high-permittivity lines of various aspect ratios.

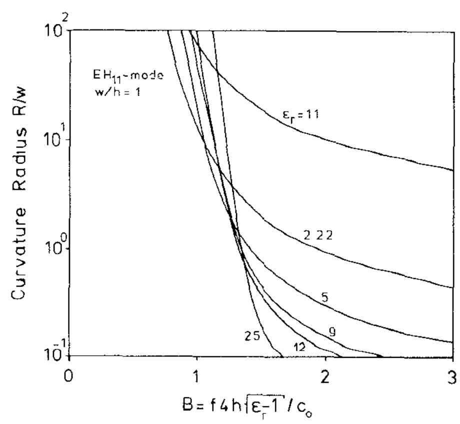

Fig. 7. The calculated normalized minimum curvature radius versus the normalized frequency for unit aspect ratio lines of various permittivities.

III. The Calculations

It is not a purpose of this paper to present an approximate calculation method for the bending losses in rectangular dielectric image lines but to present a method to calculate a minimum curvature radius to be kept in order to keep the bending losses low.

Miller [1] found that the radiation properties of curved dielectric lines are governed by the dimensionless ratio $R\lambda_0^2/r_0^3$, where λ_0 is the free-space wavelength and r_0 is the length over which the field decays by $1/e$ far away from the straight line. Modifying Miller's formula, it has been proposed by Larsen [6] and has been experimentally verified by Neumann [7] for low-permittivity dielectric rod guides that curved dielectric lines should maintain a minimum curvature radius

$$R=\frac{8\pi^2 r_0^3}{\lambda_0^2} \tag{1}$$

in order to keep the radiation losses within tolerable limits.

The field decay coefficient r_0 was calculated employing the field expansion method of the straight dielectric image line of rectangular cross section described in [10]. In Figs. 5–7 the results for the minimum curvature radius R normalized to the width w of the guide are plotted versus the normalized frequency B for low-permittivity and high-permittivity lines of various aspect ratios w/h. It can be concluded that the minimum acceptable curvature radius decreases with increasing normalized frequency B and with increasing aspect ratio w/h.

Furthermore, from Fig. 7 it can be concluded that in the case of well-guided waves ($B \gtrsim 1.3$) the acceptable minimum curvature radius decreases with the permittivity of the lines. For a given curvature radius, a minimum acceptable frequency B can be read from Figs. 5–7. For the curved line sections investigated in the experiments, the calculated minimum acceptable frequencies are indicated by brackets in Figs. 2–4.

In the case of the paraffin wax lines the radiation losses at the calculated minimum frequencies range around 4 dB for a right-angle bend in the R band and around 6 dB for a right-angle bend in the E band, while the Epsilam 10 line bends exhibited about 5-dB radiation loss at the calculated minimum acceptable frequencies in the R band. Obviously, the calculated minimum operating frequencies do not allow very low loss operation of the curved line sections. This means that in designing curved line sections, for, e.g., directional couplers or filters, for a given frequency, the curvature radius of the bends have to be chosen at least by 100 percent larger than predicted using Figs. 5–7. This result is supported by recent calculations [11] indicating that the critical parameter is not $R\lambda_0^2/r_0^3$ but $R\lambda_0^2/r_0^3 \cos^2 \theta_z$, where θ_z is the angle of inclination to the waveguide axis $\cos \theta_z = \beta/(\beta_0\sqrt{\epsilon_r})^3$ (β the phase constant of the waveguide, β_0 the free-space phase constant).

IV. Conclusions

Measurements of the radiation attenuation of curved sections in various dielectric image lines have been presented for the frequency range of 26–90 GHz. It has been shown that an approximate prediction of the minimum acceptable curvature radius or the minimum acceptable operating frequency of the bends is possible by a formula utilizing the field distribution of the straight dielectric image line. Design considerations for practical dielectric image line bends are given.

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