DIELECTRIC LINE COUPLER
(FINAL REPORT)

by

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I. Introduction

Studies on the properties of a 3dB dielectric coupler have been undertaken and three interim research reports have been issued[1-3]. This final report summarizes all the work done and presents the findings as well as the implications of this work. Also included, is a discussion of the various methods used, preferred solutions, and lessons learnt. An appropriate choice of parameters for the design of a broad-band 3dB dielectric line coupler and expected performance of the coupler are also presented. This report is in two sections; the first section summarizes the interim reports issued, as well as the various methods tried, and their results; while the second section describes the design and the performance of the recommended 3dB coupler.

II. Summary of the Interim Reports

The intention of the first report [1] was to record the presence of an erronous formula (eq. 4) in a January 1979 contract proposal document[4] and to provide the theoretical basis on which the theory of coupling can be better understood. The above mentioned erroneous formula (which is an expression for the coupling coefficient of two side-by-side coupled dielectric slabs) had been found to be copied and interpreted incorrectly from Marcatili[5]. In our first report, the structure of the proposed coupler was described. The coupler is composed of two parallel rectangular dielectric waveguides sandwiched between two parallel conducting plates. This structure is capable of supporting two types of propagating modes, namely, transverse electric modes and hybrid modes. The analytical description of the field of the TE_o mode (dominant mode), for both single and coupled dielectric lines was given. The correct expression for the coupling coefficient (the shift in the propagation constant due to coupling) was derived and found to confirm results by other authors. With the establishment of the first report, the necessary background for the development of further work was obtained.

In the second report, the transmission line equations, which govern the actual coupled fields along each line, were written. Upon making certain substitutions, the coupled transmission line equations were reduced to a set of decoupled second order differential equations. As in any system involving coupled linear circuits, we have a set of simultaneous linear differential equations which admits a particularly simple set of solutions: the normal modes of the system (symmetrical and antisymmetrical modes). Extending the formulation to cover the coupling of modes on two curved lines resulted in complicating the decoupled differential equations. A particular geometry of a 3dB dielectric directional coupler was suggested. The proposed geometry was described to consist of three sections: one linear middle section joined to two curved terminal sections. Because of the variable coupling along the curved sections a z-dependent term appeared in the decoupled differential equations. Consequently, these differential equations were found to have no closed-form analytic solutions and hence approximate methods had to be employed. Using perturbation technique, approximate expressions for the fields along the curved sections were derived. The 3 dB coupler was assumed to be excited by a unit incident wave and to have matched terminations. Two interesting results were encountered. First, despite all approximations, the coupled outputs (or more generally the fields along the two lines) were found to be exactly in quadrature all over the three sections of the coupler. Secondly, expressions for the reflection coefficient and directivity (reverse coupling) were derived. Consequently, the design requirements were enforced and hence the design equations, which calculate the coupling length as well as the correction due to the two curved ends of the coupler, were derived. For this particular geometry most of the coupling takes place along the middle linear section. Specific design parameters of a 3 dB teflon dielectric coupler were given. The corrected length of the coupler was calculated and found to be 2.5 cm. The 3 dB bandwidth was 20 GHz while the reflection and directivity due to coupling were both more than 35 dB down. Second order effects, due to varying the dimensional parameters, were investigated and found to be substantial. The bandwidth of the coupler was found to increase for stronger coupling by varying the width, the spacing, and/or the dielectric constant of the rectangular dilectric lines. The variation in the curvature of the dielectric line was found to have negligible effect on the reflection coefficient, directivity as well as bandwidth. However, the radius of curvature should be chosen substantially large so that the radiation due to curvature can be neglected. The discontinuity between the straight and curved parts of the coupler was considered to cause mode conversion as well as reflection of noticeable magnitude and hence had to be eliminated.

The incentive for the third report was to investigate the possibility of using a continuously curved 3 dB coupler with no discontinuities, thus eliminating mode conversion (that appears at the junctions) and reducing the magnitudes of the reflection coefficient and directivity. The field amplitude differential equations that govern the normal modes along the two lines were found to have no exact closed-form solutions, and hence approximate techniques had to be employed. Using a perturbation method it was mathematically difficult to extract complete and accurate expressions for the field amplitude of the forward wave. However, accurate expressions for the reflection coefficient and directivity were recovered. The magnitudes of the reflection coefficient and directivity were found to be exponentially small and hence can be neglected. Employing the WKB method (for solving the differential equations) a complete and accurate solution for the forward wave amplitudes (propagating on both lines) was extracted. Concerning transmission losses, practical transmission line conductors will have large but finite conductivity and the dielectric will have small but finite conductivity. Using approximate attenuation formulas, available in the literature, the wall and dielectric losses were calculated. The radiation due to the bending of the dielectric lines was calculated and found to be noticeable when the radius of curvature is smaller than 15 mm.

The effect of the polarization of the electric field on the coupling performance of the coupler was investigated. A 3 dB coupler fed symmetrically and antisymmetrically by the TE_o even mode (dominant mode) was found to give better frequency performance than if it was fed symmetrically and antisymmetrically by the lowest order $H_x = 0$ mode (which is also called the longitudinal sectional magnetic mode, LSM). Finally, for a 3 dB continuously curved coupler, a variation in the dimension of the guide (i.e. width and height) as well as in ε_r were found to have no substantial effect on the performance of the coupler. The only considerable effect on the bandwidth of the 3 dB coupler was found to be caused by reducing the spacing. The closer the lines, the stronger the coupling, and the wider the bandwidth. However many formulas and concepts that have been used during the course of this investigation were based on the assumption of weak coupling. In other words, all the previous analysis breaks down if the spacing d_o decreases below a certain minimum value. This limitation is determined by the requirement that $\Delta\beta/\beta_o \ll 1$, where $\Delta\beta$ gives the coupling coefficient and β_o is the propagation constant (of the propagating mode) for single line in isolation.

The various reports issued as part of this contract study are:

1) "Dielectric image line coupling." Rept. No. 49, Electromagnetics Laboratory, University of Colorado at Boulder, May 1979.

2) "Dielectric image line coupler," Rept. No. 52, Electromagnetics Laboratory, University of Colorado at Boulder, Dec. 1979.

3) "Dielectric line coupler using only curved sections," Rept. No. 61, Electromagnetics Laboratory, University of Colorado at Boulder, March 1981.

4) "Dielectric line coupler, Final Report," Rept. No. 65 Electromagnetics Laboratory, University of Colorado at Boulder, May 1981

Design, Expected Performance and Recommendations

This last section presents additional information on the geometry, design and performance of a recommended 3 dB dielectric directional coupler. The coupler is composed of two continuously curved dielectric lines (of parabolic shape), separated by a minimum distance d_o and sandwiched between two conducting plates. A suitable choice of 3 dB TE_o dielectric directional coupler parameters for a center frequency of 94 GHz is

$$a = 1.35 \text{ mm}$$

$$b = 1.27 \text{ mm}$$

$$\varepsilon_r = 2.05$$

$$R = 37 \text{ mm}$$

where a, b, ε_r and R represent the width, the height, the relative dielectric constant of the guide material, and the radius of curvature. The expected size and performance of the coupler (designed to operate at 94 GHz central frequency) is

$$d_0 = 0.5 \text{ mm}$$

$$\text{B.W.} = 20 \text{ GHz}$$

Total length of dielectric guide as used = 10 cm.

The theoretical transmission losses for this particular choice of parameters are

$$\text{Radiated losses} \simeq -95 \text{ dB}$$

$$\text{Wall losses } (\sigma_\omega = 5.8\text{x}10^5 \mho/\text{cm}) \simeq 2.7 \text{ dB/m}$$

$$\text{Dielectric losses } (\tan\delta = 4\text{x}10^{-4}) \simeq 4.5 \text{ dB/m}$$

Metal guide to dielectric guide transition loss is of the order of 0.5 to 0.75 dB.

Estimated total insertion loss (theoretical) is 2.10 dB. It may be expected that in practice the losses will be substantially greater than this because of departure of the metallic and dielectric losses from their assumed low-frequency values. The magnitudes of the reflection coefficient and directivity are extremely small and can be neglected.

The fields in the guides are very closely in quadrature.

The dielectric slabs can be guided by shallow grooves in the metal plates. No analysis of the effect of these grooves has been made, but it is not expected that any substantial change in the design or performance will ensue from the use of shallow grooves. Other methods of locating the dielectric may also be considered.

REFERENCES

(1) M. Abouzahra and L. Lewin, "Dielectric image line coupling," Report No. 49, Electromagnetics Laboratory, University of Colorado at Boulder, May 1979.

(2) M. Abouzahra and L. Lewin, "Dielectric image line coupler" Report No. 52, Electromagnetics Laboratory, University of Colorado at Boulder, Dec. 1979

(3) M. Abouzahra and L. Lewin, "Dielectric line coupler using only curved sections," Report No. 61, Electromagnetics Laboratory, University of Colorado at Boulder, March 1981

(4) Hughes report, "Integrated circuit six-port network," prepared for National Bureau of Standards at Boulder, P. 2-7, Jan. 1979

(5) E.A.J. Marcatili, "Dielectric rectangular waveguide and directional coupler for integrated optics," BSTJ, Vol. 49, Sept. 1969.

Errata

Corrections to Scientific Report No. 61

p. 6, l. 8, "10^{-2} and 10^{-3} neper/cm" to "0.3115 and 1.295 neper/m."

p. 7, Fig. 3, indicated values for curvature radiation are incorrect; it should be weaker than -40 dB in all cases.

p. 7, Fig. 3, The values of R should be doubled to "14, 26, 47" respectively.

p. 8, Fig. 4, indicated values for curvature radiation are incorrect; it should be weaker than -35 dB in all cases.

p. 8, Fig. 4, The values of R should be doubled

p. 18, l. 9, "$\frac{\pi}{4}$" to "$(\frac{\pi}{4})^2$".

p. 18, eqn. (31), "$\ln\left(\frac{4c_0^2 R}{h_0}\right)$" to "$\ln\left(\frac{16c_0^2 R}{\pi h_0}\right)$"

p. 20, l.-4, "10^{-2} neper/cm and 10^{-3} neper/cm" to "0.3115 neper/m and 1.295 neper/m."