$$V_n = \gamma^2 S_n - \frac{k_{y1n} k_{xn}}{\omega^2 \epsilon_1 \mu_0} T_n$$

$$S_n = 1 + P_{cn} \frac{\epsilon_2 k_{y1n}}{\epsilon_1 k_{y2n}}$$

$$T_n = 1 + P_{dn} \frac{k_{y2n}}{k_{y1n}}.$$

## References


[1] H. Hasegawa, "Properties of microstrip line on $Si-SiO_2$ system," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 869–881, Nov. 1971.

[2] H. Hasegawa, "M.I.S. and Schottky slow-wave coplanar striplines on GaAs substrates," *Electron. Lett.*, vol. 13, no. 22, pp. 663–664, Oct. 1977.

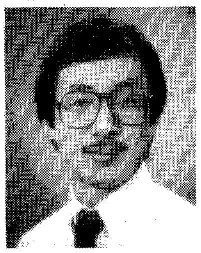
[3] D. Jäger, "Slow-wave propagation along variable Schottky-contact microstrip line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 566–573, Sept. 1976.

[4] S. Seki and H. Hasegawa, "Cross-tie slow-wave coplanar waveguide on semi-insulating GaAs substrate," *Electron. Lett.*, vol. 17, no. 25, pp. 940–941, Dec. 1981.

[5] E. M. Bastida and G. P. Donzelli, "Periodic slow-wave low-loss structures for monolithic GaAs microwave integrated circuits," *Electron. Lett.*, vol. 15, no. 19, pp. 581–582, Sept. 1979.

[6] E. Yamashita and K. Atsuki, "Analysis of microstrip-like transmission lines by nonuniform discretization of integral equations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 195–200, Apr. 1976.

[7] Y. Fukuoka, Y.-C. Shih, and T. Itoh, "Analysis of slow-wave coplanar waveguide for monolithic integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 567–573, July 1983.

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# Design of an Overlay Directional Coupler by a Full-Wave Analysis

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*Abstract* —**A full-wave analysis based on the spectral-domain method is applied to coupled overlay microstrips, coupled inverted microstrips, and coupled microstrips. Exclusive numerical data including frequency characteristics are included. A 10-dB overlay coupler was built according to the design theory, and experimental results are reported.**

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## I. Introduction

IT IS KNOWN THAT when the even- and odd-mode propagation constants are identical, the isolation of a directional coupler is theoretically infinite. However, in an inhomogeneous structure such as microstrip, this condition is not always satisfied. A dielectric overlay is one way to improve the isolation of a microstrip coupler, by which the difference in even- and odd-phase velocities can be greatly reduced or even equalized [1]–[3]. To date, most of the

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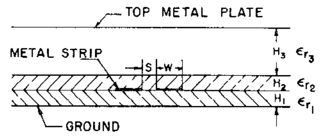


Fig. 1. Cross-sectional view of coupled microstrip lines with a dielectric overlay.

designs of overlay couplers are based on the quasi-TEM approximation. In this paper, the spectral-domain method [4] is used for a full-wave analysis with a view to designing an overlay coupler.

After the procedure for analyzing coupled line structures is introduced in Section II, we present in Section III numerical results for coupled microstrip lines, coupled overlay microstrip lines, and coupled inverted strip lines. In Section IV, directional couplers are designed and fabricated. These couplers are tested and their performance measured.

## II. Analytical Process

Fig. 1 shows the cross section of a coupled overlay microstrip line structure. A full-wave analysis which includes the frequency dependent behavior of this structure is formulated based on the spectral-domain method [4]. Note that this structure is general enough to represent two other coupled line structures to be discussed in this paper. For instance, the coupled microstrip line is obtained by letting $\epsilon_{r2} = \epsilon_{r3} = 1$. The inverted microstrip line is realized by choosing $\epsilon_{r1} = \epsilon_{r3} = 1$. Therefore, once the formulation for Fig. 1 is done, we can generate data for microstrip and inverted strip structures in addition to overlay microstrip. In all of the calculations and experiments, we let $H_3 \to \infty$.

Since the spectral-domain method is now well known, we will not describe it in detail here. Basically, it solves the eigenvalue problem in the Fourier transform domain to obtain a pair of algebraic equations that relate the axial and transverse currents on the strips with the axial and tangential transverse electric fields at the interface containing strips. These solutions are subsequently transformed to a set of linear equations by Galerkin's procedure. This set is solved for the propagation constant $\beta$ or the guide wavelength $\lambda_g$. Choice of the basis functions in Galerkin's procedure is important and, here, we used those proposed by Schmidt and Itoh [5] and Jansen [6]. They have correct edge singularities and can be analytically Fourier transformed to Bessel functions for use in the spectral-domain process. As a result of our convergence tests, we used three basis functions for calculations in this paper.

Once the propagation constant is available, we can calculate all the field coefficients in the cross section. From these quantities we can compute the characteristic impedance which is defined in this paper as [6]

$$Z_0 = 2P_{\text{avg}}/I_z^2 \tag{1}$$

where $P_{\text{avg}}$ is the average power transmitted and $I_z$ is the axial strip current.

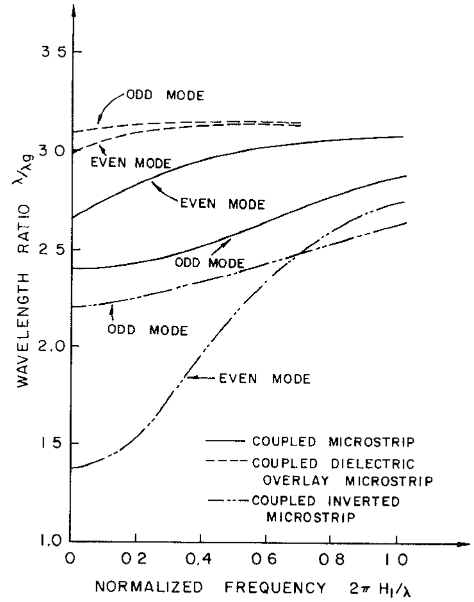


Fig. 2. Even- and odd-mode dispersion characteristics for $H_2/H_1 = 1.0$, $H_3 \to \infty$, $W/H_1 = 1.0$, $S/H_1 = 0.4$, $\epsilon_{r3} = 1.0$. For coupled microstrip, $\epsilon_{r1} = 10.0$, $\epsilon_{r2} = 1.0$. For coupled overlay microstrip, $\epsilon_{r1} = \epsilon_{r2} = 10.0$. For coupled inverted microstrip, $\epsilon_{r1} = 1.0$, $\epsilon_{r2} = 10.0$.

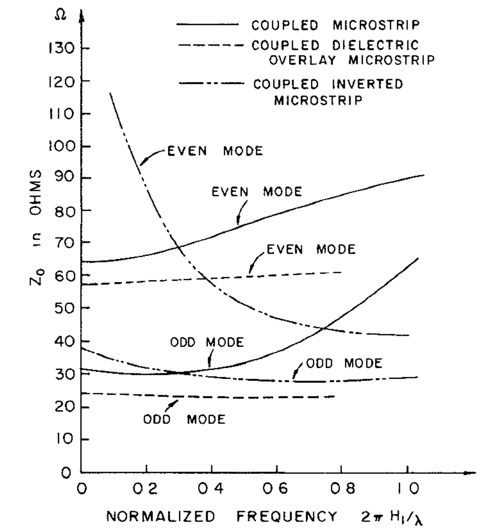


Fig. 3. Characteristic impedance versus frequency for the three structures. Parameters correspond to Fig. 2.

## III. Numerical Results

Fig. 2 shows the dispersion characteristics for three types of coupled strip structures. From this figure, we find the following: the inverted configuration provides a frequency at which the even- and odd-mode phase velocities coincide; whereas, in the overlay construction, the difference in phase velocities becomes very small though they never become equal for this particular choice of structural parameters.

Fig. 3 shows the characteristic impedance of these lines. The impedances of the overlay structures are much less frequency dependent.

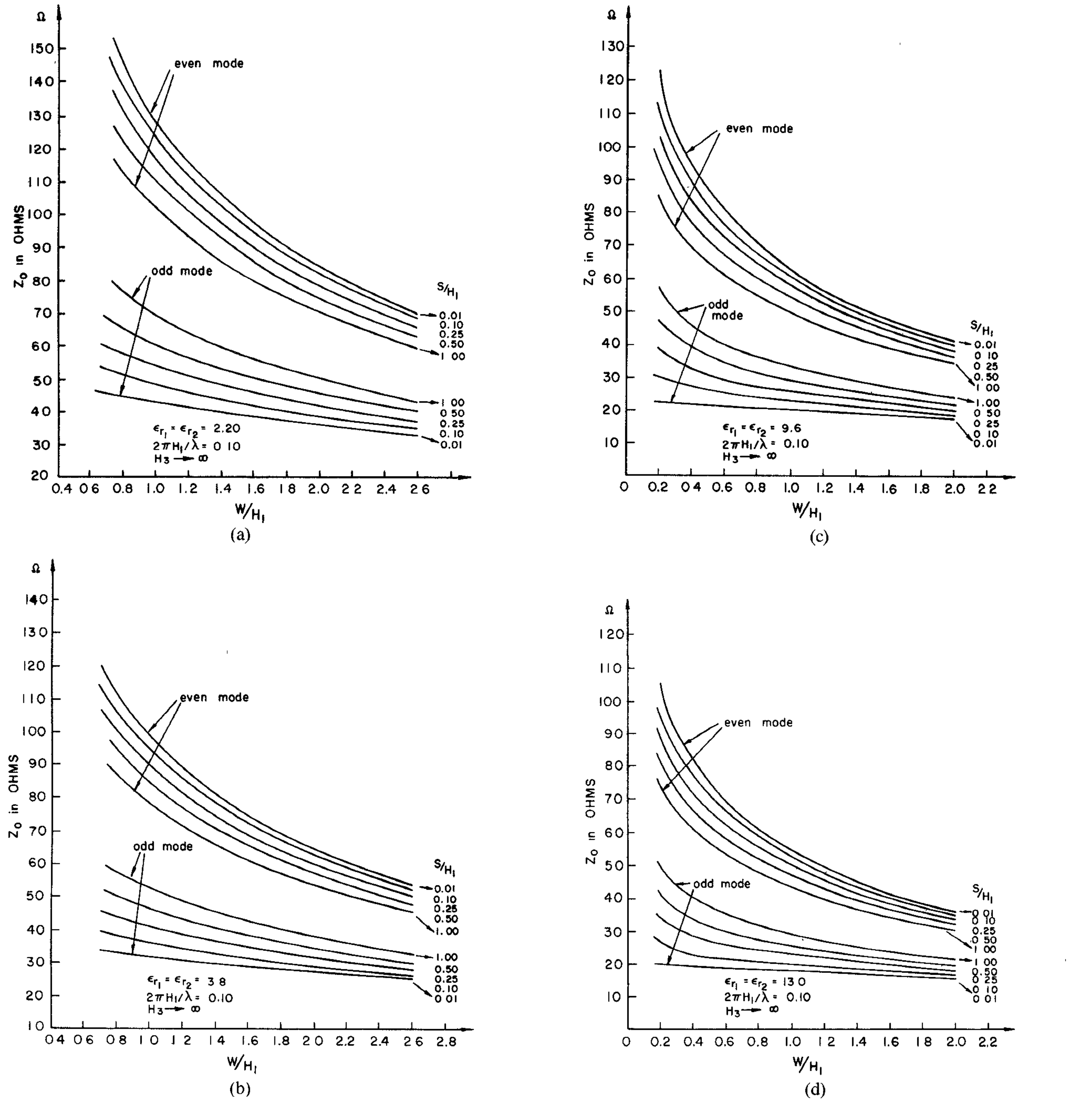


Fig. 4. Characteristic impedance versus the ratio of $W$ to $H_1$ for the overlay coupled microstrip for a number of values of $S/H_1$. $H_1 = H_2$ and $H_3 \to \infty$. (a) $\epsilon_{r1} = \epsilon_{r2} = 2.20$. (b) $\epsilon_{r1} = \epsilon_{r2} = 3.8$. (c) $\epsilon_{r1} = \epsilon_{r2} = 9.6$. (d) $\epsilon_{r1} = \epsilon_{r2} = 13.0$.

From these figures, we find that a very narrow-band high-performance coupler may be constructed from the inverted configuration. However, when wide-band operation is desired, as in most practical applications, the overlay configuration is preferred. The frequency-dependent characteristics reported in Figs. 2 and 3 cannot be found from quasi-TEM approximations.

Fig. 4 presents the even- and odd-characteristic impedances of the overlay coupled microstrip line versus the normalized strip width for four commonly used substrates at a particular frequency. Fig. 5 shows the wavelength ratio versus the normalized strip width for four different substrates and five different strip spacing $S/H_1$. It is seen that there exists particular structures for which the even- and odd-mode phase velocities are equal. Even if the phase velocities are not equal, they are generally close to each other. Fig. 6 shows the characteristic impedance and wavelength ratio versus the normalized overlay thickness. Once

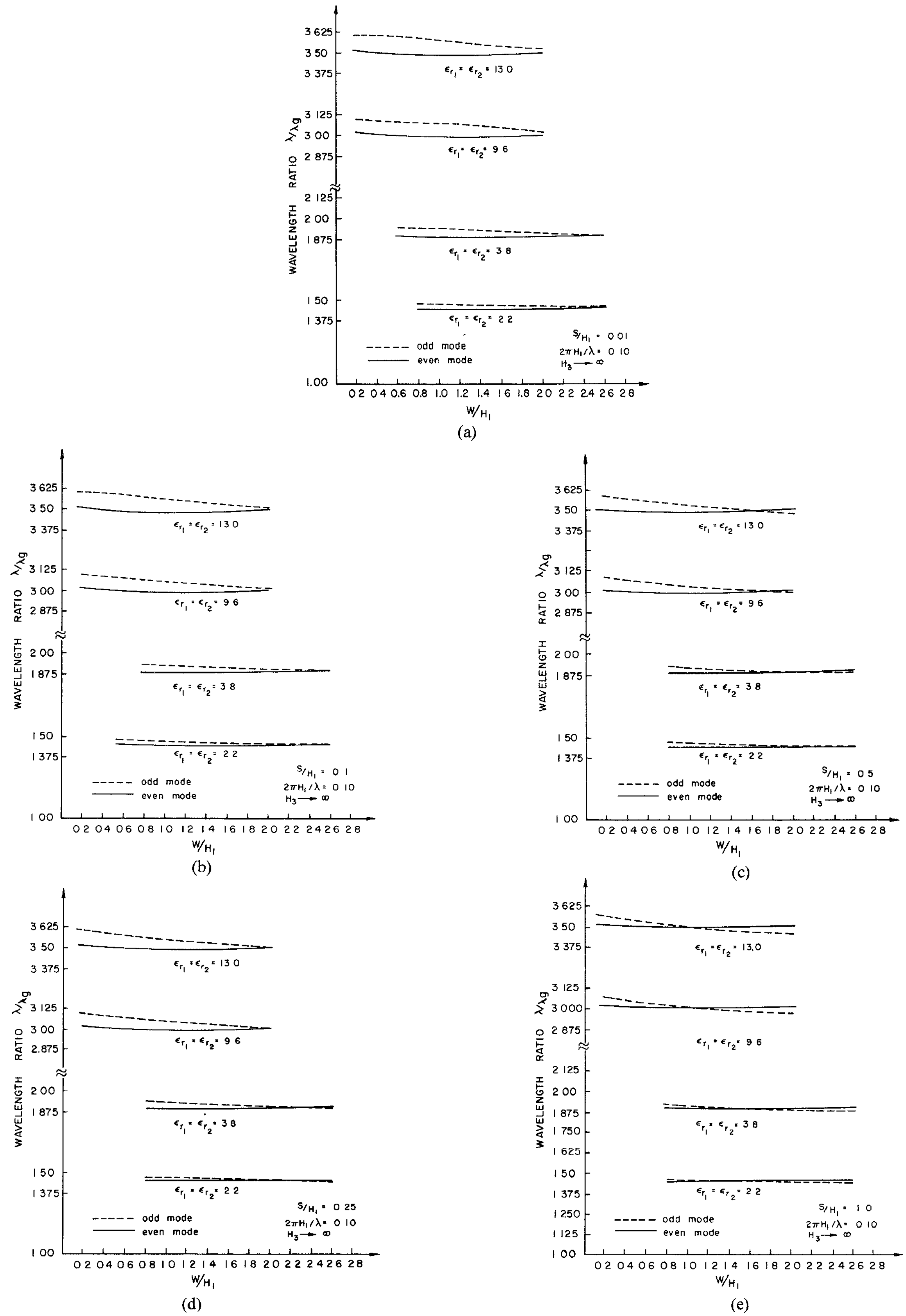


Fig. 5. Even- and odd-mode wavelength ratio versus the ratio of $W$ to $H_1$ for the overlay coupled microstrip $H_1 = H_2$, $H_3 \rightarrow \infty$, $\epsilon_{r1} = \epsilon_{r2} = 2.2$, 3.8, 9.6, and 13.0. (a) $S/H_1 = 0.01$. (b) $S/H_1 = 0.1$. (c) $S/H_1 = 0.25$. (d) $S/H_1 = 0.5$. (e) $S/H_1 = 1.0$.

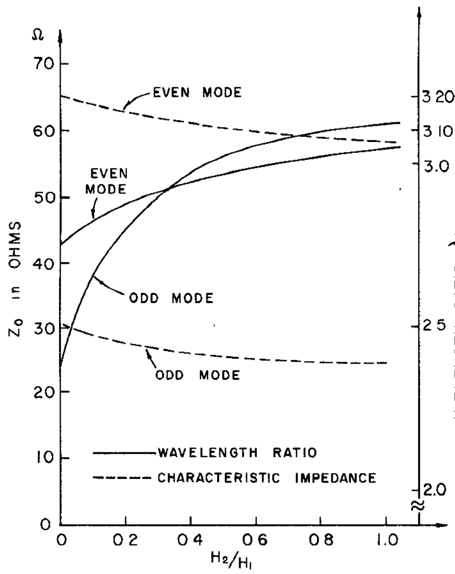


Fig. 6. Even- and odd-mode wavelength ratio and characteristic impedance versus $H_2/H_1$ for the overlay coupled microstrip. $\epsilon_{r1}=\epsilon_{r2}=10.0$, $W/H_1=1.0$, $S/H_1=0.4$, $2\pi H_1/\lambda=0.1$, $H_3\to\infty$.

again, the even- and odd-mode phase velocities can be equalized.

## IV. Design of Single-Section Directional Coupler

Once a computer program is available which calculates the even- and odd-mode characteristic impedance values $Z_0^e$ and $Z_0^o$ and the phase constants $\beta_e$ and $\beta_o$ of the coupled line, we make use of this program for designing a directional coupler.

In a hypothetical situation where $\beta_e=\beta_o$, we could proceed according to the standard approach [7]. If such were the case, the electrical length of the coupler is required to be $\beta L=\pi/2$. Assuming all the ports are terminated with $Z_{0L}$, the matching condition requires

$$Z_0^e Z_0^o = Z_{0L}^2. \tag{2}$$

The desired coupling coefficient $K$ is related to $Z_0^e$ and $Z_0^o$ via

$$K=\frac{Z_0^e-Z_0^o}{Z_0^e+Z_0^o}. \tag{3}$$

These two equations result in specific values of $Z_0^e$ and $Z_0^o$. We can find $W$ and $S$ that provide these values of impedance if all other structural parameters are fixed. We now calculate $\beta$ and find $L$.

In the present case, $\beta_e\neq\beta_o$. We, therefore, initially assume that the $\beta L=\pi/2$ condition is satisfied and find $W$ and $S$. The length $L$ is then determined from $\beta$ of the isolated line ($S\to\infty$) for the obtained value of $W$. This $\beta$ is usually close to the average of $\beta_e$ and $\beta_o$. Degradations of the coupler performance due to this choice of $L$ are studied experimentally.

The design process may be summarized as follows.

i) Choose the center frequency, the substrate material,

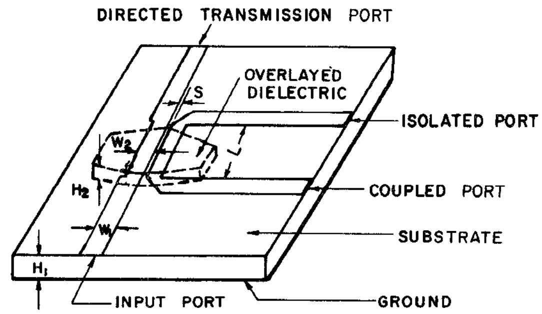


Fig. 7. Overlay directional coupler. $W_1=3.84$ mm, $W_2=3.20$ mm, $H_1=H_2=1.42$ mm, $S=0.4$ mm, $L=20.5$ mm, $\epsilon_{r1}=\epsilon_{r2}=2.48$.

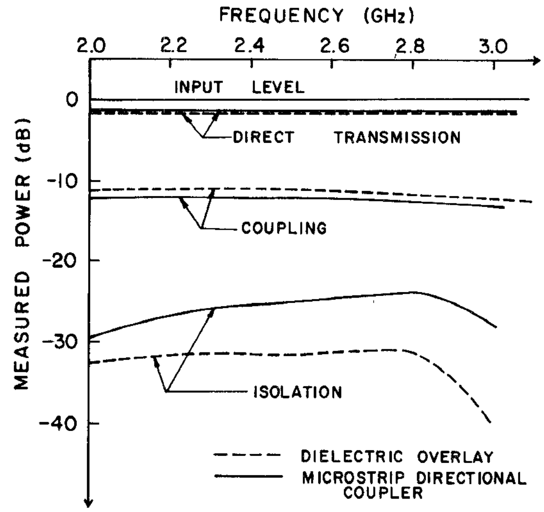


Fig. 8. Coupling and isolation of the directional coupler with and without a dielectric overlay.

and thickness. Other parameters such as the overlay material and thickness if applicable.

ii) Find $Z_0^e$ and $Z_0^o$ from (2) and (3).

iii) Obtain $W$ and $S$ values which result in $Z_0^e$ and $Z_0^o$ by using the computer program developed in Section II or the diagrams such as those in Fig. 4.

iv) If the coupling requirement cannot be satisfied or, though it is satisfactory, the value of $S$ is too small for fabrication, we may choose a different substrate which has a larger thickness and/or higher dielectric constant and repeat the processes ii) and iii).

v) Finally, calculate $\beta$ for an isolated line ($S\to\infty$) with the obtained value of $W$ and find the coupler length $L$ such that $\beta L=\pi/2$.

We have designed 10-dB, 6-dB, and 3-dB directional couplers. Since our fabrication facility is rather crude, only the 10-dB coupler was fabricated. Fig. 7 shows the structure, and Fig. 8 presents the measured results for the microstrip directional coupler and the dielectric overlay microstrip directional coupler. For these two structures, all of the dimensions are identical except for the presence or absence of the dielectric overlay. We can see that the dielectric overlay can significantly improve the isolation. This agrees with the works by Paolino [1]. A simple calculation shows that the relative propagation constant difference between the even mode and the odd mode

$$\left|\frac{\beta_e - \beta_o}{\beta_e}\right| \times 100 \text{ percent}$$

is only 0.54 percent in the dielectric overlay case and 7.35 percent in the coupled microstrip case. Additional measurements for an inverted microstrip directional coupler showed that at low frequencies, the relative propagation constant difference is large, about 12.7 percent, so the isolation is very poor.

In Fig. 7, the input and through arms of the coupler are in line with the coupling section. Experimental results showed that when these arms are perpendicular to the coupled section, the dielectric overlay did not improve the isolation. This is due to the bend existing between the transmission line and the coupled line, thus generating scattered waves. Dielectric overlays enhance the coupling of scattered waves, implying that isolation is deteriorating. In a configuration like Fig. 7 in which the input part is in line with the coupler, there is no measurable reflection caused by bends in the main line. From the network analysis [7] for any directional coupler, the magnitude of the reflected wave at the input port is equal to that of the wave appearing from the "isolated" port, implying that as the input VSWR increases, the isolation decreases. This shows that the structure shown in Fig. 7 seems to be practical.

## V. Conclusion

In this paper, the spectral-domain approach was used for studying the coupled dielectric overlay microstrip and coupled inverted microstrip. The numerical computations were carried out with a CDC Dual Cyber 170/750 computer. The typical configuration time required for a structure at a given frequency was about 1.05 s. We designed and tested microstrip and overlay microstrip couplers. The frequency characteristics are presented.

## References

[1] D. D. Paolino, "MIC overlay coupler design using spectral domain techniques," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 646–649, Sept. 1978.

[2] B. Sheleg and B. E. Spielman, "Broad-band directional couplers using microstrip with dielectric overlays," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1216–1220, Dec. 1974.

[3] K. Atsuki and E. Yamashita, "Three methods for equalizing the even- and odd-mode phase velocity of coupled strip lines with an inhomogeneous medium," *Trans. IECE Japan*, vol. 55-B, no. 7, pp. 424–426, July 1972.

[4] T. Itoh, "Spectral domain immittance approach for dispersion characteristics of generalized printed transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 733–736, July 1980.

[5] L. Schmidt and T. Itoh, "Characteristics of a generalized fin-line for millimeter wave integrated circuits," *Int. J. Infrared and Millimeter Waves*, vol. 2, no. 3, pp. 427–436, May 1981.

[6] R. Jansen, "Unified user-oriented computation of shielded, covered and open planar microwave and millimeter-wave transmission-line characteristics," *Microwaves, Opt. Acoust.*, vol. 3, no. 1, pp. 14–22, Jan. 1979.

[7] R. Levy, "Directional couplers," *Advances in Microwaves*, vol. 1, L. Young, Ed. New York: Academic Press, 1966, pp. 115–206.

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