7.2: PHASE SHIFT CHARACTERISTICS OF DIELECTRIC LOADED WAVEGUIDE*

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An investigation of waveguide phase shifting techniques was conducted recently for the purpose of establishing the design criteria of a device capable of meeting the following electrical specifications:[1] a phase shift variable over a minimum range of 360° and a maximum phase slope (or deviation) of 5° at any phase setting over at least a 10 per cent frequency band width. Mechanical simplicity, low insertion loss, rugged construction and small size are also essential characteristics.

During the course of this investigation it became apparent that the composite waveguide cross section shown in Figure 1 held considerable promise as the basis of a practical device which would meet the design requirements. The analytical expressions applicable to this cross section were derived using the transverse resonance procedure (Figure 2).

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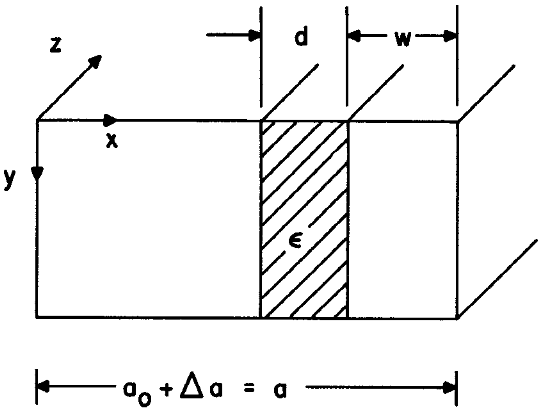

a — BROAD DIMENSION OF COMPOSITE WAVEGUIDE
a_0 — BROAD DIMENSION OF NORMAL WAVEGUIDE
Δa — CHANGE IN a
d — THICKNESS OF DIELECTRIC SLAB
w — DISPLACEMENT OF DIELECTRIC SLAB
ϵ — RELATIVE DIELECTRIC CONSTANT OF SLAB

Fig. 1.

$\lambda_{c1}, \lambda_{c2}$ — INTERMEDIATE VARIABLES
λ_g — GUIDE WAVELENGTH IN PHASE SHIFTER
k_g — PROPAGATION CONSTANT IN PHASE SHIFTER
$k_{w.g.}$ — PROPAGATION CONSTANT IN NORMAL WAVEGUIDE
λ_o — FREE SPACE WAVELENGTH
k_{diff} — DIFFERENTIAL PROPAGATION CONSTANT

(1) $$\lambda_{c1} = \frac{\lambda_o}{\sqrt{1-\left(\frac{\lambda_o}{\lambda_g}\right)^2}}$$

(2) $$\lambda_{c2} = \frac{\lambda_o}{\sqrt{\epsilon-\left(\frac{\lambda_o}{\lambda_g}\right)^2}}$$

(3) $$-\frac{\lambda_{c1}}{\lambda_{c2}} \text{TAN} \frac{2\pi}{\lambda_{c1}}\left[a-(w+d)\right] = \frac{\frac{\lambda_{c1}}{\lambda_{c2}} \text{TAN} \frac{2\pi}{\lambda_{c1}} w + \text{TAN} \frac{2\pi}{\lambda_{c2}} d}{1-\frac{\lambda_{c1}}{\lambda_{c2}} \text{TAN} \frac{2\pi}{\lambda_{c1}} w \ \text{TAN} \frac{2\pi}{\lambda_{c2}} d}$$

(4a) $$k_{w.g.} = \frac{2\pi}{\lambda_o}\sqrt{1-\left(\frac{\lambda_o}{2a_o}\right)^2}$$

(4b) $$k_g = \frac{2\pi}{\lambda_g}$$

(4c) $$k_{diff} = k_g - k_{w.g.}$$

Fig. 2.

Many results applicable to two special cases of this cross section have appeared in the literature. The two cases covered include the symmetrically placed dielectric and the dielectric in contact with one of the waveguide side walls. The solution presented here is valid for arbitrary location of the dielectric slab, and numerical results are included as a function of location.

The literature also contains a reference [2] to a phase shifting device which simultaneously varied dielectric insertion and side wall spacing to achieve flat phase shift characteristics. Since, in that structure, variable phase shift is obtained by varying the dielectric insertion within the waveguide, the configuration is difficult to analyze and optimal positioning of the moveable elements must be arrived at experimentally. In the structure considered here the dielectric slab is fully contained within the waveguide at all times. This configuration, therefore, lends itself to exact analysis by the above mentioned transverse resonance procedure.

From the analytical expressions obtained, the relationship between dielectric position, w, and wall displacement Δa which minimizes the phase error was determined. This was done over the required range of frequencies and phase settings for various combinations of d, ε, and a_o. The nature of these expressions almost precludes manual computation. Fortunately the authors had direct access to a high-speed computing facility (IBM 7090). As a result, an accurate and complete description of the propagation characteristics of this structure was obtained quickly and inexpensively. In addition, the cut-off frequency of the first higher order mode (TE_{20}) was examined in detail. The required range of variable phase shift and the maximum permissible phase deviation then determine L, the over-all length of a specific device.

k_{diff} was computed for the five cases listed in Table I where

$f = 9.1 \pm .1\,m$ kMc	$0 \le m \le 5$	
$w = .010p$ inches	$0 \le p \le 48$	
$\Delta a = .010q$ inches	$0 \le q \le 22$	initial calculation
$\Delta a = .002t$ inches	for selected values of t	refined calculation

TABLE I

	ε	a_o	d	d/a_o
1.	2.54 (polystyrene)	0.900"	0.090"	0.100
2.	2.54 "	0.900"	0.113"	0.125
3.	2.54 "	0.900"	0.180"	0.200
4.	2.54 "	1.122"	0.112"	0.100
5.	4.15 (boron nitride)	0.900"	0.090"	0.100

For convenience w was considered to be the independent variable. k_{diff} was computed as a function of Δa and f at each w. The range of Δa which yielded the smallest variation in k_{diff} over the specified frequency band was obtained by an inspection of the computed results. A refined calculation was then made over this limited range to determine Δa and the phase deviation more precisely. Computations to determine the cut-off frequency, f_{co2}, of the TE_{20} mode were made only with those values of Δa and w which resulted in minimum k_{diff} as determined by the previous calculation.

The plot of a typical computer output for the TE_{10} propagation constants is given in Figure 3. In this figure, the position of the dielectric is fixed; the wall position varies from 10 mils withdrawal to 220 mils. It is seen that at approximately Δa = 70 mils, the flattest phase response is achieved. Similar values for Δa were obtained for a complete range of values of w. From this data the curves of Figure 4 are drawn. In all subsequent plots the value of Δa corresponding to each value of w as determined in Figure 4 is assumed.

Figure 5 is a plot of variable phase shift per inch (i. e., phase shift at arbitrary setting minus initial phase shift where w = 0) for the curves of Figure 4. In all cases considered, the phase deviation is less than 4^{o} when the proper relationship between Δa and w is maintained.

Figure 6 is a plot of cut-off frequency versus dielectric displacement for minimum phase error. It is seen that if higher order modes are undesirable in the specified 10 per cent bandwidth, cases 3, 4, and 5 must be operated over a very limited range of dielectric displacement. In these cases avoiding the TE_{20} mode results in long insertion lengths. The combination of TE_{20} mode rejection, reasonable insertion length, and ease of adjustment eliminate all but cases 1 and 2 from consideration for the original design requirements. Case 2 was chosen as superior because of the shorter length required and the thicker dielectric which offers greater mechanical rigidity. For 360^{o} of variable phase shift this configuration yields a maximum phase deviation of less than 3^{o}.

To verify the calculated results, an experimental model was constructed with the parameter values of case 2. The active length of the device was 5 inches. Measurements were carefully made on a wide band phase bridge, accurate to $\pm 2^{o}$. For a range of variable phase shift of 360^{o} the maximum phase deviation measured was 5.5^{o}. The experimental values of variable phase shift per inch did not differ from the computed value given in Figure 5 by more than 3^{o}. This degree of correlation between experiment and theory certainly justifies the analytical approach to this design problem.

The above design more than meets the original electrical specifications, however, the mechanical drive of the wall and dielectric slab is somewhat complex. An investigation of a fixed wall structure which offers mechanical simplicity indicated that it could be useful for limited bandwidth applications. A set of design parameters were computed which gave

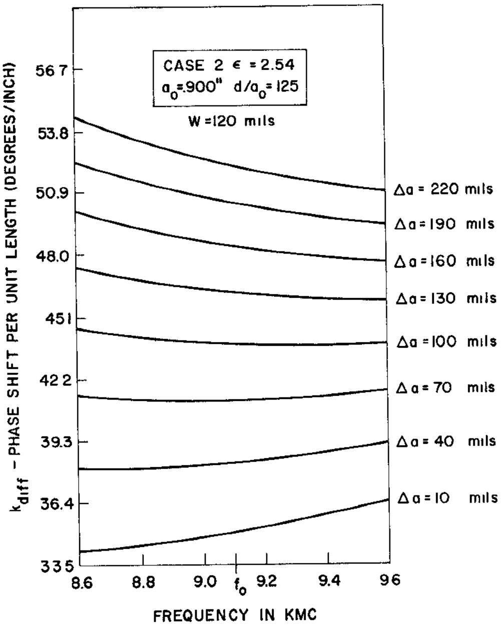

Fig. 3. Phase slope of dielectric loaded waveguide.

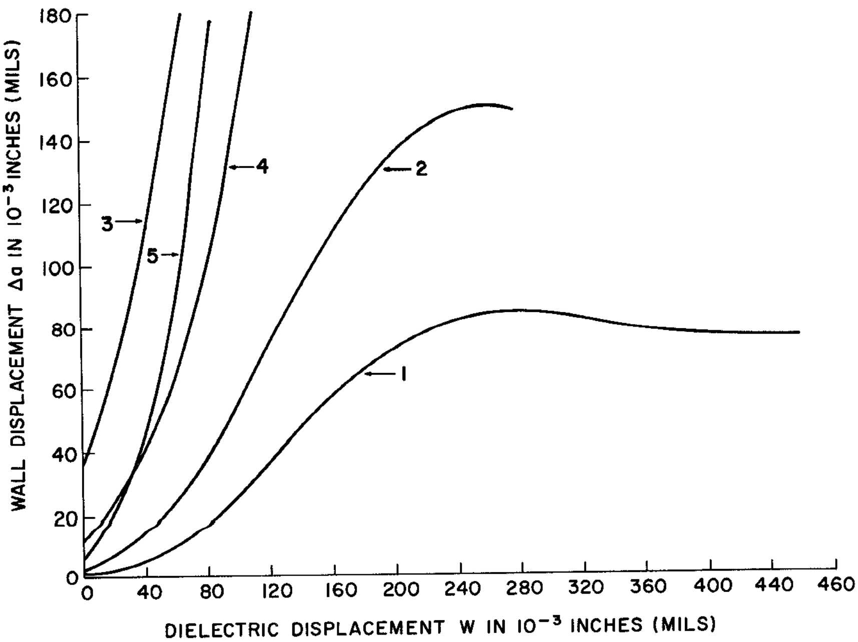

Fig. 4. Wall displacement vs. dielectric displacement for minimum phase error.

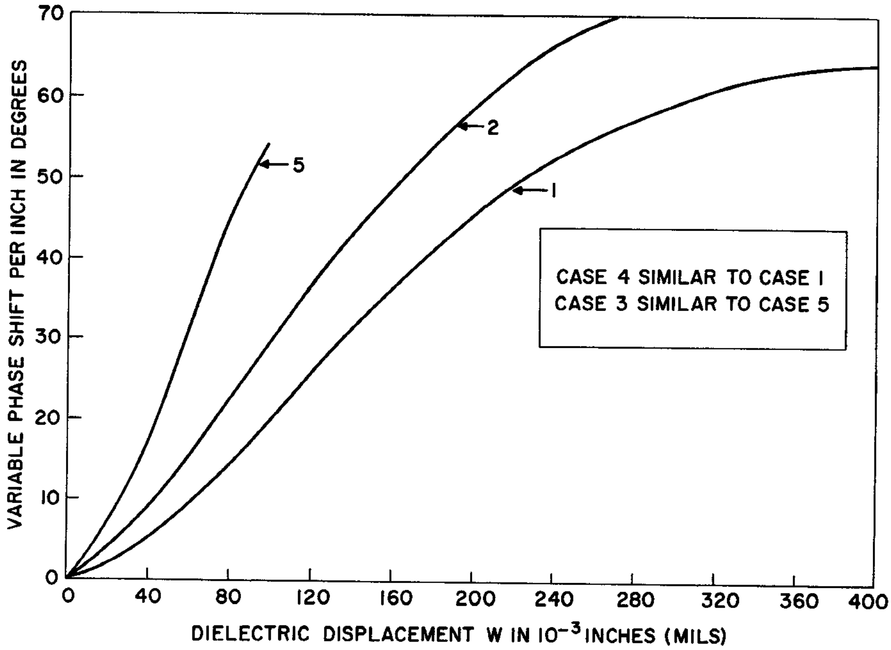

Fig. 5. Variable phase shift per inch.

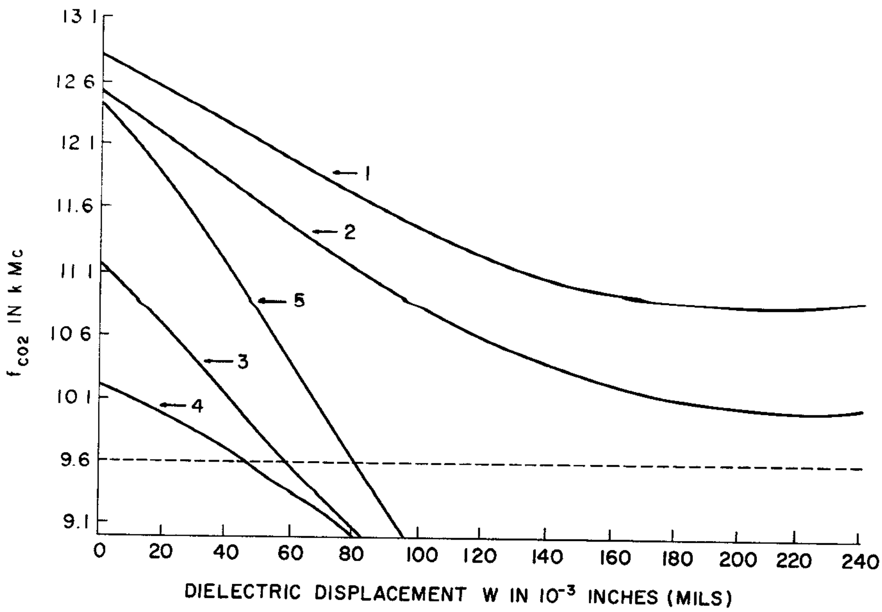

Fig. 6. Cut-off frequency of TE_{20} mode (f_{co2}).

less than 6° phase error over a 6 per cent frequency range. These were $a_o = 0.900''$, $d/a_o = 0.100$, $\varepsilon = 2.54$, $\Delta a = .040''$, $L = 6.8''$ with w still given by $0 \leq w \leq 0.480''$.

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1. The term phase shift is to be understood as differential phase shift, i. e., the absolute phase accumulation through the phase shifting device minus the absolute phase accumulation through a reference waveguide whose length is equal to the insertion length of the phase shifting device.

2. G. D. Carcy and R. E. Hovda, "A Variable Slope, Nondispersive Microwave Phase Shifter," PGMTT National Symposium, 1960.