NOVEL TYPE OF ELECTRICALLY-CONTROLLED PHASE SHIFTER FOR MILLIMETER-WAVE USE: THEORY AND EXPERIMENT

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ABSTRACT

A novel type of electrically controlled phase shifter has been designed and realized at 35 GHz, by using a piezoelectric bimorph actuator. A figure of merit as high as 270°/0.35 dB has been obtained in the Ka band, as well as an insertion loss less than 0.5 dB including the mismatch of rectangular to dielectric waveguide transition. Good agreement has been observed between predicted and measured results.

INTRODUCTION

Electrically-controlled phase shifter has found growing interest in the realization of microwave and millimeter-wave subsystem, such as scannable phased array antenna and electrically tunable filters[1,2]. By making use of piezoelectric material essentially its mechanical deformation under the applied bias voltage, a novel type of electrically controlled phase shifter has been achieved by replacing one or both metallic plates in an insulated dielectric waveguide by metallized piezoelectric bimorph actuator(Fig.1). The required phase shift can then be obtained by choosing an appropriate biasing of this actuator, leading to a modification of the mean distance between the dielectric rod and the conductor plane, and consequently the wavelength is changed.

The design procedure of such a phase shifter is based on a rigorous analysis of an insulated image line. Two theoretical methods have been used here: the Transverse Operator Analysis and the Integral Equation Method. According to the theoretical results, a prototype has been built for 35 GHz operation. A figure of merit as high as 270°/0.35 dB has been obtained in the Ka band, as well as an insertion loss less than 0.5 dB.

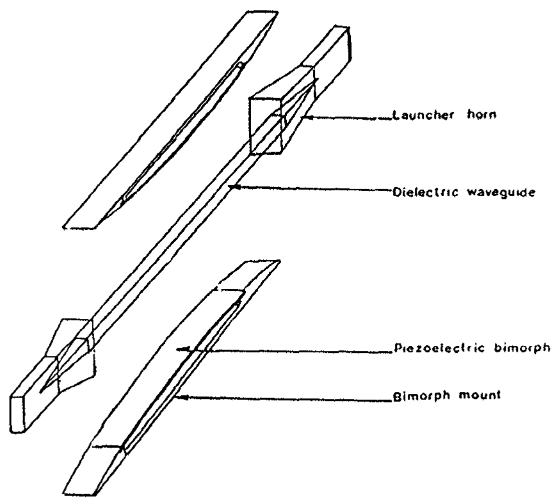

Fig.1 Montage of electrically-controlled phase shifter

THEORY

The basic structure of the phase shifter is an insulated dielectric waveguide. The propagation behaviour, namely the dispersion characteristics of the dominant-mode, has been studied by two different theoretical methods. The transverse operator method, based on an operator representation of Maxwell Equations, presents a great facility for analyzing waveguide with complex cross-section, while the Integral Equation Method, derived from the multimodal variational method, provides more accurate results notably in the low-frequency range.

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Both theories will be briefly described in the following section.

Transverse Operator Method

An isotropic waveguide can be characterized by the transverse electric fields for which the following equation holds[3]

$$\hat{L}E_t(x,y) = k_z^2 E_t(x,y)$$

with

$$\hat{L} = (k_0^2\varepsilon_r+\nabla_t^2)\bar{\bar{I}} + \begin{bmatrix}\partial_x\\ \partial_y\end{bmatrix}\begin{bmatrix}\frac{\partial_x\varepsilon_r}{\varepsilon_r} & \frac{\partial_y\varepsilon_r}{\varepsilon_r}\end{bmatrix}$$

The propagation constant k_z is associated with a variational form defined by

$$\lambda = \frac{\langle H_t, \eta_0 \hat{L} E_t\rangle}{\langle H_t, \eta_0 E_t\rangle} \qquad ,\eta_0 = \begin{bmatrix}0 & -j\\ j & 0\end{bmatrix}$$

By expanding the transverse field E_t on an complete eigenfunction basis $\{e_{tn}\}$, we can obtain the associated eigenvalue equation[3]

$$\bar{\bar{L}}.\bar{X} = \lambda\bar{\bar{\Gamma}}.\bar{X}$$

with

$$(\bar{\bar{L}})_{ij} = \langle h_{ti}, \eta_0 \hat{L} e_{tj}\rangle,\ (\bar{\bar{\Gamma}})_{ij} = \langle h_{ti}, \eta_0 e_{ti}\rangle\delta_{ij},\ \lambda = k_z^2$$

$\bar{X}$ being the expansion coefficients vector.

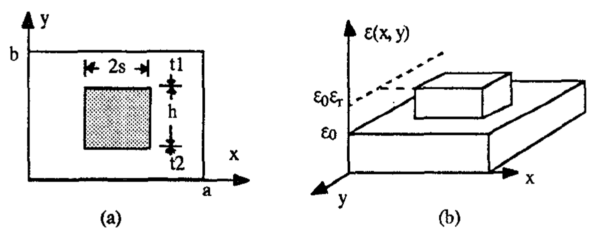

Fig.2 Theoretical model used by TOM
(a)Cross-section of insulated waveguide;
(b)Corresonding permittivity function

Application of this method to the case of an insulated dielectric waveguide consists first in identifying the permittivity function $\varepsilon_r(x,y)$ as indicated in Fig.2, and then in choosing an appropriate basis functions, here the TE-to-x and TM-to-x modes of the corresponding stratified dielectric waveguide[3]. The dominant-mode is then characterized by the largest eigenvalue of the above eigenvalue equation and the corresponding eigenvector. In practical cases, only few eigenmodes (for instance 5) are needed to provide good results.

Integral Equation Method

When the integral equation method is used, the structure is decomposed into air filled and partially filled parallel-plate waveguide as shown in Fig.3a. We have then a discontinuity at the interface x=s by considering the symmetry at x=0.

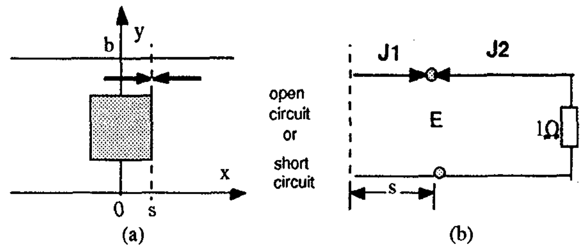

Fig.3 Theoretical model used by IEM
(a)Cross-section of insulated waveguide;
(b)Equivalent network problem

Instead of using the classical generalized transverse resonance method, in which several matrix inversions are needed[4,5], we have formulated this problem in a similar manner as the multimodal variational formulation applied to the characterization of waveguide discontinuities[6]. A surface current density vector is defined at the x=s plan by means of the following expression[6]

$$\mathbf{J} = (\mathbf{H}_t^{(1)} - \mathbf{H}_t^{(2)})\times\hat{\mathbf{x}} = \left(\sum_i y_i^{(1)}\hat{Y}_i^{(1)} + \sum_j y_j^{(2)}\hat{Y}_j^{(2)}\right)\mathbf{E}_t$$

with

$$\hat{Y}_n^{(v)}\mathbf{E}_t = (\mathbf{J}_n^{(v)}/\mathbf{N}_n^{(v)})\int \mathbf{J}_n^{(v)+}\mathbf{E}_t dy$$

$$\mathbf{J}_n^{(v)} = \mathbf{H}_{tn}^{(v)}\times\hat{\mathbf{n}},\ \mathbf{N}_n^{(v)} = \int \mathbf{J}_n^{(v)+}\mathbf{E}_{tn}^{(v)} dy$$

where $\mathbf{J}^{(v)+}$ denotes the adjoint of $\mathbf{J}^{(v)}$. $(\mathbf{E}_{tn},\mathbf{H}_{tn})$ correspond to the oblique incident TE-to-y and TM-to-y mode functions for the partially filled parallel-plate waveguide, and the TE-to-x and TM-to-x mode functions in the air filled one; $y^{(v)}$ is the reduced input admittance seen from x=s, E_t being the tangential electric field in this plane. The continuity of tangential field components across the waveguide junction can then be expressed by the following integral equation[6]

$$\langle E_t, J \rangle = 0$$

By expanding the field components on the basis of partially filled parallel-plate waveguide modes, the propagation constant will be given by the non-trivial solution condition of above equation, as well as the corresponding field distribution.

PHASE SHIFTER DESIGN

Since the phase shift is achieved by introducing a small change in the air layer thickness in an insulated dielectric waveguide, we shall first determine the dependence of normalized propagation constant k_z/k_0 on this parameter. Fig.4 shows the theoretical variation of normalized propagation constant versus frequency, as a function of the air layer thickness. Good agreement can be observed between the results obtained by these two methods, except for the lower frequency range in which the Transverse Operator Method will be less accurate as discussed in [3].

For an insulated dielectric waveguide of length L, by introducing a small change in the air layer thickness, t_1 to t_2, the phase shift is given by

$$\Delta\Phi = L.[k_z(t_2)-k_z(t_1)]$$

In practice, the change of air layer thickness is progressive due to the bimorph actuator bending(Fig.1), the correct phase shift will be given by the following relationship

$$\Delta\Phi = \int_{z_1}^{z_2} [k_z(t_2,z)-k_z(t_1,z)]dz$$

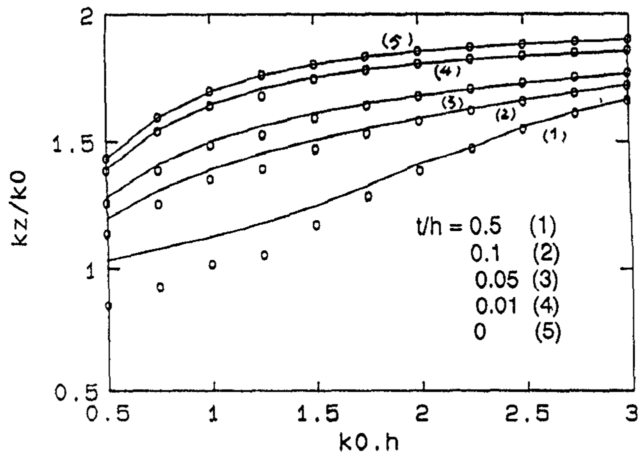

Fig.4 Normalized propagation constant versus normalized frequency;ε_r=3.8;s/h=1;t1=t2=t;
(___) Integral Equation Method;(o o) TOM

Several points should be kept in mind when designing such a phase shifter:

* an insulated guide of high permittivity provides more efficiency per unit length, but can also introduce mismatch at the extremities of the waveguide;

* small air gap between the dielectric rod and the metallized plate gives good efficiency but a precise control of relative positions may be rather difficult;

* a large displacement of the piezoelectric actuator requires more rise time and/or high switching energy.

EXPERIMENT

The theoretical and measured results of a phase shifter with one bimorph on the bottom of dielectric rod has been given in Fig.5. Good agreement can be observed between the measured phase shift and that obtained by considering the bimorph actuator bending, while the results obtained by considering uniform air gap present a relatively large error. We can see that, on one hand, the bending of bimorph actuator reduces slightly the phase shifter efficiency, and on the other hand the mismatch of the metallic to dielectric waveguide transition has been equally reduced.

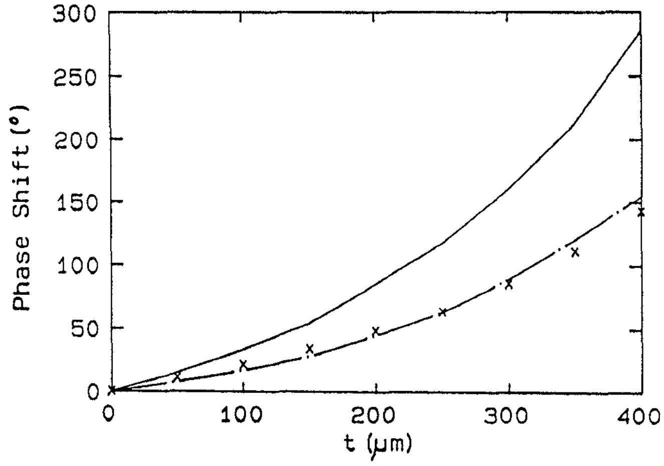

Fig.5 Comparison between theory and measurement; f=35 GHz; L=70mm; (__) Theory with uniform air gap; (-.-) Theory with actuator bending; (x x)Measured data

In Fig.6 we compare the theoretical and experimental phase shift versus actuator bending for both one and two bimorph cases at 35GHz. One can see that the two bimorph setup presents a phase shift of about 70% greater than that of one bimorph setup. The measured insertion losses are less than 0.5 dB for a 70 mm long phase shifter as shown Fig.7.

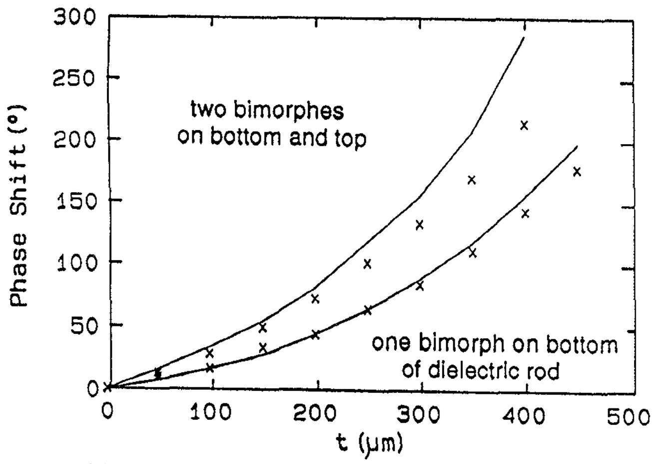

Fig.6 Phase shift versus bimorph bending; (__)Theoretical results; (x x)Measured data

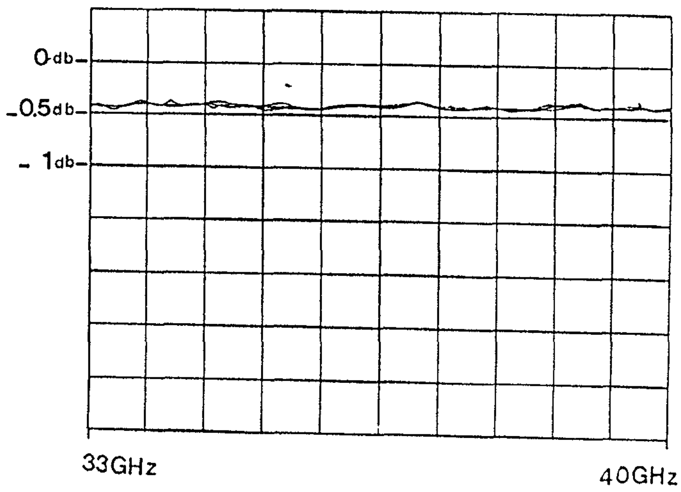

Fig.7 Measured insertion losses of phase shifter

CONCLUSION

By using a piezoelectric bimorph actuator, a novel type of electrically controlled phase shifter has been designed and realized in the Ka band. The measurements have shown a high figure of merit and low losses. The design procedure can be equally extended to the W band.

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