DOUBLE RIDGED WAVEGUIDE PHASE SHIFTERS FOR BROADBAND APPLICATIONS

El-Badawy El-Sharawy, Senior Member IEEE

Department of Electrical Engineering
Telecommunication Research Center
Arizona State University, Tempe, AZ

Abstract

This paper presents an electromagnetic mode matching analysis of dual ridged waveguide phase shifters. The waveguide is loaded with a high dielectric material between the ridges and the troughs are filled with ferrite toroids. The present structure offers nearly twice the bandwidth and less variation in nonreciprocity versus frequency as compared to the conventional dual toroidal phase shifter.

1. Introduction

Modern microwave antennas, radars, and communication systems are moving toward higher frequencies. Requirements for those systems call for reconfigurable phase shifting structures that can operate over broad bandwidth, and have low loss at millimeter-wave frequencies. Recently, a slot line dual toroidal phase shifter has been developed [2] to increase the bandwidth and nonreciprocity of ferrite phase shifters. However, slot lines have relatively high losses (250 deg/dB) as compared to waveguides (more than 500 deg/dB). In addition, the slot to ground plane connection inside a waveguide is not easy to produce.

The present paper investigates a novel approach to increase the bandwidth of waveguide phase shifters without sacrificing low loss or ease of construction. The new structure is comprised of two ferrite toroids inside a ridged waveguide. The ridges are separated by a high dielectric constant material and the troughs are filled with two toroids as shown in Fig. 1b. Since ridged waveguides have inherently a very broadband (typically 3:1), the new phase shifter will have a broadband of operation.

When a ferrite layer has two boundaries with air, the field ellipticities at the boundaries will be opposite in sign [1-4]. Since the differential phase shift results from the interaction between these elliptic fields and the magnetic material [4], the opposite ellipticities will counteract each other and result in a poor nonreciprocal behavior for single layer structures. Adding a layer of high dielectric material at one of the ferrite boundaries replaces one of the aforementioned ellipticities by a co-acting ellipticity [2-4].

The present approach is to use two oppositely magnetized ferrite layers (see Fig. 1b) in addition to the high dielectric material. Although the two magnetic layers have opposite field ellipticities, their nonreciprocity add up because of the opposite magnetizations. Note that, the high

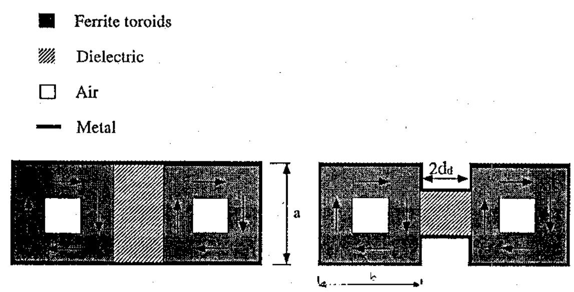

Figure 1. Geometry of the dual toroidal phase shifter a) conventional, b) ridged

dielectric constant layer is used to prevent magnetic leakage from one ferrite layer to another and to further enhance the nonreciprocal performance.

The analysis in the present work is based on the mode matching technique in the spectral domain [5-7]. Spectral domain techniques can easily be adopted for a wide variety of structures. However, the formulation of a Green's function represents a major complexity in that approach. Solving for a Green's function as a boundary condition problem is quite difficult for magnetic substrates and becomes more complicated for multilayer structures. In addition, Green's functions in such a procedure will only be useful for the specific structures for which they are derived. A more flexible approach is to find the transmission matrix [3,4] of the medium and then use this matrix to find the Green's function. The analysis is then used to calculate the propagation constant which is necessary to calculate the differential phase per unit length for different frequencies.

2. Theory

The propagation constant of an infinitely long ridged waveguide structure is found using the mode matching technique in the spectral domain [5-7]. Green's functions, as described in [3], are used to find the surface currents at the plane of discontinuity $\bar{J}(y)$ in terms of the transformed electric fields $\tilde{\bar{E}}$ using

$$\bar{J}(y) = \frac{1}{a} \sum_{i=-\infty}^{\infty} \tilde{\bar{\bar{G}}}_s(-\beta, k_{yi})\, \tilde{\bar{E}}_i(k_{yi})\, e^{jk_{yi}y} + \frac{1}{s} \sum_{i=-\infty}^{\infty} \tilde{\bar{\bar{G}}}_s'(-\beta, k_{yi}')\, \tilde{\bar{E}}_i(k_{yi}')\, e^{jk_{yi}'y} \qquad (1)$$

where the tilde (~) denotes the Fourier transform. The conducting sidewalls restrict kyi to the values $i\pi/a$, where i is even, so the Fourier transform with respect to y is discrete. Note that, kyi is different for different cross-sections of the waveguide. For the ridges, k'yi takes the discrete values of $i\pi/s$ and s is the ridge sepsration. The boundary conditions, $\bar{J}(y) = 0$, are enforced by multiplying the above equation by the field modal expansion functions ($e^{jk_{yi}y}$) for different field regions (the ridged and the trough regions)

Application of the above procedure results in an admittance matrix; the solution for the propagation constant, β, is the value that forces determinant of this admittance matrix to zero. The difference between the propagation constants of the forward and reverse waves is used to find the nonreciprocal phase shift per unit length, as $\Delta\phi = \beta_f - \beta_r$. Three to five modal functions in each direction (total of 14 modal functions including the ridged and the trough regions) have been found to be sufficient for convergence.

3. Results

Figure 2 shows the differential phase of a ridged waveguide phase shifter as compared to conventional dual toroidal phase shifter. As shown in this figure, the effects of double ridged waveguide is to flatten the differential phase over the bandwidth. For the conventional waveguide phase shifter (with s=a), the phase shift varies significantly versus frequency.

The bandwidth is limited at the upper end by the the excitation of higher order modes ant at the low end by magnetic losses of the ferrite material. For the ferrite material simulated in this paper, the low end frequency was about 6 GHz. In general, as the ridge separation increases, overmoding occurs at lower frequency, with the minimum occuring when the ridge height equals the sidewall separation; i.e. no ridges exist in the structure. Figure 3 shows the normalized propagation constant for ridged waveguide and conventional phasers. For a single mode of operation, only one solution for β should exist for the same direction of propagation. Overmoding, where more than one solution exist, starts to occur in conventional waveguide phase shifters approximately at 9.5 GHz compared to 16.0 GHz for the ridged waveguide of the same outer dimensions. Thus, the bandwidth of conventional waveguide phase shifters is about 65 % less than the double ridged phase shifter. The differential phase and bandwidth of a ridged waveguide phase shifter has been compared to that of a dual toroidal slot line phase shifter with the same ferrite and high dielectric layers [2]. For the same bandwidth, the ridge waveguide gave similar nonreciprocity to that of the slot line phase shifter .

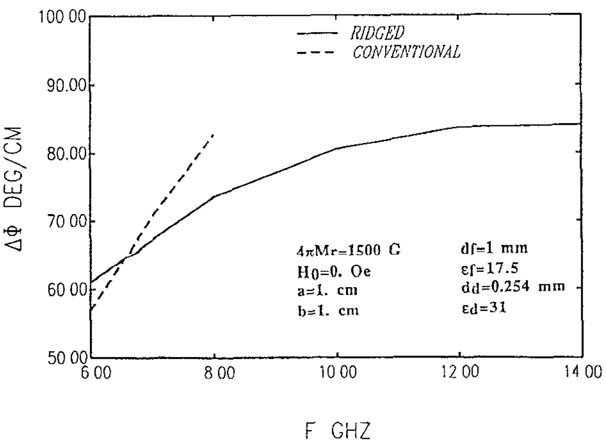

Figure 2. Differential phase of ridged and conventional waveguide phase shifters.

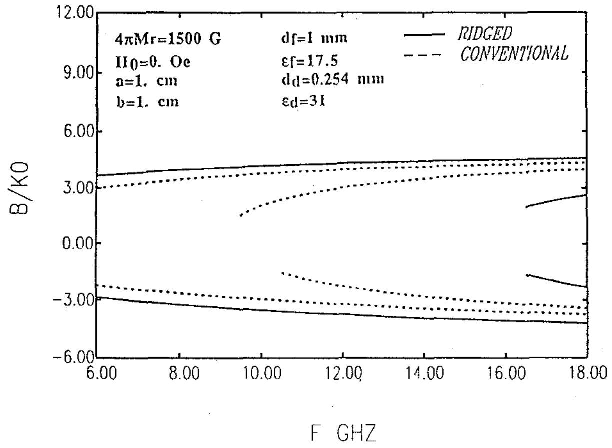

Figure 3. Normalized propagation constants for ridged and conventional waveguide phase shifters.

4. Conclusion

The double ridged waveguide employs the concepts discussed in section 1 to maximize both performance and bandwidth. Twice the bandwidth of traditional waveguide phase shifters or more with less variation in the differential phase versus frequency has been predicted for the new phase shifter. Future work will include optimizing the ridged phase shifter configuration and design to increase nonreciprocity and bandwidth.

References

1. R. Johnson and H. Jasik, **Antenna Engineering Handbook**, McGraw Hill, 1984.
2. E. El-Sharawy and C. Koza,"Dual-ferrite slot Line for broadband, high-nonreciprocity phase shifters," IEEE Trans. MTT, accepted to appear, Vol. 39, No. 12, Dec. 1991
3. E. El-Sharawy and R. Jackson, "Coplanar waveguide and slot line on magnetic substrates: analysis and experiment," IEEE Trans. Microwave Theory Tech., Vol. MTT-36, pp.1071-1079, June, 1988.
4. E. El-Sharawy and R. Jackson, "Analysis and design of microstrip-slot line for phase shifting applications," IEEE Trans., Microwave Theory Tech., Vol. MTT-38, No. 3, pp.276-283, March, 1989.
5. R. Vahldiek," A modified mode-matching technique and its applications to a class of quasi-planar transmission lines,"IEEE Trans., Microwave Theory Tech., Vol. MTT-33, No. 10, pp.916-925, March, 1989.
6. F. Lange, "Analysis of shielded strip and slot lines on a ferrite substrate transversely magnetized in the plane of the substrate," Electronics and Communication, AEU, Band 36, Hefts, pp. 95-100, March, 1982.
7. G. Bock, "New Multilayered Slot Line Structures with High Non-Reciprocity," *Elec. Lett.*, Vol. 19, No. 23, pp.966-968, Nov. 1983.