A Wide-Band Corrugated Rectangular Waveguide Phase Shifter for Cryogenically Cooled Receivers

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***Abstract*— A wide-band phase shifter rectangular in cross section with transverse corrugations on all four walls is presented in this letter. The loading for the two orthogonal modes is different and is achieved by choosing dissimilar corrugation parameters. This phase shifter measures a return loss of -25 dB or better and differential phase shift of 90°± 3.3° between 18.9–26.5 GHz. This all-metal robust phase shifter is ideal for cryogenically cooled radio astronomy receivers.**

***Index Terms*— Circular polarization, microwave circuits and systems, phase shifter, polarizer.**

I. Introduction

RECEIVER systems for most radio astronomy applications are required to have high-gain and low-noise performance over a wide bandwidth. The receiver noise is a critical parameter because of the weakness of the signals typically encountered in radio astronomy. The bandwidth requirement arises from the need to provide continuous frequency coverage with minimum number of receivers on a given radio telescope. Cryogenically cooled heterostructure field-effect transistor (HFET) amplifiers [1] and corrugated feed horns possess the above desired properties and are used routinely in radio astronomy applications. Radiation from many radio sources are strongly polarized and, hence, a polarizer is an essential component of the receiver system. Quadridged orthomode transducers which separate linearly polarized signals [2] with bandwidth ratio of 2.2 : 1 have been fabricated for frequencies below X-band. A septum polarizer [3], which separates the two opposite sense circularly polarized signals, is used at higher frequency bands but has a typical bandwidth ratio of only 1.25 : 1. Alternatively, a combination of an orthomode transducer (OMT) and a differential phase shifter is capable of discriminating between circularly polarized signals. A wide-band (1.42 : 1) OMT based on a symmetrical design which separates two orthogonal signals has been reported in the literature [4]. A phase shifter with dual-depth E-plane corrugations [5] is reported to have a bandwidth ratio of 1.32 : 1 for a differential phase shift of 90°±1° between the two orthogonal modes. A rectangular waveguide phase shifter with dielectric loading on one set of opposite walls and transverse corrugations on the other set of walls has demonstrated differential phase shift of 90°±3° over a bandwidth of 1.43 : 1 [6]. Receivers for radio astronomy applications most often operate at a physical temperature of 15 K and a phase shifter with dielectric loading is not suitable for such an environment. An all-metal phase shifter which has transverse corrugations on all four walls with a bandwidth ratio of 1.40 : 1 is reported in this letter.

II. Design

In a conventional rectangular waveguide phase shifter where only one set of walls is loaded with either dielectric or artificial dielectric, the asymptotic propagation constants for the two orthogonal modes (TE_{10} and TE_{01}) as a function of ka ($k = 2\pi/\lambda$ is the wavenumber, λ is the free-space wavelength, and a is the cross-sectional width) are shown in Fig. 1(a). The differential phase shift, as a function of ka shown in Fig. 1(b), goes through a minimum at about the center of the band where the slope of the propagation constants is the same for the two modes. For perfect amplitude match of the two fundamental modes, the axial ratio in decibels is given by

$$\text{AR (dB)} = 10\,\log\,\frac{2+[2+2\,\cos(2\theta)]^{1/2}}{2-[2+2\,\cos(2\theta)]^{1/2}} \tag{1}$$

where θ is the phase difference between the two modes. For an axial ratio of 0.5 dB, (1) gives a phase error of $\pm 3.3°$ about 90°. The conventional phase shifter has a bandwidth ratio of 1.33 : 1 for a 0.5-dB axial ratio. A phase shifter reported by Lier *et al.* [6] in 1988 with dissimilar loads has differential phase shift curve with a minimum and a maximum shown in [6, Fig. 2(b)] and is obtained by enforcing the slope of the propagation constants of the two modes to be equal at two different frequencies. Lier *et al.* measured a differential phase of 90°± 3.3° over a bandwidth ratio of 1.45 : 1.

The phase shifter reported here has transverse corrugations on all four walls of a rectangular waveguide and has a bandwidth comparable to that in [6]. A similar phase shifter reported in [7] has bandwidth only marginally larger than the conventional phase shifter. In a waveguide with transverse corrugations, for a field polarized in the Y direction (Fig. 2), the transcendental equation for the TE_{10} mode is given by

$$k_y\,\tan\left(\frac{k_y b}{2}\right) = -\frac{w}{p}\,\beta_1\,\tan(\beta_1 h) \tag{2}$$

where

$$\beta_1^2 = k^2 - \left(\frac{\pi}{a}\right)^2 \tag{3}$$

$$k_y^2 = \beta_1^2 - \beta_y^2. \tag{4}$$

Manuscript received December 20, 1996.

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Publisher Item Identifier S 1051-8207(97)03859-2.

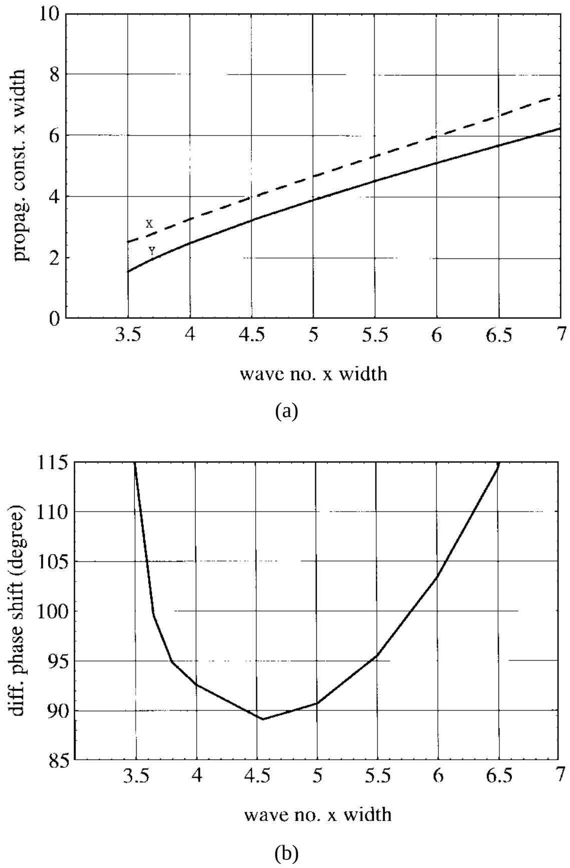

Fig. 1. Conventional rectangular waveguide phase shifter. (a) Dispersion characteristics (X-polarization orthogonal to load). (b) Differential phase shift versus frequency.

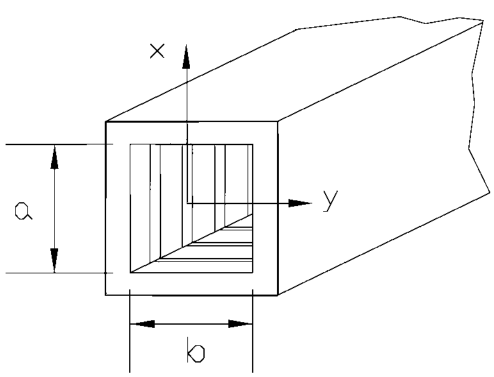

Fig. 2. Corrugated rectangular waveguide phase shifter.

Here β_y is the propagation constant for the Y-polarized mode, a and b are the cross-sectional widths, and w, h, and p are the width, depth, and pitch of the corrugations, respectively.

When β_y is greater than β_1, (2) becomes

$$k_y \tanh\left(\frac{k_y b}{2}\right) = \frac{w}{p}\beta_1 \tan(\beta_1 h). \tag{5}$$

An assumption made in arriving at (2) or (5) is that $p/\lambda \ll 1$.

By optimizing on the parameters a, b, h, and w/p, dissimilar loadings for each of the pairs of opposite walls were chosen

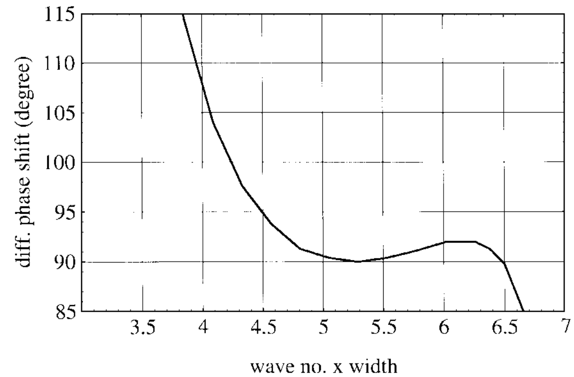

Fig. 3. Corrugated rectangular waveguide phase shifter. Differential phase shift versus frequency.

so that the differential phase shift curve has the characteristics shown in [6, Fig. 2(b)]. The devices that are coupled to the phase shifter have square cross sections at the phase shifter end which constrains the ratio of a/b to be close to unity. In this case, the ratio is $1.049 : 1$. The calculated differential phase shift between orthogonal modes as a function of frequency is shown in Fig. 3.

III. Fabrication and Measurement

A rectangular waveguide phase shifter was fabricated for the 18–26.5-GHz band. It has four corrugations per free-space wavelength at the upper band edge (λ_{high}) on all walls. One set of opposite walls has corrugations with w/p ratio of 0.1, while the other set has a ratio of 0.2. The corrugation depth is also different on each set of walls and is approximately 0.2 λ_{high}. The depth is gradually reduced to zero at both ends of the phase shifter in order to obtain good match. The length of the phase shifter is 4.180 in. Pieces that form opposite walls were milled from a single slab of brass for the purpose of uniformity and then slit. A bar stock is used at each corner for terminating the corrugations for maintaining symmetry. All the components of the phase shifter are gold plated. Corrugations on the four walls of the guide are carefully aligned before the pieces are fastened.

Measured return loss for the two orthogonal polarizations is better than −25 dB in the 18–26.5-GHz band. The differential phase shift between the two modes, measured using a network analyzer, is shown in Fig. 4. Between 18.9–26.5 GHz, the phase shift is $90° \pm 3.3°$ and between 18.1–26.5 GHz, it is $90° \pm 6.6°$ corresponding to 1-dB axial ratio. The insertion loss for either of the two modes is less than 0.2 dB.

IV. Conclusions

A wide-band phase shifter made completely out of metal with corrugations on all four walls is shown to yield a bandwidth ratio of 1.46 : 1 for 1-dB axial ratio. The phase shifter will be used in the K-band receiver of the Very Large Array (VLA) operated by the National Radio Astronomy Observatory (NRAO). The phase shifter is inside the dewar at an operating temperature of 15 K. The phase shifter is simple and easy to machine. Therefore, it is ideal for an application

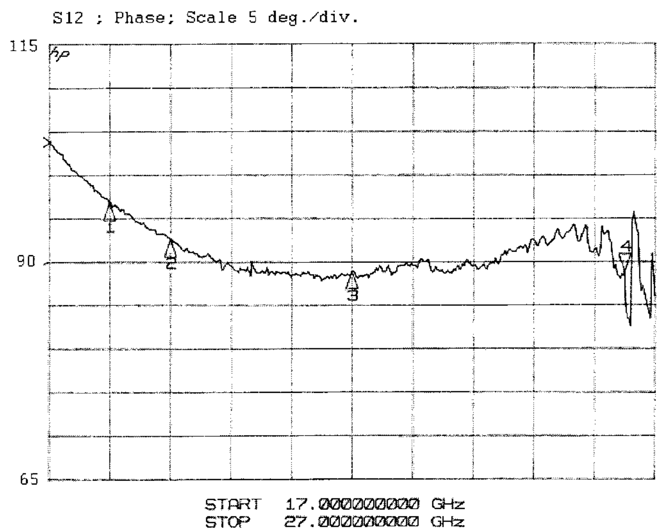

Fig. 4. Measured differential phase shift versus frequency for the corrugated phase shifter.

such as the VLA, which requires a number of polarizers for the different receivers.

A key to wide-band performance is to obtain a maximum and a minimum on the differential phase shift curve. In this letter, we have demonstrated that such a characteristic can be obtained by loading all four walls of the phase shifter with corrugations. When assembling the four walls of the phase shifter, care should be taken to provide good electrical contact at the junctions. This is critical for obtaining good return loss, which is essential for the functioning of the phase shifter.

ACKNOWLEDGMENT

The author would like to thank M. Balister, N. Horner, F. Johnson, E. Lier, V. Summers, G. Taylor, and E. Wollack for their valuable contributions. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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