Planar Noncontacting Short Circuits For Millimeter-Wave And Submillimeter-Wave Applications

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Abstract—**Adjustable planar noncontacting short circuits for both rectangular and circular waveguides have been designed and tested. The planar configuration allows these short circuits to be fabricated photolithographically, therefore reducing fabrication cost and eliminating the machining tolerance requirements of conventional noncontacting short circuits. Scale model tests show that the new short circuits can offer a return loss < 0.1 dB and linear phase variation over a single mode bandwidth. Successful application of a planar short circuit in a 300–365 GHz mixer further demonstrates the usefulness of these short circuits at high frequency.**

I. Introduction

ADJUSTABLE waveguide short circuits are often required as reactive tuners in applications involving waveguides. At frequencies above about 100 GHz, conventional contacting short circuits generally become impractical and the noncontacting type of short circuits are usually used instead. These noncontacting short circuits have been designed for both rectangular and circular waveguides. They typically operate by coupling the dominant waveguide mode into a similar coaxial mode and forming a short circuit with a series of alternating high- and low-impedance quarter-wavelength coaxial sections. Different kinds of such short circuits have been studied before. Noncontacting short circuits using a circular plunger, i.e., the center conductor, have been designed to offer a return loss < 0.1 dB and a smooth phase variation over a single mode bandwidth [1]. A rectangular plunger, centered in a waveguide with mylar adhesive tape, has also been used with some success [2]. Both of these configurations, however, require impractical machining tolerances for submillimeter-wave applications. Recently a different approach for noncontacting short circuits has been proposed that eliminates the machining tolerance requirement by using a structure that can be fabricated photolithographically. Using a metallic bar with regularly spaced holes centered in a rectangular waveguide with mylar tape, a reflection coefficient > 0.99 has been demonstrated over a 40% bandwidth [3].

In this letter, we report the design and testing of new planar adjustable noncontacting short circuits that can be fabricated using photolithography techniques, for both circular and rectangular waveguides. As the results will demonstrate, these noncontacting short circuits offer good reflection performance in both magnitude and phase over an entire single mode bandwidth.

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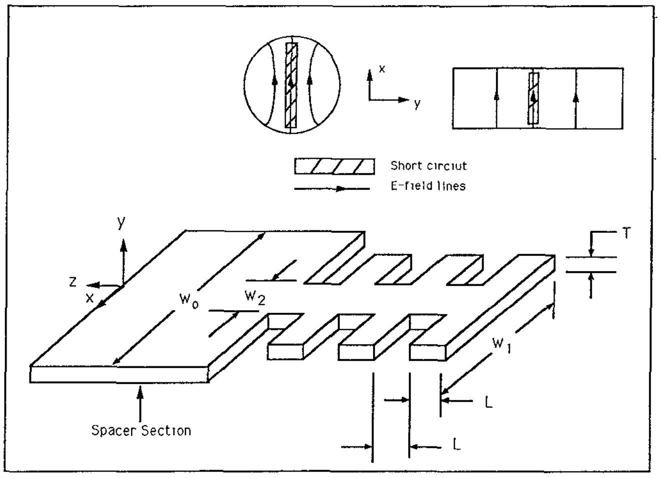

Fig. 1. Planar short circuit for circular and rectangular waveguides. The insert illustrates the placement of a short circuit in a circular and rectangular waveguide, respectively.

II. Design and Testing

As characterization of short circuits are difficult at millimeter- and submillimeter-wavelengths, the design of planar noncontacting short circuits has been carried out using scale model measurements. The (seven section) planar short circuit shown in Fig. 1 consists of alternating impedance sections, which serve the same function as in conventional noncontacting short circuits with a circular cross section, i.e., coupling the dominant waveguide mode into a coaxial waveguide mode. Their planar configurations, however, allow them to be fabricated photolithographically with sizes small enough for the entire submillimeter-wave spectrum. For efficient coupling between the dominant waveguide mode and the coaxial mode, the plane of these short circuits must be aligned with the E-plane of the waveguide mode, as shown in Fig. 1. This alignment can be maintained with a nonrotating micrometer during short circuit adjustment.

The scale model used to test the planar short circuit designs consists of coaxial-to-microstrip and microstrip-to-waveguide transitions. An HP8510B network analyzer was connected to the model and calibrated to a reference plane in the waveguide by a set of four waveguide offset short circuits of different lengths. Reflection (S_{11}) measurements for various short circuit designs were made at this reference plane. Measurement

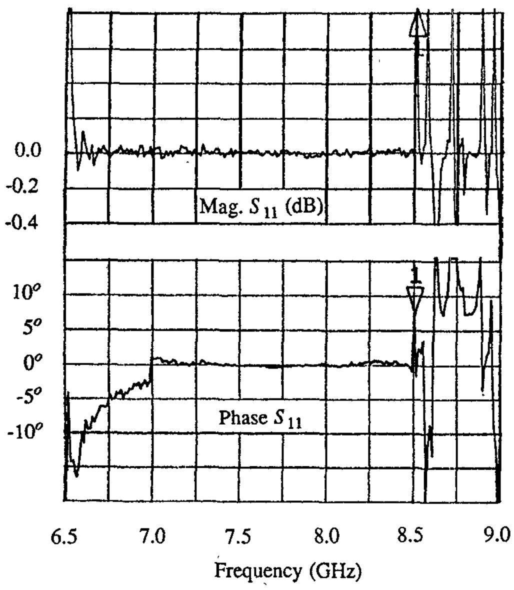

Fig. 2. Scale model measurement results for five section planar short circuit in a 27.0-mm diameter circular waveguide. Design parameters are $W_o = 25.7$, $W_1 = 22.2$, $W_2 = 5.7$, $L = 6.9$, and $T = 1$ mm. Marker 1 indicates the first resonance that limits the bandwidth.

of a fifth fixed waveguide short circuit standard indicated a calibration error that is smaller than 0.05 dB in magnitude and 1° in phase over a waveguide bandwidth [4], [5].

A. Circular Waveguide

Circular waveguide is often preferred over rectangular waveguide at submillimeter-wavelengths for its easier fabrication [5], [6]. Simple transmission line analysis [5] was used to calculate the initial length and width dimensions for a single low impedance section. S_{11} measurements for a single low impedance section backed with a cone of absorber and placed in a circular waveguide were then performed and its dimensions were adjusted in an empirical manner to yield the best reflection performance. It should be noted that the thickness of the short circuit was found to have minimal effect on measurement results, so it was made as thin as mechanically possible.

Next, using these optimum dimensions for the low-impedance sections, three section and five section short circuits were designed by an empirical procedure to give even better return loss. (More than five sections were found to offer no further improvement.) The high-impedance section was made as narrow as possible, while still offering enough physical support for the other sections. Optimum dimensions for a five section short circuit is given in Fig. 2. The widest section is the spacer section that holds the short circuit in the center of the waveguide. It has a width W_o which gives a clearance of 0.015 mm from the waveguide walls when used at 300–365 GHz.

Both the three section and five section short circuits offer a return loss < 0.1 dB and a smooth phase variation over a single mode bandwidth. The reflection response for a five section short circuit aligned with the maximum electric field of the TE_{11} mode is shown in Fig. 2 over a 6.5 GHz to 8.5 GHz bandwidth. A strong resonance occurs at 8.5 GHz,

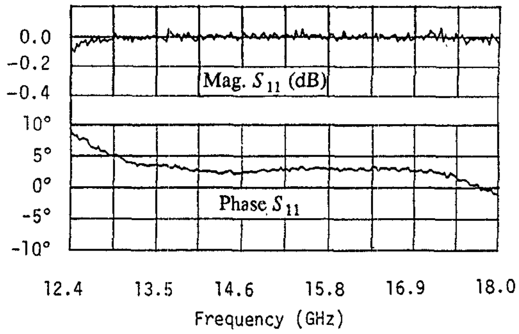

Fig. 3. Scale model measurement results for seven section planar short circuit in a Ku-band waveguide. Design parameters are $W_o = 7.1$, $W_1 = 6.6$, $W_2 = 1.0$, $L = 5.1$, and $T = 0.05$ mm.

the cutoff frequency of the second order TM_{01} mode. The nonlinear phase variation and erratic magnitude variation at around 6.5 GHz are due to 1) the rapid change in guide wavelength near the cutoff frequency of the TE_{11} mode at 6.5 GHz and 2) calibration error in a frequency range where the coupling between the microstrip and waveguide is poor.

The five section design has also been tested for performance sensitivity to lateral and axial alignment errors [5]. There is little variation in return loss as the waveguide short is moved laterally as far as the spacer section allows. However, lateral misalignment does introduce a nonlinear phase variation with frequency in S_{11}. For axial alignment errors smaller than 5°, the deviation in return loss is less than 0.1 dB, but it can reach as much as 0.6 dB for alignment errors between 5° and 10°.

B. Rectangular Waveguide

Using the same scale model design approach, similar results were obtained for planar adjustable waveguide short circuits in rectangular waveguides. These short circuits also operate by coupling the dominant waveguide mode into a coaxial mode and forming a short circuit with alternating high- and low-impedance quarter-wavelength sections. A seven section short circuit, with the dimensions given in Fig. 3, was found to offer a return loss < 0.1dB and a nearly linear phase response over the entire single mode bandwidth (Ku-band), as shown in Fig. 3. As with the circular waveguide short circuit design, the return loss was found to be relatively insensitive to the short circuit thickness, which was therefore kept as small as possible. The bandwidth over which the short circuit operates decreases as it is rotated or displaced from the yz plane shown in Fig. 1. For a 10° rotation or a displacement in the x direction by 10% of the larger waveguide dimension, the bandwidth decreases by approximately 10%. (The short circuit position can be maintained in the y direction by attaching metallic blocks to each side of the spacer section so the variation in return loss can be reduced.)

III. Fabrication and Application at Submillimeter-Wavelengths

The five section short circuit for the circular waveguide has been fabricated photolithographically and used in a 300–365-GHz mixer. The thickness of the metal is what ultimately limits the resolution of the fabrication process. To minimize the thickness, a high strength metal, beryllium copper (BeCu), is used. A thickness of 0.025 mm was chosen and standard patterning and chemical etching of the BeCu short circuit sheets was carried out by Towne Labs [7]. A five section short circuit was then used as part of the tuning circuit in a planar diode submillimeter-wave mixer [5], [6], and the mixer performance from 300 to 365 GHz was found to be competitive with the best room temperature mixers for this frequency range.

IV. Conclusion

Planar noncontacting short circuits that can be fabricated photolithographically for millimeter-wave and submillimeter-wave applications have been designed and tested. Scale model measurement results show that a return loss < 0.1 dB and linear phase variation over a single mode bandwidth can be achieved with these short circuits for either circular or rectangular waveguide. A circular waveguide short circuit design has been successfully used as part of a submillimeter-wave planar diode mixer, which further demonstrates the usefulness of these short circuits. To more definitely identify the advantages of planar short circuits over the conventional ones, a direct comparison in performance between submillimeter-wave components using these short circuits will be desirable in the future.

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