Short Papers

Analysis and Measurement of Mode Polarizers in Square Waveguide

W. R. Gaiewski, L. P. Dunleavy, and A. Castro, Jr.

***Abstract*—A general analysis approach for strip metallization structures enclosed in rectangular or square waveguide is presented. The technique involves the novel application of a commercially available 2.5-dimensional (2.5-D) method-of-moments-based (MoM) electromagnetic (EM) analysis tool to a three-dimensional (3-D) waveguide problem. Very good agreement is demonstrated between computed and measured results for several printed strip linear polarizers embedded within a square waveguide environment. This paper, to the authors' knowledge, represents the first such comparison of phase and magnitude between computed and measured data for strip grid polarizers in a waveguide environment. The developed approach involves construction of a theoretical waveguide "test fixture" and an associated theoretical de-embedding procedure. Computational advantages are expected over the alternative approach of using a finite-element-based fully 3-D analysis approach. The polarizer results have potential application to shielded versions of quasi-optic array components that have been demonstrated in open geometries, as well as to multimode antenna feeds, waveguide filters, and matching networks.**

***Index Terms*—Electromagnetic analysis, polarizers, waveguide.**

I. Introduction

Linear polarizers perform an important function in quasi-optic grid array amplifiers [1]–[3]. In these designs, the input and output waves are cross-polarized to prevent instabilities in the amplifiers. To date, most such amplifiers have been demonstrated in open environments and various analysis techniques have been used [1], [2], [4]. A square waveguide can support two orthogonal dominant modes and, hence, can also utilize the same polarization principles of unbound electromagnetic (EM) waves. Some early literature using enclosed waveguide environments for quasi-optic amplifier work has been reported [5], [6], including one study that specifically used a polarizer within a square waveguide [3]. However, the authors found little or no information available in the literature on the design or performance of waveguide-based polarizers.

In this paper, several advances in waveguide polarizer techniques are presented. The first known comparisons are reported of computed and vector S-parameters for strip grid polarizers in a waveguide environment. The computations are enabled by a novel application of a 2.5-dimensional (2.5-D) method-of-moments simulation tool (Sonnet Software's **em**) to a three-dimensional (3-D) waveguide problem. This involves the construction of a theoretical waveguide "test fixture" and an associated theoretical de-embedding procedure. This method, which calculates S-parameters from only the currents on discretized metal structures within the waveguide, should have computational advantages over the finite-element approach widely used for general 3-D structure analysis.

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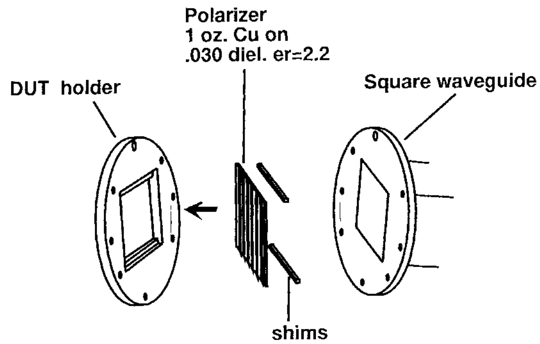

Fig. 1. DUT holder and sample polarizer for measurement fixture.

II. Fixture and Polarizer Development

The test fixture used consists of two standard C-band (WR187) coaxial–to–waveguide transitions, a pair of linearly tapered waveguide sections to match the C-band waveguide to two 1.75-in square waveguide sections and a holder for a device under test (DUT). The tapers are more than a half-wavelength long above the first cutoff frequency of the square waveguide. The DUT holder was constructed from 0.25-in solid brass, with a 1.75-in square hole in the center. This piece and a sample polarizer are shown in Fig. 1. The device is immobilized by pressure contact when the fixture is assembled and bolted. This pressure contact allows the ends of the polarizer strips to contact the waveguide sidewalls.

Rectangular waveguide is typically designed for single-mode (e.g., TE_{10}) operation. The dimensions are chosen to maximize the usable dominant-mode bandwidth while minimizing losses. A rectangular waveguide of square cross section can theoretically support exactly two orthogonal propagating modes, over a bandwidth smaller than the single-mode bandwidth for a standard rectangular guide. The TE_{10} and TE_{01} modes can propagate independently, between cutoff and the onset of the TE_{11} mode. The cutoff frequencies in gigahertz for the first six propagating modes in the square waveguide used are 3.37, 3.37, 4.77, 4.77, 6.74, and 6.74, corresponding to the TE_{10}, TE_{01}, TE_{11}, TM_{11}, TE_{20}, and TE_{02} modes, respectively. In contrast, the cutoff frequencies of the first six modes of the C-band WR187 standard waveguide sections used may be calculated to be 3.15, 6.31, 6.77, 7.5, 7.5, and 13.5, corresponding to the TE_{10}, TE_{20}, TE_{01}, TE_{11}, TM_{11}, and TE_{02} modes, respectively.

The performance of the complete empty fixture, including transitions, tapers, and square waveguide sections, was measured relative to a coaxial calibration. A nominal insertion loss, $/S_{21}/$, of approximately -0.5 dB was observed. The return loss $/S_{11}/$, displayed a worst case peak of -10 dB, but was generally better than -15 dB across a frequency range from 3.7 to 6.5 GHz. The first sign of higher order modes in this measurement was at about 6.7 GHz, where there was a notable dip in the transmission response.

A thru-reflect-line (TRL) calibration [7] was implemented that effectively removed the fixture loss and reflections from the measurement. The TRL scheme, as implemented here, also provided a measurement reference plane in the center of the waveguide fixture, at the DUT-holder reference planes. The TRL standards consisted of a thru connection (without the DUT holder), a short circuit plate, and a square waveguide delay section designed for a quarter wavelength at 4 GHz. In-fixture calibration of the network analyzer with these standards is valid over the 3.4–4.7-GHz frequency range where only the first two orthogonal modes can propagate in the square waveguide.

The polarizers were constructed on unbacked Duroid PTFE laminate ($\epsilon_r = 2.2,\ h = 30$ mil). Investigations using EM analysis indicated that thin, low-dielectric constant laminate would have negligible impact on a dominant waveguide mode at 4 GHz due to the laminate's short electrical length. A variety of strip polarizers were measured and simulated, all with good results. Each polarizer had between 1 and 15 equally spaced strips of either 20, 40, or 60 mil in width. Uniform spacing of grid lines were used in these investigations. Other configurations could be used in multimode operation, for example, to block a TE_{20} mode, while passing a higher order mode.

III. An EM-Based Waveguide Simulator

The chosen analysis method utilizes full-wave EM analysis. As an alternative, simple lumped-element equivalent circuits are known for many waveguide discontinuities. Single inductive fins and capacitive posts have been used in filtering, and lumped reactance approximations for some specific structures have been tabulated [8]. Full-wave EM analysis has clear advantages over lumped approximations for the types of structures under study in terms of generality and accuracy.

Two very popular and powerful full-wave EM analysis approaches are the finite-element method (FEM) and the method-of-moments (MoM). The finite-element approach, has the capability to analyze very general 3-D structures, however, computationally it is very demanding. This is due to the need to mesh and solve for fields in a 3-D computational volume containing the structure of interest. MoM simulators tend to be less computationally intensive for a given problem, as they rely on two-dimensional (2-D) discretization of the strip conductors. Most MoM simulators are designed to handle predominantly planar circuits, such as enclosed microstrips [9], [10]; here, a MoM simulator is applied to a 3-D waveguide problem.

The MoM waveguide fixture simulator used is shown in Fig. 2 and consists of two microstrip–to–waveguide transitions and a 13.2-in-long straight section of square waveguide with an inside dimension of 1.75 in. The geometry of the fixture simulator allows the TE_{10} and TE_{01} orthogonally polarized modes to propagate vertically through the structure. The dimensions of each of the launching strips is 78 mil by 583 mil. The strips are on unbacked dielectric substrates ($\epsilon_r = 2.2$, $h = 30$ mil) positioned 850 mil from backshorts on each end of the fixture. The orientation of the strips are such that only a single mode, either TE_{10x} or TE_{01x}, is excited or received at one time. Because no current loops are present, transverse magnetic modes are not excited. Ports were placed at the input and output microstrip terminals with reference impedances of 50 Ω. After considerable effort, it was found difficult to arrive at a microstrip launcher geometry with a broadband, low-loss and low-reflection response into the square waveguide fixture.

A good low-loss low-reflection response for the simulated fixture was achieved by cascading the EM calculated S-parameters for the simulated fixture (Fig. 2), with a pair of theoretical impedance transformer networks. This was done using HP-EESOF's **Libra** circuit simulator. The transformer networks each consist of a four-section ideal transmission-line transformer. The transformer electrical parameters were optimized for a 50-Ω match for the waveguide simulator from 3.4 to 4.6 GHz. For completeness, the characteristic impedance ($Z_{0i},\ i = 1, 2, 3, 4$) and 4-GHz electrical length in

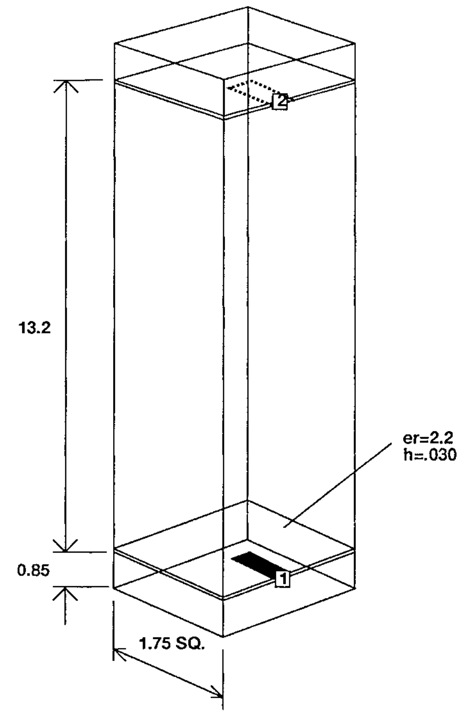

Fig. 2. Waveguide simulator which is constructed as a microstrip problem with exaggerated aspect ratios. Shown is the case for simulating the square waveguide case used in the measurements. Strip dimensions are 78 mil by 583 mil, and the substrate has $\epsilon_r = 2.2$, and $h = 30$ mil.

degrees ($E_i,\ i = 1, 2, 3, 4$) of each section used in the transformer network are as follows: $Z_{01} = 46.2\ \Omega$, $E_1 = 16.3^\circ$, $Z_{02} = 59\ \Omega$, $E_2 = 90^\circ$, $Z_{03} = 60.5\ \Omega$, $E_3 = 90^\circ$, $Z_{04} = 57.4\ \Omega$, $E_4 = 49.8^\circ$. The optimized insertion and return losses for the transformer-matched fixture simulator were better than -0.15 and -25 dB, respectively, over a bandwidth from 3.7 to 4.5 GHz.

Using an analogy to the physical waveguide fixture described previously, TRL calibration (or de-embedding) of the waveguide fixture simulator removes errors in the simulated S-parameters caused by the residual reflections of the (in this case, theoretical) transitions and establishes simulation reference planes within the waveguide. To accomplish TRL de-embedding of the waveguide simulator, three *calibration standards* were simulated using the MoM field solver. Two waveguides which differ in length by approximately one-quarter wavelength at 4 GHz were simulated. Both were similar to Fig. 2, differing only in the length of the guide. These provide the measurements of the *thru* and *line* standards for the TRL de-embedding algorithm. The *reflect* standard was a one-port short-circuited version, with the lossless top cover brought down to the reference plane. The phase of the reflection coefficient was used to determine the proper root choices in the de-embedding algorithm.

The polarizers were simulated by inserting a dielectric layer of appropriate size and constitutive parameters into the fixture simulator at the position of the DUT holder. Additional space was included to account for the entire phase length of the quarter-inch section of waveguide added by the device holder. Two orientations were used for each polarizer. In the blocking-mode orientation, conductive strips corresponding to 1-oz copper foil were placed on the dielectric layer parallel to the microstrip launches, and thus parallel to the E-field of the excited propagating mode. The performance of the pass-mode orientation was simulated by placing the conductors perpendicular to the strip launches.

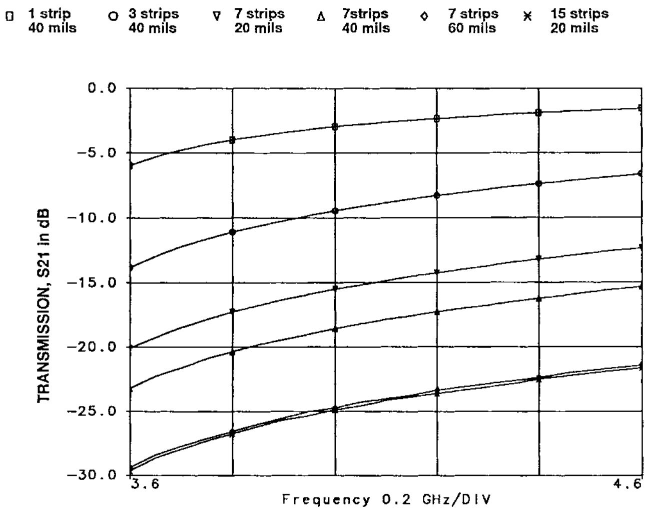

Fig. 3. Simulated attenuation of strip polarizers over frequency. The 15-strip 20-mil case and the 7-strip 60-mil case provide maximum attenuation for the devices which were considered.

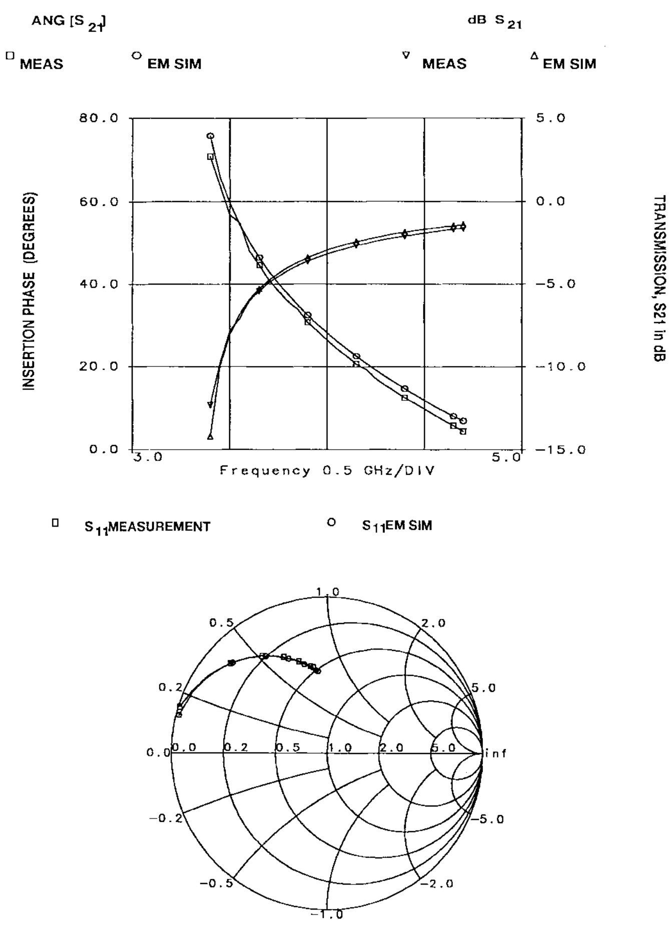

Fig. 4. Comparison of TRL calibrated measurement to TRL de-embedded EM simulation. Polarizer is one strip, 40-mil-wide block mode. Above, S_{21} attenuation in dB, and insertion phase. Below, input reflection coefficient.

IV. Measured and Simulated Results

The behavior of the strip polarizers was found to follow expected trends, with the isolation between orthogonal modes increasing rapidly with the number of strips. This is indicated in Fig. 3. The simulations predict 25 dB (or better) of isolation is possible with 15 evenly spaced thin strips. The attenuation due to a single strip is much less.

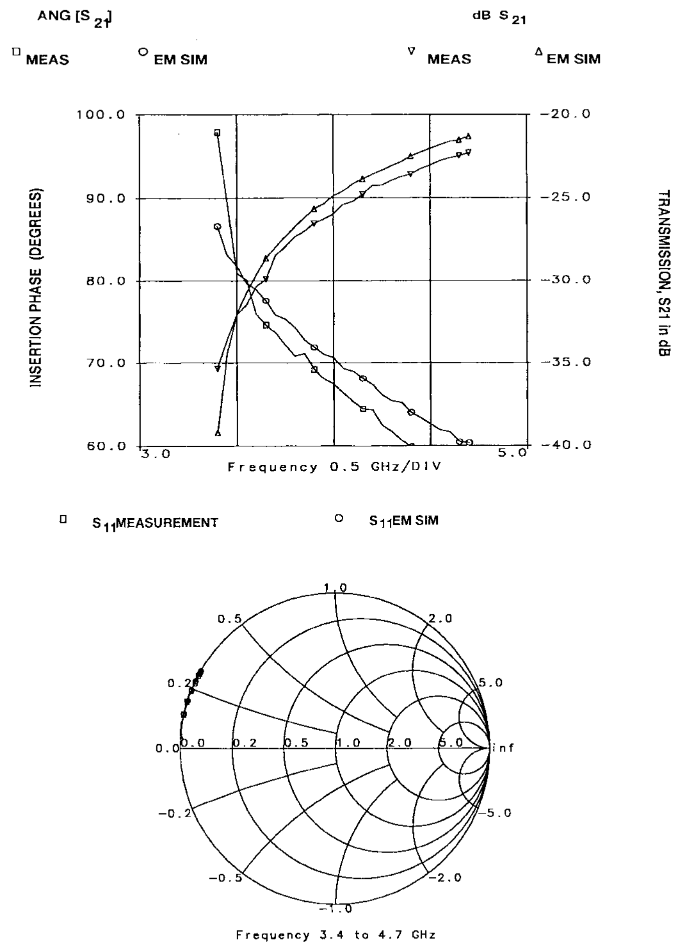

Fig. 5. Comparison of TRL calibrated measurement to TRL de-embedded EM simulation. Polarizer is 15 strips, 20-mil-wide block mode. Above, S_{21} attenuation in dB, and insertion phase. Below, input reflection coefficient.

Comparisons of the S-parameters between measurement and simulation for two cases (one strip, 40 mil and 15 strips, 20 mil) appear as Figs. 4 and 5. For the single strip case, the transmission phase error is very small, and fairly constant with frequency. Attenuation is predicted to within 1 dB, except below the cutoff knee of the waveguide. The input reflection coefficient ($S11$) tracks very well in the middle of the usable band. In the case of the 15-strip polarizer, the discrepancies between measurement and simulation are larger, but the signal levels are much lower. Error in prediction of the attenuation is less than 2 dB except at the cutoff knee. The reflection coefficient ($S11$) shows a nearly perfect, but slightly inductive, short circuit whose phase angle is properly predicted by the simulator.

In the pass mode, the polarizers can be considered essentially transparent to a signal with its electric field orthogonal to the grid. The measured pass-mode insertion loss was less than 0.1 dB across the 3.5–4.5-GHz frequency range, and differed by less than 0.03 dB between the 1- and 15-strip cases. The simulated insertion loss is less than 0.07 dB across the same range, and shows negligible difference between polarizers of differing numbers of strips and is within 0.03 dB of the measured results.

V. Conclusion

In this paper, the authors have demonstrated successful modeling of strip polarizers in waveguide using a 2.5-D MoM analysis tool. The test cases considered showed good agreement between measurement and simulations, including phase information. Good polarization isolation was achieved with the close-spaced geometries with 20–25 dB of attenuation between modes, and negligible pass-mode attenuation. The accurate prediction of the inductive behavior of these devices could enable the design of waveguide filters and matching networks using cascaded arrays of passive structures. The approach used is applicable to arbitrary metallizations and cascaded structures enclosed within rectangular or square waveguide.

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Study of a Combined Millimeter-Wave Resonator

M. A. Shapiro and S. N. Vlasov

***Abstract*—We present a theoretical investigation and measurements of a multielement open resonator composed of corrugated waveguides and plane semitransparent reflectors. A periodic-transmission-line model is used to analyze the transverse mode structure and the diffraction Q-factor of the proposed resonator. The setup containing the resonator (equipped with Bragg reflectors), mode converters, and an elliptical mirror is employed for measurements in Ka-band. Two- and three-waveguide-section resonators have been studied. The proposed resonators demonstrate good mode selectivity that permits one to utilize them in high-power millimeter-wave sources.**

***Index Terms*— Millimeter-wave resonators, transmission-line resonators.**

I. Introduction

In high-power millimeter-wave generators based on relativistic electron beams, extended oversized resonators are used to operate at the high current. To accomplish single-frequency and single-mode operation of these sources, the resonators are bound to be selective. The resonator selectivity means that diffraction losses of the operating mode are required to be less than diffraction losses of spurious modes whose transverse structure and frequency are different from those for the operating mode.

The proposed resonator achieves frequency and modal selectivity by containing several oversized waveguide sections and mirrors set coaxially with gaps [Fig. 1(a)]. Sections of an axially symmetric corrugated waveguide can be used in this resonator to provide extremely low Ohmic losses and diffraction losses for the operating mode. The period of corrugation of the waveguide wall is essentially less than the wavelength λ and the corrugation depth is a quarter wavelength $\lambda/4$ [1]–[4].

The waveguide wall is actually an impedance wall. An electromagnetic field in such an impedance-wall waveguide can be represented by a superposition of the linearly polarized modes HE_{11}, HE_{12}, HE_{13}, and so on. For the HE_{11} mode transferred through a gap between the waveguide sections, diffraction losses can be quite small since the HE_{11} mode comprises 98% of the TEM_{00} free-space Gaussian beam optimized for its waist. However, diffraction losses at the gap can be reduced considerably if we apply the mixture of the HE_{11} and HE_{12} modes composing the TEM_{00} beam precisely. The required mixture of modes can be maintained in the combined resonator if the resonator length is equal to integer multiples of the beat length between the HE_{11} and HE_{12} modes in the waveguide. Thus, the lowest linearly polarized mode of a combined resonator is represented by the TEM_{00} mode in the cross section of the gap and the HE_{11}/HE_{12}-mode mixture in the waveguide sections.

Frequency drift and a change in the transverse index lead to an increase in diffraction losses at the gaps and, as a result, to a reduction

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