Simulation and Experiment on SIW Slot Array Antennas

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***Abstract*—By etching longitudinal slots on the top metallic surface of the substrate integrated waveguide (SIW), an integrated slot-array antenna is proposed in this letter. The whole antenna and feeding system are fabricated on a single substrate, which takes the advantage of small size, low profile, and low cost, etc. The design process and experimental results of a four-by-four SIW slot array antenna at X-band are presented.**

***Index Terms*—Slot array antenna, substrate integrated circuit (SIC), substrate integrated waveguide (SIW), via holes.**

I. Introduction

WAVEGUIDE slot array antennas are an important class of microwave antennas with numerous applications such as radar and communication systems, which require narrow-beam or shaped-beam radiation patterns [1]–[4]. Resonant arrays of longitudinal slots in the broad wall of rectangular waveguides have the added advantage of very low cross-polarization levels. Design procedures for these arrays are mainly based on the work published by Elliott [5], [6] and Coetzee [4], etc. The slot spacing of such an array is one-half guide wavelength at the design frequency, in order to locate the slots at the standing wave peaks. All radiators have the same phase and their amplitude distribution must be arranged carefully to achieve the given gain and side-lobe levels.

However, rectangular waveguide components are voluminous and expensive to manufacture. High precision mechanical adjustment or a subtle tuning mechanism is needed to obtain the resonant slots at the standing wave peaks.

Recently, the substrate integrated waveguide (SIW) and substrate integrated nonradiative dielectric waveguide (SINRD) [7]–[11] have provided an useful technology for the design of microwave and millimeter-wave circuits such as filters [12], and feeding lines for antennas [8], [9], etc. Also, it can easily be connected to microstrip or coplanar circuits using simple transitions [7]. The SIW together with other types of synthesized waveguide such as SINRD can be generalized by a new concept called as "substrate integrated circuits (SICs)" that allow the integration of planar and nonplanar structures within the same substrate [13].

In this letter, we present a SIW slot array antenna, which is fed by a corporate type of microstrip power divider. The slot array and the feeding network can be fabricated on a single substrate. As a result, not only the size, weight and cost of the waveguide slot array antennas are reduced, but also the manufacturing repeatability and reliability are enhanced. Meanwhile the gain and efficiency of those antennas have only a little depression because of the dielectric loss.

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II. Design Procedure

A schematic view of SIW slot array is shown in Fig. 1. Such a waveguide is composed of two parallel arrays of via-holes, which delimit the waveguide *TE* wave propagation area. The propagation constant and the radiation loss are determined by parameters "a," "p," and "d," which denote the width of the SIW, the period and the diameter of vias, respectively.

As shown in Fig. 2, the SIW is equivalent to a conventional rectangular waveguide filled with dielectric and hence it can be analyzed just by using the width of the equivalent waveguide [14]. An experimental formula is given for the normalized width of the equivalent waveguide

$$\overline{a} = \xi_1 + \frac{\xi_2}{\frac{p}{d} + \frac{(\xi_1+\xi_2-\xi_3)}{(\xi_3-\xi_1)}} \tag{1}$$

where

$$\xi_1 = 1.0198 + \frac{0.3465}{\frac{a}{p} - 1.0684}$$
$$\xi_2 = -0.1183 - \frac{1.2729}{\frac{a}{p} - 1.2010}$$
$$\xi_3 = 1.0082 - \frac{0.9163}{\frac{a}{p} + 0.2152}.$$

The relative error of the formula is below 1% and the width of the equivalent rectangular waveguide is

$$a_{\mathrm{RWG}} = a\overline{a}. \tag{2}$$

A single longitudinal slot in the broad wall of an equivalent rectangular waveguide has been successfully analyzed by the method of moments [15]. The convenient assumptions in the theory, such as zero wall thickness and square-ended slots, are appropriate for the printed circuit fabrication. Fig. 3 exhibits the

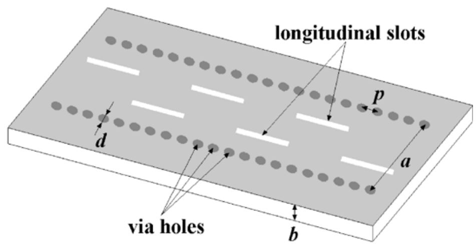

Fig. 1. Configuration of the on-substrate integrated slotted-waveguide synthesized using metallized via-hole arrays.

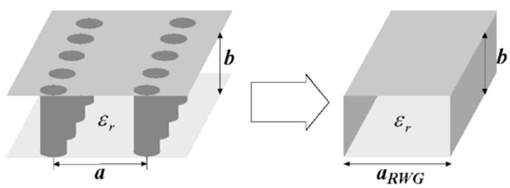

Fig. 2. Substrate integrated waveguide and the equivalent rectangular waveguide.

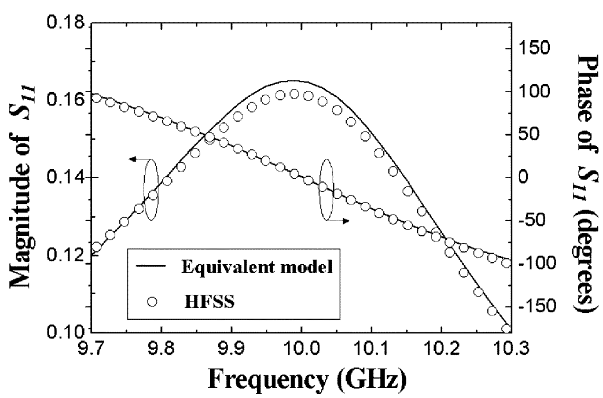

Fig. 3. Comparison of the backscattered wave obtained from the original SIW model employing the high frequency structure simulator (HFSS) and those obtained from the equivalent model. $a = 12.5$ mm, $a_{\mathrm{RWG}} = 11.86$ mm, $b = 1.5$ mm, $p = 2$ mm, and $d = 1$ mm.

comparison of the backscattered wave obtained from the original SIW model employing the Ansoft HFSS and those obtained from the equivalent model. The slot width, length, and offset relative to the waveguide centerline are 0.4, 12.38, and 0.4 mm, respectively. Excellent agreement has been observed. As a consequence, one can dispense with the costly gathering of experimental input data when designing longitudinal slot arrays fed by SIW.

To design the longitudinal slot array, an iterative technique has been developed by Elliott [5]. This procedure requires the knowledge of the scattering property of a single slot as a function of slot length and offset, since such information is used to "detune" the slot to compensate for mutual coupling. A SIW slot array can be designed using a modified Elliott's procedure [6] including the internal high order mode coupling, which cannot be ignored since the thickness of substrate is always much smaller than the width of the equivalent waveguide.

The feed network is composed of microstrip power dividers. As shown in Fig. 4, it can be fabricated on the same substrate.

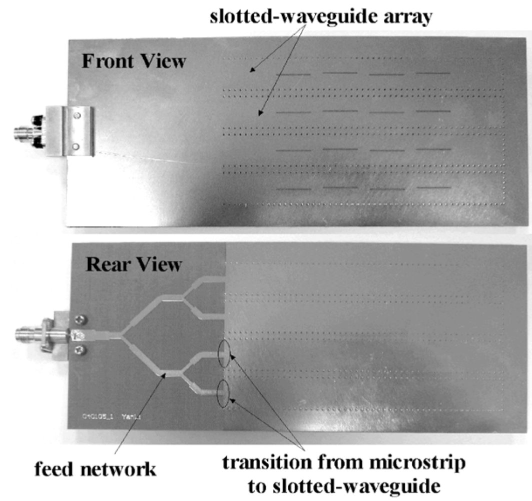

Fig. 4. Photograph of the substrate integrated slotted-waveguide array antenna. $a = 12.5$ mm, $b = 1.5$ mm, $p = 2$ mm, and $d = 1$ mm. The transitional microstrip is 2.4 mm in width.

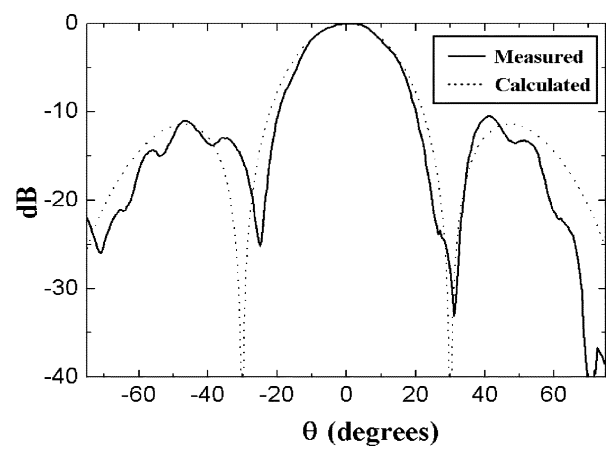

Fig. 5. Calculated and measured E-plane radiation at a frequency of 10 GHz.

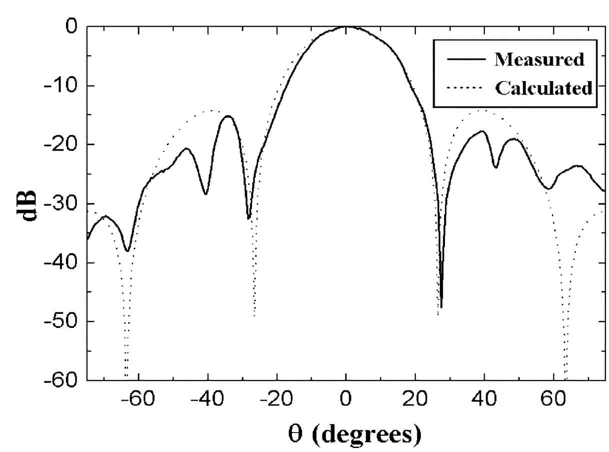

Fig. 6. Calculated and measured H-plane radiation at a frequency of 10 GHz.

The transition from microstrip to SIW has been investigated in [7]. After a careful tuning procedure, its in-band insertion loss can be better than 0.3 dB. All the SIW slots are excited with the same amplitude and phase in the design procedure.

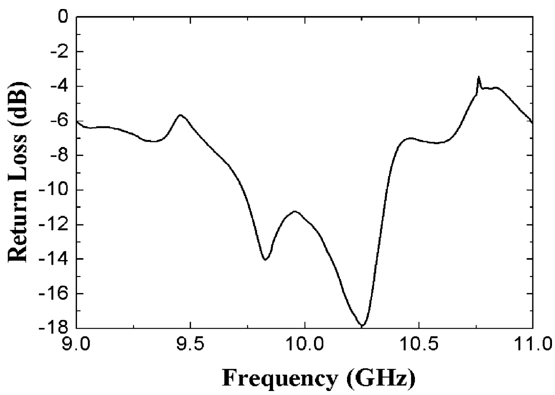

Fig. 7. Return loss of the substrate integrated four-by-four array antennas.

TABLE I
LOSS BUDGET

Calculated Directivity (dB)	**17.4**
Measured Gain (dB)	**15.7**
Transition Loss (dB)	**0.1**
Feed Network losses (dB)	**0.7**
Connector Loss (dB)	**0.4**
Unaccounted Losses (dB)	**0.5**

III. Experimental Results

A substrate with a relative permittivity of 2.4 and a loss tangent of $\tan\delta = 1\mathrm{e}-3$ was used to fabricate the SIW slot array antenna at 10 GHz. The Elliott's procedure was applied to the design of a four-by-four array with uniform aperture distribution. The method described in [4], which has employed a piecewise sinusoidal approximation for the slot electric fields, was used to calculate the radiation pattern of the array. The slot voltages are set equal, and that the longitudinal and transverse slot spaces are 16.77 and 15 mm, respectively. The measured E-plane pattern at 10 GHz is compared with the calculated pattern, as shown in Fig. 5, and the measured and calculated H-plane patterns are shown in Fig. 6. Good agreements between the predicted and measured patterns are observed from these two figures.

The return loss of the SIW slot array antenna was measured from 9 to 11 GHz, and the results are shown in Fig. 7. The Return Loss is less than -10 dB within a wide bandwidth of 600 MHz.

A comprehensive loss budget is shown in Table I. The antenna directivity was calculated to be 17.4 dB and the corresponding gain was measured using the gain-transfer method and was found to be 15.7 dB. In Table I, the transition loss refers to the power loss due to the transition from microstrip to waveguide. On the other hand, feed network losses refer to the conductor, dielectric and mismatch losses in the feed network of microstrip power dividers. Furthermore, the connector loss refers to the reflections at the input port of the antenna. All these losses were estimated using Ansoft HFSS.

IV. Conclusion

A SIW slot array antenna has been presented, which is integrated on a single substrate. Featuring the direct integration, small size, and low loss, the new structure is well suited for the design of low-cost planar array antennas at microwave and millimeter-wave frequencies. To demonstrate the proposed technique, a four-by-four array antenna with longitudinal slots on the broad wall of the SIW has been designed, fabricated and measured. The calculated and measured results show good agreements, which implies that such a type of antennas can be constructed without any tuning.

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