17th ICEE 2009
Iranian Conference on Electrical Engineering
www.icee.ir/2009

Compact Two-Layer Slot Array Antenna for K-Band Applications Based on Substrate Integrated Waveguide

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Abstract: *A compact two-layer slot array antenna at 24GHz based on substrate integrated waveguide (SIW) technology is presented. The feed waveguide is placed underneath the slot array and is coupled through slanted slots to branches of the array leading to considerable reduction in size compared to one-layer SIW slot array antennas that are fed from one end. Full-wave electromagnetic simulations show excellent gain, efficiency, and return loss.*

Keywords: Waveguide slot array antennas, substrate integrated waveguide (SIW), fixed wireless access communication.

1. Introduction

Waveguide slot arrays are an attractive but expensive choice in a wide range of microwave and millimetre-wave applications when high gain and efficiency are critical. Resonant longitudinal slot arrays offer very high aperture efficiency, low side-lobe levels, and low cross polarization. However, they usually suffer from narrow bandwidth and high cost due to high precision required in manufacturing. Moreover, when standard rectangular waveguides are used, the antenna array is large and heavy and cannot be easily integrated with high frequency printed circuits.

In recent years, the concept of substrate integrated waveguides (SIW) has enabled printed circuit technology to take advantage of the low-loss transmission in rectangular waveguides within the PCB substrate [1]. In this approach, rows of closely spaced metallic vias between two ground planes emulate the side walls of a thin rectangular waveguide. The resulting device benefits from light weight, low cost, small size, and low profile compared to its conventional metallic waveguide counterpart. Moreover, it can be easily integrated with printed circuits. Propagation characteristics of SIW have been studied by different numerical methods in several papers [2,3].

Only a few slot array antennas based on SIW technology have been reported so far [4]. They consist of a one-layer substrate and are fed from one end through a microstrip network that significantly increases the size of the antenna. Furthermore, radiation from microstrip feed lines severely compromises the low side-lobe level of the slot array.

In this paper a novel two-layer rectangular slot array antenna with 36 elements is designed at 24GHz which is suitable for Fixed Wireless Access base-stations. The feed waveguide runs underneath the main substrate layer containing the slot array and is coupled to the branches of the array via slanted slots. The proposed feeding structure results in a considerable reduction in size and eliminates unwanted radiations from feed network. Full-wave electromagnetic simulations show promising results including 21.4dB of gain.

2. Design Procedure

2.1 Modeling individual resonant slots

Design procedure of slot arrays was presented in two well-known papers by Elliott [5,6] and it is adopted in this work. A longitudinal slot, shown in Fig. 1, can be modeled as a shunt admittance $Y(x,l,f)$ in which x is the slot offset from the center, l is the slot length and f is frequency.

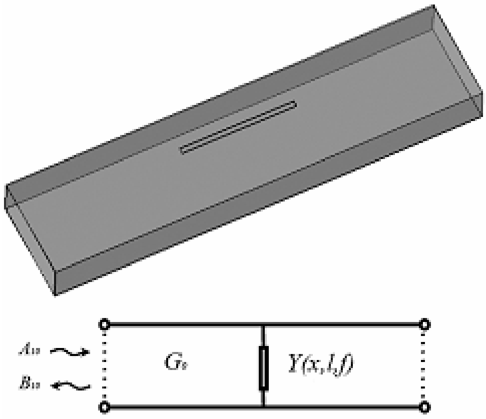

Fig. 1: Longitudinal slot and its equivalent circuit.

To obtain the normalized admittance of a longitudinal slot, a single slot was simulated in Ansoft HFSS for a range of lengths, offsets, and frequencies and then the following expression was used:

$$Y_{norm} = \frac{-2S_{11}}{1+S_{11}} \tag{1}$$

A common mechanism for feeding planar arrays is center-inclined slot [7] which is modeled by a series equivalent circuit. The slanted slot acts as an impedance transformer between the feed waveguide and the coupled branch where the radiating slots are located. This impedance transformation is expressed by the following relationship [8]:

$$Z_{norm} = \frac{S_{11}}{1-S_{11}}.Y_{norm} \qquad (2)$$

where Y_{norm} is the total active admittance that is seen at a distance $\lambda_g/4$ from the center of coupling slot in the branch line and Z_{norm} is the series impedance loading the feed waveguide. S_{11} is the input scattering parameter of the symmetric 4-port coupling junction shown in Fig. 2.

2.2 Modeling the coupling junction

Feeding slot arrays via a slotted waveguide underneath the array and coupled through centre-inclined slots was studied in [7,9] for conventional hollow metallic waveguides. As shown in Fig.2, each coupling junction consists of a slanted coupling slot and a pair of straddling longitudinal radiating slots located a quarter of guide wavelength away in the branch.

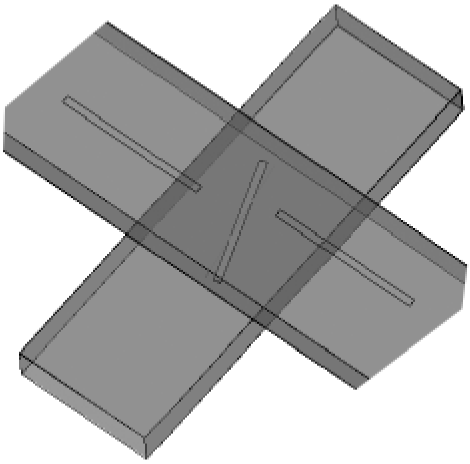

Fig. 2: Coupling junction structure.

Coupling through higher-order modes in coupling junctions changes the amplitude and phase of both the electric fields of radiating slots and that of the coupling aperture. Rengarajan in [9] shows that higher-order mode coupling effect for soft coupling configurations, in the tilt range of 0 to 15 degree, are not significant. For hard coupling configuration, in the same range of tilt angles, amplitude is not affected significantly but phase error must be corrected. This may be accomplished by changing the length of two radiating slots in the coupling junction.

2.3 Equivalence between rectangular waveguide and SIW

Recently different numerical methods, such as FDFD [2] and MoL [3], have been employed for calculation of propagation characteristics of SIW and its equivalent width. The propagation constant and the radiation loss are determined by three parameters, the width of SIW *a*, the period *p* and the diameter *d* of vias as shown in Fig. 3.

In this work the propagation constant of SIW was extracted from full-wave simulations of two sections of SIW with different lengths. If the length of one SIW is L_1 for which the phase of S_{12} is φ_1 and the length of another SIW is L_2 with the phase of its S_{12} being φ_2, the propagation constant is approximately given by:

$$\beta_{SIW} \approx \frac{|\phi_1 - \phi_2|}{|L_1 - L_2|} \qquad (3)$$

This approximation improves as the input and output excitation ports in EM simulator are better matched to the SIW dominant mode. After estimating the propagation constant we can find the equivalent rectangular waveguide width which has the same propagation constant.

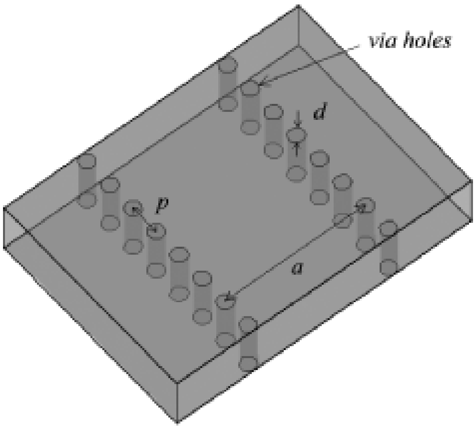

Fig. 3: SIW structure.

2.4 Transition from microstrip to SIW and array design program

Main line of the array must be fed by a microstrip line which will be connected to an SMA connector. Transition from microstrip to SIW is very important in order to maintain good impedance matching and high radiation efficiency. Reference [10] proposes a tapered transition from microstrip to SIW which has a low return loss. This transition is optimized using EM simulations to achieve the best return loss.

Finally, a computer program based on Elliott’s design procedure was developed to find the lengths and offsets of slot radiators. Due to small thickness of SIW compared to its width, the internal higher order mode coupling between the adjacent radiating slots cannot be neglected and the modified design procedure presented in [6] was implemented.

3. Simulation results

Structure of the 6×6 uniformly excited slot array is shown in Fig.4 and it was designed at 24GHz. The substrate of both layers is Duroid 5880 with thickness of 50mil and relative permittivity of 2.2. This material also benefits from a very low loss tangent (tanδ = 0.0009). The thickness of metal cladding is 17μm. All of the coupling slots have tilt angles of 6 degrees and the width of 10mil. Also the width of radiating slots is 10mil. Via diameters *d* and periods *p* are 0.4mm and 0.8mm, respectively.

To achieve maximum gain without significant grating lobes, the spacing between adjacent radiating slots was chosen to be $0.8\lambda_0$ at center frequency of 24GHz. That would require an equivalent width of 4.6mm for dielectric filled rectangular waveguide for which the actual width of SIW turns out to be 4.857mm. The final size of the array is 6.4cm×7.4cm.

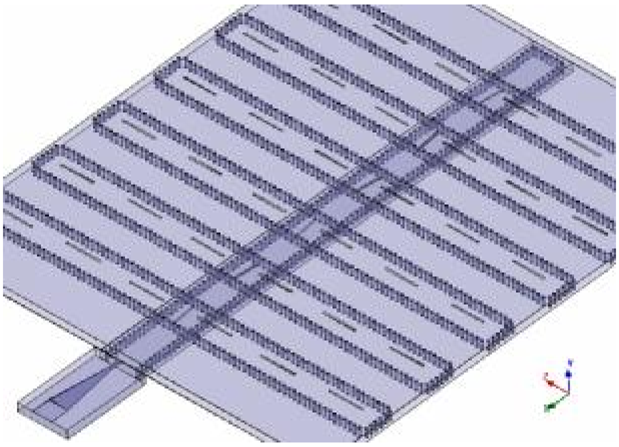

Fig. 4: Slot array structure.

The entire array was simulated in Ansoft HFSS on a dual-core AMD based computer with 8GB of memory. H-plane and E-plane patterns of the array at 24GHz are shown in Fig. 5 and Fig.6. Half power beamwidth of the array is 10.8 degrees with a peak gain of 21.4dB at broadside and radiation efficiency of 80%. Maximum side-lobe level is -12dB which is reasonable for a uniformly excited array. Note that the array is designed with the assumption of infinite ground plane while the actual antenna has a finite size. Radiation on the backside of antenna is also illustrated in Fig. 6 from which the front-to-back ratio is estimated to be around 29dB. Return loss of the antenna is plotted in Fig. 7 from 23.5GHz to 24.5GHz which shows excellent impedance matching. Due to very long simulation times, a discrete simulation at 11 frequency points were carried out and the results were interpolated in MATLAB.

Conclusion

A novel two-layer slot array antenna based on substrate integrated waveguide (SIW) technology was designed and simulated. Unlike already reported SIW slot arrays, the present design achieves considerable reduction in size by using a feed waveguide placed underneath the slot array and coupled through slanted slots to branches of the array. Full-wave electromagnetic simulations show promising results. The new design is deemed suitable for both microwave and millimetre-wave applications where low cost integration of high gain antennas with printed circuits is a priority.

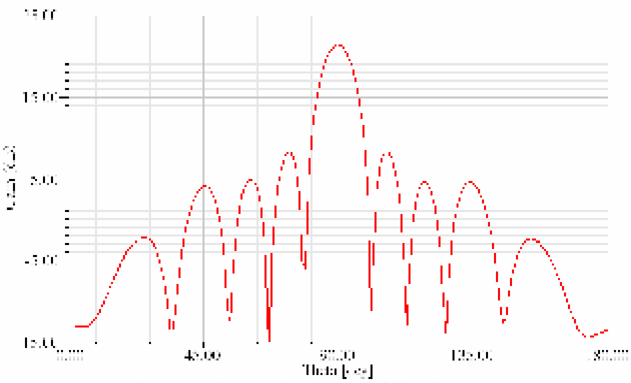

Fig. 5: H-plane gain pattern of the slot array.

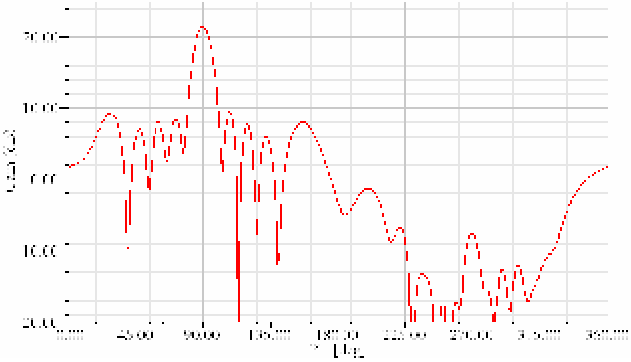

Fig. 6: E-plane gain pattern of the slot array.

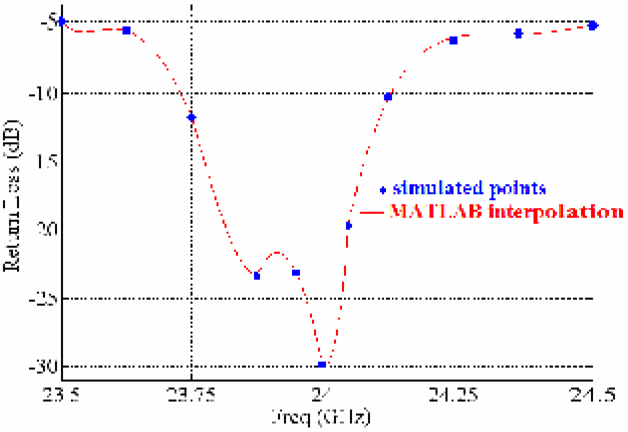

Fig. 7: Return loss of the slot array.

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