

A DESIGN SOLUTION FOR COMPACT SLOTTED WAVEGUIDE ARRAY ANTENNAS BASED ON SIW TECHNOLOGY

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Abstract: *Slotted waveguide array antenna is a crucial structure in microwave frequency antennas with many applications in radar and communications systems. Previously, slotted waveguide array antenna systems mainly used metal materials. The study of slotted array antenna based on the waveguided with SIW (Substrate Integrated Waveguide) technology is a novel approach. The paper presents the results of researching, designing, and manufacturing waveguide slot array antenna with low SLL using SIW technology in X-band. The results will be an essential basis for selecting a design solution for slotted waveguide array antenna by SIW technology to replace traditional metal slot array antennas in practical applications in X band radar antenna systems.*

Keywords: Slot array antenna; Waveguide; SIW; Microwave.

1. INTRODUCTION

The rectangular SWA principle (Slotted-Waveguide Array Antenna) [1] is the energy radiation through the slots cut on wide or narrow walls of the rectangular waveguide. This means that radiation elements are essential parts of the feeding system – a waveguide, resulting in a simple design processing without a balun or a matching network. The main advantages of SWAs are small weight, high power handling capabilities, and good performance [1]. Hence, the SWA is the ideal solution for radar, communications, navigation, and high power applications [2].

Today, radars and communications systems, based on SWAs, usually use conventional metal waveguide. The drawbacks of these metal waveguide components are their large size, weight, and quite expensive.

Recently, substrate integrated waveguide (SIW) and substrate integrated non-radiated dielectric waveguide (SINRD) [3-5] have provided a valuable technology for the design of microwave and millimeter-wave circuits such as filters [6] and feeding lines for antennas [4], etc. Also, it can easily connect to microstrip or coplanar circuits using simple transitions [3]. The SIW, together with other types of synthesized waveguide such as SINRD, can be generalized by a new concept called “substrate integrated circuits (SICs)” that allow the integration of planar and non-planar structures within the same substrate [7].

This paper presents a design method for an SWA using SIW technology, called compact SIW slot array antenna, which is fed by a combination of microstrip power dividers. The array and feeding network can be manufactured on a substrate. As a result, not only the size, weight, and cost of the slotted waveguide array antennas are reduced, but also the side and back lobe levels are reduced, manufacturing repeatability and reliability are enhanced.

2. DESIGN METHOD

2.1. Slotted Waveguide Array Antenna (SWA)

The design SWA is often based on the procedure described by Stevenson, and

Elliott [8-12], in which the waveguide is short circuit at a $\frac{1}{4}$ of wavelength from the center of the last slot. The slot spacing is $\frac{1}{2}$ of wavelength. For rectangular slots, the slot length is about $\frac{1}{4}$ of λ_0 . The resulting sidelobe level of the array antennas is related to the excitation of each element. In SWA, the excitation of each slot is proportional to its conductivity. In vertical slots on the waveguide's wide wall, the slot's conductivity changes following its displacement from the centerline to the wide wall [9]. Therefore, for each desired sidelobe level, the appropriate positioner displacement needs to be calculated carefully.

Elliott proposed two main equations that need to be solved simultaneously to determine the displacement and length values for each slot [8]. These two equations are based on Stevenson's equations [9], Babinet's principles, and also on the Taylor formula [13] and the length adjustment coefficient [14] of Oliner, in addition to Stegen's assumption on the generality of the resonant slot length.

In summary, the existing resonant SWA design process is fairly complex. It mainly relies on several equations to derive both the displacement and the length of each slot. In this paper, the authors will present a simple design process. All the slots have the same length and use sample equations to determine the slot's heterogeneous positions to achieve the desired sidelobe level. Other parameters such as distance between slots and their distance from both the feed port and the terminal will be taken from the instructions set by Elliott and Stevenson.

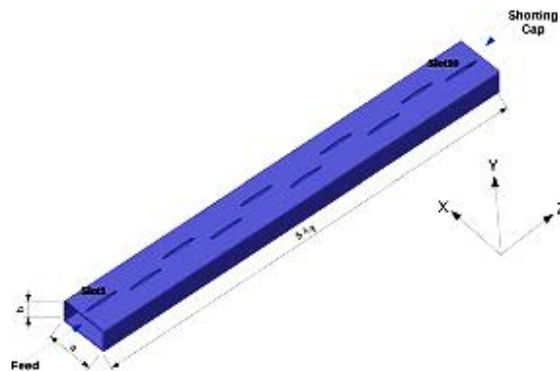


Fig. 1. Configuration of a metal waveguide slot array antenna.

For a rectangular metal waveguide of dimensions ($a \times b$), as shown in fig.1, the general rules and functions for the vertical positions of the slots on the wide wall are as follows [12, 13]:

- The center of the first slot, slot 1, is located at a distance of $\frac{1}{4}$ guided wavelength or $3\lambda_g/4$, from the feed point of the waveguide,
- The center of the final slot, located at $\lambda_g/4$ or $3\lambda_g/4$, from the waveguide terminal.
- The distance between the center of two slots is $\lambda_g/2$.
- Where $\lambda_{cut} = 2a$, λ_g is the guided wavelength calculated by the following:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - (\frac{\lambda_0}{\lambda_{cut}})^2}} \quad (1)$$

where λ_0 is the wavelength in free space and λ_{cut} is the wavelength in the waveguide.

- Slot width: $\text{Slot width} = a \frac{0.0625}{0.9}$ (2)

- Slot length: $\text{Slot length} = 0.04868\lambda_0$ (3)

2.2. SIW slot array antenna

Compact SIW slot array antenna structure is based on the SWA principle, which replaces the metallic waveguide with an equivalent dielectric substrate. A schematic view of the SIW slot array is shown in fig.2. Such waveguide is composed of two parallel arrays of holes, which define the waveguide's TE wave propagation. The propagation coefficient and the radiation loss are determined by parameters “w”, “p” and “d”, denoted the SIW's width, the period, and the diameter of vias, respectively. Using SIW technology, a non-planar metal waveguide can imitate a SIW, resulting in intrinsic planarity, and it can be manufactured in practice and more easily integrated into inputs/outputs.

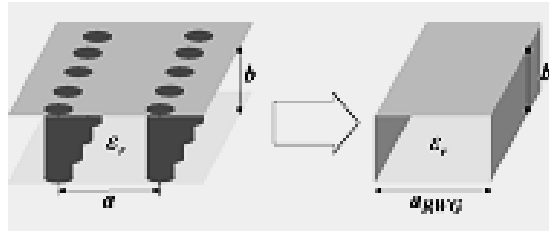
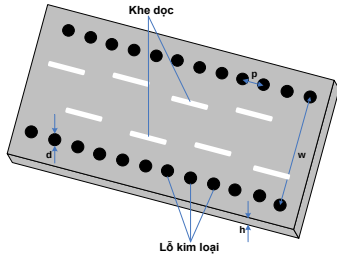


Fig. 2. Configuration of SIW slots.

Fig. 3. SIW and equivalent rectangular waveguide.

As shown in fig.2, the SIW is equivalent to a typical rectangular waveguide filled with dielectric, and therefore, it can be analyzed using only the width of an equivalent waveguide [15].

Calculations for the normalized width of the equivalent SIW are given in (4) and (5).

If W_{con} is the width of the normal metal waveguide and $\epsilon_{\text{con}} = 1$, the width of the equivalent dielectric-filled waveguide is:

$$w_{\text{eff}} = \frac{w_{\text{con}}}{\sqrt{\epsilon_r}} \quad (4)$$

From (4), dimensions of SIW are calculated as follows:

$$w_{\text{eff}} = w - \frac{d^2}{0.95s} \quad \text{and} \quad l_{\text{eff}} = l - \frac{d^2}{0.95s} \quad (5)$$

where w_{eff} , l_{eff} are the effective width and length of SIW, and w , l are the width and length of the SIW.

2.3. Design of SIW slot array antenna

To design a vertical slot array, an iterative technique has been developed by Elliott [10]. This procedure requires knowing the scattering property of a single slot as a slot length and offset function 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 [11], including the internal high order mode coupling, which cannot be ignored since the substrate's thickness 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 manufactured on the same substrate.

The transition from microstrip to SIW has been investigated in [3]. 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.

SIW slot array antenna designed with 2 x 8 slots with the specifications shown in table 1 below:

Table 1. Technical parameters of the SIW slot array antenna system.

TT	Specifications	Unit	Value
1	Frequency	GHz	9,8 ÷ 10,2
2	Standing wave ratio		≤ 2
3	Return loss	dB	< -10
4	Gain	dBi	≥ 16
5	Azimuth Half Power Beam Width (-3 dB level)	Degree	15.4 ÷ 17.5
6	Azimuth side sidelobe level	dB	≤ -18
7	Elevated Half Power Beam Width (-3 dB level)	Degree	33 ÷ 36
8	Polarization		Horizontal

Following the specifications in table 1, based on the theory given in section 2.1, the SIW slot antenna array is designed on Rogers 5880 substrate with dielectric constant $\epsilon_r = 2.2$, substrate thickness $h = 0.508$ mm, copper layer thickness $t = 0.017$ mm. The dimensions of the X-band SIW slot array antenna are shown in table 2.

Table 2. Dimensions of the SIW slot array antenna.

TT	Specifications	Unit	Value
1	Number of slots	slots	2x8
2	Length of SIW	mm	156,35
3	Width of SIW	mm	2x21
4	Slot spacing	mm	13,3
5	Slot length	mm	9,4
6	Slot width	mm	0,9
7	Hole diameter	mm	0,5
8	Hole spacing	mm	1
9	Length of short circuit (from the center of the 8 th slot)	mm	6,4
10	Length of feed (from the center of the 1 st slot)	mm	52,1

3. SIMULATION AND EXPERIMENTAL RESULTS

The simulation and manufacturing results of a SIW array antenna consisting of 2 x 8 slots at a frequency of 10 GHz are shown in fig.4 to fig.9.

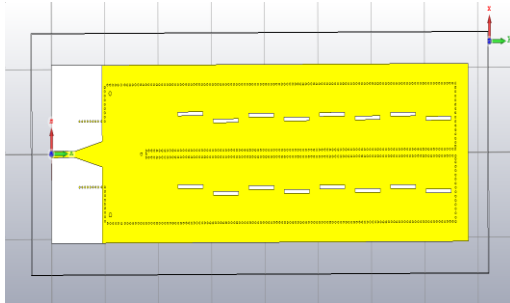


Fig. 4. Simulation on CST software of SIW slot array antenna.

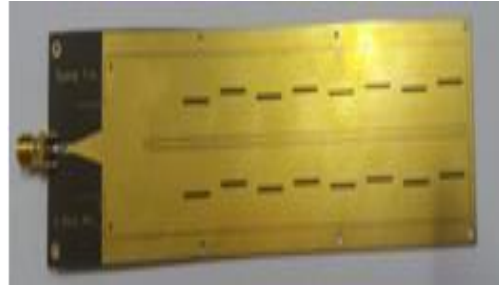


Fig. 5. Fabricated SIW slot array antenna.

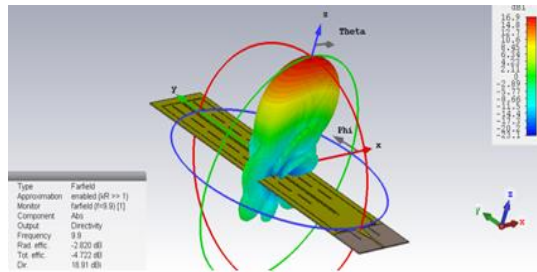
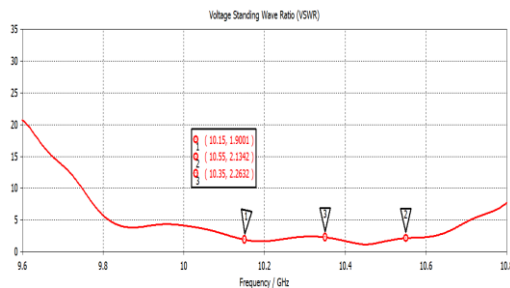
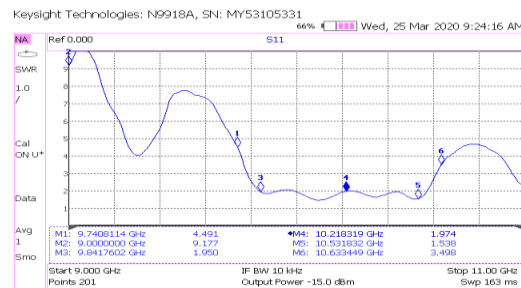


Fig. 6. Three-Dimensional Radiation Pattern of SIW slot array antenna.

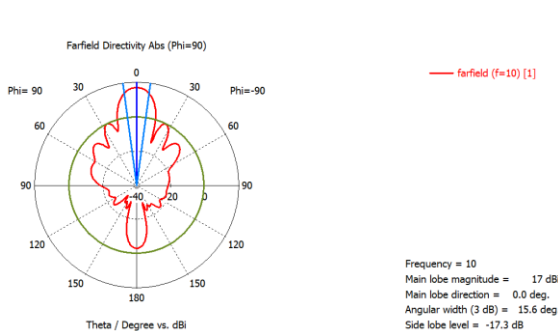


a. Simulation result

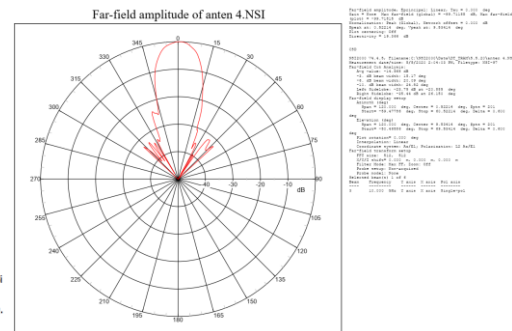


b. Measured result

Fig. 7. Standing wave ratio VSWR.



a. Simulation result



b. Measured result

Fig. 8. Radiation patterns in the azimuth angle at a frequency of 10 GHz.



Fig. 9. Radiation patterns in the elevation angle at a frequency of 10 GHz.

Table 3 presents the simulation results and actual measurement results of the SIW slot array antenna.

Table 3. Comparison of simulation results and measurement results of SIW slot array antennas.

TT	Technical parameters	Unit	Simulation results	Measurement results
1	Frequency	GHz	9,8 ÷ 10,2	9,8 ÷ 10,2
2	Voltage standing wave ratio		≤ 2	≤ 2
3	Return Loss	dB	< -10	< -10
4	Gain	dBi	≥ 16	≥ 16
5	Azimuth Half Power Beam Width (-3 dB level)	Degree	13.5 ÷ 17.4	12.9 ÷ 16.9
6	Azimuth side sidelobe level	dB	≤ -18	≤ -17.0
7	Elevator Half Power Beam Width (-3 dB level)	Degree	33.9 ÷ 36	33.0 ÷ 35.3
8	Polarization		Horizontal	Horizontal

The calculated and measured results show good agreements, which implies that such a type of antennas can be constructed without any tuning. The obtained results also demonstrate the advantage of a SIW slot array antenna: the low sidelobe levels. This parameter can also be improved by adjusting the simulation parameters and increasing the number of arrays antenna.

Dimension wise, the SIW antenna 2x8 elements (156,35x42x0,508) mm in X band is more compact than the traditional metal ODS 2x8 elements (about 400x30x60) mm. In addition, studying the power level of Rogers 5880 substrate on MVI software showed that the substrate could sustain pulsed peak power of more than 100 W. This demonstrates that the small SIW slot array antenna can be applied in practice in radar stations' antenna systems.

4. CONCLUSIONS

This paper has presented theoretical foundations for designing compact SIW slot array antennas. The integration on a dielectric substrate makes the size and

weight of the SIW slot array antenna much smaller than the conventional metal waveguide, with the benefit of low sidelobe level. This new structure is suited for planar array antenna designs at the centimeter and millimeter ranges.

The simulation and measured results of the 2x8 elements SIW slot antenna array show a good agreement between theory and practice, proving that such a SIW slot array antenna structure can replace the metal waveguide in slot array antenna systems without any adjustment.

With the development of simulation techniques and computation tools, we can develop compact SIW slot array antennas with a more significant number of slots and rows to meet the smaller azimuth plane's requirements (less than 1°) for X band antenna systems.

This article was presented at the National Conference: **Application of High Technologies in Practice - 60 years of development in the Academy of Military Science and Technology.**

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TÓM TẮT

NGHIÊN CỨU GIẢI PHÁP THIẾT KẾ ĂNG TEN MẢNG KHE ỐNG DẪN SÓNG GỌN NHẹ SỬ DỤNG CÔNG NGHỆ SIW

Ăng ten mảng khe ống dẫn sóng (ODS) là cấu trúc quan trọng của ăng ten siêu cao tần với nhiều ứng dụng trong hệ thống ra đa và thông tin liên lạc. Các hệ thống ăng ten mảng khe ODS trước đây chủ yếu được gia công trên các ống dẫn sóng bằng kim loại, các nghiên cứu thiết kế ăng ten mảng khe ODS sử dụng vật liệu chất nền điện môi là một vấn đề mới. Bài báo này đưa ra những kết quả trong nghiên cứu, thiết kế và chế tạo ăng ten mảng khe ODS sử dụng công nghệ SIW (Substrate Integrated Waveguide) trong dải tần băng X. Kết quả nghiên cứu sẽ là nguồn dữ liệu quan trọng trong việc lựa chọn các giải pháp thiết kế ăng ten mảng khe ODS sử dụng công nghệ SIW gọn nhẹ thay thế cho ăng ten mảng khe sử dụng ODS kim loại truyền thống trong các ứng dụng thực tế cho các hệ thống anten của đài ra đa băng X.

Từ khóa: Ăng ten mảng khe; ODS; SIW; Siêu cao tần.

Received Jul 30th 2020

Revised Mar 31th 2021

Published May 10th 2021

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