Sensor and Simulation Notes

Note 566

16 June 2013

Applications on Ring-Shaped Omni-Directional Waveguide Antennas

Ali Houssein Harmouch[1], Hassan Saffouh Haddad[2]

[1]Lebanese University, Tripoli, Lebanon

[2]Lebanese University, Tripoli, Lebanon

*Ali H. Harmouch, E-mail: harmush_ah@hotmail.com

Abstract

Antennas are becoming crucial in an increasingly growing number of applications namely with the emerging of the wireless internet communications, military systems like aircrafts, missiles and submarines or even oil drilling systems where efficiency, compactness and cost play a decisive role. Nonetheless, a major drawback of such solutions is that the aforementioned criteria are hard to simultaneously optimize. In this project, an innovative approach relying on using Ring-Shaped Slotted Waveguide Antenna (RSSWA) as a good alternative is presented, that allows enhancing drastically the ratio of performance versus cost and size. Simulation results along with Experimental validations will be carried out at 2.4 GHz frequency and indubitably demonstrating high effectiveness in terms of directivity and high gain given a reduced cost, shape and size. .

Index Terms – Slot, waveguide, omnidirectional, radiation efficiency, compactness, pattern, directivity, high gain, RSSWA.

1. Introduction

Slotted waveguide array antennas are increasingly used in numerous areas of applications mainly in the field of military communications as radar antennas, remote sensing antenna systems, aerospace antennas, as well as in wireless internet distribution systems since they have various advantages over other competitive antennas such as high power handling capability, low losses and good control over the side lobes. In addition, slotted waveguide antennas are light, compact, easy to fabricate and capable of withstanding radiation, thermal and vibration requirements of aircraft applications. Electromagnetic numerical techniques provide the possibility of modeling slotted waveguide antennas as well as optimizing their electrical characteristics for further advancements. The aim of this work is to simply analyze and design a high gain antenna with omnidirectional characteristics for the use as a distributing antenna for wireless internet communication systems. For such a purpose, many antenna systems have been used in recent years and many antennas have been recently developed to satisfy the market needs [1, 2 and 3].

Waveguides have been first used as guided structures with low loss and later have been applied for the use as radiating elements such as open end waveguide radiators, horn antennas and slotted waveguide antenna systems. Due to the fact that the waves are considered as travelling waves in a guide, radiating slots have been placed on the broad wall of the waveguide at the points of maximum currents and arranged in a chess order for it to operate as a broadside array with a radiation pattern having a maximum normal to the plane containing the slots [4] as shown in fig.1. It is important to notify here that the radiation pattern of the slotted waveguide antenna depends on the number of slots, the position of the slots, the spacing between adjacent slots, and the length of the slots as well as the progressive phase difference between the slots of the array.

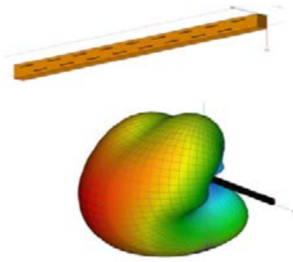

Figure1: Radiation pattern of a regular unidirectional slotted waveguide antenna.

From fig.1, it is obvious that for providing omni-directionality, using regular slotted waveguide antennas, several of such antennas are needed to be put on a tower angularly spaced in order for each one to cover a certain sector of space as developed and proposed by P. Mondal and A. Chakrabarty [3,5]. This technique is not economically competitive since the cost of the antenna system will increase. In addition, this will also lead to the appearance of some nulls in the horizontal pattern, so the Omni- directionality aimed is negatively affected. The nulls appearing in the x-y pattern in wireless internet distribution is a major drawback since some of the randomly distributed subscribers might suffer from weak signals or coverage.

In this paper a novel approach has been developed for the purpose of obtaining the desired directional characteristics. So, a folded rectangular slotted waveguide antenna made out of 30 resonant slots on the broad wall of the guide in the form of a ring has provided a perfect omnidirectional pattern with an average gain of 15 dB. The maximum size of this antenna does not exceed 60 cm in diameter and 6cm in height when placed horizontally. In comparison with other antennas used for the same purpose the designed antenna is electrically, mechanically and economically competitive since no great nulls are appearing in the pattern, very easy to fabricate, has high wind resistance, cheap and compact and can be easily attached to a tower. This makes it very convenient for use as a radiating element in WLAN networks. In addition to all above mentioned advantages, the proposed design has the shape of a circular ring which makes it suitable for use in military systems like aircrafts, missiles and submarines.

An optimization process has been made on the proposed antenna for enhancing its directional characteristics and mainly its directivity.

This paper is organized as follows. In Section 2, we formulate the method used and various considerations. In Section 3, numerical results and discussion are presented. In section 4, the RSSWA is integrated in various applications. In section 5, a convenient process to miniaturize furthermore the antenna is presented. Experimental results are shown in section 6 and concluding remarks are given in Section 7. It is further noted that slotted waveguide antennas have been considered for high-power microwave applications in the past [6, 7, 8 and 9].

2. Problem Statement

The main purpose of this study is to select the best antenna design shape that provides an omnidirectional radiation pattern, high gain, minimum side lobes, with compactness and a suitable antenna for WLAN applications at 2.4GHz. The first step started with the simulation of the already existing and well known longitudinal rectangular slotted waveguide antenna operating with the dominant TE_{10} mode at a frequency of 2.4 GHz. For the next step, the regular antenna has been folded to have the shape of a circular ring and in order for it to obtain an omnidirectional radiation pattern with no significant nulls. Simulations have been made on a 15 dB slotted waveguide antenna having around 30 slots that are placed specifically in a chess order over the broad wall of the guide in order for them to form a broadside array of equally phased slots. This combination of resonant slots resulted in a pattern with a maximum normal to the plane containing the slots which is in our case the radial direction in cylindrical coordinates. Furthermore, an optimization of the antenna is accomplished throughout a series of simulations to optimize the radiation efficiency. For more improvement, an adjustment of the slot shape, position and width as well as mode excitation of the antenna has been made to provide the desired results. Feko simulations are based on the Method of moments described by the formulas listed below.

$$\hat{t} \cdot \int_S \bar{G}(\vec{r}, \vec{r}\,') \cdot \vec{J}(\vec{r}\,') dS' = \frac{4\pi i}{k\eta} \hat{t} \cdot \vec{E}^{i}(\vec{r}) \quad (1)$$

$$\bar{G}(\vec{r}, \vec{r}\,') = \left(\bar{\mathrm{I}} - \frac{1}{k^2} \nabla \nabla' \right) g(\vec{r}, \vec{r}\,') \quad (2)$$

$$g(\vec{r}, \vec{r}\,') = \frac{e^{ik|\vec{r} - \vec{r}\,'|}}{|\vec{r} - \vec{r}\,'|} . \quad (3)$$

Where $\vec{r}$ stands for a vector on surface S, $\hat{t}$ denotes a unit tangent vector on S, and $\vec{J}(\vec{r})$ is the induced surface current.

FEKO is a suite of tools that is used for electromagnetic field analysis of 3D structures. FEKO simulations are based on the Method of Moments (MOM) solution to Maxwell's equations and features several extensions to the MOM for the solution of complex problems, including large structures and complex dielectrics or human tissue. Various output parameters can be computed and displayed in a number of formats to make FEKO a leading electromagnetic simulation software suite. It enables users to solve a wide range of electromagnetic problems.

3. Numerical results

As a start, the rectangular waveguide section was designed first in order to allow the dominant TE_{10} mode to operate in the waveguide at the desired frequency used by wireless internet networks which is around 2.4GHz. The design process started with the design of a ring – shaped slotted waveguide antenna with 18 slots that has been calculated and estimated to provide a gain of 12 dB Simulations made on this antenna have shown a clear omni-directionality but with some un-roundness in the horizontal pattern. This un-roundness results in an inadequate behavior for all users located around the radiating antenna which limits its importance. Results on this antenna are shown below in fig.2 and fig.3.

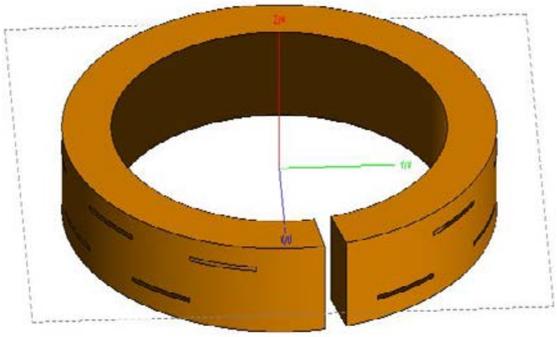

Figure2: Ring-shape slotted waveguide antenna (RSSWA) with 18 slots (12 dB) at 2.4 GHz.

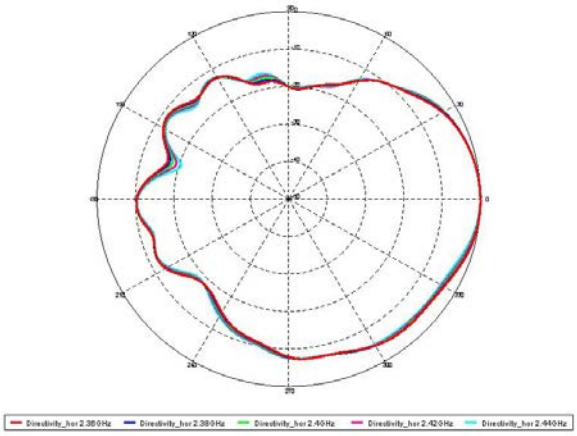

Figure3: Radiation pattern of an (RSSWA) with 18 slots in x-y plane at various frequencies.

Thus, when the operating frequency is varied within the range 2.35GHz to 2.45 GHz, the radiation pattern has shown similar results making the antenna have a broadband behavior and this will be shown later on also when determining the power reflection loss versus frequency. This is also considered one more advantage in favor of this designed antenna.

In spite of the fact that the pattern is showing good enough directional characteristics, an optimization process has been made on the antenna for it to provide the best results. For this purpose, it has been decided to increase the number of slots in the ring-shape waveguide antenna from 18 slots to 31 slots (from 12dB to 15dB gain). This idea has been suggested in order to provide uniformity in the horizontal pattern and to minimize the un-roundness in the pattern. Simulations were made on this antenna at multiple frequencies, where results are shown in fig.4 and fig.5.

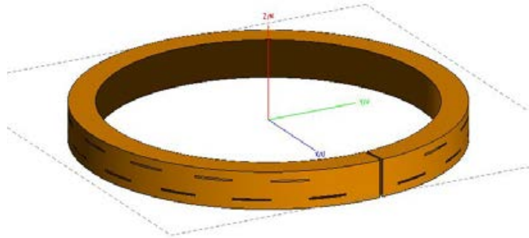

Figure 4: Horizontally mounted RSSWA with 31 slots
(15 dB) at 2.4 GHz.

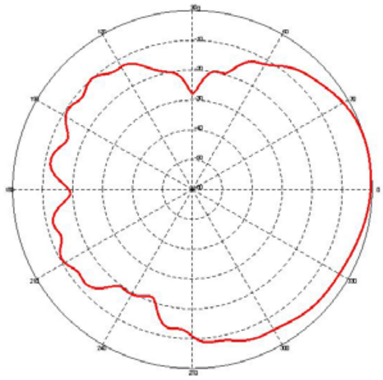

Figure 5: Radiation pattern of an (RSSWA) with 31 slots in x-y plane at 2.4 GHz.

From the results shown above, one may notice that a little improvement has been achieved on the antenna performance; however this was on the expense of the antenna size and cost. Therefore it has been decided to vary the orientation of the antenna in space in order for the antenna to operate with different polarization states (vertical and horizontal polarization) and the antenna would look like the one shown in fig.6.

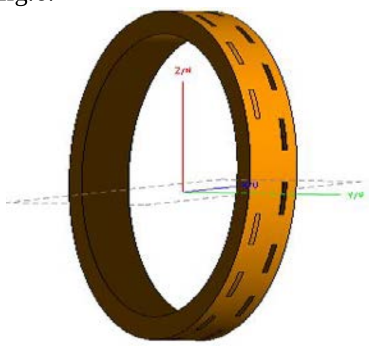

Figure 6: Vertically mounted (RSSWA) with 31 slots (15 dB) at 2.4 GHz.

Feko simulations on this antenna have shown great performance i.e. near omni-directionality in x-y horizontal plane and great gain in the vertical plane as shown in fig.7, fig.8 and fig.9. It is obvious in fig.7 that an approximate null is appearing in the pattern and it is minimized as the radius of antenna is becoming bigger. This observation leads us to a new optimization line in which the curvature of the antenna is to be considered. In addition to the curvature effect, the un-roundness in the radiation pattern is due to the reflections inside the waveguide which lead to some destructive interference at some angles.

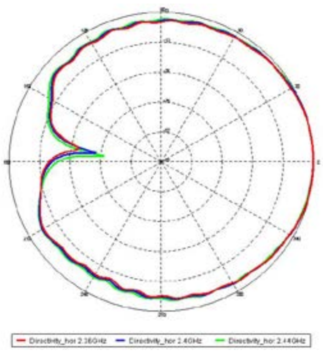

Figure 7: Radiation pattern of a vertically mounted (RSSWA) with 31 slots in x-y plane at various frequencies

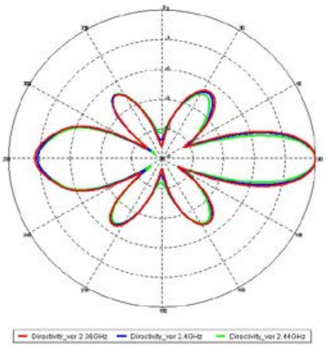

Figure 8: Radiation pattern of a vertically mounted (RSSWA) with 31 slots in the vertical plane at various frequencies

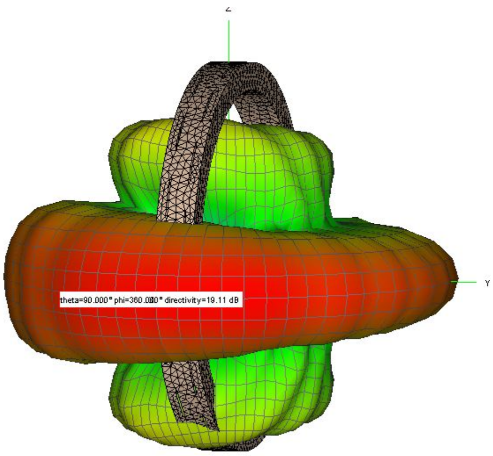

Figure 9: 3-D Radiation pattern of a vertically mounted (RSSWA) with 31 slots.

4. Integrated RSSWA in multiple Applications

Based on the obtained results shown above, various applications have been made on the RSSWA and have shown a great significance in terms of electrical and mechanical characteristics. The results are illustrated below depending on each application.

4.1 Optimal Design for Military Applications

In addition to the great directional characteristics, the designed antenna has the shape that suits some of the fast moving vehicles used in military communications such as missiles, aircrafts and so on. This may open a new era in the design of compact antennas for such systems. The RSSWA can clearly be integrated in a missile shape as shown in fig.10.

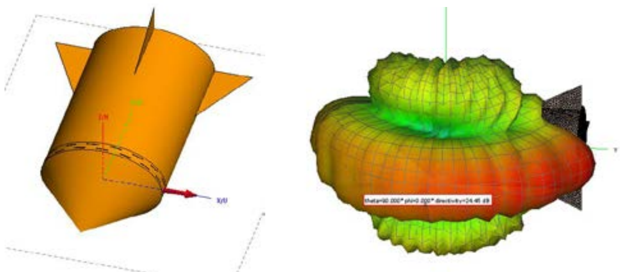

Figure 10: Integrated RSSWA in a missile with its simulated 3-D Radiation Pattern.

4.2 Optimal Design for Earth Drilling Devices

In other applications, like digging devices for searching petroleum deep in earth, digging devices are usually equipped with different types of antennas that might be mechanically not suitable. In such cases the proposed antenna is a good solution since it fits the shape of the cylindrical digging device and provides significant radiation efficiency for such systems as shown in fig.11.

Table 1: Miniaturization of the RSSWA using Silicon.

Antenna Type	Directivity	Average Gain [dB]	Weight [Kg]	Dimensions [cm]
RSSWA filled-with-Air	Omni-directional	15	1.23	63.6 × 6.38 × 4.5
RSSWA filled-with-Silicon	Omni-directional	15	0.65	31.2 × 3.1 × 2.2

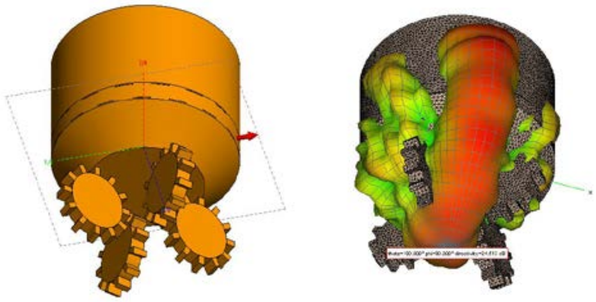

Figure 11: Integrated RSSWA in an Oil Drilling Device with its simulated 3-D Radiation Pattern.

5. Miniaturization of the RSSWA

One of other advantages of this antenna is that it can be filled either by air or by any other dielectric with higher relative permittivity that permits us to miniaturize the size of the antenna without varying the operating frequency also without modifying its directional characteristics. For example, the silicon dielectric used in this case has $\boldsymbol{\varepsilon}_r = 4$ and the difference in dimensions is shown in fig.12 and table1.

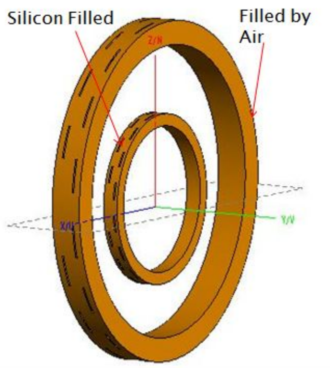

Figure 12: 2 RSSWAs (15dB) one filled with Silicon and the other filled by Air.

6. Experimental results

To verify that simulation results are reflecting exactly the performance of the designed antenna, a series of experimental trials have been made on the fabricated antenna shown in fig.13 at the Notre Dame University (Louaize, Lebanon) antenna laboratory. The tested antenna, which is made out of copper plates of 1mm thickness, filled by air, has been excited by a quarter wavelength monopole (at f = 2.4GHz) and connected to the inner broad wall just a quarter wavelength distant from the first edge of the guide. As per the end edge of the rectangular waveguide different configurations for this edge can be applied, starting from no edge, piston edge, lossy dielectric absorbing edge, or simply a conducting edge. However, in this paper, the tested model had the simplest configuration which was a conducting surface edge. The conducting edge sets up standing waves in the antenna via reflections at the conducting surface. A traveling wave antenna can also be tried in future experiments by introducing a lossy-dielectric absorbing edge. It is noted that several parameters of this antenna are available for optimization, including the radius of curvature in future studies. The waveguide dimensions of 6.38 cm x 4.5 cm used in our measurements is non-standard. The standard waveguide for this S-band frequency of 2.4 GHz is WR 340 (USA), or WR 9A (British) or R 26 (IEC). This standard waveguide [10, 11] has inner dimension of 8.636 cm 4.318 cm. Future studies in this area need to be done with standard waveguides.

Using the anechoic chamber facilities the antenna was placed on a rotator and connected to a spectrum analyzer that collected the data and showed graphical representation of the fields in both planes. Results have shown almost a similarity between measurements and simulations and are shown below in fig.14.

Figure 13: The fabricated antenna with 18 slots

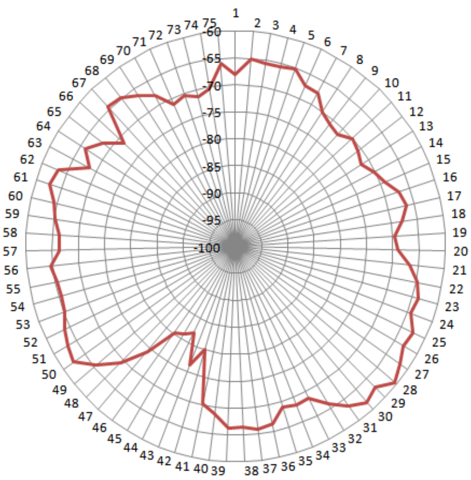

Figure 14: Measured radiation pattern in x-y plane with 18slots

Based on the scattering parameters obtained using Feko simulations, the antenna has shown great impedance matching with a negligible reflection loss of about -34 dB as shown in fig.15.

Figure 15: Reflection loss versus frequency

From figures 16 and 17 it is obviously shown that the designed antenna is properly matched which makes it convenient for use as a transmitting element.

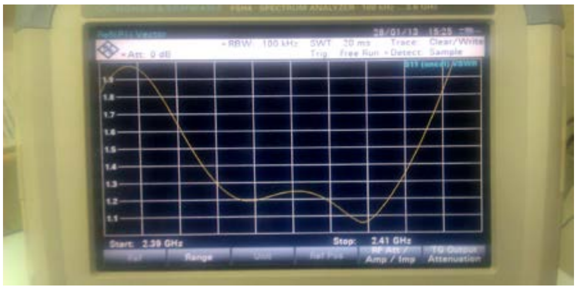

Figure 16: VSWR versus frequency

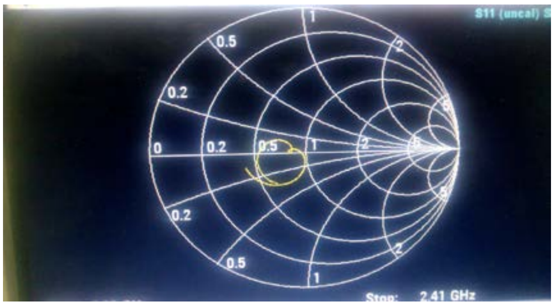

Figure 17: Smith Chart Graph

7. Conclusions

As a conclusion, the ring – shaped slotted waveguide antenna (RSSWA) finds lots of applications in the communication market and is considered very effective as a radiating antenna for wireless internet applications since it provides almost equal or uniform coverage for users living in the surrounding environment with high gain. Its characteristics make it suitable to be use in aircrafts and other fast moving vehicles since it can perform desirably without affecting their aerodynamic characteristics compared to others. In addition, the antenna is light, compact and easy to fabricate which makes it very competitive in the antenna market. For more improvement, an adjustment on the number, shape, size and position of the slots can be conducted for reducing sidelobes as well as enhancing the bandwidth of this antenna. In addition, an optimization of the curvature of the antenna is to be taken into consideration in order to eliminate totally the drawbacks of the pattern.

Acknowledgements

Special thanks to all coauthors involved in this research as well as to Dr. Elias Nassar for spending his time measuring the antenna parameters at Notre Dame University's laboratory and also for Mr. Mohammad Saffouh Haddad who used whole new advanced techniques in order to fabricate the prototype of the RSSWA.

References

[I] T. Takeshima, “X-band omni-directional double-slot array antenna,” Electron Eng., vol. 39, pp. 617-621, Oct 1967

[2] R.W. Lyon and A. J. Sangster, “Efficient moment method analysis of radiating slots in a thick-walled rectangular waveguide,” Proc. Inst. Elect. Eng. Part H, vol. 128, pp. 197-205, Aug. 1981.

[3] A. J. Sangster and H. Wang, “Resonance properties of omnidirectional slot doublet in rectangular waveguide,” Electronics Letters, vol. 29, pp., 1618, No. 1, 1993

[4] Balanis, C. A., Antenna Theory: Analysis and Design, 3rd Edition, New Jersey, John Wiley & Sons, Inc., 2005.

[5] P. Mondal and A. Chakrabarty “Slotted Waveguide Antenna with Two Radiation Nulls” IEEE transactions on antennas and propagation, vol.56, No.9, September 2008.

[6] Clifton C. Courtney, Donald E. Voss and Tom McVeety, Antenna Beam Steering Concepts for High Power Applications, January 2004, SSN 491, Sensor & Simulation (EMP-1), Summa Notes, UNM.

[7] Carl E. Baum, Sidewall Waveguide Slot Antenna for High Power, Sensor and Simulation Note 503, August 2005.

[8] SSN 547, Naga R. Devarapalli, Carl E. Baum, Christos G. Christodoulou and Edl Schamiloglu, An Iterative Search Algorithm for Designing Bends in Electromagnetic Structures, Sensor and Simulation Note 547, October 2009.

[9] Naga R. Devarapalli, Carl E. Baum, Christos G. Christodoulou and Edl Schamiloglu, Design of a rectangular waveguide narrow-wall longitudinal-aperture array using microwave network analysis, Sensor and Simulation Note 548, October 2009.

[10] C. D. Taylor and D. V. Giri, **High-Power Microwave Systems and Effects**, Taylor and Francis Publishers, 1994.

[11] D. V. Giri, “**High-Power Electromagnetic Radiators- Nonlethal weapon and Other Applications**, Harvard University press, 2004.