AMSE JOURNALS –2015-Series: Modelling A; Vol. 88; N° 1; pp 41-52

Submitted Feb. 2015; Revised March. 23, 2015; Accepted April 15, 2015

Enhancement of Directional Characteristics of Sectional Cylindrical Slotted Waveguide Antennas

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Abstract

Base station Cellular Systems and even Outdoor Wi-Fi Systems require omni-directional efficient antennas to provide an acceptable service within the cell site. Conventional antennas used for this purpose are mainly micro-strip patch antennas in the form of a circular array. However, these antenna elements suffer from low efficiency due to the additional losses involved in the feeder line as well as in the material from which the patch antenna is formed. These major drawbacks can be eliminated by introducing a sectional slotted waveguide array that consists of N longitudinally distributed slots at specific positions, and with specific dimensions in order for the antenna to provide high directional efficiency, compactness, high wind resistance and surely high power handling capability.

A series of simulation results have been done on the proposed antenna at the desired 2.4GHz frequency and show a significant gain of about 15dBi over the desired frequency band.

Key words

Sectorized, Sectional, slotted waveguide, radiation efficiency, array, gain, bandwidth, wind resistance.

1. Introduction

Antennas, today, are used in many systems especially in wireless internet communications and Radar applications where high power handling capability, high gain, and proper polarization along with reliable mechanical characteristics are needed. However, these parameters are very hard to simultaneously optimize, there is always a trade-off in between. In this paper, a Sectional Cylindrical Slotted Waveguide Antenna (SCSWA) is presented. The purpose of this paper is to provide an optimized version of cylindrical slotted waveguide antennas by simply selecting first the optimum dimensioning of the sectional waveguide then the optimum position, number, shape and size of the slots within the waveguide's sectional wall. Such configurations are suitable to be used in Wireless internet distributing systems and radar applications. [1,2]. Obviously, to provide 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 [3,4].

In this research, the example of one 90 degrees SCSWA is considered. A series of simulation results have been done on the proposed antenna at the desired 2.4GHz frequency and show a significant gain of about 15dBi over the desired frequency band demonstrating high effectiveness in terms of directional efficiency given a reduced cost, simplicity of fabrication with optimized size and shape.

In comparison to 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, it is very easy to fabricate, has high wind resistance with cheap manufacturing cost.

2. Problem Statement

The ultimate goal of this research is to have a defined number of sectional SCSWAs accordingly with the given application of choice that will always form the shape of one cylinder in terms of shape and combined can cover the whole surrounding area. Different configurations can be considered, such as 4 SCSWAs each covering a 90 degree sector.

Then, to select the best positioning and design for the slots of the sectional cylindrical slotted waveguide antenna in order to provide an Uni-directional radiation pattern, high directivity, minimum side lobe levels and compact size in comparison with other already existing antennas in market, in order for the antenna to be suitable for Wireless Internet applications at the 2.4GHz frequency in comparison with the latest researches that consisted of using just one slotted waveguide antenna instead of a set in order to minimize costs , space and interference in between [5,6]. The first step started with observing and comparing antennas that can be found in the market for these applications. One of the best in class antennas used in market for WLAN applications is the panel antenna. It consists of an array of patches. This antenna has very high gain, but has so many down sides. This antenna is being used in a certain way that a set of panel antennas covers the whole surrounding area, where each panel covers a certain sector as shown in figures 1 & 2 below. But, the biggest challenge for such antennas is the low efficiency due to the additional losses involved in the feeder line as well as in the material from which the patch antenna is formed. Now, using regular slotted waveguide antennas, a similar configuration is needed to be put on a tower yielding almost identical results.

Figure 1: Four Panel antennas mounted on a tower.

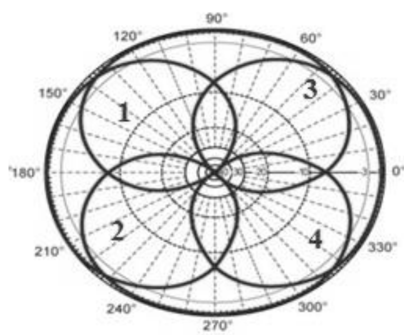

Figure 2: Horizontal (XY) Radiation Pattern for the Four Panel Antennas.

But, both come with the cost of space and also many mechanical issues. Thus, SCSWAs here have the advantage of either how many the number of the set is, they will always form one structure which is a cylinder as shown in figure 3 below.

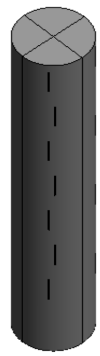

Figure 3: 4 Sectional Cylindrical Slotted Waveguide Antennas.

3. Numerical Results & Design

In order to determine the dimensions of the waveguide for a 2.4 GHz center frequency, calculations were performed using free space inside the waveguide. So the first parameter to be calculated was the radius of the guide [1]:

$$fc = \frac{\chi'_{mn}}{2\pi a\sqrt{\mu\xi}} \quad (1)$$

Where:

- χ'_{mn}: represents the zeros of the derivative of Bessel's function.
- a: Radius of the guide.
- fc: Cut-off Frequency.

There are standard dimensions and type designations for each cut-off frequency and each operating mode. But this only takes place for circular waveguides. In this research, a sectional waveguide needs to be calculated so only the cut-off frequencies between C22 and C25 will be used for this research's calculations (1.79GHz and 2.1GHz respectively).

For hollow circular waveguides, the standard nomenclature uses subscripts m and n to denote individual modes, like TE_{mn}. In contrary, for sectional waveguides, m is not an integer (irrational number) and it becomes awkward to use five or more digits to denote the first subscript of the wave. Some authors have used fractions and the letter π, but the most feasible proposal is the integer p as the first subscript, and n as the second, thus denoting the modes as TE_{pn} for example. p denotes the number of half-period variations of the modal field, when an observer moves at a constant radius from one end wall. This fact can also be described by saying that p represents the number of axial planes along which the normal component of the electric vector vanishes for TE modes [1].

The following equation (2) explains the relation between the subscripts m and p:

$$m = \frac{p\pi}{\varphi_0} \qquad (2)$$

Where φ_0 is the sectional angle of the waveguide as shown in the figure below [2]:

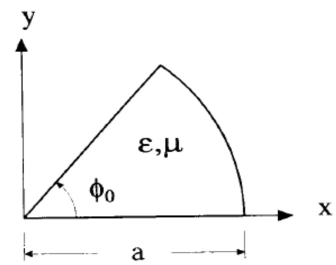

Figure 4: Cross section of a Sectional Circular Waveguide.

In this research, the sectional angle taken as an example is φ_0=90° for many reasons. First of all, if each SCSWA has a 90° angle so a total of four antennas can be mounted together into one structure at a base station, and thus compare them to sectorized panels put into similar configurations. Second, if φ_0=90° this will yield a simplification of the equation (2) to m=2p. This simplifies greatly the calculation of χ'_{mn}. Since for other values of φ_0, the m subscript in χ'_{mn} will become an irrational number.

Using MATLAB, the zeros of the derivative of Bessel's function of the first kind were determined.

Table 1: Zeros of deriv. of Bessel's function for φ_0 = 90 degrees.

p m\ n	1	2	3	4
0 0	3.831706	7.015587	10.17347	13.32369
2 1	3.054237	6.706133	9.969468	13.17037
4 2	5.317553	9.282396	12.68191	15.96411
6 3	7.501266	11.73494	15.26818	18.63744

From table 1, the smallest value for χ'_{mn} is for the TE11 where χ'_{11} = 3.054237. This yielded that the dominant mode for a sectional waveguide of φ0 = 90° is TE11.

Next, for the length of the waveguide, it was computed in terms of the desired number of slots along with the given guide's wavelength, so that the spacing between slots is of a half guide's wavelength.
And now, for the excitation of the guide with the dominant TE11 mode, a quarter wavelength monopole was used as a probe, positioned at a quarter guide's wavelength from the short ended wall of the antenna. It is represented in the blue dot in figure 4 below.

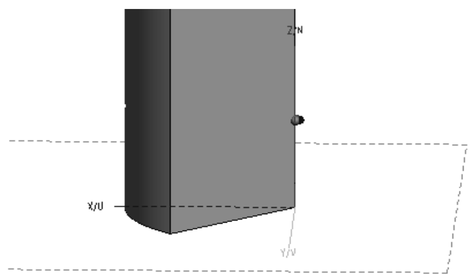

Figure 4: Simulated Geometry of the SCSWA.

Next step was to add 7 slots on the outer surface of the waveguide. Now, the position of the slots on the outer wall (the curved wall) is crucial as it is going to affect the radiation pattern of the antenna. The antenna has an array of slots, the array of elements should be broadside (all elements of the array should be excited with the same phase) as shown in figure 5 below.

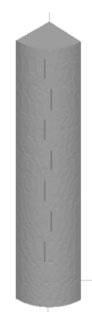

Figure 5: Simulated Model of the SCSWA.

4. Simulation Results

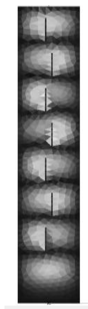

Figure 6: Charges Distribution along the Waveguide's Wall.

This first design has attained a maximum gain of 11.417dBi. From figure 6, since the charges accumulate at one end of each slot and the charge distribution is the opposite of that of the current distribution (maximum charge means minimum current) [7-12], this concedes the rules of a broadside array, where the slots are excited with the same phase.

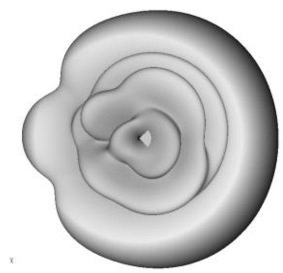

Figure 7: 3D Radiation Pattern for the SCSWA in dBi (Top View XY).

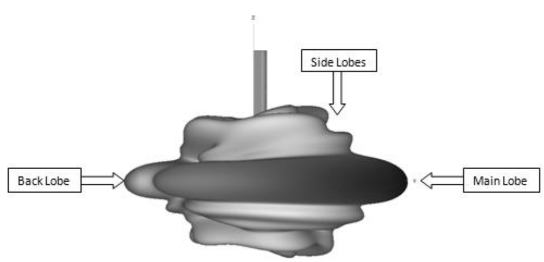

Figure 8: 3D Radiation Pattern for the SCSWA in dBi (Side View XZ).

From Figure 7 and 8, it can clearly be seen that the antenna has a unidirectional pattern, with some side lobes level and a back lobe. The back lobe has a maximum value of -8 dB (normalized) where as at a

-10dB the side lobes or back lobe are considered negligible in comparison with the main lobe of the antenna. These side lobes and back lobe are being shown in figure 8 above.

Also, it can be clearly seen that the SCSWA is matched with a resonance frequency of 2.4GHz as shown in figure 9 below.

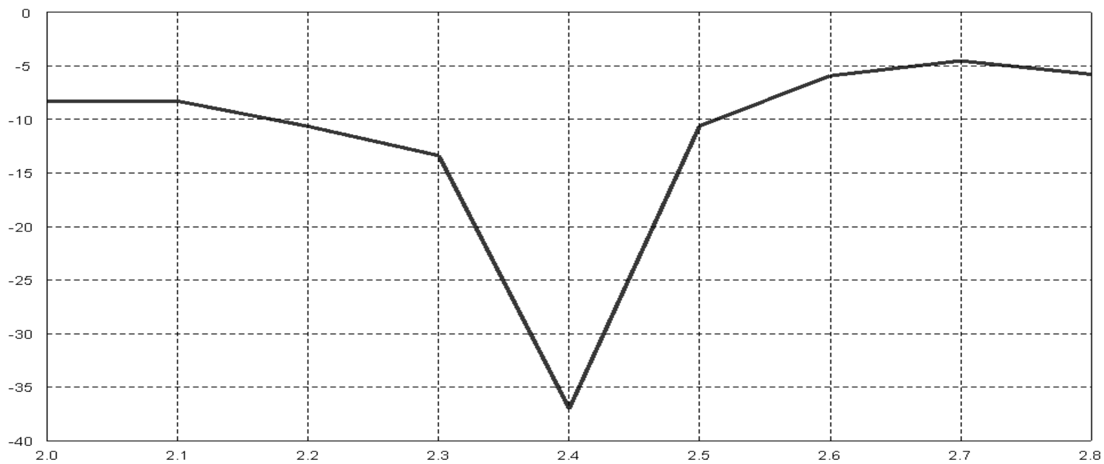

Figure 9: S11 Parameter in dB at a 2.4GHz operating frequency.

So, now begins the optimization process of the SCSWA.

5. Optimum Design

The optimization process was divided into three stages:

- Improving Directivity.
- Minimizing Side-Lobe Levels.

5.1. Varying the Cut-Off Frequency:

First optimization is used in order to improve the directivity of the SCSWA. It consists of varying the cut-off frequency of the guide accordingly from 1.6 GHz to 2.3GHz. Varying this parameter affected both the radius and the length of the waveguide. Since the radius is related to fc from equation (1) and even the length is related to the guide's wavelength (spacing between slots) which is in its turn related to fc having always the same operating frequency. Comparable dimensions are shown in figures 10 and 11 below.

Figure10: Variation of the Radius a of the SCSWA accordingly with fc.

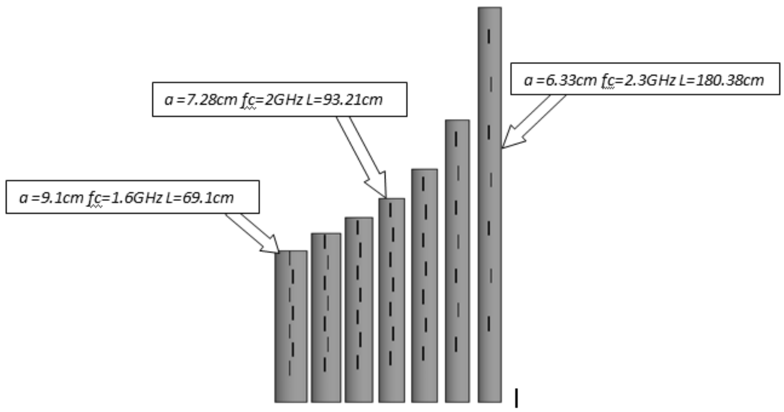

Figure 11: Variation of the Length of the SCSWA respectively with fc.

From figures 10 and 11, it is clear that the radius of the guide is inversely proportional to its length. Now, for the impact of this optimization on the radiation pattern of the SCSWA, radiation for each and every one of these SCSWA were compared together and the two patterns that had the lowest side lobe levels are shown in figure 12.

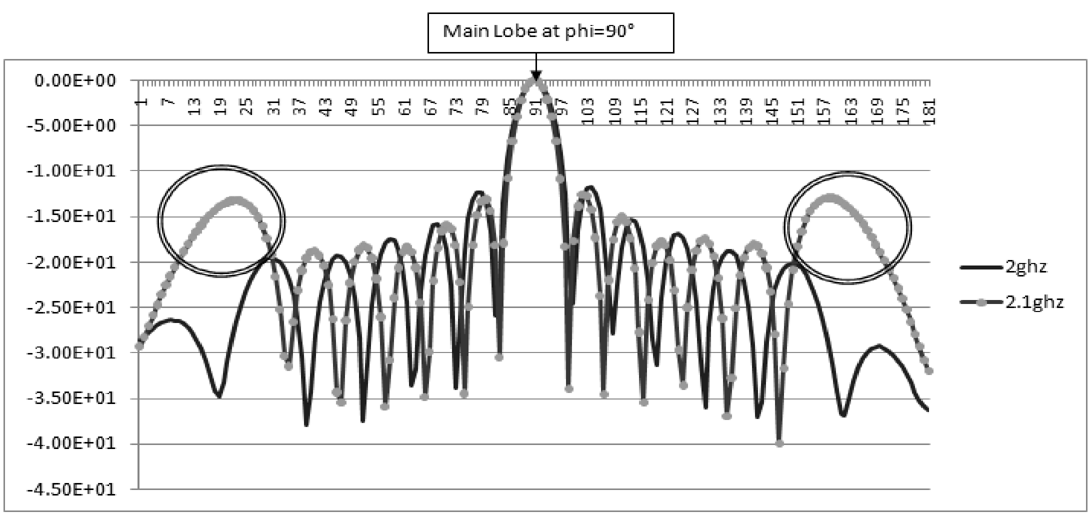

Figure 12: Comparison of the Radiation Patterns (Normalized) of the Two SCSWAs.

From figure 12, it is evident that the modeled SCSWA that has an fc=2GHz has the best radiation pattern between models since it has the lowest side lobe levels.

So the best model from this optimization in terms of radius, length and in terms of directivity is not the smallest model nor the biggest but the compromise between the radius and length of the waveguide. What is noticeable from this optimization is that all of these waveguides operate at 2.4GHz, as if there is only one unique volume that should be met for each operating frequency on the inside of the slotted waveguide in order to get the optimum electrical characteristics.

5.2. Optimization of the Slots Positioning:

The centerline of the waveguide is shown in the following figure 13.

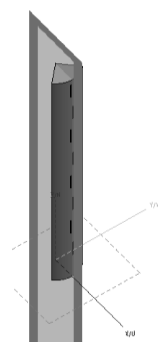

Figure 13: Center Plane as a Reference to the Slots Positioning.

Varying the slots positions in terms of degrees from centerline has improved greatly the directivity of the antenna as shown in the figure 14 below.

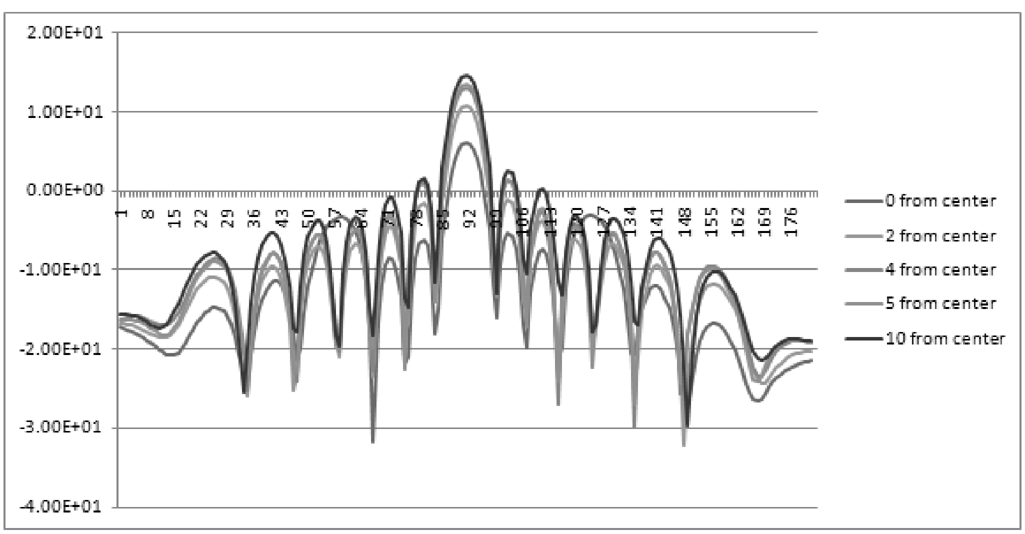

Figure 14: Effect of the Variation of the Slots Positions on the directivity (in dB).

It is evident that when the slots get further from the centerline of the waveguide wall the gain gets higher to reach a 15dBi for the 10 degrees position from centerline which is very convenient since this optimization does not affect the design of the antenna mechanically nor adds any limitations.

Conclusion

As mentioned earlier, Alteration on the Bessel's function were successfully conducted in order to find the different parameters and dimensions of a sectional waveguide. Simulations results were conducted on the 90 degree Sectional Cylindrical Slotted Waveguide Antenna (SCSWA) at the 2.4GHz frequency band on FEKO software based on previous broadside array antenna theories. The directional characteristics along with the radiation efficiency were all improved to meet to a far extent the targeted goal of this research.

Many optimization Processes were conducted that yielded a number of optimum designs in terms of electrical characteristics with a compromise in the mechanical specifications that was found at a 2GHz cut-off frequency. It is noteworthy to say that the antenna can have many more optimizations such as a better positioning for the slots array, more shapes for the slots in order to alter the polarization state of the antenna or even change the shape and sectional angle in order to meet the type of application it is going to be used in, with also scale the bandwidth of the antenna accordingly using different optimizations.

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