Sensor and Simulation Notes

Note 491

January 2004

Antenna Beam Steering Concepts for High Power Applications

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ABSTRACT

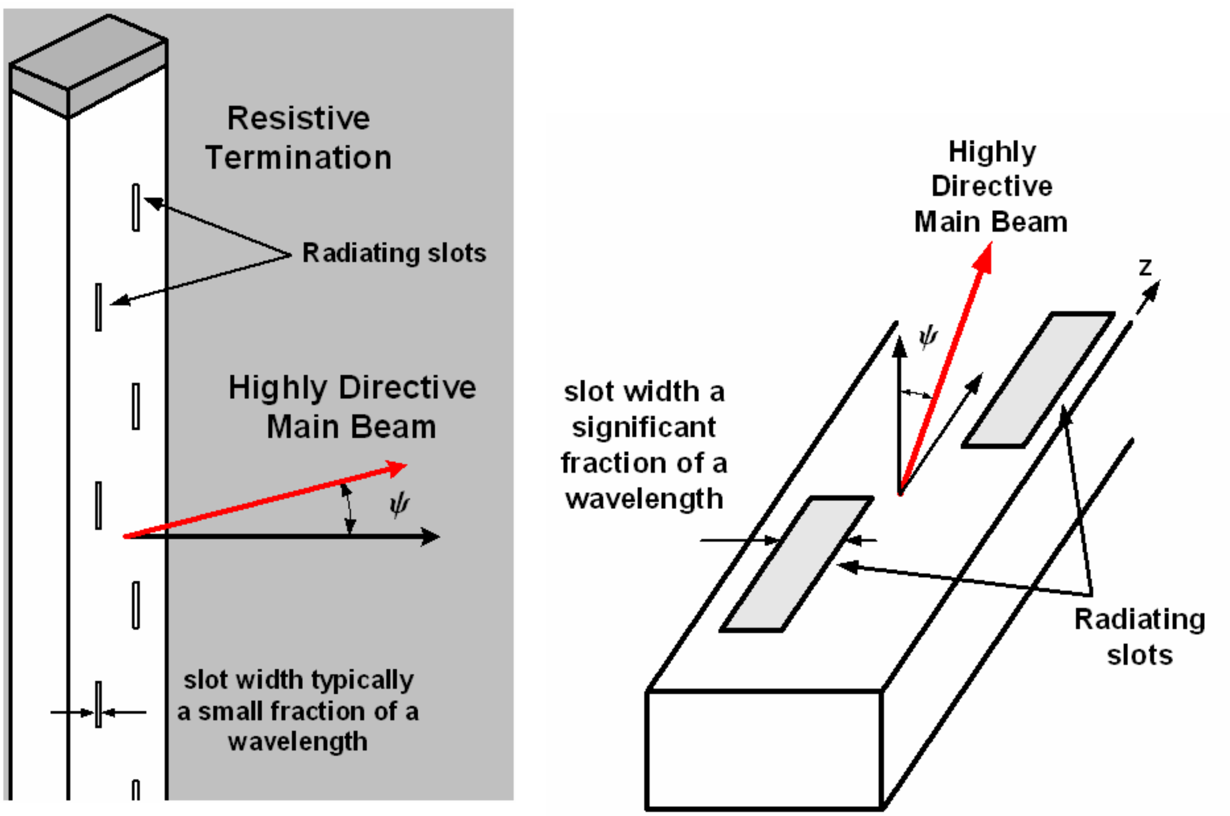
There is considerable interest in antennas that are high power capable, conformal to their host platform, and beam peak steerable. These attributes are often at odds with one another, but in this paper we will discuss approaches to mechanically steer the direction of the peak beam of a high power-capable, large-slot array antenna. The large-slot array antenna is formed from a collection of large apertures in the broad wall of standard rectangular waveguide. This gives the antenna inherently conformal properties with many types of platforms, and its large slots accommodate high power. Traditionally, the slot spacing (as a fraction of wavelength) of a slot array determines the direction of the radiated main beam of the antenna, and beam steering is accomplished by varying the frequency. But HPM narrowband sources are typically incapable of changing their operating frequency on the time scales normally associated with the concept of operations of HPM missions. In this paper we will show that beam steering can be accomplished by moving in or out, or deforming, the narrow wall of the rectangular waveguide. Two concepts are presented. The first considers the mathematically tractable wave properties (guide wavelength, propagation constant) associated with simple variations in the dimension of the broad wall of rectangular waveguide. The second approach involves the deformation of the narrow walls. The properties of this second approach are investigated through finite difference time domain simulation. To conclude this paper, an example is presented which demonstrates the beam steering capability of a large slot array in standard WR-650 waveguide.

Acknowledgement - This work was supported in part by the Air Force Research Laboratory, Directed Energy Directorate, under a Small Business Innovation for Research (SBIR) Phase I program, Contract No. F29601-03-M-0101.

1. Introduction

There is considerable interest in antennas that are high power capable, conformal to their host platform, and beam peak steerable. These attributes are often at odds with one another, but in this paper we will discuss approaches to control the direction of the peak beam of a high power-capable, large-slot array antenna.

One type of traditional waveguide slot array antenna utilizes narrow (in terms of wavelength) slots in the broad wall of the guide, as shown in Figure 1a. The high power-capable, large-slot array antenna concept is formed from a collection of large apertures in the broad wall of standard rectangular waveguide, as shown in Figure 1b. This gives the antenna inherently conformal properties with many types of platforms, and its large slots accommodate high power. Traditionally, the slot spacing (as a fraction of wavelength) of a slot array determines the direction of the radiated main beam of the antenna, and beam steering is accomplished by varying the frequency. But HPM narrowband sources are typically not frequency tunable on the time scales normally associated with the concept of operations of HPM missions.



(a) (b)

Figure 1. Slot arrays in the broadwall of rectangular waveguide: (a) standard, low power capable, waveguide slot array; and (b) Voss Scientific's high power capable, large-slot waveguide array antenna concept.

In this paper we will show that beam steering can be accomplished by moving in or out, or deforming, the narrow wall of the rectangular waveguide. Two concepts are presented. The first considers the mathematically tractable wave properties (guide wavelength, propagation constant) associated with simple translation of the width of rectangular waveguide. The second approach involves the deformation of the narrow walls. The properties of this approach are investigated through finite difference time domain simulation. These investigations show specific dependence of the wavelength and propagation constant as a function of the guide's broadwall dimension, or deformation of the narrow wall. To conclude this paper an example is presented which demonstrates the beam steering capability of a large slot array in standard WR-650 waveguide.

2. Rectangular Waveguide Geometry and Operating Characteristics

Rectangular waveguide is defined by a width (b) and a height (a), with standard guide typically exhibiting a 2:1 width to height ratio, $b/a = 2$. For purposes of our discussion, Figure 2 gives the coordinates and geometry of rectangular waveguide. For fundamental, or dominant mode propagation in standard rectangular waveguide [Ref. 1] the electric field distribution of the TE_{01} mode in the guide is given by

$$E_x = A \sin \frac{\pi}{b} y e^{-jk_z z}, \quad E_y = 0, \text{ and } E_z = 0. \qquad (1)$$

where $A =$ amplitude constant, $b =$ broadwall dimension, and $k_z =$ propagation constant.

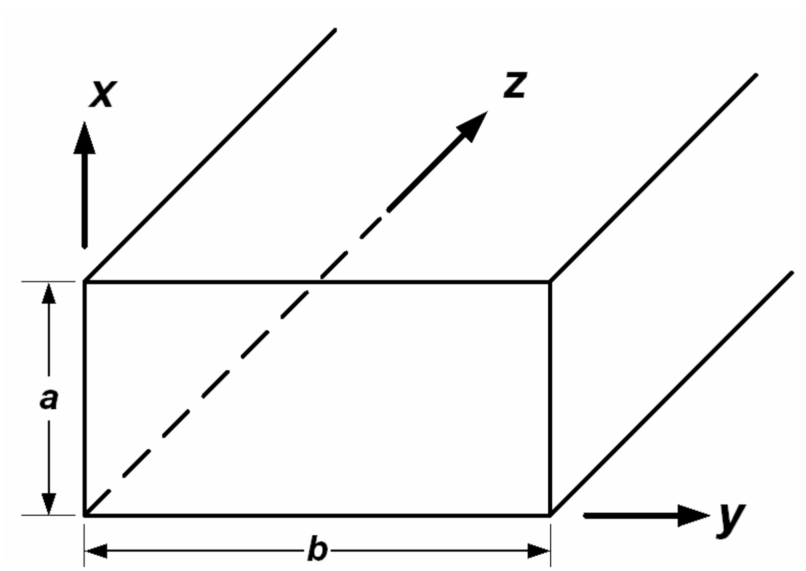


Figure 2. Rectangular waveguide is defined by a width (b) and a height (a).

The cutoff frequency in such a rectangular waveguide filled with free space is given by

$$(f_c)_{01} = \frac{c_0}{2b} \tag{2}$$

where $c_0 = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ = speed of light in vacuum. Consequently, the cutoff wavelength is $(\lambda_c)_{01} = 2b$, and the cutoff wave number, k_c, of the TE_{01} mode is given by

$$(k_c)_{01} = \frac{\pi}{b} \tag{3}$$

The mode's TE_{01} mode propagation constant (dropping the mode-specific notation with the understanding that the TE_{01} mode is intended from here on) is given by

$$k_z = \frac{2\pi}{\lambda_0}\sqrt{1-(f_c/f)^2}\ , \tag{4}$$

where $f_c = \frac{c_0}{2\pi}k_c$, and its wavelength is

$$\lambda_g = \frac{2\pi}{k_z}. \tag{5}$$

The normalized guide wavelength of the fundamental mode in standard rectangular waveguide as a function of the normalized broadwall width (both parameters normalized to the independent parameter free space wavelength λ_0) is shown in Figure 3. Also shown in the figure are the values of the guide's cutoff ($b/\lambda_0 = 0.5$) and of its first overmode ($b/\lambda_0 = 1$). The normal operating band for standard rectangular waveguide is also indicated in the figure. Nominally, the operating bandwidth for standard rectangular waveguide falls within the values $1.25\times f_c$ and $1.85\times f_c$. For reference, the normalized value of guide wavelength for WR-650 operating at 1.3 GHz is indicated in the figure.

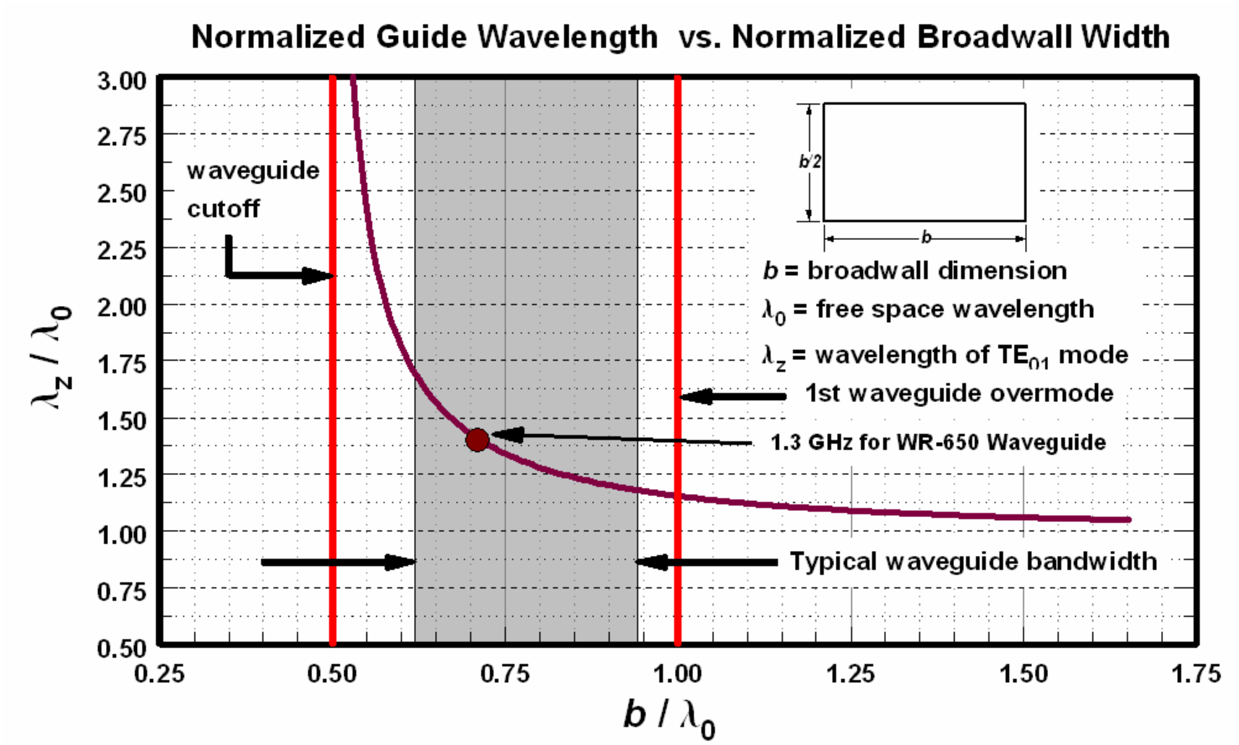


Figure 3. **Guide wavelength of the fundamental mode in standard rectangular waveguide. The independent parameter is the free space wavelength λ_0.**

3. Dependence of Wave Properties on Broadwall Width

As described the section above, the guide wavelength and propagation constant of the propagating wave are functions of the broadwall dimension (for a fixed frequency). Or, equivalently, the guide wavelength and propagation constant are functions of the operating frequency (for a fixed value of the broadwall dimension).

To better illustrate the former dependence, values of the guide wavelength (normalized to the free space wavelength) and propagation constant (normalized to the free space wave number) are shown in Figure 4 as a function of the normalized broad wall dimension for $f_0 = 1.3$ GHz ($\lambda_0 = 0.2306$ meter $= 9.079$ inch, and $k_0 = 27.245$ meter^{-1}). In this case the broadwall is normalized to the value of the broad wall dimension of WR-650 rectangular waveguide ($b_0 = 6.5$ inch, $a = 3.25$ inch). The guide wavelength at 1.3 GHz of the fundamental mode in WR-650 rectangular waveguide is $\lambda_{g0} = 0.322$ meter. The graph of Figure 4 shows considerable variation in the propagating modes parameters as the dimension of the broad wall is varied only slightly. Specifically, the change in the normalized propagation constant and normalized guide wavelength is approximately 15% for a variation in the broadwall of ± 1 inch from the nominal value ($b_0 = 6.5$ inch). The percent variation is determined as

$$\text{Percent variation} = \sqrt{\left|1-\frac{\lambda_{g1}}{\lambda_{g0}}\right| \times \left|1-\frac{\lambda_{g2}}{\lambda_{g0}}\right|} \tag{6}$$

where $\lambda_{g0} =$ guide wavelength for the broadwall dimension of 6.5 inch, $\lambda_{g1} =$ guide wavelength for the broadwall dimension of 5.5 inch, and $\lambda_{g2} =$ guide wavelength for the broadwall dimension of 7.5 inch. A similar relation is used to determine the variation of the normalized propagation constant.

Now consider the case where $f_0 = 1.12$ GHz frequency ($\lambda_0 = 0.268$ meter $= 10.539$ inch, and $k_0 = 23.27$ meter^{-1}), and the nominal waveguide dimensions remain those of WR-650. A change in the broadwall dimension of ± 1 inch from its nominal value ($b_0 = 6.5$ inch) results in changes to the propagation constant and guide wavelength of approximately 43%!

The obvious conclusion is that the closer to cutoff one operates, the greater amount of phase variation can be achieved with a fixed displacement of the waveguide broadwall dimension. The other observation is that a greater amount of variation (percentage wise) is achieved by decreasing the broadwall dimension than by increasing it.

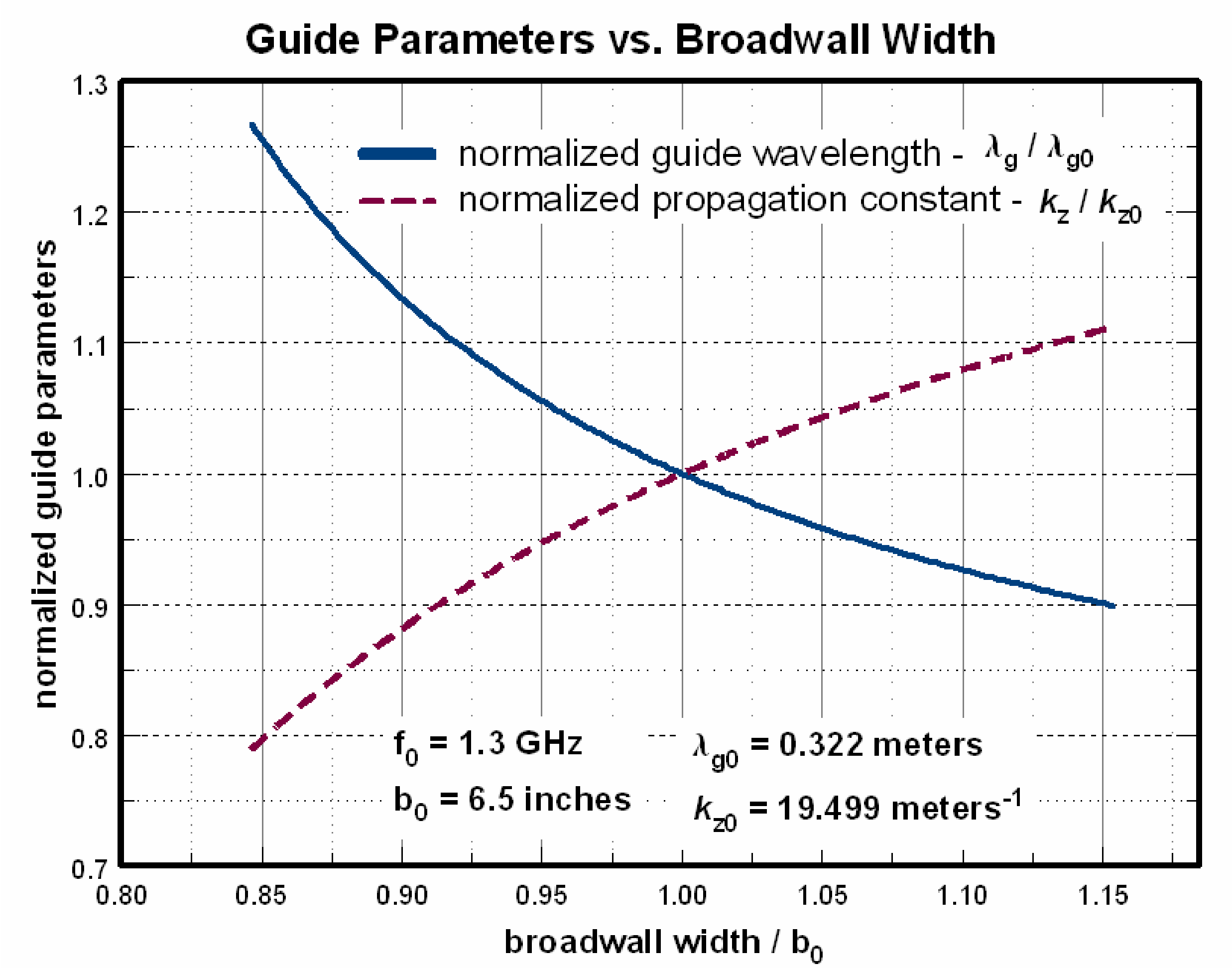


Figure 4. **The normalized guide wavelength and propagation constant of a wave in the TE_{01} mode propagating at 1.3 GHz as a function of the broadwall width.**

4. Direction of the Main Beam of a Waveguide Slot Array

The radiated pattern of a non-resonant, traveling wave, slotted waveguide array, with slots placed on alternating sides of the broadwall centerline, can be determined as follows [Ref. 2]. The array factor that describes the radiated field of the slot array is

$$F = \sum_{n=1}^{N} a_n e^{j(k_0 \sin\psi - k_z)nd + jn\pi} \tag{7}$$

where $k_0 = 2\pi/\lambda_0 =$ free space wave number, $a_n =$ slot amplitudes, and $\psi =$ direction of pattern peak (see Figure 1). For the radiation from all slots to add in phase in the $\psi -$ direction,

$$(k_0 \sin\psi - k_z)d + \pi = 2m\pi\,, \tag{8}$$

or,

$$d = \frac{(2m-1)\pi}{k_0 \sin\psi - k_z} = \frac{(2m-1)\lambda_0\lambda_g}{2(\lambda_g \sin\psi - \lambda_0)}. \tag{9}$$

Choosing $m = 0$ and solving for $\sin\psi$: $\sin\psi = \frac{\lambda_0}{\lambda_g} - \frac{\lambda_0}{2d}$.

The bounds

$$-1 \le \sin\psi \le +1$$

imply

$$\frac{\lambda_0\lambda_g}{2(\lambda_0+\lambda_g)} < d < \frac{3\lambda_0\lambda_g}{2(\lambda_0+\lambda_g)}.$$

This imposes the following restriction on the possible directions for the beam peak

$$-\frac{\pi}{2} < \psi < \sin^{-1}\left[\frac{2\lambda_0 - \lambda_g}{3\lambda_g}\right]$$

For example, consider standard rectangular waveguide operating in fundamental mode at 1.12 GHz. The free space wavelength is $\lambda_0 = 10.54$ inch, $\lambda_g = 18.00$, and the beam peak range is

$$-\frac{\pi}{2} < \psi < \sin^{-1}\left[\frac{2\times 10.54 - 18.00}{3\times 18.00}\right] = 3.3 \text{ degrees.}$$

The design of the slotted waveguide array now proceeds by selecting a beam peak direction, and then computing the slot separation. Choosing a pattern peak angle of $\psi_{peak} = 0$ degrees for a broadside peak, then the guide slot spacing is determined as

$$d = -\frac{\lambda_0\lambda_g}{2(\lambda_g \sin(0) - \lambda_0)} = \frac{-(10.54)(18.00)}{2[0 - 10.54]} = 9.00 \text{ in}$$

and adjacent slots are placed on opposite sides of the waveguide broadwall centerline with the distance from the centerline governing the amount of power coupled out of each slot and the slot impedance.

5. Mechanical Beam Steering Concepts

Two mechanical methods to steer the beam of a waveguide slot array are described in the proceeding sections. Each concept changes the cross sectional geometry of the rectangular waveguide in a manner that alters the wavelength and propagation constant of the guide's propagating mode. Changes in the direction of the main beam are then a consequence.

5.1 Mechanical Beam Steering Concept No. 1

In Figure 5 is shown the cross section of a rectangular waveguide. As indicated in the figure the narrow walls are slid in and out, in tandem, to adjust the dimension of the broadwall of the rectangular waveguide. As described above, when the broad wall dimension changes, the propagation properties adjust accordingly.

Implementation of the above concept at high power could be a challenge mechanically. Depending on the power propagated down the guide, there may be insulation requirements (vacuum, SF_6, or even oil). The manner in which the insulation would be contained within or around the guide would then be a mechanical design issue and challenge. It's well known that the electric current associated with the TE_{01} mode changes direction in the guide's corners. Consequently, the sliding surfaces between the narrow and broad walls would need to maintain intimate contact to minimize the contact impedance in the corners. Failure to do so could result in unwanted sparking and plasma generation in the guide. The next concept described below avoids some of the mechanical challenges through a unique deformation of the narrow wall, rather than sliding surfaces against one another.

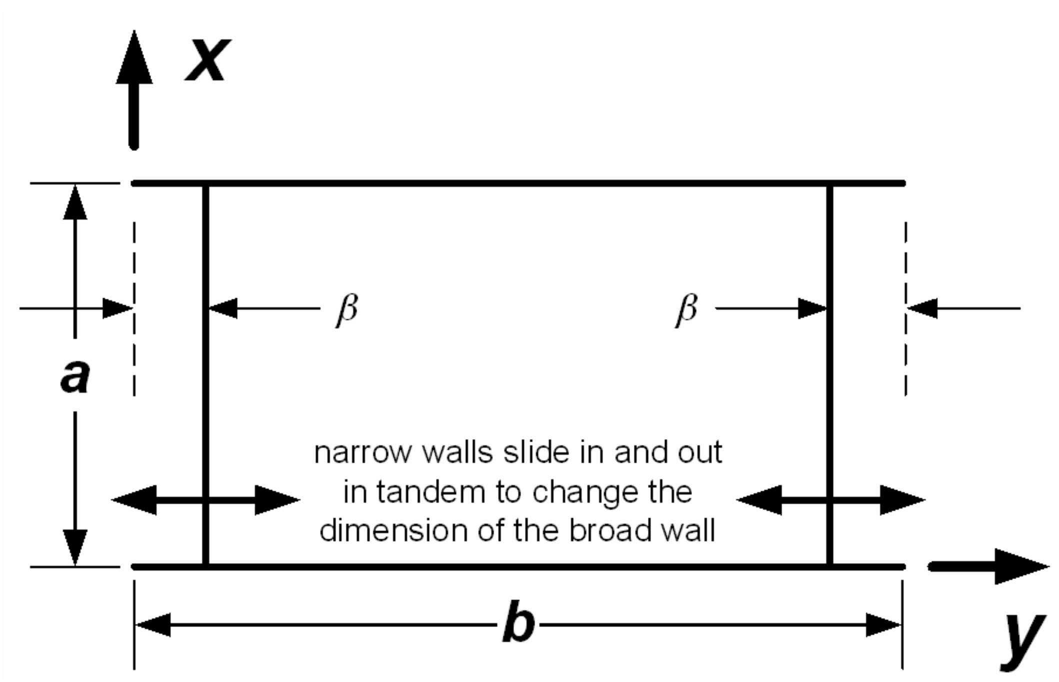
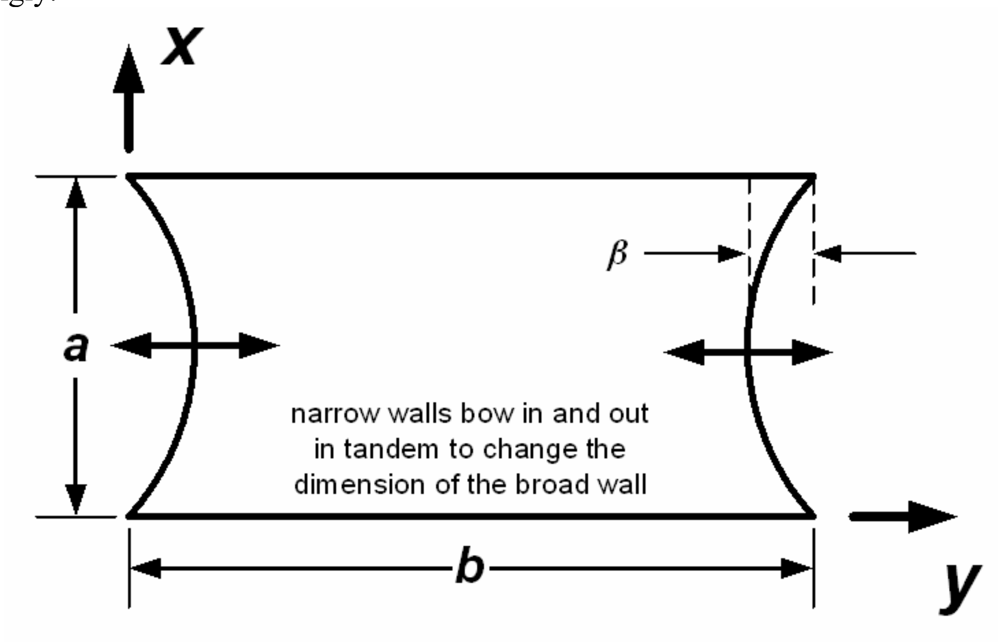


Figure 5. The narrow walls are slid in and out, in tandem, to adjust the dimension of the broadwall of a rectangular waveguide.

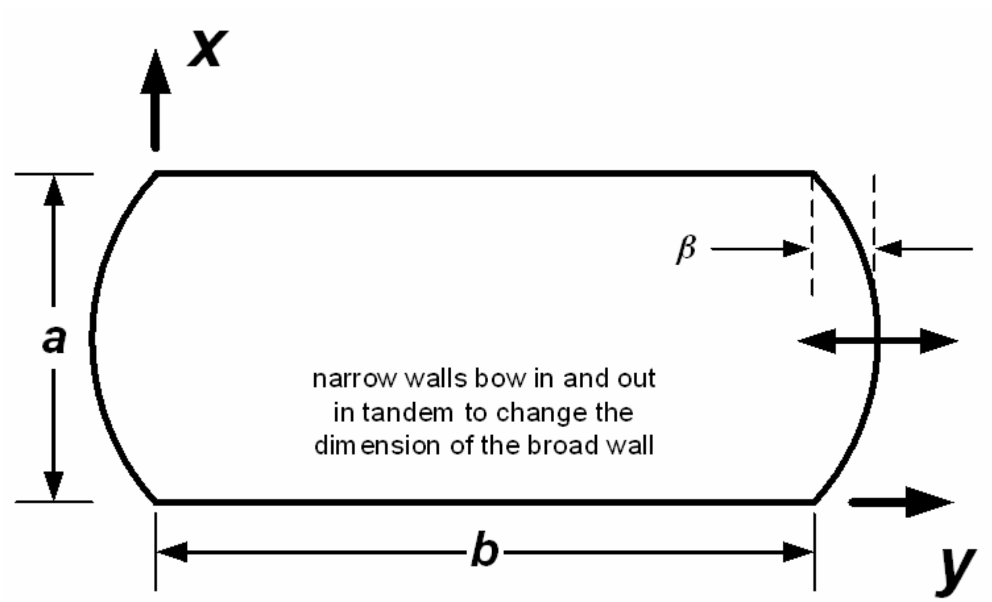
The changes in the guide wavelength and propagation constant as a function of the dimension of the broad wall dimension are indicated in Figure 3 and Figure 4.

5.2 Mechanical Beam Steering Concept No. 2

In Figure 6a and Figure 6b is shown the cross section of a rectangular waveguide. As indicated in the figure the narrow walls are bowed in and out, in tandem, to adjust the dimension of the broad wall of a rectangular waveguide. Though we present specific evidence later in this paper, we assert now that as the contour of the narrow wall is changed, the propagation properties adjust accordingly.



(a)



(b)

Figure 6. The narrow walls are bowed in and out, in tandem, to adjust the dimension of the broadwall of a rectangular waveguide: (a) narrow walls are bowed in; and (b) the narrow walls are bowed out.

This concept has significant mechanical and electrical advantages over the one described above. There are no seams between the narrow and broad walls, so insulation can be easily maintained within the envelope of the guide interior. And there is no need to maintain intimate contact among the sliding surfaces. For high power operation, Concept No. 2 is clearly superior.

To determine the dependence of the guide wavelength and propagation constant as a function of the deformation of the narrow wall (as indicated in Figure 6), finite difference – time domain simulations of several geometries were conducted. A 5 foot length of nominal WR-650 waveguide was defined with one end of the guide closed and the other end open to free space. An excitation was specified at the closed end, and the grid size was 0.0625 inches. The FDTD simulation time step size was 3.082 ps, and the simulation was run for 5,000 time steps. A different value of β was specified for each of eight simulations: β = -0.5, -0.375, -0.25, -0.125, +0.125, +0.25, +0.375 and +0.5 inches. Since the deformation, quantified by the parameter β, was carried out in tandem, the maximum / minimum cross sectional dimension of the xy-plane in the y-direction is $b+2\beta$. When the simulation concluded, contours of the magnitude of the E_y-component of the electric field distribution in the guide were generated, and the distance between adjacent field nulls was measured. From these measurements values of the guide wavelength and propagation constant as a function of the parameter β were determined for Concept 2. These values are given in Table 1.

Table 1. Values of the guide wavelength (λ_z) and propagation constant (k_z) as a function of the parameter β for nominal WR-650 waveguide dimensions and the operating frequency of f_0 = 1.12 GHz (λ_0 = 10.55 in). Values for both mechanical concepts are shown as determined though simulation and analytical calculation.

β (in)	Maximum cross sectional dimension in y-direction (in)	λ_z Concept 1 (in)	k_z Concept 1 (m^{-1})	λ_z Concept 2 (in)	k_z Concept 2 (m^{-1})
-0.5	5.5	35.15	7.04	24.97	9.91
-0.375	5.75	25.95	9.53	22.34	11.07
-0.25	6.0	21.94	11.27	20.44	12.10
-0.125	6.25	19.51	12.68	19.12	12.94
0.	6.5	18.00	13.74	18.00	13.74
+0.125	6.75	16.92	14.62	17.56	14.09
+0.25	7.0	16.04	15.42	16.66	14.85
+0.375	7.25	15.42	16.04	16.32	15.16
+0.5	7.5	14.89	16.62	15.50	15.96

Also given in Table 1 are the corresponding values for Concept 1. One notes that Concept 1 offers a greater tuning range, as expected since the entire narrow wall is translated, but the values for Concept 2 are not far different.

6. Example

To demonstrate the capability of the mechanical concepts presented here to steer the beam of a waveguide slot array, an 8 array was defined, and the direction of the beam peak was determined. For expediency a dipole array in free space was used as a surrogate structure for the waveguide slot array. Shown in Figure 7 are the radiated patterns of an 8-element slot array with the broadwall width as a parameter for WR-650 waveguide (nominal) and 1.12 GHz. One notes that changes to the broad wall of just 1 inch total (β = +0.5 inch) results in a 5-degree change in the beam direction. Simulations were also run for values of $\beta < 0$, but are not shown in the figure for clarity.

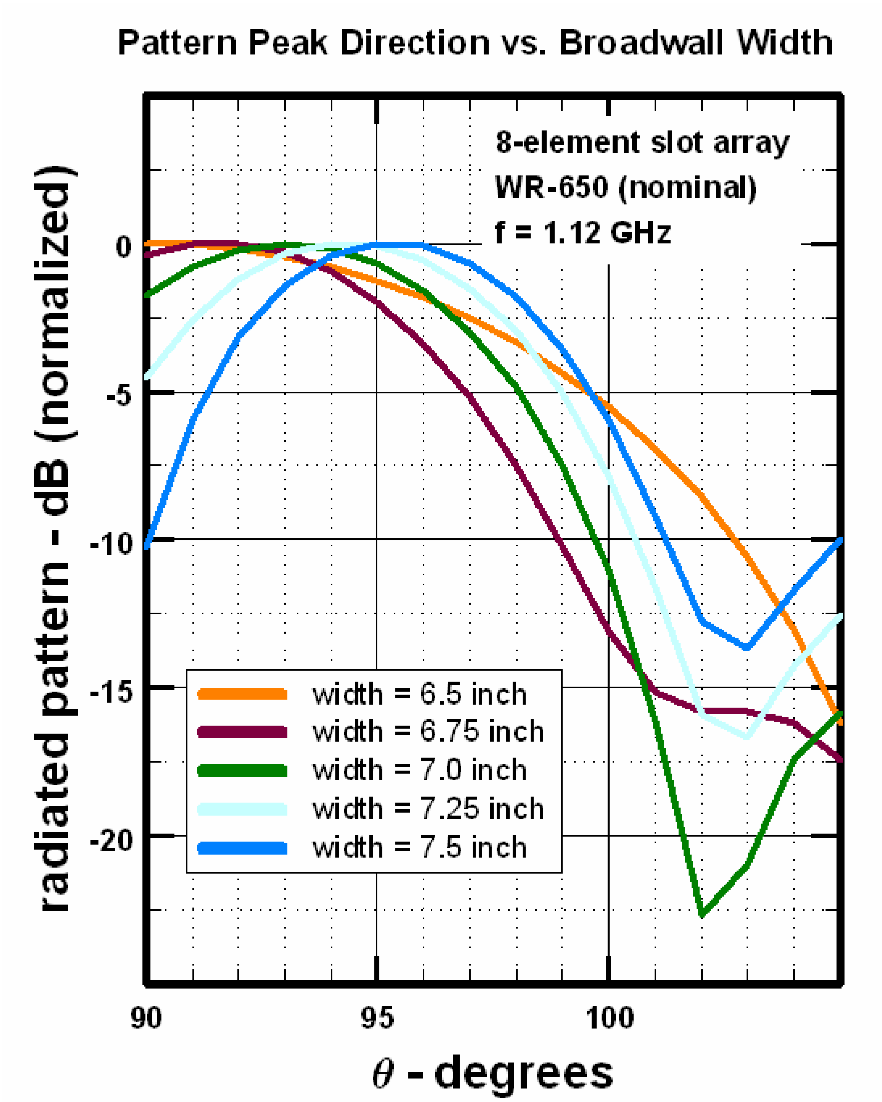


Figure 7. **The radiated pattern of an 8-element slot array (simulated by a dipole array). The pattern's direction of peak gain moves as a function of the broadwall width. The waveguide is WR-650 (nominal) and the frequency is 1.12 GHz.**

Given in Table 2 are the values of the beam peak direction as a function of the broad wall width (defined by β) for WR-650 waveguide (nominal) and is 1.12 GHz. A steering range of +5 and −9 degrees is indicated in the table. The beam steering is not symmetrical about values of β (see Figure 3 and Figure 4). Finally, the asterisk in Table 2, for data associated with β = -0.375 and β = -0.500, indicates that the beam begins to break up, and no longer has a single peak direction.

Table 2. Summary of the change of the beam peak as a function of the broadwall width. The waveguide is WR-650 (nominal) and the frequency is 1.12 GHz.

Broadwall width (in)	β	Peak direction (deg)
5.50	-0.50	81*
5.75	-0.375	83*
6.00	-0.25	85
6.25	-0.125	88
6.50	0.00	90
6.75	0.125	92
7.00	0.25	93
7.25	0.375	94
7.50	0.50	95

7. Conclusion

In this paper we have explored mechanical concepts for beam steering high power capable, conformal antennas. In particular we have considered two specific methods to steer the direction of the beam peak associated with a large-slot, waveguide slot array antenna. The first technique proposes beam steering by simple translation of the narrow walls of a standard rectangular waveguide to adjust the broadwall dimension. We gave specific relations of fundamental mode guide wavelength and propagation constant for variations in the dimension of the broadwall of rectangular waveguide. The second proposed approach involved the deformation of the narrow walls of the rectangular guide. The properties of this second approach were investigated through finite difference time domain simulations of the associated geometries. The simulation results showed that similar guide wave properties (wavelength, propagation constant) could be achieved by slightly deforming the narrow wall. To conclude this paper an example was presented which demonstrated the beam steering capability of a large slot array in standard WR-650 waveguide.

The important results of this investigation are as follows: (1) for maximum beam steering it is necessary to operate in frequency near (at, even below) the lower end of the frequency band of the guide; (2) the beam steering is not symmetrical as a function of β (the translation or deformation parameter); and (3) the second technique, while slightly less capable in terms of beam steering capability, is preferred for mechanical and electrical reasons.

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