The Design of Ultra-Wide-Band Antennas
with Narrow Beamwidths

A Thesis
Presented in Partial Fulfillment of the Requirements for
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by

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DEDICATION

This thesis is dedicated to my Family. They have, and always will be, a great source of support and understanding.
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CHAPTER I
INTRODUCTION

Ultra-Wide-Band Antennas have many applications. In a radar cross section (RCS) range, a single ultra-wide-band antenna can replace a large set of narrow-band antennas used to cover the frequency range of interest. This savings of antenna volume is also very useful for satellite applications where space and weight must always be minimized. An ultra-wide-band antenna can also enhance radar detection capabilities. It is even claimed that an ultra-wide-band antenna used with a pulse radar may be able to detect stealth targets. These applications and others make the ideal ultra-wide-band antenna a very interesting subject.

A novel approach to an ultra-wide-band antenna was developed by Lai [1]. This antenna type was further refined by Sinopoli [2] and was named the Slotline/Bowtie Hybrid Antenna (SBH). This antenna is a very desirable approach to the ultimate wide-band-antenna in that it holds its beamshape well over frequency, has low side lobes and crosspol levels, and maintains a low VSWR. In the previously cited work, research focused on applications that required typical beamwidths between 40 and 60 degrees. There are however applications where either the E- or H-plane beamwidths, or both, need to be much narrower.

A particular application that will motivate the requirements for the antenna designs found in this thesis is illustrated in Figure 1. This figure depicts the target zone of a near field RCS range and shows the beamwidths required for the antenna to properly illuminate the target. For this range, it is desired to make vertically and
Figure 1: Near field RCS range.
horizontally polarized measurements, therefore two antennas will be needed. The vertically polarized antenna will have a narrow E-plane and a broad H-plane while the horizontally polarized antenna will have a broad E-plane and a narrow H-plane.

To familiarize the reader with the basic operating principles of this antenna type a general description of the SBH is presented in Chapter 2. This is followed by Chapter 3, which focuses on the design considerations necessary to achieve narrow beamwidths. Chapter 4 will present the design and measurements of the vertically polarized antenna for the near field RCS range, while Chapter 5 will present the same material for the horizontally polarized antenna. Chapter 6 will then integrate these two designs to produce one antenna that has both a narrow E- and H-plane pattern.
CHAPTER II

The Slotline/Bowtie Hybrid Antenna

2.1 Introduction

The driving reason behind the design of the Slotline/Bowtie Hybrid was the need for an antenna that maintained a plateau like main beam over a wide frequency range. Ideally, this plateau like pattern will take the form of a constant amplitude over a given beamwidth with no side lobes. The ideal pattern is of course unrealizable, but by thinking of how to implement it one can gain valuable insight into the research and development behind the SBH antenna presented in this thesis.

2.2 Ultra-Wide-Band Radiator

The starting point for the evolution of the SBH radiator is the ultra-wide-band, infinite biconical antenna (see Figure 2). It has an E-plane pattern that is the same as the desired ideal pattern. The antenna functions as a spherical wave transmission line and one can see that at a given radius, the field is uniform between the cones and zero inside the cones. This is intriguing, however an antenna of infinite size is infinitely impractical. To make it physically realizable we truncate the transmission line to a finite length and add a termination which provides a gradual transition to free space. The terminations shown are elliptical, however other terminating geometries are possible. By using the gradual termination versus a knife edge discontinuity, one expects to see a decrease in main beam interference effects and side lobe levels.
INFINITE BICONICAL ANTENNA

TRUNCATION TO A FINITE LENGTH (CROSS SECTIONAL VIEW)

REDUCTION OF ANGULAR WIDTH (TOP VIEW)

SIDE VIEW

FRONT VIEW

BOWTIE RADIATOR

TOP VIEW

Figure 2: Evolution of the SBH radiator.
It is also noted that by reducing the antenna to a finite length, the pattern will deviate from the ideal and the lowest frequency of operation will be determined by the physical size.

The next important consideration is that a plateau like pattern is required in the H-plane. Finite and infinite bicones are omnidirectional in the H-plane, therefore another modification is necessary. This is accomplished by reducing the angular width of the antenna as seen in Figure 2, giving the antenna some H-plane directivity.

The final evolution process is extremely practical. This antenna is to be a real, physical structure and the facility and cost of construction must be considered. This being the case, the final bowtie radiator is fabricated with flat triangular plates that follow the E-plane contour of the antenna. A picture of a typical SBH is presented in Figure 3.

Figure 4 shows the E-plane view of the SBH design. The constituent parts are the slotline feed, the transition region, the linear region, and the elliptical rolled edge termination. The purpose of the transition region is to act as an impedance transformer between the slotline and linear region. It is comprised of a Vivaldi exponential which gradually tapers out to match the slope of the linear region. The linear region defines the main body of the horn. Its characteristic parameters include its length, and \( \theta \), the flare angle it subtends. Chapter 3 will illustrate how the choice of flare angle determines the E-plane beamwidth, and how the length effects the bandwidth of the antenna. The last section is the elliptical termination which is added to gradually transform the antenna fields to free space radiated fields.

Figure 4 also contains a view of the bowtie plate which is attached to the E-plane contour. The bowtie plate angle, \( \phi \), will be shown in Chapter 3 to be the parameter that controls the H-plane beamwidth.
Figure 3: Picture of a typical SBH antenna.
a) side view of SBH

b) top view of unattached Bowtie Plate

Figure 4: Components of the SBH radiator.
2.3 Ultra-Wide-Band Feed for the SBH Radiator

In order to maximize the antennas dynamic range, the frequency response for the antenna feed must be as wide or wider than that of the antenna itself. An additional concern is that one wants equal current magnitudes on each bowtie plate. Hence, the last stage of the feed must be a balanced transmission line. An ultra-wide-band feed which meets these criteria is the Y-Y transition. It was originally developed by Schiek and Köhler [3], and then modified by Lai [1]. The modified Lai version is shown in Figure 5.

The Y-Y transition is comprised of microstrip and slotline transmission line components. Microstrip is a popular and well understood transmission line, however slotline is not so common. A cross section of a slotline and its field structure are shown in Figure 6. The slotline consists of a narrow gap or “slot” in a conductor which is attached to one side of a dielectric substrate. It is important to note that slotline is an inherently balanced transmission line. By the nature of the E-field lines, there are equal and opposite charges on either side of the slot. These equal charge magnitudes then travel normal to the page, creating the balanced current distribution.

An analysis of the Y geometry for either transmission line is facilitated with Figure 7. One can see that at the end of one leg of the Y there is a short circuit and at the other there is an open circuit. Each of these terminations produce reflection coefficients that are 180 degrees out of phase from each other. The reflected waves travel the same distance back down the legs and cancel each other as they enter the main branch of the Y.

Coupling between the microstrip and slotline is accomplished due to the physical orientation of the two junctions. Since the slotline is an inherently balanced
1. SLOTLINE
(Bottom side of substrate)

2. MICROSTRIP
(Top side of substrate)

3. FULL TRANSITION
(Viewed from top side)

Figure 5: Microstrip to slotline Y-Y transition.
Figure 6: Cross section of slotline transmission line.
(Short)
\[ \Gamma = -1 \]

(Open)
\[ \Gamma = 1 \]

Figure 7: Analysis of the Y geometry function for either microstrip or slotline.
transmission line, once the energy is coupled into it, one has a balanced feed structure.

The broadband nature of the Y-Y transition is exhibited in Figures 8 and 9. There one can see the normalized transmitted and reflected power for two concatenated Y-Y transitions. In Figure 8, we see very effective transmission up to about 12 GHz, after that transmission is a little lower but still acceptable, never falling below -10 dB. The strong transmission characteristic evidenced in Figure 8, leads us to expect a low reflection for this configuration. Figure 9 confirms this for the concatenated transitions. The $S_{11}$ remains below -10 dB over virtually the whole frequency band. To illustrate the low reflection another way, a single Y-Y transition was time gated from the original data. The VSWR for this time gated transition is shown in Figure 10. The average VSWR is about 1.2, and the maximum, which occurs at 45 MHz is only 1.6. The only limitation to the frequency response of this scheme is that the reflections at the end are truly separated by 180 degrees, and that the effective locations for the reflections are truly equidistant from the Y junction. The low frequency VSWR increase seen here is attributed to the fact that the slotline open circuit begins to deviate from an ideal open at the lower frequencies.

2.4 Typical Patterns of a SBH

A typical SBH E- and H-plane pattern are shown in Figure 11. One should note that the pattern level is relatively flat across a large portion of the main beam and then drops off quickly and smoothly. The side lobe levels are nice and low at approximately 30 dB down. These patterns are characteristic of the full frequency band. At the lower end of the band there will be a slight rounding of the main lobe, and at the higher end there may be a slight ripple in the plateau section of
Figure 8: $S_{21}$ of two concatenated Y-Y transitions.

Figure 9: $S_{11}$ of two concatenated Y-Y transitions.
Figure 10: VSWR of a single Y-Y transition (Time gated).
Figure 11: Typical principal plane patterns of a SBH antenna.

The main lobe. These effects are expected to occur as the aperture size in terms of wavelengths changes. However, they may be minimized by properly designing the antennas geometry.

2.5 Summary

The geometry and properties of the SBH have been introduced along with a balanced, ultra-wide-band feed. Physical parameters that define electrical performance were also introduced, namely the linear section length, flare angle ($\theta$), and bowtie plate angle ($\phi$). Finally, principal plane cuts of a SBH were shown to illustrate its plateau-like main beam.
CHAPTER III
Design Considerations for a Narrow Beam SBH Antenna

3.1 Introduction

Typically, the design process begins with specifications for each of the principal plane patterns of the antenna. Satisfying these specifications is then accomplished by properly defining the shape of the antenna structure, and hence the currents that travel over it. A great facilitator to this design process is the fact that the design for the E-plane, and the design for the H-plane are independent of each other [1]. Specifically, the variables defining the E-plane contour effect mainly the E-plane pattern, and the variables determining the H-plane geometry effect mainly the H-plane pattern.

Using this knowledge, one can break up the design into two steps. The E-plane pattern will be shown to be dependent on the flare angle, linear section length, and ellipse shape. The dominant variable defining the H-plane pattern will be shown to be the bowtie plate angle. Additionally, it will be demonstrated that a dielectric insert introduced into the throat of the antenna can further improve the H-plane beamwidth with little impact on the E-plane pattern.
3.2 E-plane Design

There are four major variables which define the E-plane geometry. They are the flare angle, linear section length, ellipse major axis, and ellipse minor axis (see Figure 4). To illustrate the effects that each of these variables have on the E-plane pattern and 3 dB beamwidth, the patterns are predicted for various cases using a two dimensional Moment Method solution [4]. The 2-D Moment Method solutions correspond quite well with measured results and are obtained quickly in comparison to a 3-D Moment Method approach. Figure 12 shows the main beam for a typical measured E-plane pattern and its calculated results.

![Graph showing measured and calculated E-plane patterns](image)

**Figure 12:** A comparison of measured and calculated SBH E-plane patterns.
3.2.1 Length/Bandwidth Relation

As expected for a finitely sized antenna, the lowest frequency of operation is a function of the antenna's physical size. Since one of this antennas main facets is its ability to maintain a pattern shape over frequency, the lowest frequency of operation is defined as the frequency at which the pattern shape begins to degrade from its mid-band form. The physical size of the antenna will be specified by its total length. This is defined as the length of the linear section plus the length of the ellipse semi-major axis.

Figure 13 compares low and mid-band patterns for a generic SBH with a 70 degree flare angle. The pattern corresponding to a 12 wavelength long antenna

![2-D calculated far field E-plane patterns for a 70 degree flare angle, generic SBH.](image)

Figure 13: 2-D calculated far field E-plane patterns for a 70 degree flare angle, generic SBH.
represents a typical mid-band pattern. Observing the pattern for the two wavelength long antenna one notices that its shape is not characteristic of the mid-band pattern. However, for the four wavelength long antenna, one does see a strong resemblance to the mid-band pattern.

This comparison is presented again in Figure 14 for a 30 degree flare angle. Again one observes that the four wavelength long antenna pattern is characteristic of the mid-band pattern; whereas, the two wavelength long antenna pattern is not. This behavior establishes the relation between the total antenna length and lowest frequency of operations as:

$$L + A = 4\lambda_{\text{max}}.$$  \hspace{1cm} (3.1)

Figure 14: 2-D calculated far field E-plane patterns for a 30 degree flare angle, generic SBH.
The highest frequency of operation is defined on the same basis as that for the lowest frequency. It is the frequency at which the pattern begins to degrade from its mid-band form. Our mid-band pattern is by definition an acceptable approximation to a high frequency, plateau like main beam. Therefore in theory, the pattern will not degrade as frequency increases and one should not have an upper frequency limit. In practice however, there is an upper frequency limit which is determined by how precisely the antenna is constructed. The total bandwidth is thus determined at the low end by the four wavelength long criteria and at the upper end by the quality of construction of the antenna and feed network.

3.2.2 Flare Angle

The E-plane variable that has the largest effect on the E-plane beamwidth is the flare angle, \( \theta \). For the simplified case of geometrical optics, the beamwidth and flare angle are the same. Therefore, for higher frequencies and larger flare angles, it is not unreasonable to expect that the beamwidth is directly proportional to the flare angle. This reasoning does not hold for small flare angles however. For an infinitesimal flare angle one would expect a very broad pattern. Therefore for small flare angles the beamwidth and flare angle are inversely proportional. As the flare angle increases, one would then expect to see the 3 dB beamwidth initially decrease, reach a minimum, and then increase. This is illustrated in Figure 15 where the 3 dB beamwidth of a generic SBH is plotted versus flare angle for various antenna electrical lengths.

To implement a narrow E-plane for the SBH over a large frequency band, it is critical to choose a proper flare angle. This choice may be made to achieve a minimum attainable beamwidth at a specific frequency, or it may be made to minimize the beamwidth throughout the frequency band. For the data presented in
Figure 15: Calculated E-plane 3 dB beamwidth as a function of flare angle.

Figure 15 a flare angle of 25 degrees will produce a minimum attainable beamwidth of 14 degrees for a 12 wavelength long antenna. The price for this choice is that the beamwidth when the antenna is 4 wavelengths long will be twice as large at 28 degrees. Likewise, a flare angle of 40 degrees will minimize the four wavelength long beamwidth and increase the 12 wavelength long beamwidth. Either of these choices may be appropriate depending on the specified requirements for the E-plane. If the requirements call for an overall minimum beamwidth throughout the band, a nice compromise may be attained for a flare angle of 35 degrees. There one sees that the beamwidths are relatively low, with a small deviation.
To fully design for the E-plane, an initial choice of flare angle is made Figure 15. After deciding on an ellipse geometry, this choice is then optimized by calculating patterns for flare angles in the region of interest.

3.2.3 Ellipse Shape

The next dependent variable in the E-plane is the ellipse shape. The major function of the elliptical termination is to reduce the antennas side lobes by replacing a knife edge discontinuity with a more gradual one. To be effective, the minimum radius of curvature of the ellipse must be greater than 1/4 wavelength at the lowest frequency of operation [5]. Relating this criteria to the major and minor axes of the ellipse, one obtains that:

$$\frac{B^2}{A} \geq \frac{\lambda_{max}}{4}. \quad (3.2)$$

Note that A is half the length of the ellipse major axis, and B is half the length of the ellipse minor axis.

A secondary contribution from the ellipse is that it comprises part of the total electrical length of the antenna. There is a low frequency criteria for bandwidth (Equation 3.1), but as of yet there is no criteria for dividing the length between the ellipse and linear section. This invokes another variable called the Linear Section Ratio (LSR). It is defined as the ratio of the linear section length (L) to the total antenna length (L+A). Figure 16 compares LSRs of .5 and .75 for two antennas with the same total length and ellipse dimensions determined by Equation (3.2).

Examining these two families of curves one should notice two points. The first is that there is less beamwidth variation versus frequency for the .5 LSR case. The second is that the absolute minimum beamwidths attainable are lower for the .75 LSR case. Again, depending on the application, either of these points may be beneficial. If a steady pattern shape has more value than a narrow beam, a low LSR
Figure 16: Calculated E-plane 3 dB beamwidths as a function of flare angle for two different LSR values.

should be used. If the criteria calls for a little higher gain at high frequencies, a high LSR should be used.

In choosing an LSR it is recommended to remain between the values of .5 and .75. For values between .75 and 1.0 interference effects in the main beam are easily created. For values less than .5 it is believed that adverse effects will appear in the H-plane. As was seen for the flare angle, the process to establish the LSR is to make an initial choice of LSR and then optimize this by examining actual calculated patterns across the bandwidth of interest.
3.2.4 E-plane Design Summary

The primary element of the antenna geometry to be decided upon is the total antenna length. Given the specified lowest frequency of operation, the total antenna length should be determined by Equation 3.1. Once the length is established, an initial choice of flare angle is made using Figure 15. Next, an initial LSR is chosen which determines the lengths of the linear section and ellipse major axis. Given the ellipse major axis and lowest frequency of operation, the ellipse minor axis is then determined from Equation 3.2.

This basic design is used to calculate patterns which are then compared to the pattern specifications. Undoubtedly, some variables will need to be optimized to fully satisfy the pattern specifications. Using the knowledge of how each variable effects pattern performance, the variables are necessarily adjusted and patterns recalculated. Typically, only a few iterations are necessary to achieve the desired results.
3.3 H-plane Design

The only variable of control for the H-plane is the bowtie plate angle (see Figure 4). Lai performed an empirical study of this parameter and found that for larger bowtie plate angles, the H-plane 10 dB beamwidth was a linear function of the bowtie plate angle [1]. In order to investigate the behavior for smaller bowtie plate angles, further experimentation was performed and combined with Lai's original database. The 3 dB beamwidths based on these studies are presented as a function of both bowtie plate angle and electrical antenna length in Figure 17. Examining this figure one should note the near linear relationship between the bowtie plate angle and the

![Graph showing 3 dB beamwidths as a function of bowtie plate angle.]

Figure 17: Measured H-plane 3 dB beamwidths as a function of bowtie plate angle.
3 dB beamwidth for plate angles greater than 30 degrees. For plate angles less than 30 degrees, one observes that the 3 dB beamwidth is relatively constant.

To design for a minimal H-plane beamwidth, it is seen that nothing is gained by choosing the bowtie plate angle to be less than 30 degrees. For applications that require minimum 3 dB H-plane beamwidths of 35 to 40 degrees, this is an acceptable solution. However, if the requirements call for even narrower beamwidths, they may be achieved with the addition of a dielectric insert in the throat of the SBH.
3.4 Effects of Dielectric Insert on Antenna Performance

In an effort to further minimize the H-plane beamwidth, a modification was made to the original SBH design. This modification consists of filling the volume between the bowtie plates with a dielectric insert as shown in Figure 18. To investigate how the effects of the insert vary with dielectric constant, dielectric constants of 1.05 and 2.1 are used as inserts and compared to the no insert case. Performance issues that are to be examined are the VSWR and pattern performance. The test antenna for these comparisons will be a SBH with a 60 degree flare angle, 20 degree bowtie plate and total antenna length of 9.8 inches.

![Figure 18: SBH with dielectric insert.](image-url)
3.4.1 VSWR Effects

Figures 19, 20, and 21 illustrate the effect that the dielectric constant of the insert has on the VSWR of the SBH. Figure 19 shows the VSWR for no insert and is useful as a reference in displaying the change in VSWR with dielectric constant. Comparing Figures 19 and 20 one notices that the introduction of the 1.05 dielectric constant insert produces only a slight change in the VSWR from the no insert case. It is also noted that for both cases, the maximum VSWR is only 2.0. Figures 19 and 21 show that the VSWR for a 2.1 dielectric constant insert changes appreciably from the no insert case. From 2 to 7 GHz there is a noticeable increase and the new maximum is now 3.0.

![Graph showing VSWR vs Frequency](image)

Figure 19: Measured SBH VSWR with no insert.
Figure 20: Measured SBH VSWR with an insert dielectric constant of 1.05.

Figure 21: Measured SBH VSWR with an insert dielectric constant of 2.1.
With the introduction of the dielectric, one creates two new discontinuities. These are at the SBH throat where the insert begins and at the SBH aperture where the insert ends. To examine the reflections caused by these discontinuities the impulse response for the two different inserts are compared to the impulse response for the no insert case. Figure 22 illustrates the reflections seen for the no insert case. Reflections of interest are the throat reflection at 3 ns and the aperture reflection at 4.5 ns. Reflections before 3 ns are attributed to the feed structure and are neglected for now. Comparing Figures 22 and 23, one observes that the 1.05 dielectric insert throat reflection is virtually the same as that for the no insert case and that the aperture reflection is only about 1.5 dB higher. As shown earlier, this change had little effect on the VSWR. Figures 22 and 24 show that the 2.1 dielectric insert has a noticeably higher reflection at both the throat and aperture in comparison to the no dielectric case. The throat reflection increases approximately 5 dB and the aperture reflection increases 15 dB. It is also noted that for the 2.1 dielectric insert, the throat reflection is larger than any reflections from the feed structure. Both of these reflections are attributed to the increase in VSWR for the 2.1 dielectric insert. Based on these VSWR results, one must use a low dielectric constant for this application.
Figure 22: Impulse response for a SBH with no insert.

Figure 23: Impulse response for a SBH with an insert dielectric constant of 1.05.
Figure 24: Impulse response for a SBH with an insert dielectric constant of 2.1.
3.4.2 H-plane effects

The effect of the dielectric insert on the H-plane 3 dB beamwidth is presented in Figure 25. As evidenced in this figure, the addition of an insert results in a sharply reduced 3 dB beamwidth. Examining the no insert case, one notices that from 4 to 18 GHz the beamwidth is relatively constant at 40 degrees. Comparing this to the data for the two inserts, it appears that the inserts reduce the beamwidth across the entire frequency band of operation. Figures 26, 27, and 28 show the H-plane patterns for all 3 cases at frequencies of 6, 10, and 14 GHz, respectively. These figures explicitly show the beamwidth reduction and the subsequent gain increase that is expected from the new patterns. It is noted that although the 3 dB beamwidth

![Graph](image)

Figure 25: H-plane beamwidths versus frequency for inserts with varying dielectric constants.
reduction is approximately the same for each dielectric, the gain increase is larger for the 2.1 dielectric. This difference is easily attributed to pattern shape, in general, the pattern of the 2.1 dielectric is narrower overall than the 1.05 dielectric.

The physical insight for the beam narrowing is attributed to at least three effects. The first is that the effective wavelength in the dielectric is smaller than that of free space, therefore the aperture appears to be electrically larger. This effect is minimal for the 1.05 dielectric, but will be noticeable for the 2.1 dielectric. The second effect is that with a dielectric loading, much like a capacitor, the fringe fields will be reduced and concentrated in the dielectric. Again, this will be much more noticeable for the 2.1 dielectric than the 1.05 dielectric. The third effect is related

Figure 26: H-plane Patterns at 6 GHz for inserts with varying dielectric constants.
Figure 27: H-plane Patterns at 10 GHz for inserts with varying dielectric constants.

Figure 28: H-plane Patterns at 14 GHz for inserts with varying dielectric constants.
to the material's ability to increase the magnitude of the field at the aperture by "funnelling" energy from the throat to the aperture. This is essentially the same principle that is used in channeling light in fiber optic cables. The principle is illustrated in Figure 29 for the dielectric constant of 1.05. For this material, the critical angle of incidence is 77.4 degrees, therefore any plane wave that strikes the insert interface at an angle larger than that will stay within the dielectric. The field inside the insert may be considered as an array of Huygens sources that emanate plane waves. For these sources, one then knows that plane waves travelling at angles up to 22.6 degrees off axis will make it to the aperture before leaving the dielectric. The overall effect on the aperture distribution is that field levels will be intensified in the aperture plane directly in front of the dielectric and reduced just to either side of it. This mechanism is effective for surprisingly low values of dielectric constant as well as large ones, provided that the bowtie plate angle is small.

From this study it is concluded that either value of dielectric constant will provide the desired H-plane results. Since the beamwidth results are so similar for each value, a choice leads to the 1.05 dielectric constant value. It is effective and as seen in the last section has a better VSWR performance than the 2.0 dielectric constant value.
Figure 29: Illustration of the dielectric insert's effect on the aperture field.
3.4.3 E-plane effects

As stated earlier, the design of the SBH has been greatly facilitated by the fact that the design of the E- and H-planes are mutually exclusive of each other. As a consequence, for the dielectric insert to be an attractive modification one would like for its effects to only be observed in the H-plane and not in the E-plane. Figure 30 compares the 3 dB E-plane beamwidths for the inserts under investigation with the no insert case. By inspection, one should observe that the beamwidths of the no insert case and 1.05 dielectric case are very similar; whereas the 2.1 dielectric's beamwidths are much narrower. Figure 31 shows the E-plane patterns for each of these cases at 10 GHz. The patterns of the no insert case and the 1.05 dielectric are

![Graph showing E-plane beamwidths versus frequency for inserts with varying dielectric constants.](image)

Figure 30: E-plane beamwidths versus frequency for inserts with varying dielectric constants.
very similar as would be expected. The 2.1 dielectric pattern is quite a bit different. Instead of the characteristic plateau like pattern associated with a large flare angle, it has a more peaked shape with a narrow beamwidth.

From the E-plane study, it is concluded that 1.05 is a superior choice in that its E-plane pattern is virtually the same as that for the no insert case. This permits all of the design procedures of Section 3.2 to still be used. The 2.1 dielectric did yield a much lower beamwidth for the given flare angle; however, it compromised the independence of the design for the E- and H-planes.
3.5 Summary

This chapter has described the process for designing a SBH with a narrow E-plane and/or H-plane pattern. For the E-plane design, the effects of the linear section length, flare angle and ellipse shape were presented along with guidelines for choosing the variables such that the E-plane beamwidth is minimized. General results showed that a proper E-plane design could produce E-plane beamwidths in the neighborhood of 20 degrees for most of the operating bandwidth. The H-plane 3 dB beamwidth for the standard SBH was shown to be directly dependent on the bowtie plate angle. The minimum attainable beamwidth for the standard SBH was approximately 35 to 40 degrees. To reduce the H-plane beamwidth further, a modification to the SBH was made by inserting a dielectric material in the throat of the antenna. It was shown that for an insert dielectric constant of 1.05, the H-plane beamwidth could be reduced to 20 degrees with little effect on the VSWR and E-plane pattern performance.
CHAPTER IV

Design and Measurements of a Narrow E-Plane Pattern Antenna

4.1 Requirements

The design method introduced in Chapter 3 will now be applied to produce a SBH with a narrow E-plane pattern. This implementation serves as a method to both validate the design process and illustrate real, achievable results.

The initial step for any design is to establish the desired requirements for the performance of the antenna. For this antenna, the requirements are that the beamwidth be minimized in the E-plane but not the H-plane, that the side lobes be minimal, and that the VSWR be below 2. The frequency range of operation is initially defined as 2 to 12 GHz and as a practical consideration, the physical size of the antenna is limited. A quantitative summary of these requirements is given in Table 1.

4.2 E-plane Design

The first variable to be determined in the E-plane geometry is the total antenna length. Since it is known that increasing the antenna length increases the antenna bandwidth, the initial choice for antenna length will be 15 inches, which is close to the size of our maximum depth. Given this length, Equation 3.1 then determines that the minimum frequency of operation will be near 3 GHz. Examining the requirements one notes that there is one beamwidth specification below this at 2 GHz. This is not extremely critical however because it is also noted that the required beamwidth at 2
Table 1: Requirements for a SBH with a narrow E-plane pattern.

 Requirements for the Narrow E-Plane Design

Principal Plane 3dB Beamwidths

<table>
<thead>
<tr>
<th>Freq (GHz)</th>
<th>E-Plane (deg)</th>
<th>H-Plane (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>32 (±3)</td>
<td>38 (±3)</td>
</tr>
<tr>
<td>4</td>
<td>23 (±3)</td>
<td>45 (±3)</td>
</tr>
<tr>
<td>8</td>
<td>17 (±3)</td>
<td>47 (±3)</td>
</tr>
<tr>
<td>12</td>
<td>23 (±3)</td>
<td>50 (±3)</td>
</tr>
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Sidelobe Levels

<p>| | |</p>
<table>
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<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2 to 4 GHz</td>
<td>15dB</td>
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<tr>
<td>4 to 12 GHz</td>
<td>20dB</td>
</tr>
</tbody>
</table>

VSWR

<p>| | |</p>
<table>
<thead>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum VSWR</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Max. Dimensions

<p>| | |</p>
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<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>15.6 in</td>
</tr>
<tr>
<td>Width</td>
<td>15.6 in</td>
</tr>
<tr>
<td>Depth</td>
<td>15.6 in</td>
</tr>
</tbody>
</table>
GHz is 50 percent larger than that required at 4 GHz. As seen in Chapter 3, as the frequency is lowered below the minimum frequency of operation the pattern becomes broader than its mid-band form. Therefore the chosen length may be adequate to satisfy the 2 GHz specification. If it is not sufficient, the antenna length should be increased for the next design iteration.

The next major variable to define is the flare angle. The requirements dictate the need for a beamwidth minimum at 8 GHz. For a 15 inch long antenna this means that the beamwidth minimum should occur when the antenna is 10 wavelengths long. Interpolating between the 8 and 12 wavelength curves in Figure 15, one notes that a flare angle of approximately 30 degrees will accomplish this.

The last part of the geometry to be defined is the ellipse. To determine the semi-major axis length a choice for the linear section ratio (LSR) of the antenna must be made. Examining Figure 16 one notes that for a 10 wavelength long antenna with a 30 degree flare angle and LSR of .5, the minimum beamwidth is only about 20 degrees. For the same length and flare and an LSR of .75, one notes that the beamwidth is close to 15 degrees. This information leads to a nominal choice for the LSR of 2/3. An LSR of 2/3 for a 15 inch long antenna results in values of 10 inches for the linear section length (L), and 5 inches for the semi-major axis length (A). Given A and the lowest frequency of operation, the semi-minor axis length (B), is then determined by Equation 3.2 to be 2.75 inches.

These parameters constitute the initial design and are used to calculate E-plane patterns with the 2-D Moment Method code. Any discrepancies between the calculated patterns and the requirements are then corrected by modifying the parameters and reiterating the analysis procedure. The final geometric parameters for this design are presented in Table 2.
Table 2: Final geometric parameters for a SBH with a narrow E-plane pattern.

**Final Parameters for the Vertically Polarized Antenna**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Section Length (L)</td>
<td>10.04 in (25.5 cm)</td>
</tr>
<tr>
<td>Flare Angle (θ)</td>
<td>33 degrees</td>
</tr>
<tr>
<td>Ellipse Semi-Major Axis (A)</td>
<td>4.92 in (12.5 cm)</td>
</tr>
<tr>
<td>Ellipse Semi-Minor Axis (B)</td>
<td>1.97 in (5 cm)</td>
</tr>
<tr>
<td>Bowtie Plate Angle (ϕ)</td>
<td>41 degrees</td>
</tr>
</tbody>
</table>

![Diagram](image_url)
4.3 H-plane Design

Examining the requirements for the H-plane pattern, one notes that the nominal H-plane 3 dB beamwidth is 45 degrees. Referring to the empirical plot in Figure 17 this leads to an initial choice for the bowtie plate angle of 40 degrees. There is no computer modelling method used in the H-plane design. Therefore to confirm the choice of bowtie plate angle, a physical model of the antenna is built and tested. Experimental iteration is expected for this process so the initial model typically has a larger bowtie plate angle than the angle chosen via Figure 17. This procedure was used for this antenna and yielded a final choice for the bowtie plate angle of 41 degrees.
4.4 VSWR Performance

Figure 32 demonstrates the VSWR for this design from 2 to 18 GHz. As called for in the requirements, one notes that the VSWR remains below 2.0 for most of the frequency band. The only encroachment on the requirement occurs at 3.75 GHz where the VSWR peaks just over 2.0.

![Graph of VSWR vs Frequency](image-url)

Figure 32: VSWR for the narrow E-plane SBH.
4.5 E-plane Pattern Performance

The E-plane patterns for this design were measured from 2 to 18 GHz and are shown in Figures 33 to 49 at 1 GHz increments. As a general trend, it is noted that between 2 and 12 GHz there is a gradual reduction of both the beamwidth and the side lobe level which promotes an increase in directivity. The characteristic pattern shape for these frequencies is a traditional "single hump" pattern with its maximum level occurring on boresight. Between 13 and 15 GHz the "single hump" characteristic evolves into the plateau like pattern shape which is characteristic of SBH antennas. As the frequency increases still further, this ideally flat plateau is seen to slightly degrade as a dip in the pattern develops on the axis of the antenna.

To summarize the 3 dB beamwidth performance, all measured 3 dB beamwidths are plotted versus frequency along with the required nominal beamwidths and their tolerances in Figure 50. As seen in the figure, the measured beamwidths are all within the allowed ranges for the required frequencies. The side and rear lobe performance of the antenna is summarized in Figure 51. As seen in this figure, the average side lobe level is about -20 dB from 2 to 18 GHz. It is also noted that there is a slight infringement on the side lobe requirement from 4 to 6 GHz. The requirement calls for the side lobes to be -20 dB or less when in actuality the values at 4, 5 and 6 GHz are -16, -17, and -17.5 dB, respectively. There is no rear lobe requirement, however one can see that the rear lobe is nominally -30 to -40 dB.

Using the given beamwidth requirements from 2 to 12 GHz, the bandwidth of the antenna is 6 to 1. It is interesting to note however that although there are no specifications for higher frequencies, the 14 GHz performance is very similar to the 4 to 12 GHz requirements. A 14 GHz upper frequency limit yields a bandwidth of 7 to 1. To further extend the upper frequency for the antenna a more accurate
construction method must be implemented. A noticeable asymmetry is initially seen in the plateau of the pattern at 15 GHz. This is attributed to the inaccuracy of the antenna's construction relative to the wavelength at this high frequency.
Figure 33: Measured E-plane of the narrow E-plane design at 2 GHz.

Figure 34: Measured E-plane of the narrow E-plane design at 3 GHz.
Figure 35: Measured E-plane of the narrow E-plane design at 4 GHz.

Figure 36: Measured E-plane of the narrow E-plane design at 5 GHz.
Figure 37: Measured E-plane of the narrow E-plane design at 6 GHz.

Figure 38: Measured E-plane of the narrow E-plane design at 7 GHz.
Figure 39: Measured E-plane of the narrow E-plane design at 8 GHz.

Figure 40: Measured E-plane of the narrow E-plane design at 9 GHz.
Figure 41: Measured E-plane of the narrow E-plane design at 10 GHz.

Figure 42: Measured E-plane of the narrow E-plane design at 11 GHz.
Figure 43: Measured E-plane of the narrow E-plane design at 12 GHz.

Figure 44: Measured E-plane of the narrow E-plane design at 13 GHz.
Figure 45: Measured E-plane of the narrow E-plane design at 14 GHz.

Figure 46: Measured E-plane of the narrow E-plane design at 15 GHz.
Figure 47: Measured E-plane of the narrow E-plane design at 16 GHz.

Figure 48: Measured E-plane of the narrow E-plane design at 17 GHz.
Figure 49: Measured E-plane of the narrow E-plane design at 18 GHz
Figure 50: Measured E-plane 3 dB beamwidths versus frequency for the narrow E-plane design.

Figure 51: Measured E-plane side and rear lobe levels versus frequency for the narrow E-plane design.
4.6 H-plane Pattern Performance

The H-plane patterns from 2 to 18 GHz are shown in figures 52 to 68. Examining the patterns one notes that the anticipated plateau like pattern is achieved around 4 GHz and effectively maintains the same width and shape up to 18 GHz. From 2 to 4 GHz the plateau is not quite fully formed and the 3 dB beamwidth is consequentially narrower than that for the fully formed plateau.

The H-plane 3 dB beamwidth summary is presented in Figure 69. The beamwidth is nominally 45 degrees from 4 to 18 GHz, and somewhat less from 2 to 4 GHz. The measured beamwidths of the antenna are seen to fully meet the requirements at 2, 4, and 8 GHz and are just below the requirements at 12 GHz.

Side and rear lobe performance is presented in Figure 70. For this principal plane, at specific frequencies, there were symmetric and asymmetric side lobes in the main beam portion of the pattern. Illustrative examples of this phenomenon may be seen in the 4 and 5 GHz patterns. These side lobes produced an erratic side lobe summary due to the fact that they were present at some frequencies and not at others. Many of these irregularities may possibly be removed with a more refined construction and therefore neglected. The side lobe summary presented here is conservative however, and the effects of these side lobes are included. Considering these effects one still notes that the average side lobe level is around -20 dB and that the measured performance is still rather close to the requirements. The rear lobe level is similar to that for the E-plane with a nominal value of -35 dB.

By examining the quality of the patterns above 12 GHz it is determined that the useful bandwidth of this antenna is only 6 to 1 which is just enough to satisfy the antenna requirements. Higher frequency patterns demonstrate a lack of symmetry that appears when mechanical perturbations become large in terms of wavelengths.
Figure 52: Measured H-plane of the narrow E-plane design at 2 GHz.

Figure 53: Measured H-plane of the narrow E-plane design at 3 GHz.
Figure 54: Measured H-plane of the narrow E-plane design at 4 GHz.

Figure 55: Measured H-plane of the narrow E-plane design at 5 GHz.
Figure 56: Measured H-plane of the narrow E-plane design at 6 GHz.

Figure 57: Measured H-plane of the narrow E-plane design at 7 GHz.
Figure 58: Measured H-plane of the narrow E-plane design at 8 GHz.

Figure 59: Measured H-plane of the narrow E-plane design at 9 GHz.
Figure 60: Measured H-plane of the narrow E-plane design at 10 GHz.

Figure 61: Measured H-plane of the narrow E-plane design at 11 GHz.
Figure 62: Measured H-plane of the narrow E-plane design at 12 GHz.

Figure 63: Measured H-plane of the narrow E-plane design at 13 GHz.
Figure 64: Measured H-plane of the narrow E-plane design at 14 GHz.

Figure 65: Measured H-plane of the narrow E-plane design at 15 GHz.
Figure 66: Measured H-plane of the narrow E-plane design at 16 GHz.

Figure 67: Measured H-plane of the narrow E-plane design at 17 GHz.
Figure 68: Measured H-plane of the narrow E-plane design at 18 GHz.
Figure 69: Measured H-plane 3 dB beamwidths versus frequency for the narrow E-plane design.

Figure 70: Measured H-plane side lobe levels versus frequency for the narrow E-plane design.
4.7 Impulse Performance

The impulse response of this antenna relative to the boresight response is shown in Figures 71 to 73 for both the E- and H-plane patterns. Figure 71 contains the self normalized boresight response, it is an ideal band limited impulse. By comparing this to the normalized response for other directions, the phase dispersion relative to the boresight response may be identified. This dispersion will be evidenced by a widening of the pulse and/or a ringing after the main pulse. Figure 72 shows the E-plane response 15 degrees off of boresight. Examining this figure, one notes that the pulse has the same width and virtually no ringing after the initial pulse; however, the magnitude of the pulse has decreased from that seen for the boresight response, as one should expect. H-plane pulse performance is exhibited in Figure 73 for an angle 25 degrees off of boresight, and the pulse performance looks very good. The constant pulse width and lack of ringing confirms that there is negligible dispersion across the full field-of-view of the antenna.
Figure 71: Boresight normalized impulse response for the narrow E-plane design.

Figure 72: E-plane normalized impulse response 15 degrees off boresight for the narrow E-plane design.
Figure 73: H-plane normalized impulse response 25 degrees off boresight for the narrow E-plane design.
4.8 Summary

The focus of this chapter has been a SBH with a narrow E-plane. The design for each principal plane was presented as well as the antennas VSWR, pattern, and impulse performance. VSWR performance was excellent, the maximum value observed from 2 to 18 GHz was just over 2.0. The nominal E- and H-plane 3 dB beamwidths were 20 and 45 degrees, respectively, and the side lobe and rear lobe levels were effectively -20 dB and -35 dB, respectively. Additionally the useful bandwidth of the antenna was seen to be 6 to 1 and the impulse performance demonstrated that there is negligible pulse dispersion over the main beam of the antenna.
CHAPTER V

Design and Measurements of a Narrow H-Plane Pattern Antenna

5.1 Requirements

The next design calls for a SBH with a narrow H-plane pattern. To accomplish this, the dielectric insert recommended in Section 3.4 will be used as an integral part of the design. The other requirements for this antenna call for a broad E-plane, low side lobes, and a VSWR below 2.0. As in Chapter 4, the required frequency range of operation will be 2 to 12 GHz and the size of the antenna will be limited. A quantitative summary of these requirements is presented in Table 3.

5.2 E-plane Design

The first variable to determine is the antenna length which is directly related to the lowest frequency of operation for the antenna. The lowest frequency of operation for this antenna is the same as that for the narrow E-plane antenna. Therefore, a natural choice for antenna length would be the same, namely 15 inches.

The next variable to choose is the flare angle. Averaging the E-plane 3 dB beamwidths in Table 3, one obtains a nominal beamwidth of 48 degrees. Referring to Figure 15, it is seen that a 60 degree flare angle produces beamwidths of approximately 48 degrees.

Before proceeding further with the design, it is wise to examine the geometry of the antenna in light of the restrictions on the antenna's dimensions. Using a flare
Table 3: Requirements for a SBH with a narrow H-plane pattern.

Requirements for the Narrow H-Plane Design

Principal Plane 3dB Beamwidths

<table>
<thead>
<tr>
<th>Freq (GHz)</th>
<th>E-Plane (deg)</th>
<th>H-Plane (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>44 (±3)</td>
<td>54 (±3)</td>
</tr>
<tr>
<td>4</td>
<td>42 (±3)</td>
<td>42 (±3)</td>
</tr>
<tr>
<td>8</td>
<td>53 (±3)</td>
<td>29 (±3)</td>
</tr>
<tr>
<td>12</td>
<td>53 (±3)</td>
<td>23 (±3)</td>
</tr>
</tbody>
</table>

Sidelobe Levels

<table>
<thead>
<tr>
<th>Freq Range</th>
<th>Sidelobe Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 to 4 GHz</td>
<td>15dB</td>
</tr>
<tr>
<td>4 to 10 GHz</td>
<td>20dB</td>
</tr>
</tbody>
</table>

VSWR

<table>
<thead>
<tr>
<th></th>
<th>Maximum VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

Max. Dimensions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>7.2 in</td>
</tr>
<tr>
<td>Width</td>
<td>15.6 in</td>
</tr>
<tr>
<td>Depth</td>
<td>15.6 in</td>
</tr>
</tbody>
</table>

76
angle of 60 degrees with the same linear length and ellipse as for the narrow E-plane antenna, one finds that the width of the antenna will be 20 inches. A drawing of the oversized antenna is shown in Figure 74. Examining this figure, it is obvious that to reduce the antennas width, either the flare angle or total length must be reduced. Of the two, the antenna length has a smaller impact on the E-plane beamwidth, therefore it makes a good candidate for modification.

As described in Chapter 3, the E-plane design process relies on the 2-D Moment Method code which provides a convenient tool for iterating the design variables. Several different iterations were necessary to achieve the design for this antenna. The final choice of variables which satisfied the electrical requirements are listed in

![Figure 74: Oversized design for the narrow H-plane pattern antenna.](image-url)
Table 4. It is noted that these variables resulted in a final width of 15.9 inches, which still exceeds the width requirement. In order to conform to the width requirement, one of the last sections of the ellipse was adjusted towards the axis of the antenna in a linear fashion. A theoretical calculation with this modified ellipse resulted in virtually the same electrical performance as that for an unmodified ellipse.

5.3 H-plane Design

It is no coincidence that the H-plane pattern performance of the dielectric filled antenna in Section 3.4 and the requirements for this antenna are the same. The development of Section 3.4 was performed with these requirements in mind. Therefore to generate the desired H-plane patterns, this antenna will be comprised of a 20 degree bowtie plate and contain a dielectric insert with a dielectric constant of 1.05.
Table 4: Final geometric parameters for a SBH with a narrow H-plane pattern.

Final Parameters for the Horizontally Polarized Antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Section Length (L)</td>
<td>3.94 in (10 cm)</td>
</tr>
<tr>
<td>Flare Angle (θ)</td>
<td>60 degrees</td>
</tr>
<tr>
<td>Ellipse Semi-Major Axis (A)</td>
<td>5.90 in (15 cm)</td>
</tr>
<tr>
<td>Ellipse Semi-Minor Axis (B)</td>
<td>2.36 in (6 cm)</td>
</tr>
<tr>
<td>Bowtie Plate Angle (φ)</td>
<td>20 degrees</td>
</tr>
<tr>
<td>Dielectric Constant of Insert (εᵣ)</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Top View

Front View

Side View

15.6 in 8.8 in 5.25 in
5.4 VSWR Performance

Figure 75 demonstrates the VSWR for this design from 2 to 18 GHz. As called for in the requirements, one notes that the VSWR remains below 2.0 for the entire frequency band.

![Diagram showing VSWR vs. Frequency]

Figure 75: VSWR for the narrow H-plane SBH.
5.5 E-plane Performance

The measured E-plane patterns for this design are shown in Figures 76 to 92 at 1 GHz increments. One notes that the pattern shape is initially characterized by a rounded peak which evolves into the plateau like peak at approximately 5 GHz. The rolloff from the plateau is relatively quick and the side lobes in the pattern are typically only minor ripples at the base of the main beam. Examining the quality of the patterns, one notes that pattern symmetry is held up to 18 GHz. This yields a usable bandwidth of 9 to 1 which is more than sufficient to meet the established requirements.

To summarize the 3 dB beamwidth performance, all measured 3 dB beamwidths are plotted versus frequency along with the required nominal beamwidths and their tolerances in Figure 93. The nominal beamwidth appears to be around 55 degrees and one notes that the beamwidth requirements are fulfilled at all but the lowest frequency, 2 GHz. The side and rear lobe performance of the antenna is summarized in Figure 94. The average side lobe level is around -18 dB and it is noted that from 2 to 12 GHz the levels are somewhat higher than the requirements. This however, should not be a problem. The typical problem from side lobes arises when there is a high radiation level in an undesired direction. For this case, one notes that the ripple in the side lobes is small and that the envelope formed by the sidelobe peaks continues to decrease at a uniform rate following the main beam drop off. Therefore there are no heightened radiation levels in undesired directions. Finally, the average rear lobe is approximately -28 dB.
Figure 76: Measured E-plane of the narrow H-plane design at 2 GHz.

Figure 77: Measured E-plane of the narrow H-plane design at 3 GHz.
Figure 78: Measured E-plane of the narrow H-plane design at 4 GHz.

Figure 79: Measured E-plane of the narrow H-plane design at 5 GHz.
Figure 80: Measured E-plane of the narrow H-plane design at 6 GHz.

Figure 81: Measured E-plane of the narrow H-plane design at 7 GHz.
Figure 82: Measured E-plane of the narrow H-plane design at 8 GHz.

Figure 83: Measured E-plane of the narrow H-plane design at 9 GHz.
Figure 84: Measured E-plane of the narrow H-plane design at 10 GHz.

Figure 85: Measured E-plane of the narrow H-plane design at 11 GHz.
Figure 86: Measured E-plane of the narrow H-plane design at 12 GHz.

Figure 87: Measured E-plane of the narrow H-plane design at 13 GHz.
Figure 88: Measured E-plane of the narrow H-plane design at 14 GHz.

Figure 89: Measured E-plane of the narrow H-plane design at 15 GHz.
Figure 90: Measured E-plane of the narrow H-plane design at 16 GHz.

Figure 91: Measured E-plane of the narrow H-plane design at 17 GHz.
Figure 92: Measured E-plane of the narrow H-plane design at 18 GHz.
Figure 93: Measured E-plane 3 dB beamwidths versus frequency for the narrow H-plane design.

Figure 94: Measured E-plane side and rear lobe levels versus frequency for the narrow H-plane design.
5.6 H-plane Performance

The measured H-plane patterns from 2 to 18 GHz are shown in Figures 95 to 111 at 1 GHz increments. Examining the patterns, one observes 3 different pattern shapes that exist in this frequency range. The first pattern shape occurs from 2 to 5 GHz and is characterized by a shoulderless main beam with its side lobes located at the main beam's base. From 6 to 11 GHz, the pattern then evolves into a second configuration which is characterized by a pair of shoulders that appear 10 dB down from the peak of the main beam. The third pattern shape exists from 12 to 18 GHz. It is characterized by a trident like peak which occurs when the previously mentioned shoulders develop into actual side lobes. Examining the quality of the patterns one notes that pattern symmetry is held up to 14 GHz. The useful bandwidth is however only 6 to 1. It is restricted by the appearance of the side lobes at 12 GHz.

The H-plane 3 dB beamwidth summary is presented in Figure 112. The 3 dB beamwidth is seen to steadily decrease with frequency to an apparent asymptote of approximately 15 degrees. It is also noted that the beamwidth requirements were met at 8 and 12 GHz, and were actually below the requirements at 2 and 4 GHz, which was preferred. The side and rear lobe performance for the H-plane is presented in Figure 113. One notes that the side lobe level remains below the required values up to 11.5 GHz. For frequencies above this, the side lobe level rises to -10 dB as the main beam's shoulders develop into side lobes. The rear lobe performance of the antenna is much more steady. The average rear lobe level is approximately -35 dB.
Figure 95: Measured H-plane of the narrow H-plane design at 2 GHz.

Figure 96: Measured H-plane of the narrow H-plane design at 3 GHz.
Figure 97: Measured H-plane of the narrow H-plane design at 4 GHz.

Figure 98: Measured H-plane of the narrow H-plane design at 5 GHz.
Figure 99: Measured H-plane of the narrow H-plane design at 6 GHz.

Figure 100: Measured H-plane of the narrow H-plane design at 7 GHz.
Figure 101: Measured H-plane of the narrow H-plane design at 8 GHz.

Figure 102: Measured H-plane of the narrow H-plane design at 9 GHz.
Figure 103: Measured H-plane of the narrow H-plane design at 10 GHz.

Figure 104: Measured H-plane of the narrow H-plane design at 11 GHz.
Figure 105: Measured H-plane of the narrow H-plane design at 12 GHz.

Figure 106: Measured H-plane of the narrow H-plane design at 13 GHz.
Figure 107: Measured H-plane of the narrow H-plane design at 14 GHz.

Figure 108: Measured H-plane of the narrow H-plane design at 15 GHz.
Figure 109: Measured H-plane of the narrow H-plane design at 16 GHz.

Figure 110: Measured H-plane of the narrow H-plane design at 17 GHz.
Figure 111: Measured H-plane of the narrow H-plane design at 18 GHz.
Figure 112: Measured H-plane 3 dB beamwidths versus frequency for the narrow H-plane design.

Figure 113: Measured H-plane side and rear lobe levels versus frequency for the narrow H-plane design.
5.7 Impulse Performance

The impulse response of this antenna relative to the boresight response is shown in Figures 114 to 116 for both the E- and H-plane patterns. Figure 114 contains the self normalized boresight response, it is an ideal band limited impulse. By comparing this to the normalized response for other directions, the phase dispersion relative to the boresight response may be identified. This dispersion will be evidenced by a widening of the pulse and/or a ringing after the main pulse. Figure 115 shows the E-plane response 25 degrees off of boresight. Examining this figure, one notes that the pulse has the same width and virtually no ringing after the initial pulse; however, the magnitude of the pulse has decreased from that seen for the boresight response, as one should expect. H-plane pulse performance is exhibited in Figure 116 for an angle 15 degrees off of boresight, and the pulse performance looks very good. The constant pulse width and lack of ringing confirms that there is negligible dispersion across the full field-of-view of the antenna.
Figure 114: Boresight normalized impulse response for the narrow H-plane design.

Figure 115: E-plane normalized impulse response 25 degrees off boresight for the narrow H-plane design.
Figure 116: H-plane normalized impulse response 15 degrees off boresight for the narrow H-plane design.
5.8 Summary

The focus of this chapter has been a SBH with a narrow H-plane pattern. The design for each principal plane was presented as well as the antennas VSWR, pattern, and impulse performance. VSWR performance was excellent, the maximum value observed from 2 to 18 GHz was just under 2.0. The nominal E-plane beamwidth was 55 degrees, and the average E-plane side and rear lobe levels were -18 dB and -28 dB, respectively. For the H-plane, the 3 dB beamwidth decreased with increasing frequency. Beamwidth values of note are 45 degrees at 2 GHz, 22 degrees at 12 GHz, and 15 degrees at 18 GHz. The H-plane side lobe levels were -25 dB below 12 GHz and -10 dB above 12 GHz. The average rear lobe level was -35 dB. The useful bandwidth of this antenna was seen to be 6 to 1 and the impulse performance demonstrated that there is negligible pulse dispersion over the main beam of the antenna.
CHAPTER VI

Design and Measurements of a Narrow E- and H-Plane Pattern Antenna

6.1 Requirements

The two previous chapters have presented antenna designs that have a narrow pattern in one principal plane and a wide pattern in the other. For other applications, the pattern may be required to be narrow in both principal planes. Therefore, this chapter will integrate the designs of Chapters 4 and 5 to produce an antenna with both a narrow E- and H-plane. No specific requirements will be imposed on the antenna; however, the performance of each plane will be compared to the results of the previous chapters.

6.2 Design

The design for this antenna directly relies on the independence of the design of the E- and H-plane patterns of the SBH. This makes it possible to directly combine the designs of the two previous chapters. Hence, the flare angle, linear section length, and ellipse shape will have the same values as those used for the narrow E-Plane design. Similarly, the bowtie plate angle and insert dielectric constant will be the same as used in the narrow H-plane design. The values of all geometric parameters are presented in Table 5.
Table 5: Final geometric parameters for an SBH with a narrow E- and H-plane pattern.

**Final Parameters for the Narrow E- and H-Plane Design**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Section Length (L)</td>
<td>10.04 in (25.5 cm)</td>
</tr>
<tr>
<td>Flare Angle (θ)</td>
<td>33 degrees</td>
</tr>
<tr>
<td>Ellipse Semi-Major Axis (A)</td>
<td>4.92 in (12.5 cm)</td>
</tr>
<tr>
<td>Ellipse Semi-Minor Axis (B)</td>
<td>1.97 in (5 cm)</td>
</tr>
<tr>
<td>Bowtie Plate Angle (ϕ)</td>
<td>20 degrees</td>
</tr>
<tr>
<td>Dielectric Constant of Insert (εᵣ)</td>
<td>1.05</td>
</tr>
</tbody>
</table>

![Diagram of the narrow E- and H-plane design](image)
6.3 VSWR Performance

Figure 117 demonstrates the VSWR for this design from 2 to 18 GHz. As noted in the figure, the VSWR remains below 2.0 for the entire frequency band.

Figure 117: VSWR for the narrow E- and H-plane SBH.
6.4 E-plane Performance

The measured E-plane patterns for this design are shown in Figures 118 to 134 at 1 GHz increments. As a general trend, it is noted that between 2 and 10 GHz there is a gradual reduction of both the beamwidth and the side lobe level which promotes an increase in directivity. The characteristic pattern shape for these frequencies is a traditional “single hump” pattern with its maximum level occurring on boresight. Between 11 and 14 GHz the “single hump” characteristic evolves into the plateau like pattern shape which is characteristic of SBH antennas. As the frequency increases still further, this ideally flat plateau is seen to slightly degrade as a dip in the pattern develops on the boresight direction of the antenna. Comparing these patterns to the E-plane patterns for the narrow E-plane pattern design, one notes that the patterns are very similar. The only noticeable differences are that the plateau has formed a little earlier in frequency for this case, that the plateau has a little more of a ripple to it, and that the rolloff from the plateau is not quite as quick as for the wide plate version.

To summarize the 3 dB beamwidth performance, the measured 3 dB beamwidths are plotted versus frequency in Figure 135. The beamwidth minimum is approximately 17 degrees at 7 GHz and the nominal beamwidth is approximately 25 degrees over the 2 to 18 GHz frequency range. The side and rear lobe performance of the antenna is summarized in Figure 136. The average side lobe level is near -20 dB and the average rear lobe is approximately -35 dB.
Figure 118: Measured E-plane of the narrow E- and H-plane design at 2 GHz.

Figure 119: Measured E-plane of the narrow E- and H-plane design at 3 GHz.
Figure 120: Measured E-plane of the narrow E- and H-plane design at 4 GHz.

Figure 121: Measured E-plane of the narrow E- and H-plane design at 5 GHz.
Figure 122: Measured E-plane of the narrow E- and H-plane design at 6 GHz.

Figure 123: Measured E-plane of the narrow E- and H-plane design at 7 GHz.
Figure 124: Measured E-plane of the narrow E- and H-plane design at 8 GHz.

Figure 125: Measured E-plane of the narrow E- and H-plane design at 9 GHz.
Figure 126: Measured E-plane of the narrow E- and H-plane design at 10 GHz.

Figure 127: Measured E-plane of the narrow E- and H-plane design at 11 GHz.
Figure 128: Measured E-plane of the narrow E- and H-plane design at 12 GHz.

Figure 129: Measured E-plane of the narrow E- and H-plane design at 13 GHz.
Figure 130: Measured E-plane of the narrow E- and H-plane design at 14 GHz.

Figure 131: Measured E-plane of the narrow E- and H-plane design at 15 GHz.
Figure 132: Measured E-plane of the narrow E- and H-plane design at 16 GHz.

Figure 133: Measured E-plane of the narrow E- and H-plane design at 17 GHz.
Figure 134: Measured E-plane of the narrow E- and H-plane design at 18 GHz.
Figure 135: Measured E-plane 3 dB beamwidths versus frequency for the narrow E- and H-plane design.

Figure 136: Measured E-plane side and rear lobe levels versus frequency for the narrow E- and H-plane design.
6.5 H-plane Performance

The measured H-plane patterns from 2 to 18 GHz are shown in Figures 137 to 153 at 1 GHz increments. At lower frequencies the pattern shape is essentially a "single hump" pattern with a very quick rolloff, producing a narrow 3 dB beamwidth. As the frequency increases to approximately 10 GHz one notes the creation of the same sidelobes that were observed for the narrow H-plane pattern design. Rather than occurring 10 dB down from the peak as they did for the narrow H-plane pattern, they are now observed 15 dB down at their initial frequency. As the frequency continues to increase, the high side lobes become more pronounced and the 3 dB beamwidth decreases.

The H-plane 3 dB beamwidth summary is presented in Figure 154. The 3 dB beamwidth is seen to steadily decrease with frequency to an apparent asymptote of approximately 15 degrees. This performance is almost identical to that observed for the narrow H-plane pattern antenna. The side and rear lobe performance for the H-plane is presented in Figure 155. The average sidelobe level is approximately -16 dB, and the average rear lobe is approximately -35 dB. The rear lobe performance of this antenna is essentially the same as that of the narrow H-plane pattern design however the side lobe performance is not. Comparing figures 113 and 155 one notes that over the 2 to 12 GHz range the average side lobe level of the narrow H-plane antenna was -25 dB, while for this antenna it is about -18 dB.
Figure 137: Measured H-plane of the narrow E- and H-plane design at 2 GHz.

Figure 138: Measured H-plane of the narrow E- and H-plane design at 3 GHz.
Figure 139: Measured H-plane of the narrow E- and H-plane design at 4 GHz.

Figure 140: Measured H-plane of the narrow E- and H-plane design at 5 GHz.
Figure 141: Measured H-plane of the narrow E- and H-plane design at 6 GHz.

Figure 142: Measured H-plane of the narrow E- and H-plane design at 7 GHz.
Figure 143: Measured H-plane of the narrow E- and H-plane design at 8 GHz.

Figure 144: Measured H-plane of the narrow E- and H-plane design at 9 GHz.
Figure 145: Measured H-plane of the narrow E- and H-plane design at 10 GHz.

Figure 146: Measured H-plane of the narrow E- and H-plane design at 11 GHz.
Figure 147: Measured H-plane of the narrow E- and H-plane design at 12 GHz.

Figure 148: Measured H-plane of the narrow E- and H-plane design at 13 GHz.
Figure 149: Measured H-plane of the narrow E- and H-plane design at 14 GHz.

Figure 150: Measured H-plane of the narrow E- and H-plane design at 15 GHz.
Figure 151: Measured H-plane of the narrow E- and H-plane design at 16 GHz.

Figure 152: Measured H-plane of the narrow E- and H-plane design at 17 GHz.
Figure 153: Measured H-plane of the narrow E- and H-plane design at 18 GHz.
Figure 154: Measured H-plane 3 dB beamwidths versus frequency for the narrow E- and H-plane design.

Figure 155: Measured H-plane side and rear lobe levels versus frequency for the narrow E- and H-plane design.
6.6 Impulse Performance

The impulse response of this antenna relative to the boresight response is shown in Figures 156 to 158 for both the E- and H-plane patterns. Figure 156 contains the self normalized boresight response, it is an ideal band limited impulse. By comparing this to the normalized response for other directions, the phase dispersion relative to the boresight response may be identified. This dispersion will be evidenced by a widening of the pulse and/or a ringing after the main pulse. Figure 157 shows the E-plane response 15 degrees off of boresight. Examining this figure, one notes that the pulse has the same width and virtually no ringing after the initial pulse; however, the magnitude of the pulse has decreased from that seen for the boresight response, as one should expect. H-plane pulse performance is exhibited in Figure 158 for an angle 15 degrees off of boresight, and the pulse performance looks very good. The constant pulse width and lack of ringing confirms that there is negligible dispersion across the full field-of-view of the antenna.
Figure 156: Boresight normalized impulse response for the narrow E- and H-plane design.

Figure 157: E-plane normalized impulse response 15 degrees off boresight for the narrow E- and H-plane design.
Figure 158: H-plane normalized impulse response 15 degrees off boresight for the narrow E- and H-plane design.
6.7 Summary

The focus of this chapter has been a SBH with a narrow E- and H-plane pattern. It is based on the two previous antenna designs, and as such, it represents an initial design for this application. The VSWR, pattern, and impulse performance were all presented and compared to the previous results for the antennas with only one narrow principal plane. The VSWR was comparable to both previous designs. It remained below 2.0 from 2 to 18 GHz. E-plane patterns were compared to the results for the narrow E-plane pattern design. The average beamwidth was nominally 25 degrees. This was 5 degrees wider than that for the previous design. E-plane side and rear lobe levels were virtually the same in each design at -20 and -35 dB, respectively. H-plane patterns were compared to the results for the narrow H-plane pattern design. The H-plane 3 dB beamwidth performance for both of these antennas was nearly identical. Beamwidth values of note for this antenna are 46 degrees at 2 GHz, 21 degrees at 12 GHz, and 16 degrees at 18 GHz. The H-plane side lobe levels for this antenna were -16 dB, which is 9 dB higher than for the previous design. The rear lobe performance was virtually the same in each design at -35 dB. Finally, it was shown that similar to the other designs, the impulse performance exhibited negligible pulse dispersion over the antenna's main beam.

As stated earlier, this antenna represents an initial design for an antenna with a narrow E- and H-plane. After reviewing the pattern results, it is clear that the E-plane pattern has a problem with the dip in the main beam at higher frequencies, and the H-plane pattern has a problem with the shoulders forming side lobes at higher frequencies. It is suspected that the antenna length is an issue in that this antenna has a narrow pattern in both planes, or more gain. Note that this issue can initially be evaluated using the E-plane pattern code. Once the length is established, the
H-plane pattern can be evaluated using a prototype antenna. Finally, it is suspected that the H-plane pattern problem is most likely caused by leakage from the throat of the antenna and is only partially corrected by the dielectric insert.
CHAPTER VII
Summary

This thesis has introduced a design process that achieves narrow beamwidths for SBH antennas. The design for the E-plane pattern was presented as a function of the antenna's total length, flare angle, and ellipse shape. The effects of each of these parameters was introduced as well as the guidelines for choosing proper values that will produce minimal E-plane 3 dB beamwidths. It was seen that for larger bandwidths, the average 3 dB beamwidth could be designed to be 20 degrees and that for some frequencies, minimum beamwidths as low as 14 degrees could be achieved.

In order to design for the H-plane pattern, two alternatives were presented. If the required H-plane beamwidth is larger than 40 degrees, a design may be implemented by simply choosing a proper value for the SBH's bowtie plate angle. If the required beamwidth calls for a much tighter H-plane 3dB beamwidth, this may be achieved with a modification to the standard SBH. This modification entails filling the volume of the SBH throat with a dielectric insert. It was shown that an insert dielectric constant of 1.05 will reduce the H-plane beamwidth as desired and have little impact on the antenna's VSWR and E-plane pattern. Using this technique, the minimum beamwidths observed approached 15 degrees at 18 GHz.

In order to validate the design process and illustrate achievable results, three different antennas were designed, built, and tested from 2 to 18 GHz. The first antenna was designed to have a narrow E-plane pattern and a broad H-plane pattern.
Its nominal beamwidths were 20 and 45 degrees, respectively, for the E- and H-planes. Its average side lobe level was -20 dB, and its average rear lobe level was -35 dB.

The second antenna was designed to have a broad E-plane pattern and a narrow H-plane pattern. The E-plane 3 dB beamwidth was rather constant over frequency and had an average value of 55 degrees. The H-plane 3 dB beamwidth decreased with frequency. Its values ranged from 45 degrees at 2 Ghz to 15 degrees at 18 GHz. The rear lobe level was rather steady throughout the bandwidth and averaged -35 dB. The E-plane side lobe level was also rather constant, it averaged -18 dB. The H-plane side lobe level was not so steady. Its average value was -25 dB below 12 GHz, and -10dB above 12 GHz.

The third antenna design combines the effects of the first two by implementing a narrow E- and H-plane pattern. The E-plane beamwidth had a minimum value of 17 degrees at 7 Ghz and averaged 25 degrees for the whole band. The H-plane 3 dB performance was very similar to that of the second antenna. The beamwidth decreased with frequency and ranged from 45 degrees at 2 GHz to 16 degrees at 18 Ghz. Average sidelobe levels were -20 dB for the E-plane and -16 dB for the H-plane. The average rear lobe levels in both planes were -35 dB.

In general, all of these SBH designs are useful approximations to the ideal UWB antenna. The beamwidth is for the most part constant over frequency, the side and rear lobe levels are low, the VSWR is very reasonable, and the phase dispersion is negligible throughout the main beam.
BIBLIOGRAPHY


