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Study of Band Millimeter Wave Antipodal Tapered Slot Antennas – Portable and High Gain

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ABSTRACT

Millimeter wave applications such as automobile radar, high-definition video, and high-resolution photography are using more and more high gain directional antennas. The wide bandwidth, high gain, and linear polarization of the Vivaldi antenna, often called the Tapered Slot Antenna (TSA), make it a viable substitute. However, there are design constraints such as eliminating external circuitry for space-constrained applications and enhancing gain without increasing area. The goal of this study is to provide low-profile, antipodal tapered slot antennas that are easier to integrate into systems at the system level and have better gain and radiation characteristics. A metamaterial-loaded Antipodal Elliptically Tapered Space Antenna (AETSA) with a high gain and small dimensions is proposed in the thesis for the 20–40 GHz frequency range. The AETSA incorporates an Isosceles Trapezoidal Dielectric Lens (ITDL) to increase gain by 1.1 dB. It is built on an RT/Duroid 5880 substrate. The ITDL is equipped with a new kind of broadband metamaterial that improves gain and stabilizes radiation pattern without increasing the antenna's size. The antenna shows improved gain and respectable impedance matching across 20–40 GHz. This work aims to improve the gain and radiation characteristics of the antipodal elliptically tapered slot antenna. Two proposed designs are the modified Antipodal Tapered Slot Antenna (ATSA) and the modified Antipodal Elliptically Tapered Slot Antenna (MAETSA). A constant radiation pattern over the 20–40 GHz frequency range is produced via a special transition between the MAETSA's feed and taper portions. By 0.3 dB across the higher frequency band, the antenna gains. In addition, the ATSA is small and adds 1.66 dB over the working spectrum. After testing and fabrication, case studies show that the prototype is suitable for millimeter wave imaging systems. The main objective of the thesis is the design of an antipodal tapered slot antenna for space-constrained broadband millimeter wave applications. It proposes two distinct antenna designs: one with a bandpass filter based on Half Mode Substrate Integrated Waveguide (HMSIW) and the other with rectangular corrugations. In order to regulate the band throughout a frequency range of 21.6–40 GHz, the first design employs a periodic structure with three horizontal slots and two gaps. Rectangular corrugations and an RSITSV bandpass filter optimized by a single parameter are used in the second design. across 23.5–25 GHz, the antenna with an integrated bandpass filter exhibits a gain variation of 1.53 dB, and across 25–40 GHz, the gain is almost constant at 11–11.92 dB.

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INTRODUCTION

An overview of millimeter wave technology, including its benefits and drawbacks, is provided in this chapter. This chapter includes a thorough review of antennas and related millimeter wave design methodologies, followed by a discussion of millimeter wave applications. This chapter also introduces the Vivaldi, or tapered slot antenna, and discusses its applicability for wideband high gain millimeter wave applications. Additionally, the fundamental varieties of Vivaldi or tapered slot antennas are examined, their drawbacks are emphasized, and the research question is presented. A summary of earlier research on design strategies for tapered slot antennas to improve performance is next. Subsequently, the outstanding issues are delineated, constituting the research stimulus for the thesis. The paper's goals, contributions, and outline are finally provided.

Wireless communication has completely changed the scientific, social, and economic landscape in recent years. In the end, it has established a cross-disciplinary connection between the resource and its recipient. With consistent advancements in wireless technology over many decades, including the use of both hardware and software, such communication has become possible. If electromagnetic waves (EM waves) are the basic building block of wireless technology, then an antenna serves as the launch or reception point for EM waves. Only a small frequency range, typically between 10 MHz and 10 GHz, has been used for wireless communication up to this point due to issues with antenna design, supporting electronics' bandwidth limitations, and signal attenuation at higher frequencies. These elements discourage using the underutilized high frequency spectrum. Wireless systems and standards are envisioned towards the millimeter radio frequency bands as a result of the increasing need for bandwidth closing the doors to wireless communication. Research and development at every previous barrier to exploit the underutilized high frequency spectrum is essential.

II. BACKGROUND

Here are some key insights from recent research on band millimeter wave antipodal tapered slot antennas:

Improved Design Efficiency: A three-layer air-filled substrate integrated waveguide (AFSIW) antipodal linearly tapered slot antenna (ALTSA) design shows a narrower beamwidth and higher radiation efficiency compared to conventional designs, making it highly efficient for array configurations (Ghiotto et al., 2017).

Enhanced Multi-Beam Coverage: A millimeter-wave multi-beam antenna using rotated antipodal linear tapered slot antenna (ALTSA) elements achieves wide angle coverage and low mutual coupling between elements, suitable for various applications (Zhang et al., 2010).

Broadband Performance: Combining substrate integrated waveguide (SIW) and coplanar waveguide (CPW) feeds in ALTSA designs offers broadband performance with consistent gain, beamwidth, and low cross-polarization across a wide frequency range (Taringou et al., 2013).

High Gain and Wideband Applications: Antipodal Fermi tapered slot antennas with sine corrugation offer high gain and wide bandwidth, making them ideal for short-range wireless communications and imaging applications (Briqech et al., 2015).

Optimization for Circular Polarization: Waveguide-fed circularly polarized antipodal curvedly tapered slot antennas (ACTSAs) provide excellent circular polarization performance, suitable for high frequency applications (Liu et al., 2016).

In summary, advancements in the design and optimization of millimeter wave antipodal tapered slot antennas contribute to enhanced performance in beamwidth, efficiency, multi-beam coverage, and broadband capabilities, meeting the needs of modern wireless communication and imaging systems.

III. PROBLEM IDENTIFICATION AND RESEARCH OBJECTIVES

Overall, the antipodal tapered slot antenna is a robust design known for its performance across a range of technical specifications, lending itself well to advanced communication and radar technologies.

1. The task at hand is developing a more efficient, compact antenna while surmounting technical obstacles such as weight and space limitations. Effective signal transmission requires high gain, yet it may be difficult to increase it without becoming larger or more complicated. A dielectric lens's use necessitates geometry and material property optimization. The design of materials, electromagnetic compatibility, and bandwidth performance become more challenging with the use of broadband metamaterials. It is a major technical problem to integrate these components into a single antenna design such that they work together without sacrificing their separate efficacy.
2. Beam tilt, unique transitions, antenna gain augmentation, novel dielectric lens, and

broadband metamaterials are some of the problems that the AETSA antenna design must overcome. The new transition attempts to increase performance while retaining antenna performance, while the beam tilt problem impacts the efficiency and accuracy of signal transmission. Improving the antenna's gain for effective, long-range signal transmission while maintaining size, efficiency, and other operational factors is the aim. Compatibility is key when using broadband metamaterials, since they improve antenna performance across a large frequency range. Combining these improvements presents a difficult technical task.

3. The primary difficulty is in creating an antenna that can enhance gain and function efficiently across a wide frequency range without compromising performance. To improve productivity and efficiency, creative engineering is needed. To improve the antenna's radiation pattern and efficiency, specialized radiating fin structures, dielectric lenses, and broadband anisotropic metamaterial structures are used. The seamless integration of these technologies into a single, unified antenna design is necessary to guarantee that every part fulfills its intended purpose without creating additional issues like cost or complexity. For efficient signal transmission and reception over long distances or in difficult signal conditions, this strategy is essential.
4. The primary difficulty is in the smooth integration of a new bandpass filter with an antipodal tapered slot antenna to produce a filtenna. Constant broadband gain across a large frequency range is the aim in order to guarantee dependable signal transmission and reception. For applications like as communications and radar systems, the design must also provide a consistent radiation pattern across the whole working spectrum. The RF front-end requires the filtenna to perform many tasks, which simplifies the system design as a whole. Taking into account physical dimensions, connection, impedance matching, and compatibility with current technologies, the design should make system level integration simpler.

The objectives of this research work are summarized as follows:

(i) To create a high-gain, small-sized Antipodal Elliptically Tapered Slot Antenna (AETSA) that is loaded with a unique broadband metamaterial and a dielectric lens.

(ii) To suggest a unique transition for addressing AETSA's beam tilt and to further enhance antenna gain via the use of broadband metamaterials and innovative dielectric lenses.

(iii) To use broadband anisotropic metamaterial structures, dielectric lenses, and specialized radiating fin structures to construct an antipodal tapered slot antenna with the goal of increasing gain over the whole broadband frequency range (lower, mid, and higher frequencies).

(iv) To build an antipodal tapered slot antenna that is combined with a new bandpass filter (filter+antenna=filtenna) in order to provide a stable radiation pattern and continuous broadband gain. Additionally, the antenna may be used for several functions in the RF front-end, making system-level integration simpler.

IV. METHODOLOGY

The Substrate Integrated Waveguide (SIW) technology and its variants like Half Mode Substrate Integrated Waveguide (HMSIW) encompass the advantages of both microstrip as well as waveguide technology. They are emerging approaches for designing compact, low loss and cost-effective devices. As compared to SIW, the width of HMSIW is reduced to half and hence the area is also halved. Thus, HMSIW retains the advantages of SIW and also helps in miniaturization. In general, at high frequencies, broadband bandpass filters can be designed effectively using HMSIW technology. The HMSIW based filter is more efficient than other integrated bandpass filters as it has advantages of small size, light weight, low loss, ease of integration, and less fabrication complexity. Therefore,

HMSIW based filter can be easily integrated with the antipodal tapered slot antenna without any external matching circuitry to achieve wideband control.

To design the bandpass filters proposed in this Chapter, we make use of HMSIW which decides the lower cut-off frequency. The SIW and HMSIW structures are depicted in Fig. 1 and Fig. 2 correspondingly. The design considerations of HMSIW are derived from those of SIW and they are summarized below.

Substrate Integrated Waveguide (SIW) design considerations

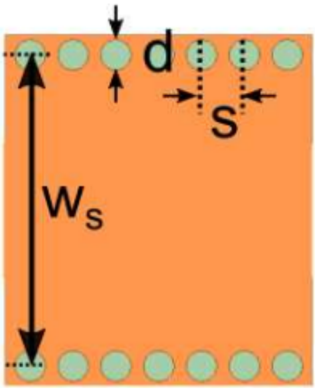


Figure 4.1: SIW structure top view.

$$w_s = \frac{c}{2\sqrt{\varepsilon_r} f_{TE_{10}}} \quad (1)$$

$$d < w_s / 8 \quad (2)$$

$$0.05 < \frac{s}{\lambda_c} < 0.25 \quad (3)$$

$$1 < s/d < 2 \quad (4)$$

where, d is the via diameter, s is the space between vias and w_s is the width of SIW. The effective width of SIW (w_{siweff}) is given as follows:

(ii) Half Mode Substrate Integrated Waveguide (HMSIW) design considerations:

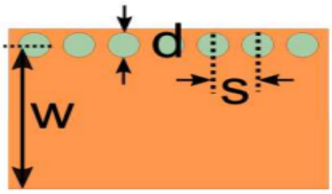


Figure 4.2: HMSIW structure top view.

The effective width of HMSIW ($w_{hmsiweff}$) is half of that of SIW and is given as follows:

$$W_{hmsiweff} = W_{siweff} / 2 \quad (5)$$

By considering fringing fields,

$$W = W_{hmsiweff} + \Delta \quad (6)$$

$$\frac{\Delta w}{h_s} = \left(0.05 + \frac{0.30}{\varepsilon_r}\right) \times ln\left(0.79\frac{w^2_{hmsiweff}}{h^3_s} + \frac{104w_{hmsiweff} - 261}{h^2_s} + \frac{38}{h_s} + 2.77\right) \quad (7)$$

where, h_s is the thickness of the substrate. The fundamental quasi mode for HM-SIW is given as follows

$$f_{TE_{0.50}} = \frac{c}{4\sqrt{\varepsilon_r} w} \quad (8)$$

V. RESULTS AND ANALYSIS

Parametric studies on the impact of important factors on the radiation design, gain, and bandwidth of the antenna are included in this section. Based on adjusting and optimizing these settings, the simulation results are shown. Additionally included are the measured findings, measurement setup, and the constructed prototype.

The fourth antenna (Fig. 1) provides a regulated bandwidth. Over the regulated frequency range of 21.6–40 GHz, a satisfactory impedance match is achieved using parametric analysis and g1 and g2 fine tuning. Figure 1 shows how these factors affect the proposed antenna #4's reflection coefficient. The HMSIW determines the subordinate cut-off occurrence, while g1 and g2 determine the higher cut-off occurrence.

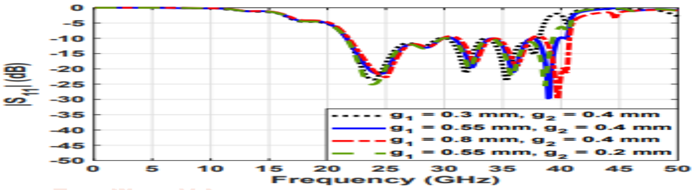


Figure 1: Effect of parameters g_1 and g_2 on the likeness constant of the planned antenna (antenna #4).

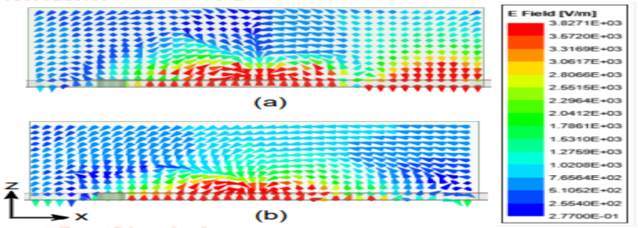


Figure 2: Electric field circulation at 39 GHz and mode change at HMSIW to stripline progress: (a) without openings and (b) with spaces.

Figures 2(a) and 2(b) portray the rechargeable field circulation at the HMSIW to stripline progress for the recommended receiving wire #4 with and without openings, individually. It is seen that the proposed radio wire #4's mode change at HMSIW to stripline progress (TE0.50 to TEM mode) happens with a diminished field dispersion subsequently the half-plane with the expansion of ground plane openings. Alongside a diminished side curve level, this likewise creates a consistent radiation design in the E-plane.

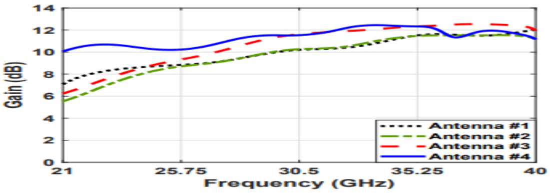
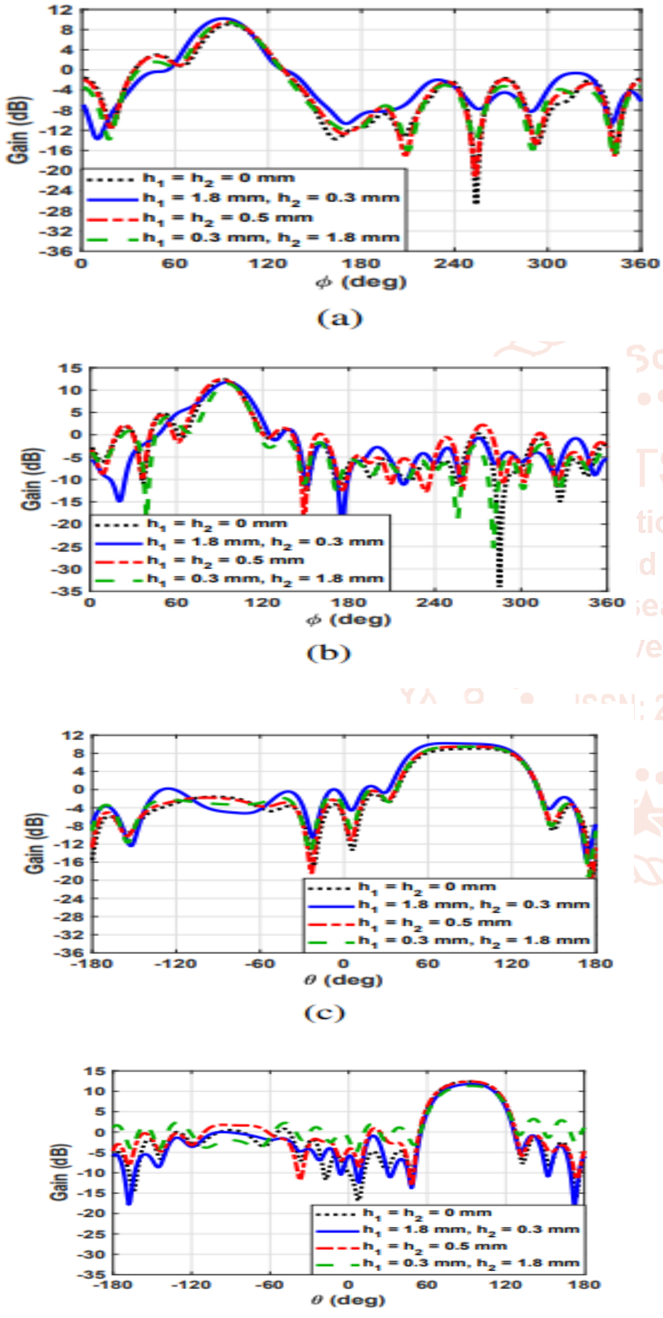


Figure 3: Acquire versus recurrence for the proposed radio wires.

Gain is increased by the corrugations, which direct the electric field toward the antenna aperture. We use a = 1 mm to represent the magnitude of sinusoidal corrugations. Figure 5.3 shows a comparison of the gains that the suggested antennas achieve. The gain of antenna #4 is 10–12.44 dB for the 21.6–40 GHz regulated bandwidth.

The E-and H-plane radiation plans for radio wire #4 at 25 GHz and 39 GHz for various potential gains of the space lengths h1 and h2 are shown in Fig. 4 (a)-(d).



(a)

(b)

(c)

(d)

Figure 4: The receiving wire #4 radiation design is as per the following: (a) E-plane at 25 GHz, (b) E-plane at 39 GHz, (c) H-plane at 25 GHz, and (d) H-plane at 39 GHz.

The optimal values of h1 and h2 are 1.8 mm and 0.3 mm, respectively, to produce a steady E-plane pattern. The suggested antenna has a prototype made. Using the 10 MHz–67 GHz Keysight PNA-X-N5247A network analyzer, the antenna reflection coefficient is determined.

VI. CONCLUSIONS

An isosceles trapezoidal-shaped dielectric lens is added for gain improvement to an antipodal elliptically tapered slot antenna for 20–40 GHz. To improve gain and radiation pattern characteristics, a special metamaterial with split ring resonators and a dual thin wire structure was placed on top of the lens. The suggested antenna, measuring 0.83 cm3, has a good gain, a reasonable size, and a constant emission pattern. Because of its performance, the antenna was determined to be appropriate for millimeter wave applications. With a steady radiation pattern and a uniform current distribution, the modified AETSA (MATSA) was designed to improve gain and radiation characteristics. A Semi-Dodecagon shaped Dielectric Lens (SDDL) was added, which enhanced the radiation pattern and gain. The suggested metamaterial-loaded antenna showed enhanced radiation pattern stability, gain, and compact dimensions.

In E- and H-planes, the suggested antenna beat the most sophisticated antenna designs in terms of gain, size, and radiation pattern stability. Another use for it was as a millimeter wave imaging transceiver, demonstrating its effectiveness in high resolution systems. The summary of the antenna's performance was compared to the most sophisticated antenna designs. A system-level integration feature created to support space-constrained broadband millimeter wave applications is the antipodal tapered slot antenna. It is supplied by a special bandpass filter design #1 that offers a large passband of 21.6–40 GHz with respectable impedance matching. This configuration is based on HMSIWs. The effectiveness of the antenna was confirmed using a prototype that included a bandpass filter.

The suggested antenna had a controlled bandwidth from 21.6 to 40 GHz, with a gain variation of 2.03 dB over the regulated range up to 36 GHz. The antipodal tapered slot antenna was fed by a special HMSIW-based bandpass filter configuration #2, which allowed for a tightly watched bandwidth between 23.5 and 40 GHz. With a constant emission pattern, the antenna showed a gain of 9.47–11.92 dB across 23.5–40 GHz. Future studies could examine whether antipodal tapered slot antennas are suitable for millimeter wave sub-surface imaging, whether the suggested antenna can be used as a transceiver in a wideband millimeter wave imaging system, whether reconfigurable frequency, pattern, and polarization can be used for Multiple Input Multiple-Output (MIMO) applications, and whether antenna design is appropriate for stealth applications. The wide bandwidth, focused emission pattern, and high gain of the antipodal tapered slot antenna make it a good choice for MIMO systems. However, a major obstacle to its utilization is its structural architecture. There are very few other approaches that are more appropriate for building tiny antennas than substrate integrated waveguide technology and its modifications. This may be looked at in future studies on RCS reduction of compact antipodal tapered slot antennas.

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