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A High Gain 60GHz Antipodal Fermi-Tapered Slot Antenna Based on Robust Synthesized Dielectric

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Abstract — A high performance antipodal fermi taper slot antenna based on unique synthesized dielectric is presented for UWB radar applications at 60GHz band. Specifically, the synthesized dielectric is implemented based on machined holes concentrates only at aperture area to improve its mechanical robustness for lengthy antenna. Further, it is able to suppress back lobe level by 2.5 dB through curving tapered end of the antenna. Concurrently, sine corrugations and dielectric loading are adopted to improve radiation pattern and gain of the antenna for over 20dB.

Index Terms — Beamforming, corrugation, dielectric, tapered slot antenna, ultra-wideband.

1. Introduction

Emergence of Ultra-wideband technology (UWB) in mm-wave regime has sparked active interests on multi-gigabit wireless communications and high resolution imaging radar. Unlicensed frequency bands allocated in between 60GHz and 100GHz have become the prime focus for such developments. Planar traveling wave antennas, particularly tapered slot antenna (TSA) have gained popularity for adoption in UWB systems due to its wide bandwidth and moderate gain with high portability. EM waves in such antenna propagates along the substrate lies within the tapered slot and radiates as the separation between taper conductors hits half of free space wavelength. Many geometry variants of TSAs have been reported to improve performance metrics of antennas in different aspects. The distinctions between these TSAs lie mainly on the taper profiles, feeding mechanisms and corrugation patterns at the side edges. TSA with exponential taper profile (Vivaldi antenna) was first introduced by Gibson in 1979 [1]. Due to higher changing rate of taper width, it can achieve wider bandwidth and lower sidelobe levels than linear taper slot antenna (LTSA) and constant width slot antenna (CTSA) [2]. Further introduction of periodic corrugation slots at side edges [3], [4] helps improving the antenna gain and reduce cross polarization level by suppressing radiation fields in undesired directions. More recent reported Fermi TSAs have been found to excite radiation better in corrugation structures than others [5] while promoting greater flexibility in antenna design. As for the feeding mechanisms, the antipodal version of TSA [6] is generally more preferred for achieving wider bandwidth and lower radiation than the conventional coplanar version. Nevertheless, the performance of TSAs is highly susceptible to dielectric properties and thickness. According to [2], the effective thickness of TSA should fall within 0.005 to 0.03 times of free space wavelength, λ_0 for optimum performance. This translates into mechanically fragile substrate at mm-wave frequencies even with adoption of low dielectric constant materials. In order to accommodate thicker substrate, the effective dielectric constant of substrate could be reduced by introducing air slots within it. Specifically, periodical air holes [7] are more preferred than large air slots [4], [8] to realize mechanically robust mm-wave antennas. Under such method, air holes are machined throughout the substrate with

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controlled ratio between air hole diameter and substrate area. Nevertheless, most mm-wave TSAs (>60GHz) reported up to date are restricted to electrical length of less than $10\lambda_0$ where limited gain can be achieved.

In this paper, a high gain 60GHz antipodal TSA with electrical length of $10\lambda_0$ is reported for the first time using synthesized dielectric. Unlike others, the synthesized dielectric is realized through selectively machining arrays of periodic holes spread along the tapered region. Further, it combines several techniques simultaneously to realize high performance TSA. These include dielectric loading, sine corrugation and curved tapered ends.

2. Antenna Design

The antipodal version of TSA consists of a symmetrical pair of tapered conductors that lie at both sides of substrate with one of them serves as ground. The antenna aperture where the synthetic dielectric lies is defined by the area in between the conductors. Figure. 1(a) shows the design schematic of antenna with dimension parameters labeled. The antenna is fed by microstrip line at one end where its input matching is controlled mainly by line widths (W3, W4) and curvature radii (R1, R2). Meanwhile, the top and bottom view of the TSA prototype mentioned is shown in Figure. 1(b). Note that a pair of holes have been drilled on the ground microstrip conductor for mounting 1.85mm coax connector. The main design elements are detailed as follows:

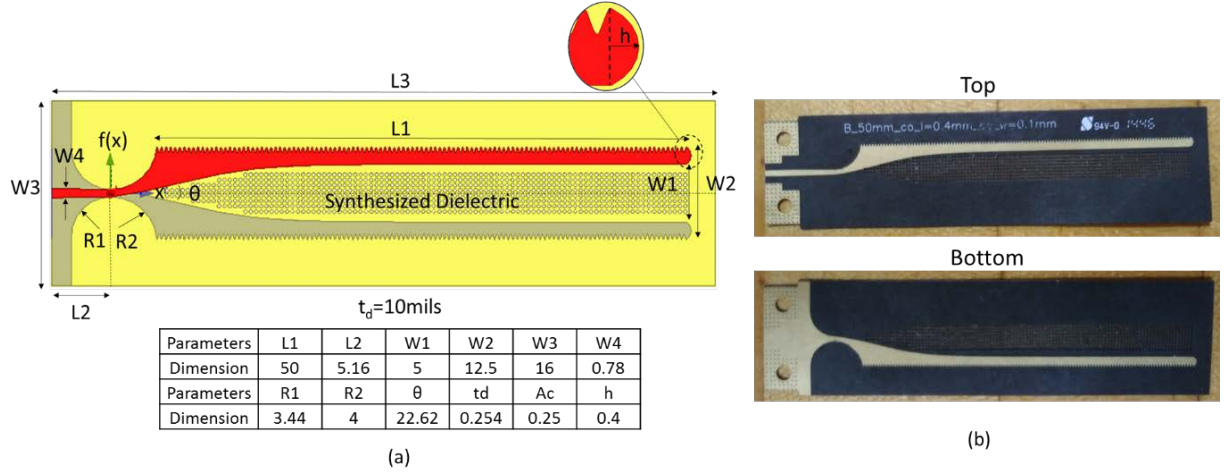


Fig. 1. Fermi-Sine corrugated antenna design with partial synthesized dielectric and curved tapered end.

2.1 Tapered Profile

The TSA is developed based on fermi tapered profile [3], [9] to facilitate higher degree of design freedom while achieving low side lobe levels. In this work, the fermi equation in [9] is further generalized for application on antipodal type of TSA where tapered conductors cross over each other at the feeding point. It could be expressed in terms of width of microstrip feeding conductor, w as follows:

$$f(x) = \frac{a+w}{1+e^{-b(x-c)}} - w \quad (1)$$

In this case, the asymptotic value of taper width is unaltered, i.e. $\lim_{x \rightarrow \infty} f(x) = a$. The gradient of the taper profile function at inflection point, c becomes $(a + w)b/4$. The crossover point of 2 symmetrical tapered sections occur at

$f(x)=0$ where $x = c - \ln\left(\frac{a}{w}\right)/b$. At $x=0$, both tapered sections completely overlap each other as they are transformed into microstrip section of width w . The fermi tapered function in (1) could be rewritten as (2) for $x=0$:

$$f(0) = \frac{a+w}{1+e^{bc}} - w = -w/2 \quad (2)$$

Thus, the relationship between design parameters of antipodal fermi TSA could be described in terms of feeding metal width, w as follows:

$$bc = \ln\left(1 + \frac{2a}{w}\right) \quad (3)$$

Here, the optimized values used for coefficients b and c are 0.3 and 6 respectively.

2.2 Dielectric Substrate

The antenna proposed is fabricated on Roger 5880 substrate material that has dielectric constant of 2.2 and thickness of 10mils. Such thickness is necessary to achieve required mechanical robustness for antenna length beyond $10\lambda_0$ at 60GHz. Optimization of effective dielectric thickness, t_{eff} (within 0.005 to 0.03 times of free space wavelength) could be accomplished by reducing its effective dielectric constant, ϵ_{eff} based on the following relationship [2]:

$$t_{eff} = t(\sqrt{\epsilon_{eff} - 1}) \quad (4)$$

As compared to [7], it is accomplished by selectively introducing arrays of periodic holes in the antenna aperture where electromagnetic waves propagates and radiates. This is because synthetic dielectric outside aperture has much less influence on radiation characteristic and could introduce significant degradation in mechanical robustness if entire region is machined. Based on [7], the effective dielectric constant of synthetic substrate filled with arrays of periodic holes is given as:

$$\epsilon_{eff} = \epsilon_r \left(1 - \frac{\pi D^2}{4W^2}\right) \quad (5)$$

Where, D is the diameter of air holes and W is the spacing between them. Thus, the effective dielectric thickness, ϵ_{eff} could be controlled by adjusting D/W ratio. The dimension D and W chosen in this work are 0.12mm and 0.343mm respectively which corresponds to resulted t_{eff} of $0.02\lambda_0$ in aperture area. A study is conducted to analyze the impact of hole diameter on antenna gain performance using electromagnetic simulation tool, HFSS. As shown in Figure. 2(a), synthetic dielectric with larger hole diameter has larger peak gain (0.5dB improvement for hole diameter= at 65GHz) at higher frequencies since the effective substrate capacitance becomes smaller. Another investigation is also carried out to compare the impact of synthetic dielectric slot in aperture area against those outside aperture area on gain performance of antenna. The results in Figure. 2(b) shows that TSA based on machined holes outside the tapered aperture has closer gain performance as those without synthetic dielectric (<0.2dB difference at 65GHz). This shows that the dielectric constant is altered more effectively when placed in the tapered aperture.

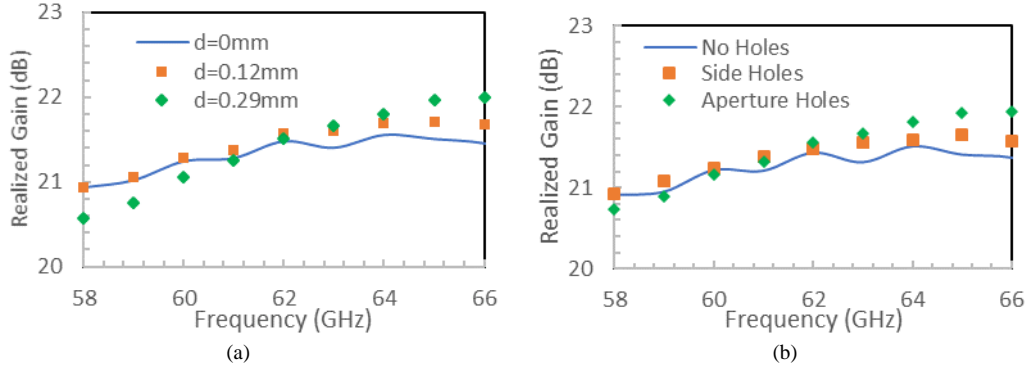


Fig. 2. Realized gain performance versus (a) hole size and (b) location of dielectric holes

2.3 Curved tapered end with sine corrugation

Meanwhile, periodical corrugations are introduced at both sides of TSA to improve radiation characteristics of TSA. As compared to [4], both sine type of corrugation pattern [4] and curved tapered ends are used together to improve the radiation characteristic of TSA. Based on [4], the sine corrugation profile function could be described by $A \sin(ky)$ where A is the amplitude and k is the angular frequency. The sine corrugation coefficients, A and k are optimized based on [4] and determined to be 0.25 and 16 for best performance. The sine corrugation is preferred as it reduces the effects of current disruption on the sharp angled edges and eliminate antiphase waves in the aperture [4]. In addition to that, rectangular dielectric loading of 2.5mm in length is introduced to improve gain performance of the TSA.

3. Results & Discussion

The performance of the TSA described is characterized through measurement from Keysight 58GHz~66GHz RF system for validation of electromagnetic simulation results by HFSS. Figure. 3(a) shows the gain and return loss performances of antipodal taper slot antenna presented. It exhibits average gain of greater than 20dB over 61GHz~66GHz band with return loss of better than 20dB. The simulated data has been validated by showing close correlation with measurement data. The slight discrepancies in between measurement data and simulation data is due to fabrication tolerance and alignment precision between transmitting and precision antennas. The radiation pattern in Figure. shows excellent symmetry (up to -17dB) while showing side lobe level of less than -17dB in E-field and less than -21dB in H-field. As a result of relatively long antenna, the presented TSA could achieve higher resolution with narrow beamwidth of less than 11 degree. Meanwhile, the cross-polarization level is better than 30dB for both E-and H-planes.

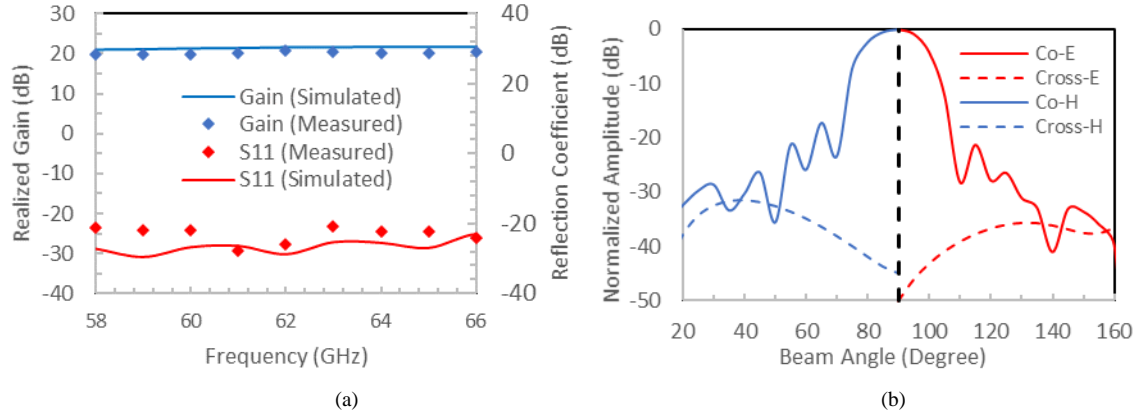


Fig. 3. (a) Realized gain and reflection coefficient versus frequency. (b) Radiation pattern of E- and H- fields.

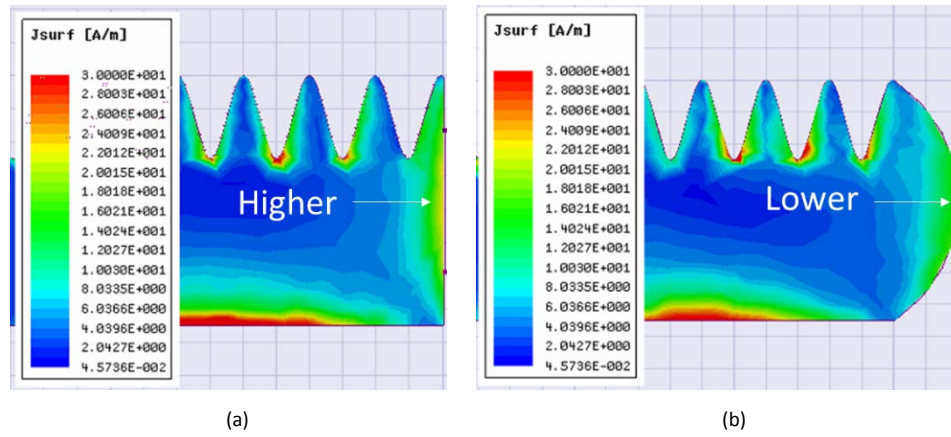


Fig. 4. (a) Current distribution comparison for (a) TSA without curved tapered end and (b) with curved tapered end.

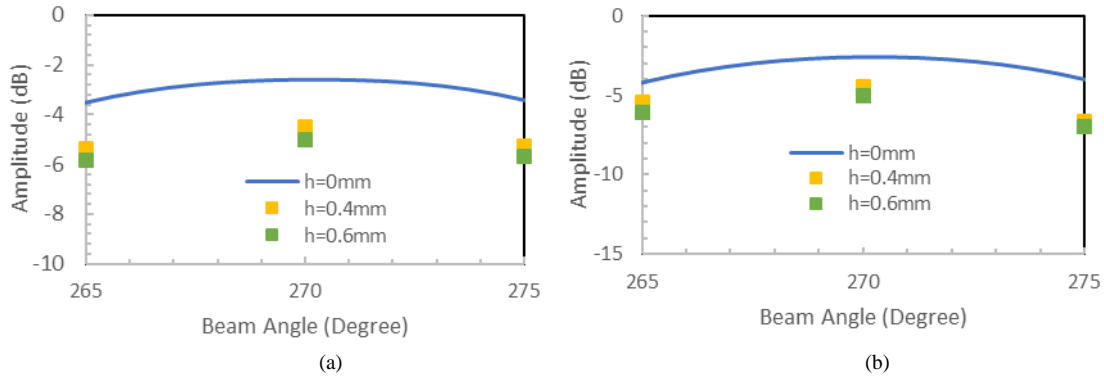


Fig. 5. Back lobe level at (a) E-plane and (b) H-plane for different curvature height, h at taper end.

Next, the effect of curve radius at taper end on back lobe level of antenna at beam angle of 270 degree is examined. Based on the analysis of current distribution in Figure. 4(a), (b), the TSA version without curved taper

end exhibits stronger undesirable current density at the edge which contributes to radiation loss [10]. Consequently, considerable improvement (2.5 dB in both E- and H-field) in back lobe level is observed for TSA with curved tapered end (Figure. 5(a), (b)). The amount of improvement in back lobe level saturates as the height of elliptical curvature (or sag), h_4 increases beyond 0.4mm ($0.08\lambda_0$).

4. Conclusion

In this paper, an antipodal fermi taper slot antenna is presented for wideband operation at 60GHz band. Particularly, the equation on fermi tapered profile has been improved to cover its relationship with width of feedline conductor. Partial synthesized dielectric with machined holes at tapered aperture is demonstrated to improve mechanical robustness of lengthy TSA ($>10\lambda_0$) in millimeter-wave design. Further analysis presented shows that curved tapered end with appropriate curvature height could be used to suppressed back lobe level by more than 2.5dB. The antenna presented is attractive for used in high resolution short range radar given its superior gain and narrow beamwidth.

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