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Through Wall Imaging Radar Antenna with a Focus on Opening New Research Avenues

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ABSTRACT

This review paper is an effort to develop insight into the development in antennas for through wall imaging radar application. Review on literature on antennas for use in through wall imaging radar, fulfilling one or more requirements/specifications such as ultrawide bandwidth, stable and high gain, stable unidirectional radiation pattern, wide scanning angle, compactness ensuring portability and facilitating real-time efficient and simple imaging is presented. The review covers variants of Vivaldi, Bow tie, Horn, Spiral, Patch and Magneto-electric dipole antennas demonstrated as suitable antennas for the through wall imaging radar application. With an aim to open new research avenues for making better through wall imaging radar antenna, review on relevant compressive reflector antennas, surface integrated waveguide antennas, plasma antennas, metamaterial antennas and single frequency dynamically configurable meta-surface antennas are incorporated. The review paper brings out possibilities of designing an optimum through wall imaging radar antenna and prospects of future research on the antenna to improve radiation pattern and facilitate overall simple and efficient imaging by the through wall imaging radar.

Keywords: Through wall imaging radar; Ultra-wide band antenna; Structural modification; Antenna loading; Optimising radiation pattern; Compact portable antenna; Simple efficient imaging

1. INTRODUCTION

Continued research and development in Through Wall Imaging Radar (TWIR) is making it an effective force multiplier both in military and civil domain[1,2]. TWIR finds its application in the detection and identification of the intent of targets hidden by the wall in both hostage rescue and counter terrorism operations. Antennas play a pivotal role in making TWIR effective. Thus, extensive researches are being carried out to design suitable TWIR antennas.

This paper reviews literatures fulfilling requirements of TWIR antennas with a focus to open up new research avenues. Expectations of TWIR antennas are illustrated below bringing out clearly that no literature / design simultaneously fulfils all the requirements[3,4,5].

(a) Frequency of Operation: TWIR is required to operate at low frequency ($\leq$1 GHz) for higher penetration through the wall. To achieve imaging resolution Ultrawideband (UWB) operation is required[3,4].

(b) Gain: High and stable gain throughout the UWB are required to detect target at greater depth behind the wall and to make the system more sensitive[3,4].

(c) Radiation Pattern and Beam Width: Throughout the UWB, stable radiation pattern with minimum distortion is required to minimise complexity of TWIR design. Antenna design, to minimise ringing effect for full bandwidth (BW) utilisation, is also an important requirement. Unidirectional radiation pattern is required to ensure the focus of RF energy on wall and target and high front to back ratio ensures neutrality on user's presence. There is a requirement of high isolation between transmit and receive antenna so that low-power reflected from the target is not masked by mutual coupling between the transmit and receive antenna. In addition, for a practical online fast solution, the beam-width of the antenna is to be controlled such that it covers the entire region of target presence, taking minimum time[4].

(d) Compactness and Portability: TWIR antenna is required to be low profile, light weight and compact for easy portability. For all these reasons, planar design is preferred and also for easy integration with other sub-systems of planar TWIR PCB. Requirement of amenable bulk production at low cost also is a design parameter[3,4,5].

(e) Facilitate Overall simple and efficient Imaging by TWIR: Most TWIR employs UWB for imaging targets. Requirement of antenna design facilitating better and online fast image reconstruction with less hardware intensiveness is there. UWB has an adverse effect when the wall is non homogenous and non-uniform requiring complex and time-consuming imaging and focusing techniques. This brings out the requirement of single frequency operation acquiring the benefits of UWB operation from dynamic alterable look angles[4].

Antennas, which addresses all or most of these requirements simultaneously, is the optimum antenna for

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TWIR application. However, most of the single antenna design does not fulfil all the requirements optimally simultaneously. Antennas, which have the potential to address various combinations of the requirements as highlighted above in the UWB range and thus explored in various TWIR literatures are Vivaldi, Bow-tie, Horn, Patch, Spiral and Magneto Electric Dipole antennas. Optimum variants of these antennas are being reviewed in this paper. Literatures also reports antenna types like plasma, metamaterial, surface integrated waveguide, compressive reflector, fractal and dynamic configurable meta-surface, which demonstrates properties that can fulfil the requirement of TWIR. However, research on these antennas is mostly limited to higher frequencies. Key and important papers covering these antennas and relevant to TWIR are also being reviewed with an aim to open up new possibilities to improve functionalities of TWIR antennas.

2. UWB ANTENNAS FOR TWIR WITH HIGH AND STABLE GAIN

After Federal Communication Commission (FCC) designated 3.1 to 10.6 GHz as unlicensed UWBin2002, thereafter, most of the TWIR development is concentrated utilising this band. In the UWB, lower the frequency better the penetration in the walls for reaching higher depth targets, while higher the BW greater the image reconstruction resolution obtained. Literatures reports various techniques adopted to enhance BW of operation with stable and high gain, while keeping other parameters like Voltage Standing Wave Ratio (VSWR), radiation pattern, dispersion, etc., within acceptable limit. Three such techniques relevant for TWIR antennas, namely structural modification, loading of the antenna and using reflectors are reviewed in the succeeding subparagraphs.

2.1 Structural Modification

Numerous effective structural modifications of basic antennas aimed at modifying the input impedance of the antenna have been reported in literature. Over the entire targeted large BW, getting the desired variation of input impedance of the antenna for easy and proper impedance matching and getting suitable electric current distribution in the antenna, are the ultimate requirements for enhancing BW. For gain enhancement and stability of the gain throughout the BW, current active region to be increased/added in a controlled manner at desired locations of the antenna for increasing antenna directivity. For TWIR applications, structural modification of Vivaldi, Bow tie, Patch, Spiral and Horn antennas have shown promising results in obtaining UWB characteristics with stable high gain.

2.1.1 Vivaldi Antenna

Conventional Vivaldi antenna as presented by Gibson[6] has a shape as shown in Fig. 1. This shape is defined by the exponential expansion of $Y = \pm A * \exp(PX)$, where Y is half separation distance, X is length determining the gain and P is the magnification factor determining the beamwidth. As X become large and positive the imparted energy leaves the guided structure and for large and negative X, the wave becomes more tightly bound to the conductor. Thus, conventional Vivaldi antenna suffers from low gain varying from 4 dBi to 8 dBi depending on frequency[7] and BW of the order of 3:1 for typical gain of 6 dBi[6].

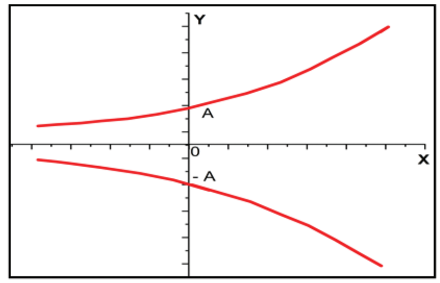


Figure 1. Expansion Law of Conventional Vivaldi[6].

Various structural modifications on conventional Vivaldi antennas have been reported in the literatures for enhancing BW, gain and making the gain stable within the BW of operation for TWIR application. This includes optimising opening rate of exponential tapper of Vivaldi antenna with addition of linear and circular slots at the locations where current distribution is weak[7], including uniform corrugation with constant decreasing rate along the exponential section[8], adding metallic strips in the centre of the antenna apertures at both sides[9], adding a number of grating elements at the opening end of exponential slot[10], incorporating periodic edge slot, copper directors and trapezoid shaped dielectric lens all simultaneously[11]. These techniques as given at[7-9,11] are diagrammatically shown in Fig. 2(a), (b), (c) and (d) respectively. These techniques could yield an average gain of approx. 8 dB with 2/3 dB variation in the UWB licence band. These structural modifications either prevent current activity near the edges of the antenna, which do not contribute to end-fire radiations as affected by periodic edge slot or increase current activity in the centre of the aperture as affected by copper directors or assist in focussing radiation in the end fire direction as affected by dielectric lens[11]. Modifications, which prevent current activities in the desired region are effective at lower end of operational BW while which assist in focussing radiation in a desired direction are more effective at upper frequency limit[11]. Figure 2(d) depicts this concept of enhancing BW of Vivaldi antenna by using periodic edge slots

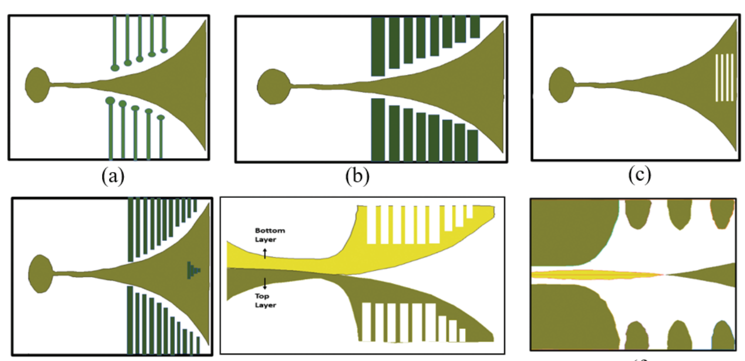


Figure 2. Enhancing BW and Gain of Vivaldi antenna by adding (a) Linear and circular slots[7], (b) Uniform corrugation[8], (c) Metallic strips in the centre[9], (d) Periodic edge slots and Dielectric Lens[11], (e) Nine Optimised slits in BAVA[13], (f) Elliptical Curves along the edge[14].

to increase the low end of the operating BW and dielectric lens to enhance the upper frequency limit of the operation.

Modification on variant of Vivaldi antenna with varying number of radiated layers and their direction is also promising in enhancing BW and gain. Compares[12] conventional planar Vivaldi antenna, Antipodal Vivaldi antenna (AVA) and Balanced Antipodal Vivaldi antenna (BAVA) working in 2 to 4 GHz band with size, substrate and flaring angle remaining same and brings out that BAVA has best return loss, coplanar Vivaldi has highest gain and AVA has best radiation characteristics. In[13] BAVA is etched on a single substrate with 9 slits of optimised height on both arms giving an overall gain of 10 dB for the entire UWB (3.1-10.6 GHz) as depicted in Fig. 2(e). In[14], AVA has been optimised for TWIR application by adding three additional elliptical curves at the edge sides acting as radiation flares and eight grating elements along the taper. This resulted in impedance BW covering entire UWB (3.1 -10.6 GHz) with gain varying from 7.8 dBi to 14.04 dBi. Figure 2(f) depicts this concept of adding additional elliptical curves at the edges to enhance BW. Literatures like in[11,13,15,16] reports Array using the optimised Vivaldi element antennas. Maximum gain reported for this array structure is 15 dB[13] covering the entire UWB range.

2.1.2 Bow Tie Antenna

Ideally, bow tie antenna is specified only by angles and thus is frequency independent. The input impedance of bow tie antenna depends primarily on this flaring angle[17]. Conventional bow tie antennas having a linear flaring angle, which is shown in Fig. 3, do not facilitate gradual impedance matching, necessitating complex impedance matching for the whole targeted BW. This is the major bottleneck in achieving wide band performance with stable gain[17]. In addition, structure of conventional bow tie antennas does not provide a smooth path for current flow in the entire antenna having sharp and abrupt corners contributing to undesired reflections.

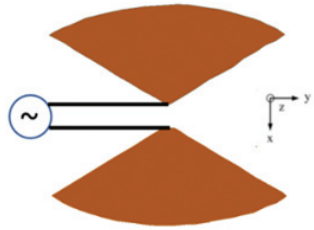
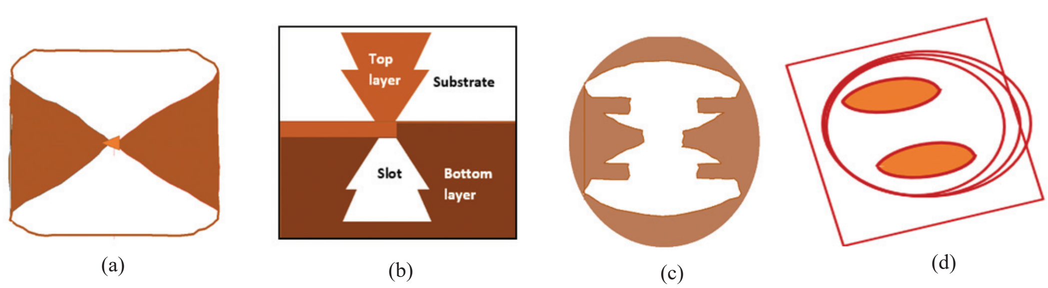


Figure 3. Conventional bow tie antenna[17].

Literatures reports various structural modifications of bow tie antennas suitable for TWIR applications. Proposed[17] a self-grounded bow tie by connecting radiating element on ground with an extended angle of 60^0 as shown in Fig. 4(a). This antenna demonstrated a BW of 02 to 15 GHz with S11 below 7 dB for whole band & directivity of 5 to 8 dBi.[18] reports a fractal self-complementary bow tie antenna with fractal repetition having a triangular and rectangular patch and it's complimentary on its ground plane. This yielded S11<-10 dB impedance BW of 2.88 to 11.58 GHz with gain varying from 1.5 to 5 dB. Figure 4(b) depicts the structure used. Reports[19] a sectorial bow tie antenna having a gradual varied sectorial structure with folding arms and four rectangular patches as shown in Fig. 4(c). This gives an impedance BW of 1.35 to 3.71 GHz with gain of 8.43-10.02 dBi. In[20] an elliptical bow tie antenna optimised by adding five loops around with offsetting of these loops acting as directors to enhance gain. This demonstrates an impedance BW from 420 MHz to 5.5 GHz with an average gain of 7.2 dBi and peak gain as 9.5 dBi. Figure 4(d) depicts the innovative use of offsetting of loops to enhance gain. Demonstrates[21] a configuration that can be used simultaneously with other structural modification to enhance gain and BW. It reports that by placing one arm of the bowtie antenna on radiating plane and the other on ground plane operating at 0.8 to 1.34 GHz an average increase of 0.25 dB in antenna gain and 12% enhancement in BW can be achieved.

2.1.3 Miscellaneous Structure Modified Antennas

Several structural modifications of spiral, patch and horn have been carried out for TWIR application. Reports[22] a 0.5 to 1.2 GHz, 2 arm 22 turn multiple cut-corners spiral antenna with a reflecting cavity having right hand circular polarised (RHCP) gain of 4-8.98 dBic. Angle size of the cut corner gradually decreases from inside to outside. Big angle cut corner facilitate high frequencies whereas small angle cut corner low frequencies. Figure 5(a) depicts the concept of cut corners in which two turn cut corners are shown. In[23,24] Archimedean spiral antenna has been used as TWIR antenna which provide broad BW but suffers from serious dispersion effects. Presents[25] a circular patch with a semi elliptical slot inserted in ground plane at the back of the substrate as shown in Fig. 5(b). This achieves impedance BW of 4.40 to 10.60 GHz for measured six resonant frequencies in this band with gain varying from 6.1 to 9.1dBi. Presents[26] a shifted arc antenna with a defected ground structure in which 05 uneven slots are added in ground. Figure



(a) (b) (c) (d)

Figure 4. Concept for Enhancing BW & Gain of Bow Tie antenna. (a) Self-grounded[17], (b) Fractal repetition on self-complementary structure[18], (c) Sectorial antenna with folding arms and rectangular patches[19], and (d) Offsetting of Loops acting as Director[20].

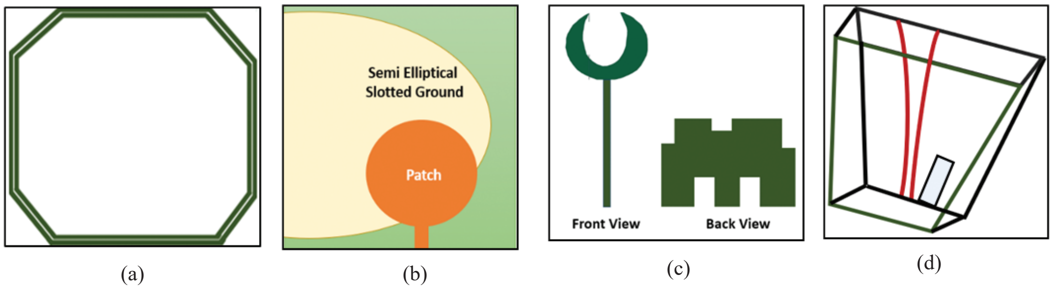


Figure 5. Structural modifications of spiral, patch and horn for TWIR application. (a) Concept of cut-corners spiral antenna[22], (b) Circular Patch with a semi elliptical slot in ground plane[25], (c) Shifted arc antenna with a defected ground structure[26], and (d) Double ridge Horn antenna[31].

5(c) depicts front and back view of this antenna. A BW of 2.8 to 15.6 GHz with a gain of around 6.05 dB has been achieved. Horn antenna for TWIR application reported in[27] has a BW of 1.5 GHz but a huge gain of 21.5 dB. Also reports TWIR systems using Horn antennas[28-30]. Application of horn antennas are restricted because it is bulky and non-compact structure (for example rectangular front is 32.5 cm x 16.5 cm for[27]). Reports[31] a double ridge Horn antenna, as TWIR antenna. Two irregular ridges are placed in flare of the horn with one ridge having a slot as shown in Fig. 5(d). These ridges increase the electrical cavity length giving a BW of 0.8 to 6.0 GHz with an average gain of 8 dBi. Many literatures also report use of Horn as a transmitter antenna because of huge gain it offers and other antennas like Vivaldi, Patch as receiver antennas like in[32-34].

2.2 Antenna Loading

In general, tapered resistive loading enhances the BW of the antenna at the cost of reduction of efficiency. Whereas, tapered reactive loading is a non-dissipative method of BW enhancement, where the loading act as a secondary source of radiation. However, the resulting BW due to reactive loading is less as compared to resistive loading and hence an optimal combination of resistive and reactive loading is preferred[35]. Presents[36] a cavity backed bow tie with a resistive loading obtaining BW 1 to 4 GHz with a boresight gain of 5 to 9 dBi. Top layer of this antenna loaded with dielectric is shown in Fig. 6(a). In[35] tapered inductive loading is realised by a wire bow tie antenna with wires having increasing radius from 0.3 to 3.2 mm (as the flare angle increases max till 160°) for having a variation in self-inductance. Here, the inductive loading increases the antenna BW by 50% for centre frequency of 450 MHz. Figure 6(b), which is taken from[35], represents this effective way of inductive loading to enhance BW. Another loading technique used in waveguide antennas, such as Horn antenna, is to ridge load the flare part of the antenna. In[31], a BW of 0.8 to 6 GHz with an average gain of 8 dBi is obtained by loading a horn antenna with double ridge. The Ridge loading expands the single mode (TE10) range before the higher order modes occur broadening the maximum usable bandwidth. Figure 5(d) shows a double ridge loading of Horn antenna. Use of metamaterial loading for enhancement of gain and BW has recently been reported in Vivaldi antenna for TWIR and shows high potential for further research. Reported[37] that by loading Anisotropic zero index metamaterial (AZIM) along the aperture of Vivaldi antenna as shown in Fig. 6(c), a directivity enhancement of 2.6 dB is obtained. AZIM cells control the direction of emission and concentrate the EM energy in a small angular desired area, thereby enhancing the gain.

2.3 Using Reflectors

Employing reflectors to concentrate the RF energy in the desired direction is a well-known method to enhance BW and specially the gain. Presents[38] a microstrip antenna covering frequency of 1.5 to 3.0GHz for TWIR application. This antenna has a reflector to achieved a gain of 5.5 to 7.5 dBi. In[39] for improving vital sign monitoring using TWIR, a self-injection locked radar system using a planar 2x2 array antenna using frequency selective surface (FSS) has been presented. Gain is enhanced to 15.2 dB with 82% efficiency by placing modified Jerusalem cross shaped FSS in array of 8x6 units in front of the antenna. Literatures also presents backing by cavity to enhance the gain as given in[36], where cavity backed bow tie antenna has been proposed. It is inferred that better the controlled reflective surface better will be the gain/BW achieved. Metamaterials,

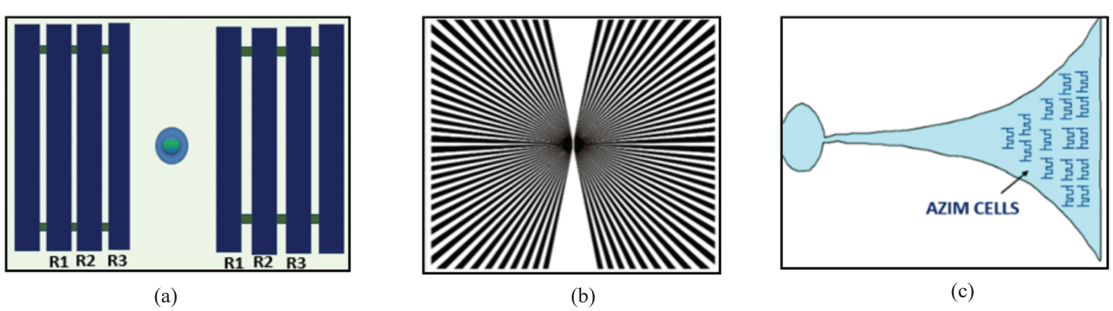


Figure 6. Antenna loading for enhancing BW for TWIR application. (a) Resistors loaded Top layer of Cavity backed Bow Tie antenna[36], (b) Inductive loading by wire Bow Tie antenna[35], and (c) AZIM loading at the aperture of Vivaldi Antenna[37].

such as artificial magnetic conductor (AMC) acts like a perfect magnetic conductor (PMC) and are being used as reflective plane to enhance radiation and thereby increase in gain and also BW of antennas[40]. The ability of PMC to provide zero-degree reflection phases at its resonance frequency has resulted in power gain > 2 dB[40]. BW enhancement by 100% has also been reported by using metamaterial as component of the antenna or as a superstrate[40]. Particular to TWIR application, [41] demonstrates a crossed dipole bow tie antenna working at 0.8 to 1.34 GHz with its arms both in radiating and ground plane backed by AMC metasurface. 3x3 AMC square patches each containing a slotted square ring placed at the bottom of this dual bow tie antennas increases the overall gain by 231.2 % to 8.81 dB. This structure backed by AMC is depicted in Fig. 7.

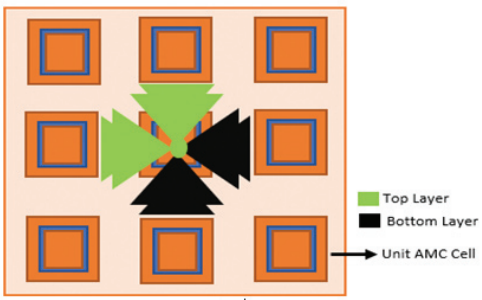


Figure 7. Cross dual-arm bow tie antenna baked by AMC Metasurface to enhance gain[41].

3. IMPROVING RADIATION PATTERN

Magneto electric (ME) dipole antennas, Metamaterial patch antennas and plasma antennas allow controlled/desired radiation characteristic. ME dipole antennas have been utilised in TWIR, however metamaterial and plasma-based antennas have been demonstrated for working mostly at much higher frequencies. In[42], an ME Dipole with '+' sign shape metallic element with rectangular slots placed horizontally acting as electric dipole and this electric dipole placed over a vertical rectangular wall shorted with ground acting as magnetic dipole is presented. Figure 8 depicts the design/arrangement of the antenna. In this arrangement both electric and magnetic dipole can be excited simultaneously resulting in symmetry in radiation pattern. This antenna reports a BW of 1.05 to 2.55 GHz with nearly constant gain of 9 dB +/- 1 dB. In[43] an ME dipole antenna with rectangular backed cavity working at 1.5 to 2.5 GHz demonstrates about 30 dB front to back ration (FBR) which is much better than Vivaldi antennas (12.5 dB) but having a slightly smaller gain than Vivaldi antenna. Reports[44] a metamaterial-based antenna for 5.8 GHz doppler radar with a capability to confine radiated beam in a narrow angle normal to the antenna's plane unlike, typical patch antenna. The double negative index metamaterial transmitter antenna has an array of 12 x complementary split ring resonators on top of the patch acting as a negative permittivity and a 30 x cross strip lines gaps designed to obtain negative permeability at the bottom ground plane. Directional but non-symmetric beam for BW of 3.5 to 8.0 GHz obtained with gain of 6.5 dB at 5.8 GHz. Receiver antenna is made of near zero epsilon metamaterial giving a high gain of 11.33 dB. Presents[45] a plasma based circular polarised ME dipole antenna with reconfigurable radiation characteristics. Constituents of the antenna i.e., electric dipole, magnetic dipole and the feeding dipole, all having plasma as conducting medium instead of metal. Radiation characteristics are reconfigurable by changing the plasma frequency of the components of the antenna and an optimum impedance BW of 1.64 GHz to 3.7 GHz with a stable gain of 10.7 dB with 95% efficiency and an FBR of 20 dB have been obtained.

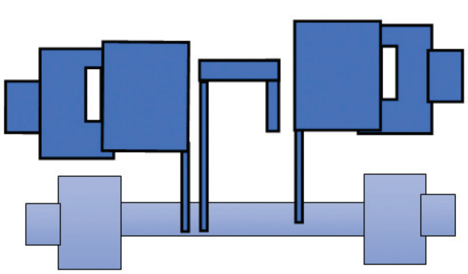


Figure 8. Design concept of magneto electric dipole antenna to improve radiation characteristics[42].

4. COMPACT AND PORTABLE TWIR ANTENNA

For making the antenna compact the electrical length of the antenna has to be increased. Compact techniques like shorting walls or pins, folded configurations, use of high dielectric constant material and surface etching techniques are common[46] and not being reviewed here. Relevant to TWIR system, horn and spiral antennas have high gain and high BW but is bulky and non-planar and not amenable for low-cost bulk production. Double ridges are utilised inside[31] cavity of the horn to increase the electrical length and reduced the length of the antenna by half for frequency band 0.8 to 6.0 GHz with an average gain of 8 dBi. Presents[47] a Gaussian profile Horn antenna and achieves a 40 % reduction in length. In this technique vertical corrugations and horizontal corrugations at throat region of the horn are applied for mode conversion from TE_{11} to HE_{11} and creating right mix for hybrid modes, which assist in reducing the size. In[48-50] Substrate Integrated Waveguide (SIW) technique has been used to get a planar equivalent horn antenna and accrue benefits of both planar and non-planar guided structures and facilitate integration of horn antenna on a low-cost PCB. SIW act as planar because metal vias act as narrow walls of the horn antenna as shown in Fig. 9. As illustrated in[49,50] the diameter of the metallic vias '*d*' is dependent on guided wavelength λg, which is corresponding the cut-off wavelength of TEm0 modes, as per Eqn (1) given below. Equation (2) gives the dependence of distance between two consecutive vias '*s*' on '*d*'. These parameters are related to width 'w' of SIW as given in Eqn (3), where 'a' is the width of the waveguide, i.e., distance between two parallel metallic vias[49].

$$d < \lambda g / 5 \tag{1}$$

$$s \le 2d \tag{2}$$

$$w = a - \left(1.08 \times \frac{d^2}{s}\right) + (0.1 \times d^2 / a) \tag{3}$$

SIW horn has an abrupt transition from the waveguide horn filled with dielectric to free space and thus offer limited

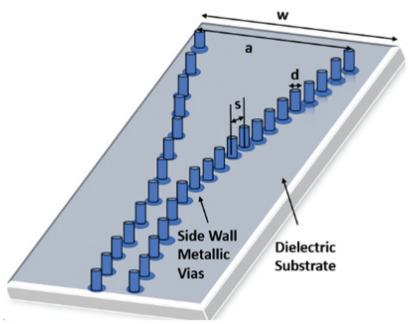


Figure 9. SIW horn antenna[49].

BW and gain. In[48], operating at 30.1 to 30.3 GHz, by using some metal and metal free square pixels at the flare of the SIW horn and optimally placing them using a genetic algorithm to control the radiated field at the aperture to achieve smooth transition of impedance. In this case, 10.11 dBi gain has been obtained. Reports[50] X band (waveguide cut-off at 6.3 GHz) two element SIW horn array with 9.6 dB gain. To make horn antenna light weight and have advantage of low cost and rapid fabrication, proposes[51] 3D printing and conductive spray coating and achieved 80% reduction in weight. Another technique to make antenna compact is fractal design, in which space filling capacity inherent in the design, increases the electrical length of the antenna. In[52] a compact antenna operating in dual frequency of 3.6 and 6.4 GHz, employing fractals in the hexagonal geometry is presented. The compactness resulted in radiating patch of 26 mm x 30 mm operating with an average gain of 4.2 dBi. For making the helical antennas compact in the frequency band TWIR,[53] proposes an orthogonally circular polarised printed quadri-filar helical antenna, which has a BW of 600 MHz with centre frequency at 3.4 GHz. It provides an isolation of 62.78 dB which is desirable for receiving very low reflected signal.[54]reports a multiple cut corner (of varying sizes) planar square spiral antenna operating in 0.5 to 1.2 GHz with a gain of 4-8.96 dBic. Width of the designed planar spiral is 13.4% lower than conventional circular spiral antenna having a geometric size of 0.282m×0.282m×0.133m. As explained in [40] use of metamaterial in antenna also assist in compactness, reducing size by up to 50%. It is to be noted that most of the techniques reviewed here have the potential to be used for achieving compactness for the application of TWIR operating at unlicensed UWB, especially the SIW technique, but are yet to be used extensively on ground for TWIR applications.

5. FACILITATING OVERALL SIMPLE AND EFFICIENT IMAGING BY TWIR

Various techniques, such as, compressive reflector antenna (CRA), frequency dependent beam scanning, utilising metamaterial (MTM) leaky wave antenna and imaging by TWIR utilising dynamically reconfigurable meta-surface antenna (DMA) has the potential to simplify the overall TWIR system and make the imaging more efficient and effective.

Presents[55] compressive horn antenna in 60 to 90 GHz, fabricated by inserting a 3D printed pseudorandom shaped dielectric material in the aperture of the pyramidal horn antenna to code the wave-field in the spatial domain, which are dynamically changed. These codes are designed so that the successive measurements have reduced the number of mutual overlapping information as compared to conventional suboptimal phased array imaging, employing many transmitting and receiving antennas[56]. TWIR antenna, employing CRA will have the potential to make imaging and sensing efficient and enable compressed sensing performed on under sampled measured data making the overall system fast.

Reports[57] an MTM leaky wave antenna operating at the frequency band of TWIR, which demonstrates scanning from -50^0 to 30^0 when the frequency varies from 1.85 to 2.85 GHz. This antenna is able to detect targets at different locations without additional tuning mechanism reducing system complexity, size, and cost.

Conventional method of fine resolution imaging by TWIR uses Synthetic Aperture Radar (SAR) or Multi Input Multi Output (MIMO) antennas. SAR antennas suffers from long scanning time, making the system slow and MIMO radars are hardware intensive employing number of transmitters and receiver antennas. In addition, usage of UWB for imaging has inherent issue for in-homogenous and uncharacterised wall, where distortion of the return signal is different for each frequency, necessitating complex compensation and autofocusing process. To solve the above-mentioned issues,[58] presented a single frequency TWIR system utilising dynamically reconfigurable meta-surface antenna (DMA). DMA is a single port electrically large antenna, which can provide range resolution on a single frequency due to the many oblique look angles it provides. For monotone frequency of 19.03 GHz, this DMA configuration has a span of 40 cm having 112 complimentary electric LC resonators (cELC), which can be turned off/on by PIN diodes. Figure 10 presents a schematic of this DMA. By utilising sufficient number of on/off combinations of these PIN diodes, DMA can obtain information equivalent to a MIMO system without employing hardware intensive MIMO antennas and the image can be reconstructed within less than a millisecond, which is much faster than the SAR system. For imaging, due to the usage of single frequency, the DMA system does not require complex wall compensation and autofocusing algorithms like UWB systems and are cost effective due to requirement of generation of only one frequency.

Figure 10. DMA with cELC turned on/off by PIN diodes with red and green colour representing the binary behaviour of the diodes[58].

6. LATEST RESEARCH ON TWIR ANTENNA

This section discusses recent research efforts on antennas relevant to TWIR application, providing insight on ongoing thrust of research.

One of the key areas of focus is to enhance the efficiency of TWIR antennas using methods as presented in[59-63]. In [59] and [60] SIW feed is used to enhance an efficiency at X-band of operation. Demonstrates[61] improved gain and efficiency by using higher modes of TE_{30} and TE_{50} of a SIW leaky wave antenna, instead of the fundamental mode, while[62] uses metal vias connecting the upper and lower dipoles placed diagonally on a unit cell to enhance efficiency. In all these methods efficiency is increased beyond 50% by achieving a full 360° phase shift with a smooth slope in the band of operation. Array optimisation methods, taking into consideration radiation pattern of each element of an array, has also been used to enhance efficiency[63].

Next key area of thrust, published in recent papers, is customising the radiation pattern and more importantly controlling the radiation patterns as per the requirement. Addresses[64-69] this research issue. Manipulates[64] TE modes of a metasurface antenna to customise radiation pattern, uses[65] active metasurface unit embedded with varactor diode for beam steering and beam shape reconfiguration, while[66] demonstrates method to digitally code a graphene metasurface and dynamically adjust the phase gradient along the metasurface plane to control the radiation pattern. Presents[67] an axial mode helical antenna surrounded by an array of 25 plasma antennas working at centre frequency of 927 MHZ, which can be individually switched on and off controlling the overall beam width. SIW based leaky wave antennas are also being used for obtaining wide scanning angles as presented in[68,69].

Recent research work in improving imaging efficiency relevant to TWIR include work presented in[70,71], which give methods based on Alternating Direction Method of Multipliers (ADDM) to reconstruct images obtained by CRA in real time by dividing the sensing matrix appropriately. CRA with digitised metamaterial absorbers (MMA) has been reported in[72] to create highly uncorrelated special and spectral codes, which resulted in increasing sensing capability of CRA.

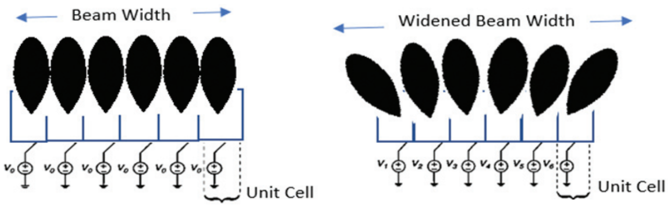
7. FURTHER RESEARCH AVENUES

Based on the review presented, this section brings out future research potential to improve the functionalities of TWIR antennas. Over the years, getting optimum results from structural modification of conventional antennas for TWIR applications has matured. Even techniques of loading the antenna and using reflective techniques to enhance gain and BW have also matured. However, combination of these techniques simultaneously, has the potential to give better results with higher stable gain in the targeted BW. Research avenues are open to use metamaterial in TWIR antenna and enhance the gain and thus the sensitivity of the system.

As for research avenues for further improving radiation characteristics of TWIR antennas, inspirations may be drawn from[45], which demonstrated an ME dipole-based plasma antenna discussed in section 3. The gain and BW enhanced optimum TWIR antenna may be made of plasma instead of copper. Radiation characteristics of plasma antenna are controlled by physical dimensions of plasma column and/ or DC ionising voltage. Thus, the use of plasma will allow electrical control of the radiation characteristics facilitating in getting desired radiation pattern as per the location of the target/ characteristics of the wall[73]. The TWIR plasma antenna promises unique advantages like radiation reconfigurability as per requirement, lightweight and turned on and off in a very short time negating any ringing effect[73].

Reviewed literatures in section 4 outlines SIW as an effective research effort for making horn antenna suitable for TWIR applications by making it compact, planar and amenable for low-cost bulk productions. Main research challenge here is to control the electric field at the aperture of the horn antenna so as to solve the inherent SIW horn antenna, the issue of impedance mismatch at aperture due to presence of dielectric and low thickness of the substrate. For operating as planar version of Horn antenna for TWIR, methods have to be researched to overcome the degradation of SIW antenna performance when substrate thickness is smaller as compared to an operating wavelength of TWIR and due to abrupt impedance transition from waveguide horn to free space[48]. Inspiration may be drawn from methods used in[48], working at a higher frequency of 30.2 GHz and discussed in section 4.

From the review presented in section 5, it is evident that extensive research potential also exists in designing the TWIR antenna for reducing the complexity of TWIR system and making it imaging efficient. Drawing inspiration from[55], research for CRA reflector working at TWIR BW may be undertaken. In addition to waveform spatial coding by using pseudorandom scatters as used in[55], spectral coding by making the surface of the reflector with metamaterial may also be used simultaneously, enabling TWIR imaging to be fast and more efficient, requiring a smaller number of measurements, when compared to those required by Nyquist sampling criterion[56]. Demonstration of single frequency DMA working at 19.03 GHz in[58], as discussed in section 5, opens up research possibilities of using DMA as TWIR antenna. Potential of getting a 3D system using 2D aperture DMA for TWIR application may also be explored as future research work. In addition to taking advantage of different look angles of DMA to obtain a robust image equivalent to a MIMO using a single frequency, as demonstrated in[58], scanning and BW controlling feature of MTM antenna[74], can be incorporated to get a better functionality in TWIR antenna. When the voltage distribution at each cell of the MTM is uniform, it has frequency dependant beam scanning as demonstrated in[57] and discussed earlier. When voltage distribution to unit cell of the MTM is non-uniform, each cell radiates towards different angle and the resultant radiation beam widen. Thus, by controlling the voltage applied to each cell, the beam pattern of the antenna can be varied[74] as demonstrated in[75], the HPBW is increased by 43% to 200% as compared to uniformly biased case. Figure 11 demonstrates this concept of controlling the overall beam width of MTM antenna. This feature of the leaky wave MTM can be used to overcome the highly inefficient method of scanning every point in space since much of the 3D space is empty. TWIR antenna exploiting these features can do course to fine 3D



(a) (b)

Figure 11. Beamwidth control of MTM antenna: (a) Narrow beamwidth with uniform voltage distribution in each cell and (b) Wide beamwidth with non-uniform voltage distribution[74].

Table 1. Summary of research avenues in TWIR antenna

Ref.	Method/ Technique	Potential	Issues to be solved by Further research
[41]	Meta-material as meta-surface	Gain enhancement (8.8 dB[41] by 200% gain enhancement)	Narrow band (Inherent issue with Meta-material)
[45]	Plasma based ME dipole	Optimum radiation characteristics (stable gain of 10.7 dB over 77% BW and FBR of 20 dB[45])	(a) Plasma excitation method (b) Constant current flow (c) Stable and repeatable plasma volumes
[48],[49][50]	Surface Integrated Waveguide	Compact and planar horn (75% reduction in overall size[49])	Impedance mismatch at aperture
[55],[56],[70],[71],[72]	Compressive Reflector Antenna	Efficient and fast imaging for real time operation	Suitable arrangement for waveform spatial coding and spectral coding
[58],[60],[61],[65],[66]	Dynamically Reconfigurable Metasurface antenna	(a) Single frequency imaging (b) 3D Scanning without hardware intensive antennas	(a) Spatial diversity using single frequency (b) Compactness for portability (span of 40 cm having 112 cELC [58])
[59], [61], [64]	Manipulating higher TE modes	Gain enhancement (16.4 dBi [59]) and efficiency improvement (43% [59])	Complex in design (additional structures to excite higher order modes [59,61,64])
[67]	Combination of Plasma and metallic antenna	Reconfigurable radiation pattern without decreasing efficiency	(a) Asymmetry in radiation gain (9 to 13 dB[67]) (b) Bulky in nature (25 plasma reflectors surrounding axial helical antenna [67])
[68]	SIW Leaky wave antenna	Wide beam scanning angle (80° scan angle including backward scanning[68])	Acceptable gain at sub 10 GHz (9.5 dBi at 16.7 GHz and gain reduces with decrease in frequency[68])

scan to recursively zoom in on the region with large reflected power without employing hardware intensive antennas as done in[76].

More specifically, to improve the performance of TWIR antenna, use of metamaterial and metasurface[41] may be employed to enhance gain. The plasma based ME dipole technique[45,59] is another potential area to be explored to obtain optimum radiation characteristics of antennas. A compressive reflector antenna technique[55-56,70-72] may also be adopted to make the imaging fast and efficient. Further, a single frequency imaging technique [58,60,61,65,66] may be explored to make the 3D scanning less hardware intensive and SIW leaky wave technique[68] could be used to obtain a wide beam scanning angle. Table 1 summarises research avenues in TWIR antennas, potential of the same and the respective issues that requires research solution.

8. CONCLUSION

The manuscript provides in depth review of literatures on TWIR antennas to give an insight into development in this field. Suitable variant of vivaldi, bow tie, spiral, horn, patch and magneto electric dipole antennas proposed as TWIR application, have been reviewed for their capability of providing UWB, stable gain and desired radiation pattern. With an aim to open up avenues for further research, to improve functionalities of TWIR antennas, antennas such as; plasma, metamaterial, SIW, compressive reflector and dynamically configurable metasurface antennas have been discussed. The review paper contributes in bringing out possibilities of designing an optimum TWIR antenna and presents future research possibilities including facilitating simple and efficient imaging by TWIR.

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In the current study, he did extensive literature review, collated relevant information, and analysed the information so as to find research gap and present avenues for further research in improving Through Wall Imaging Radar Antennas.

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In the current study, he conceived the idea of this study, guided in selection of relevant information and logical presentation of the same. He enriched the content of this study by his experience in this field and approved the final manuscript.