Through Wall Imaging Radar Based on Micro-Doppler Features

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***Abstract*—This paper discusses and aims to construct an inexpensive through wall imaging radar system. The system involves a main processor board, transmit and receive system, a dedicated software and a phased array design to identify living targets based on micro-Doppler features through occlusions. The intention of making the device affordable resulted in a new hybrid antenna which incorporates the ease of construction of the wave-guide antenna and the gain of conical horn antenna. The paper also studies the efficacy of the broad-band Vivaldi antenna and its variation with different parameters encountered during the designing phase. The dedicated software consists of a Java based GUI with JNI calls to C member functions to carry out processor intensive computations. The receive end software is influenced by GNU Radio project**

***Index Terms*—Through Wall Radar, Vivaldi, FMCW Radar**

I. INTRODUCTION

THE ability to localize and image human targets inside a building or remote area can be critical or beneficial in certain situations extending to both civilian and military purposes. Particularly when military situations are concerned, the threat of concealed armed assailants is rather common and the lack of building floor-plan and other construction details only increases the risk to the combing party. These threats can be greatly alleviated if a system that is capable of detecting the presence of living objects through occlusions can be devised. Through Wall Imaging Radar(TWIR) systems are an EM based answer to the problem. The main objective of this project was to devise ways of making it cheaper without compromising on the accuracy of the radar. The rest of the paper is divided into five sections. *Section II* articulates the objectives of the project. *Section III* deals with choosing a spectrum for the Radar. *Section IV* deals with the study of the most widely used antenna for the purpose of through wall imaging [2]. *Section V* deals with building the radar itself and *Section VI* deals with results and discussion of future prospects for the project.

II. OBJECTIVES

The objectives of this project are:

1) To design a low cost and efficient system for TWIR
2) To design an efficient antenna for transmission and reception of the radio frequency (RF) signals of the radar system, of desired frequency range, bandwidth, radiation pattern, beam-width, impedance, directivity, gain, standing wave ratio (SWR) and polarization
3) To design and explore new type of antenna suitable for the purpose of the problem, other than the existing antennas
4) To design a radar processor on a printed circuit board (PCB) for analysing radar return signals and the processing system for the transmission and reception of the RF signals
5) To test, analyse, learn and articulate the performance and operation of designed TWIR system

III. FEASIBILITY OF TWIR IN RF SPECTRUM

The primary reason for the increase in cost of imaging radars is due to the operation of device in spectrums where very few massively commercialized devices are based. Noting this, we decided to build the TWIR in the RF spectrum. Before venturing ahead, we needed a model for understanding how the penetration of RF through a concrete wall takes place. This feasibility modelling was done and simulated on CST Microwave Studio.

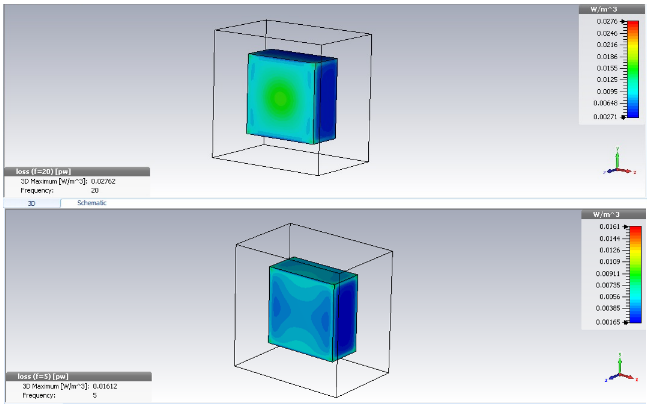


Fig. 1: A comparison of RF penetration through a concrete wall at 20GHz and 5GHz respectively

From Figure 1, its clear that the RF penetrated deeper when the frequency was 5GHz as opposed to 20GHz since the greater area of shades of dark green and yellow in the first sub-figure indicate higher power loss. This observation is also supported by the expression for *skin-depth*.

$$\delta = \sqrt{\frac{2p}{2\pi f \mu}} \tag{1}$$

Where δ denotes the *skin-depth(m)*, p denotes the *resistivity(Ω.m)*, f denotes the *frequency(Hz)* and μ denotes the *permeability(H/m)*. Therefore, as frequency increases the skin-depth decreases vis-vis the penetration depth of the impinging RF wave decreases.

With these results at hand, we decided on using the C-Band for our TWIR system. Figure 1 proves that the higher the frequency in the RF spectrum the lower the penetration depth and because the C-Band being the WLAN 5GHz band has massively commercialized devices working in this band which implies that VCO's, Mixers and PLL's to name a few, in this band will be extremely inexpensive compared to other bands.

IV. VIVALDI AERIAL

The Vivaldi Aerial [1][3] developed by P Gibson in 1979 is one of the most used antennas in phased array TWIR systems. This is primarily because of their easy construction, the laterally flat structure implies stack-ability and they are broad-band. In Frequency-modulated continuous-wave (FMCW) systems, the range resolution is determined by the bandwidth of the TWIR system. Larger the bandwidth available, greater is the range resolution. Since Vivaldi antenna operates over a large bandwidth, all these factors make it one of the most used antennas for TWIR.

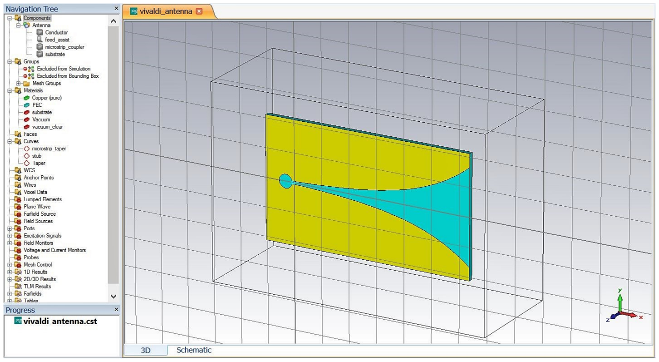


Fig. 2: Modeling a Vivaldi Aerial in CST MS

Its characterized as a travelling wave antenna with end-fire radiation pattern and as with most travelling wave antennas, its gain depends on the length of the structure. Since Vivaldi antenna for industrial purposes are manufactured on expensive substrates such as Rogers which offer a tightly controlled relative permittivity to accurately design the antenna hence a trade-off between cost and gain is reached. Therefore, to use the Vivaldi antenna in a TWIR system would imply that we achieve either low cost and low gain or high cost and high gain which defeats our purpose of making the device inexpensive.

The taper width which defines the opening rate of the exponential slot is given by the expression

$$Y = Ae^{pX} \tag{2}$$

The narrow channel of the slot line binds the energy of the travelling wave in a sort of guiding manner similar to those offered by wave-guides. This implies that shorter the taper-width more is the energy concentrated in the slot. Equation 2 defines the general expression for designing Vivaldi Antenna. Y defines the half separation width (m), X defines the length (m) and p the magnification factor which defines the beam width, with 3dB beam width taken as 50. The expression used by us to design the antenna is

$$Y = 0.7e^{0.05X} \tag{3}$$

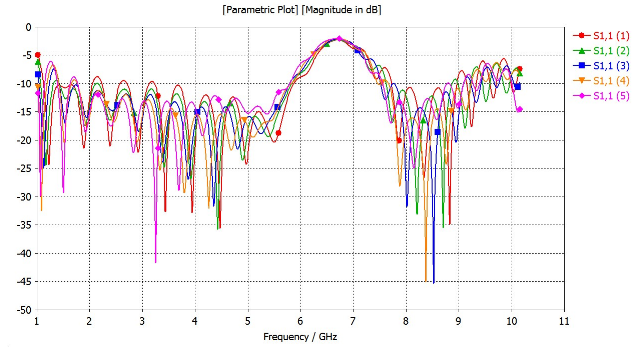


Fig. 3: S-Parameter Variation With Taper Width

The maximum opening width is given by the expression

$$2Y = \frac{c}{f_o\sqrt{\epsilon_r}} \tag{4}$$

Where c is speed of EM wave (m/s), fo is the center frequency(Hz) and ϵ_r is the dielectric constant of the substrate (F/m). Substituting the values, gives us Y as 14.85mm which is used to find X as 74.956mm. From Equation 3, its clear that the taper width influences primarily the directivity of the antenna since the opening rate "p" defines both the tapering and the magnification factor. Therefore, the variation in S-Parameter with taper width is very minimal giving rise to nearly identical responses as indicated by Figure 3. The microstrip to slot line transition [4][5] was designed to feed the slotline. For improving bandwidth to multiple octaves, the slotline and microstripline were terminated using radial stubs.

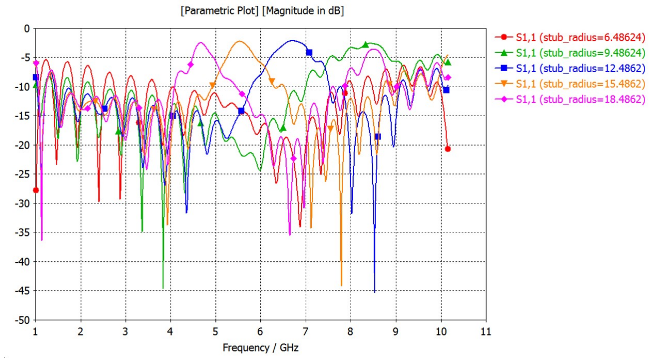


Fig. 4: S-Parameter Variation With Stub Radius(mm)

The stub radius defines the matching in the micro-stripline to slotline feed, changing its radius shifts the bandwidth in which this feed is most resonant. Stub radius is nominally chosen to be one-quarter wavelength which implies that increasing it should decrease the frequency where the response is resonant. From Figure 4, the response concerning stub radius “18.462mm” is shifted left towards lower frequencies when compared to the other variations as expected.

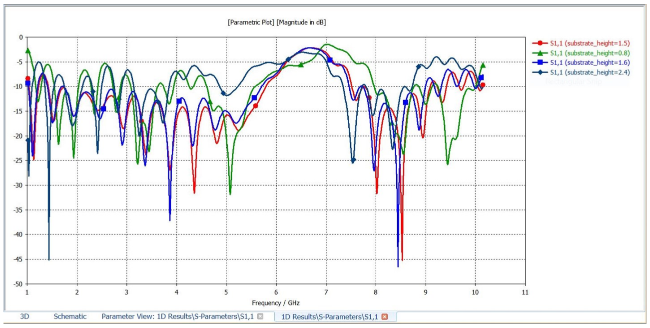


Fig. 5: S-Parameter Variation With Substrate Height

A two-layered copper clad board essentially consists of copper on the top and bottom layers and a dielectric-medium sandwiched in-between. In essence, this setup is exactly similar to that of a capacitor wherein the capacitance is inversely proportional to the distance between the plates or in this case the substrate height. Therefore, variation in the substrate height changes the capacitance and hence the bandwidth of the antenna response. Consequently, too small or too large a substrate height quells bandwidth as observable from Figure 5. The S-Parameter belonging to the substrate with height 1.5mm fares the best for the chosen frequency range.

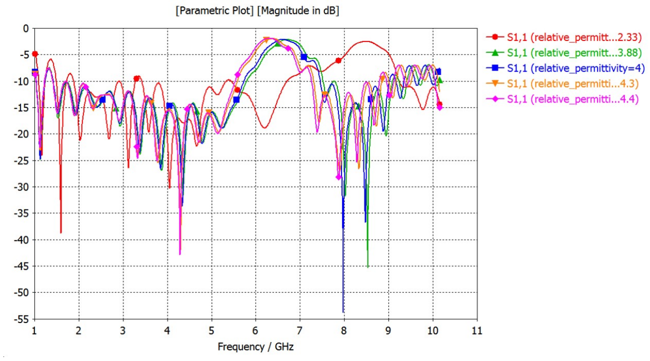


Fig. 6: S-Parameter Variation With Relative Permittivity

The relative permittivity of the antenna contributes most to the ability to miniaturize an antenna. Higher relative permittivity in general implies smaller antennas. We observe from Figure 6 that unless these changes are substantial, the response of the Vivaldi Aerial does not change much with change in relative permittivity.

From these simulations we chose to use FR4 substrate with relative permittivity 4.3 and substrate thickness 1.6mm. The final manufactured Vivladi Aerial was tested at *Raman Research Institute, Bengaluru* and Figure 7 illustrates the observed S-Parameter variation with frequency.

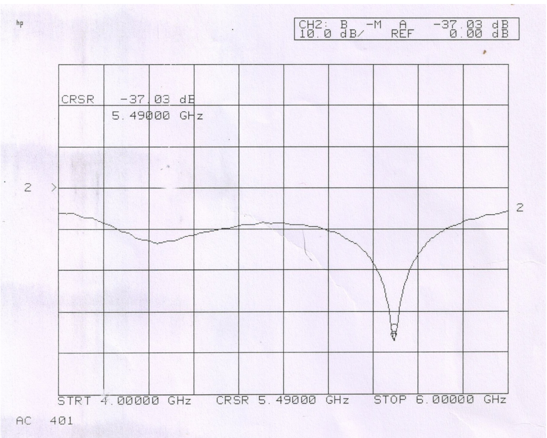


Fig. 7: S-Parameter of the manufactured Vivaldi Antenna tested at Raman Research Institute

Owing to the lack of standardization in FR4 manufacturing, the relative permittivity of the procured boards can vary substantially from the values considered during the designing process. Fortunately, in our case, the manufactured antenna performed better than the simulated case as is evident from Figure 8 below. However, the shift in resonant frequency is clearly observable. This could render the antenna un-usable in most cases but having predicted such variations, we had designed the system to be usable throughout the entire C-Band.

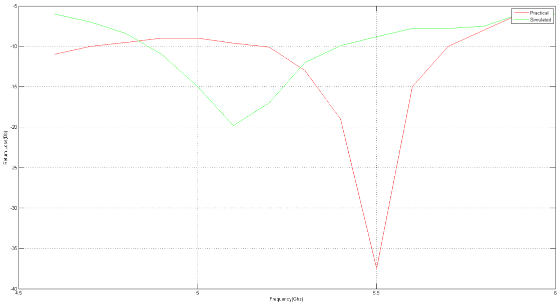


Fig. 8: Comparison of S-Parameter in Manufactured and Simulated cases

V. HARDWARE IMPLEMENTATION

The radar processor PCB design is split into primarily three parts. The first part deals with the power supply unit which is tasked with delivering the power free from any ripples. The second part deals with the RF portion which is tasked with the chirp generation and hetero-dyning. The third and final part deals with sampling, transfer of samples and on board processing.

The board does not consist of any dedicated ground or power planes but for most purposes layer 1 and layer 2 can be considered as ground and power plane respectively even though signals are routed on all four layers. Upon invoking the command to initiate the sweep, the on-board processor writes the content of the fractional-N PLL* which generates voltage steps. These steps are fed to the voltage controlled oscillator (VCO)* which generates the corresponding chirp. A part of

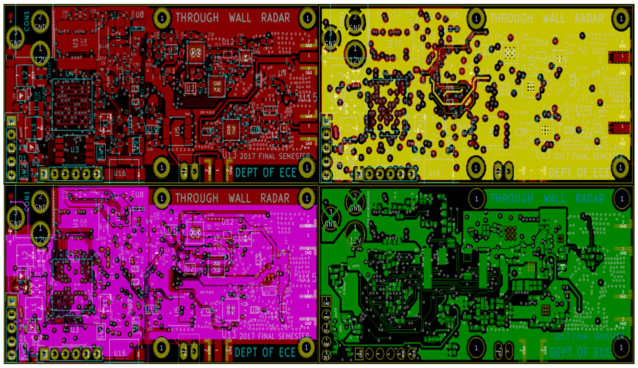


Fig. 9: The 4 layers of the Board. Top Layer, Layer 2, Bottom Layer and Layer 1 Clockwise from the Top.

this chirp is fed back to the PLL to lock the signal whereas the other part is fed to the power amplifier. The output of the power amplifier is fed to a 14 dB coupled line coupler for distributing power between the signal used for transmission and signal used for local oscillator (LO)* drive. The LO drive is fed into a 1:1 balun* to convert the single ended signal to double ended as per the mixer* requirement and in-order to minimize common mode noise.

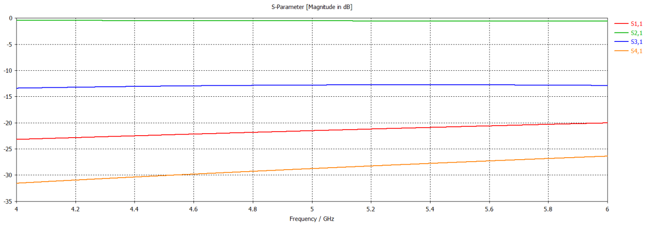


Fig. 10: S-Parameter of the 14dB Coupled Line Coupler

On the receiving side, the received signal is fed to a two stage low noise amplifier* and then passed through a 1:1 balun followed by to the mixer. The mixer being active prevents the need for an amplifier stage following the mixer. The intermediate frequency (IF) output is passed into a high pass filter (HPF)* and then sampled. The samples are sent to the computer over universal serial bus (USB)* by the processor which are then filtered using Hanning window and an FFT of the filtered output is taken to predict the existence of a target and the range to it. An optional delay-line canceller is also present for removing stationary objects.

An optional IF out* has been added in case the on-board ADC* should not work or a better external ADC is available to sample the IF. The microstrip traces used to route the RF signals have *mitered bends* [6][7] which help in reducing the capacitance introduced by 90 degree bends, thereby preserving the original impedance on the microstrip trace. The first problem faced while implementing the PCB design was the choice of substrate. FR4 could not be used since we had faced issues regarding the reliability of the information supplied to us about the substrate specification by the manufacturer. Rogers and other industry standard substrates normally used for C band and above are quite expensive. The substrate we decided on using is ISOLA 185HR which is documented for usage from 1 GHz upto 10 GHz. It has a dielectric constant of 3.88 and a loss tangent of 0.0235 at 5 GHz. Hence, it proved to be suitable for implementing the design.

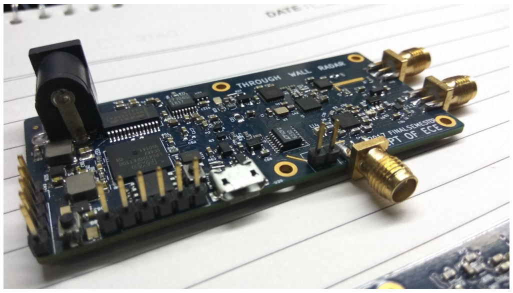


Fig. 11: The TWIR Processor Board

VI. Test Results and Discussions

Fig. 12: The TWIR System using the new antenna "Frustum Fed Antenna" and a Parabolic Reflector to improve gain

TWIR systems typically require very high gain in-order to precisely locate targets in the $\theta - \phi$ span. But as seen under the discussion in Vivaldi Aerial that gain can be improved only if the size of the antenna itself is increased which increases the cost. To remove this issue, we created a hybrid of Conical Horn and Cylindrical Waveguide Antenna which we christened the "Frustum Fed Antenna". Figure 12 shows the Frustum Fed Antenna used in conjunction with Parabolic Reflector to improve the gain.

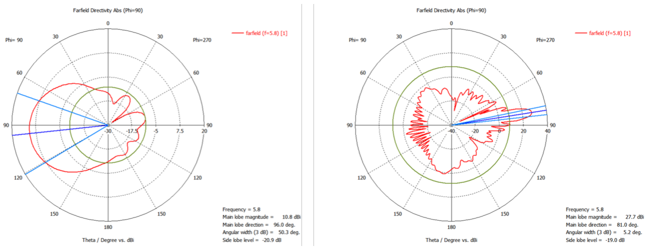
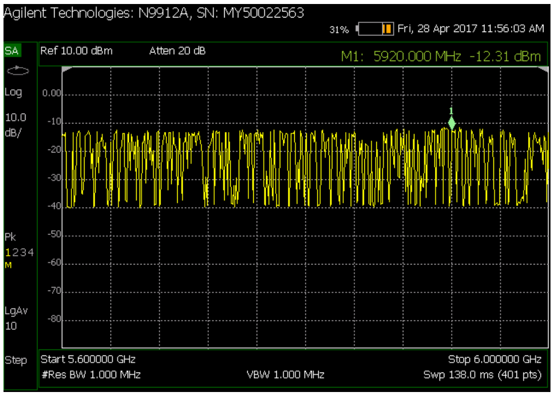


Fig. 13: Improvement in Directivity upon using a Parabolic Reflector

Figure 13 shows the improvement in directivity upon using the Parabolic Reflector.

In-order to test if the board was indeed working as desired, the TX output was connected to a spectrum analyzer and transmitted the FMCW wave while keeping the RX terminated.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Stop 6.000000 GHz
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VBW 1.000 MHz
Swp 138.0 ms (401 pts)

Fig. 14: The FMCW Sweep observed in the Spectrum Analyzer

With the transmission part working, we tested the receive part by placing the TWIR system behind a 4cm thick wall and walking towards the wall on the opposite side.

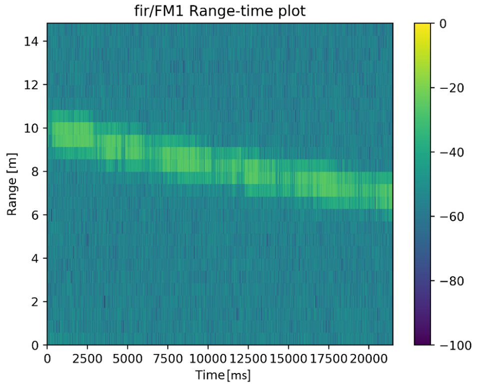

Fig. 15: The TWIR system correctly detecting our position as we walk towards the wall

The smearing observed in the receive plot (Figure 15) we believe is due to the lack of multi-path rejection functionality on the board.

VII. FUTURE WORK

Since TWIR is an emerging topic of research there is a huge scope of improvement possible for our design. Some of the possible future work includes

- Implementation of phased array system to control beam widths electronically and to replace the bulky Parabolic Reflector.
- Improved gain Frustum Fed Antenna for better detection.
- Facility to differentiate human beings from other moving objects based on the observed periodicity of the micro-Doppler features.
- Add multi-path rejection functionality to remove smearing in the receive plot.

VIII. CONCLUSION

A through wall imaging radar (TWIR) was successfully built along with the antennas and the software and gave satisfactory results. A new type of antenna was designed for the purpose of through wall detection. The new Frustum Fed Antenna provided better results compared to its counterpart antennas and is also a low cost antenna thereby satisfying our objective of building a low cost TWIR system.

ACKNOWLEDGEMENT

We are grateful to Head of ECE department of PESIT, Head of ECE department IISc and faculty of RRI for the provision of all necessary facilities and continuous encouragement throughout this project.

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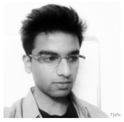

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