A Simple Bow-tie Slot Antenna for FMCW Radar Application

by Michael Moon

Abstract -- This paper presents an approach to designing a broadband antenna for radar applications. Specifically, the antenna in this paper was designed for a frequency modulated radar, which requires high bandwidth and moderate directivity. Several different geometries were attempted to obtain the final antenna which is resonant in the 2.4GHz ISM band, with fractional bandwidth of 26% and a directivity of 7.5dBi. A prototype of the final design was fabricated and tested, with reasonable agreement found between simulated and actual data.

I. Introduction

A bowtie antenna is a common adaptation of the more general biconical antenna. It is a broad bandwidth antenna made from two triangular pieces of metal, each fed at its tip. The bowtie antenna is a natural extension of the dipole antenna, and shares a similar radiation pattern and polarization. The difference lies in that while the resonant frequency of a dipole antenna is solely specified by its length, the bowtie antenna is specified by the angle between the two triangles. Since the variation in distance between the two edges of the bowties will change as you move up or down the triangle, there exist many resonant frequencies for which the antenna can radiate. An infinite bowtie would have infinite bandwidth, since the antenna would look the same at any wavelength.

A slot antenna is an antenna that uses a slot cut into the radiating surface that it is mounted on. Babinet's principle as applied to antenna theory states that the radiation pattern and impedance of an antenna to its dual are linearly related. Their impedances follows the following relation:

$$Z_{metal}\, Z_{slot} = \eta^2/4,$$

With η being the intrinsic impedance of free space[1]. Figure 1 shows a standard bowtie antenna on the left, with the slotted version of the same antenna on the right. The only difference between them will be their impedance, as explained above, and their E and H fields will be reversed. This means that while the standard antenna may have been vertically linear polarized, its complementary antenna will be horizontally polarized.

With any slot antenna there will be a large backlobe present. The main beam of the antenna will be broadside to the surface it is mounted on, but considerable radiation will be emitted (and received) through the substrate and out

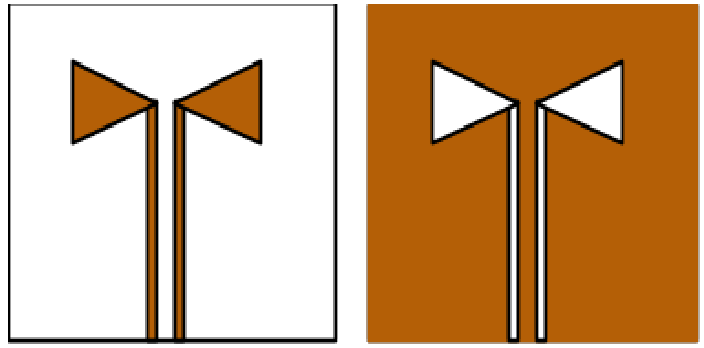

Fig 1: Generic Bowtie Antenna and its complement (fed by transmission lines)

the back. In a radar application this is not desirable, as the antenna should only radiate in the direction it is intended. While there are several solutions to this problem, the one explored in this project is to mount the slot antenna in a quarter wavelength(λ/4) spaced cavity[2]. In general, a cavity spaced at λ/4 behind the slot will add about 3dB of gain to the frequency its spaced at. This happens because the wave will travel λ/4, reflect off the wall of the cavity (adding another λ/2 shift), and then return λ/4, adding constructively to the main lobe. The design tradeoff is that while it will add constructively at one frequency, it will add destructively at other frequencies, and will negatively affect the broad bandwidth needed for an FM radar[3].

Bandwidth is directly proportional to the resolution that an FM radar can provide. This is because the received signal is mixed with the outgoing signal, which itself oscillates over a large bandwidth. The difference in frequencies can be used to determine the distance to an object using the following formula:

$$R = \frac{c \times |\Delta f|}{2 \times (df/dt)}$$

Where c is the speed of light, Δf is the measured change in frequency, df/dt is the frequency shift per unit time, and R is the distance to the target. Resolution is related to the peak to peak frequency deviation by:

$$\Delta R = \frac{c}{2 \times BW}$$

So it can be seen that the bandwidth of the radar is inversely proportional to the achievable resolution, and therefore a broad-band antenna is desirable.

II. Antenna Design and CEM Simulations

Simulations were performed for this project using EMPro, a computational electromagnetics suite which solves Maxwell's Equations numerically to simulate antenna radiation patterns. More specifically, the finite element method was used to solve for the far fields for the different antenna geometries, as well as to find return loss and VSWR. Both return loss and VSWR are measures of how much well matched an antenna is to it's source. A good antenna will radiate most of the power sent to it, while a poor antenna will reflect considerable power back at the sender.

The initial design consisted of a co-planar bowtie slot antenna mounted on a Polyflon PTFE substrate (εr = 2.05), fed by a 50Ω CPW transmission line. Other key properties of the substrate included a 0.062" height, and copper thickness of 35μm. A teflon based substrate was chosen for durability and tunability. Teflon is not as fragile as ceramic based substrates, but is still soft enough to cut with a sharp knife. Since many geometries were built and tested, it saved time to quickly enlarge slots with a utility knife.

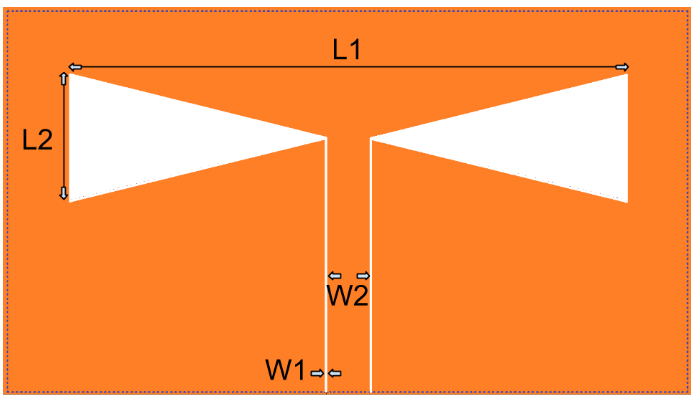

Fig 2: Antenna Schematic

Dimensions of the antenna can be seen in the schematic in figure 2. Using the formula from Shanmugananthan, L1 = $1.6\lambda/\sqrt{\varepsilon r}$ = 139mm, L2 = $0.5\lambda/\sqrt{\varepsilon r}$ = 43mm[3]. W1 = 10 mils and W2 = 400 mils were found using a standard formula for 50Ω CPW feeds[4]. The dotted line signifies the edge of the copper, and is spaced approximately (L2)/2 from the top and sides of the antenna.

S Parameters define the input-output power relationship between different ports in an electrical network. As an example, if we have two ports in a network, then S21 is a measure of the power transferred from port 1 to port 2. S11 in our case represents the amount of power reflected from the antenna. If S11 equals zero, this means all of the power is reflected, and none is radiated. If S11 is -10dB, this means 90% of the power is radiated and only 10% is reflected. An antenna is considered matched where its S11 is less than or equal to -10dB[6].

Once our design was created in EMPro, simulations were run and numerous revisions were made. See figure 3 for an image of the antenna in EMpro.

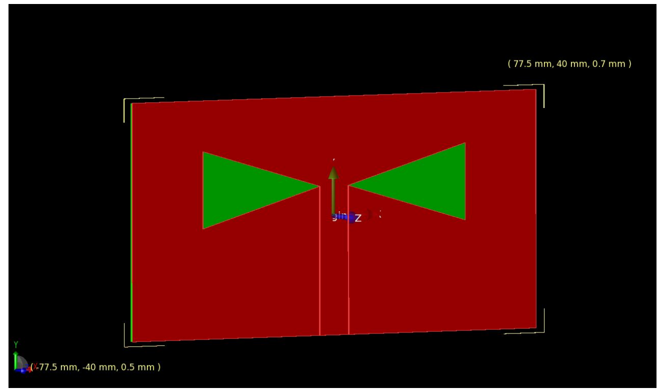

Fig 3: Antenna in EMPro

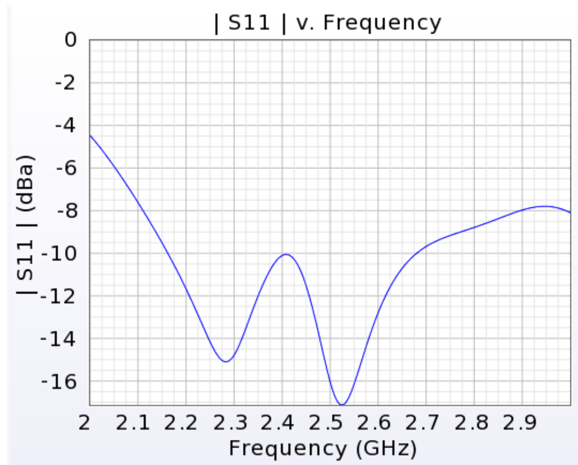

Figure 4: S11 vs Frequency, simulated in EMPro

The S11 in figure 4 shows a fractional bandwidth of (2.7-2.15)/2.4 = 23%, which classifies the antenna as broadband. The antenna impedance is shown in figure 5, and good 50Ω matching can be seen from 2.1GHz to 2.7GHz. Ideally the resistance (real part of the impedance) should be exactly 50Ω across the band, while the reactance (imaginary part of impedance) should be 0Ω.

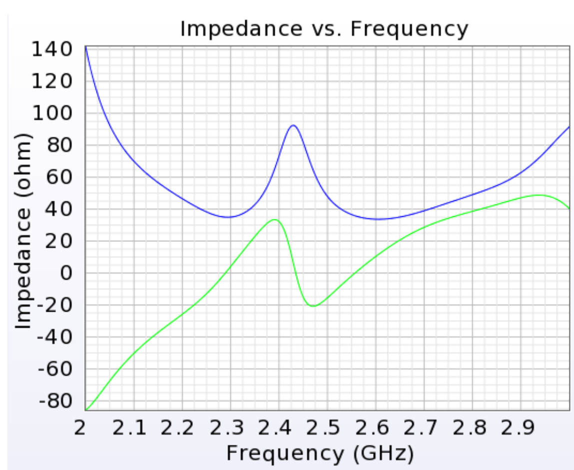

Fig 5: Simulated antenna impedance. The top curve is resistance, bottom curve is reactance.

Simulations also showed a directivity of approximately 4dBi broadside to the antenna. The unit dBi signifies how much more directive an antenna is than an isotropic radiator, or one that radiates equally in all directions. For the intended application a directivity of greater than 2 was desired, so this antenna more than met the directivity criterion.

II. Antenna Fabrication and Bench Testing

The antenna was fabricated using the same materials as simulated, a Polyflon PTFE substrate with copper cladding. Gerber files were created from the EMPro simulation which were then used by a milling machine to cut the slots into the substrate. One practical issue worth noting is that real microwave boards aren't perfectly flat, so in certain areas the slots had to be cut deeper than others to remove all of the copper. The author recommends keeping the substrate packaged and on a flat surface until right before milling.

A standard 50Ω SMA was soldered onto the antenna feed, and tested with a network analyzer. Preliminary results showed larger than expected bandwidth, as seen in figure 6, with a 33% fractional bandwidth. Experimental testing showed large front and rear lobes as expected, with minimal radiation endfire to the antenna.

Note also the spur at 2.4GHz in both the simulation and the experimental results: while not ideal, the spur is still below the 10dB line, so the antenna still resonates at that frequency. The spur is most likely due to the copper not being symmetric on the top and bottom of the slots.

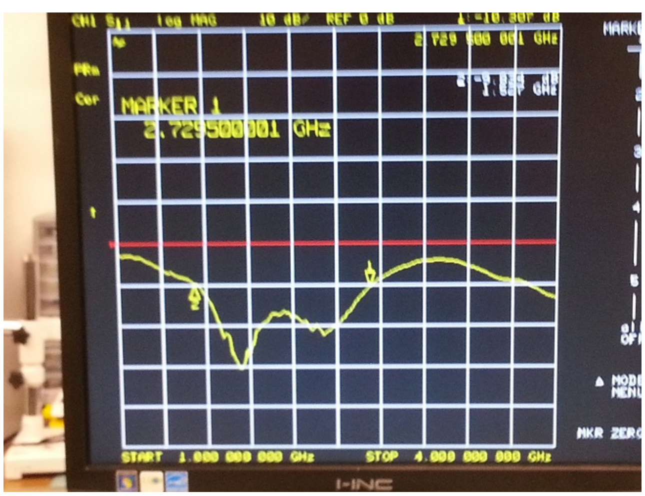

Fig 6: S11 vs Frequency on network analyzer. The far right marker is at 2.73GHz, and the left marker is at 1.9GHz

Figure 7 shows the finished antenna being tested with a network analyzer. Lacking an appropriately sized SMA or a balun to feed the antenna, a matched transmission line was run behind the antenna to the SMA to balance the currents.

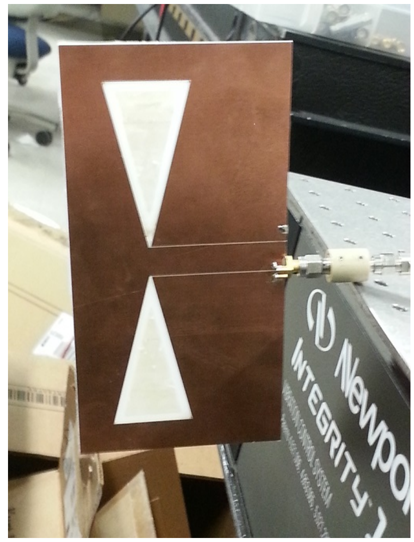

Fig 7: Finished antenna

III: Cavity Fabrication and Testing

A cavity now needed to be constructed, and both circular and rectangular structures were considered. Ultimately, for ease of prototyping and cost, a rectangular box structure was chosen. See figure 8 for the cavity along with the antenna. Spacing was determined to be 3 cm, which is approximately λ/4 at 2.4GHz.

The cavity was built using copper tape and cardboard. Another design that worked well was circular, and consisted of two pizza plates (one lined with copper) taped together, with the antenna mounted on top.

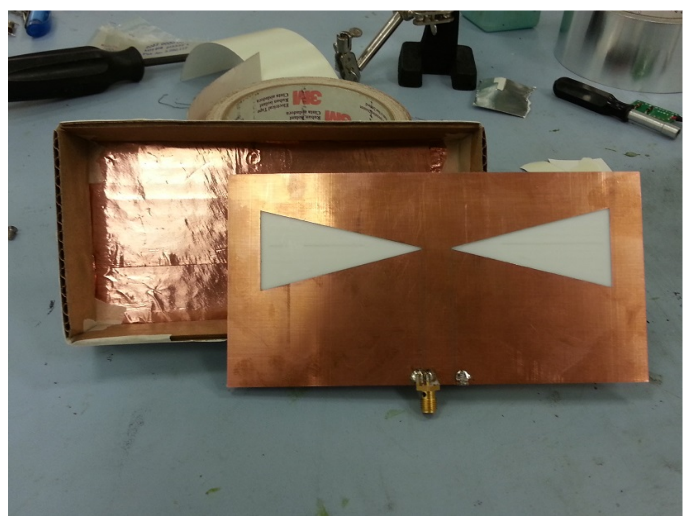
Fig 8: Finished antenna with Cavity

Additional testing was done with a network analyzer and showed reduced fractional bandwidth of 26%, but much better return loss (-35dB) at 2.4GHz, the center frequency of the radar. See figure 9 for the network analyzer results, and figure 10 for the antenna built into the cavity.

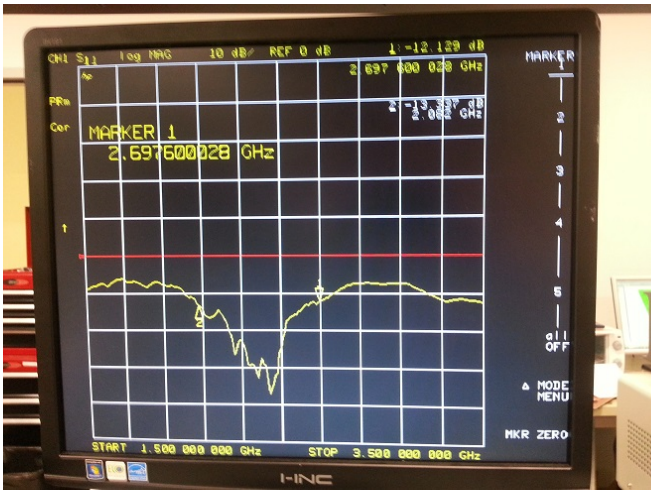

Fig 9: S11 vs Frequency with Attached Cavity

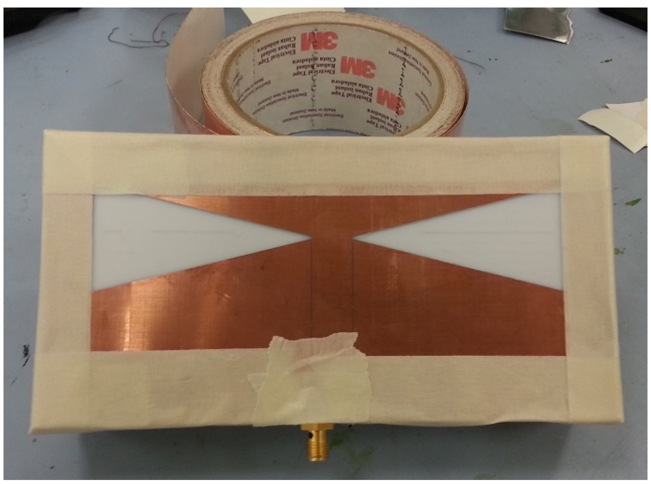

Fig 10: Finished Antenna attached to Cavity

III: Anechoic Chamber Testing

Formal testing of the antenna took place in an anechoic chamber. An anechoic chamber is a room designed to completely absorb electromagnetic radiation. Cleaner results can be found testing in an anechoic chamber because there is no external radiation incident on the antenna: after calibration, the precise radiation pattern of the antenna can be determined. Figure 11 shows the antenna on a rotating pedestal in an anechoic chamber.

A transmit antenna will radiate directly at the antenna under test(AUT), over a broad range of frequencies. The AUT will rotate 360 degrees so a complete radiation pattern can be determined. The gain of the antenna can also be determined in the anechoic chamber, in terms of S21 parameters, which tells us how much of the power radiated from a normalized transmit antenna is successfully received by the AUT.

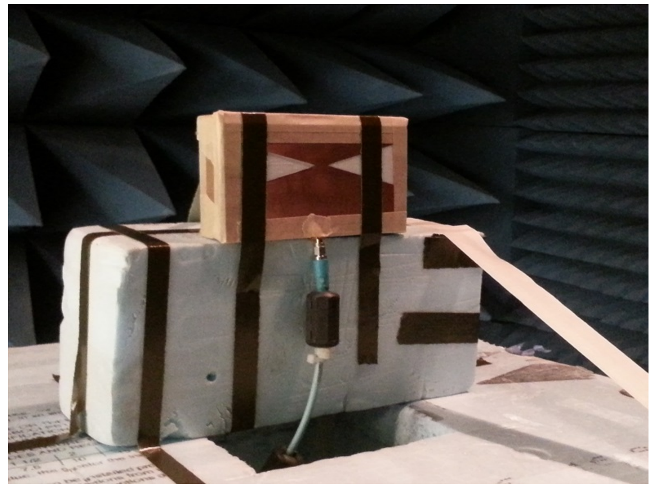

Fig 11: Antenna in an anechoic chamber

The gain of the antenna was experimentally determined to be an average of 7.5dBi from 2-2.8GHz. 0 dBi is the gain of an isotropic antenna, or one that radiates equally in all directions. A gain of 3dBi means an AUT has twice as much gain as an ideal isotropic radiator at that frequency. See figure 12 for the gain of the antenna. Therefore our AUT absorbs over 4 times as much power as an ideal radiator.

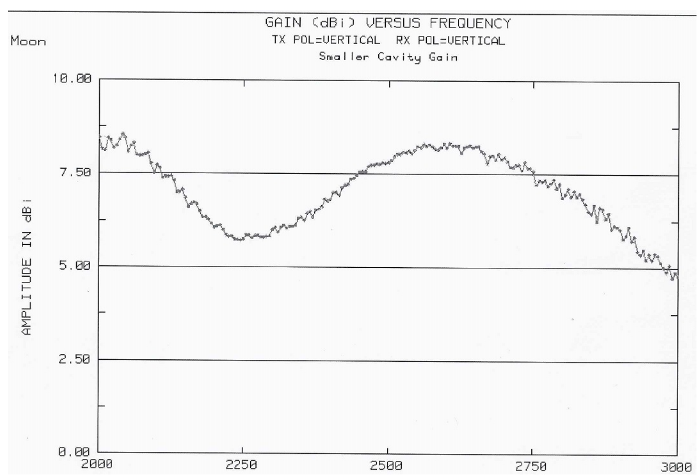

Fig 12: Gain vs Frequency

The radiation pattern of the antenna was found for 10 discrete frequencies evenly spaced between 2 and 3GHz. The patterns were very similar, except at the very high end where a large null in the front of the antenna became very pronounced. See attached figures 13, 14 and 15 for the radiation patterns at 2.0, 2.4, and 3.0 GHz.

The final test that needed to be performed was isolation between two antennas. For this test an additional antenna needed to be constructed, and both would need to be tested simultaneously. Ideally we would want to see around 60dB of isolation between transmit and receive

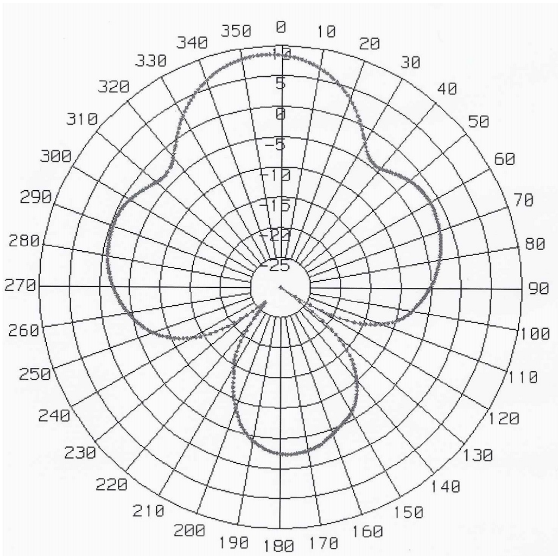

Fig 13: Radiation Pattern at 2.0 GHz

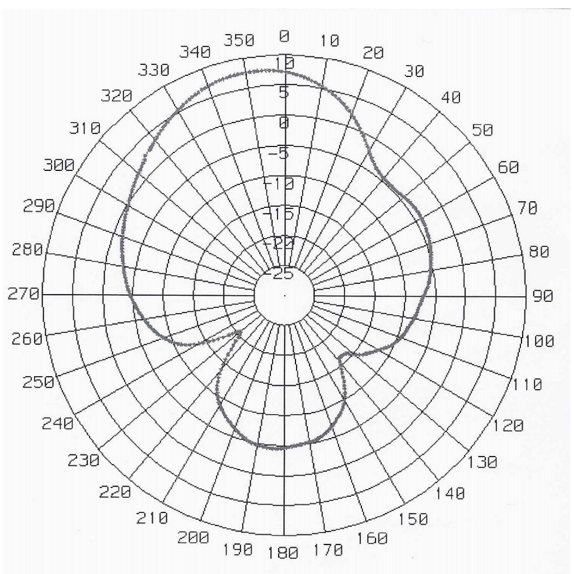

Fig 14: Radiation Pattern at 2.4GHz

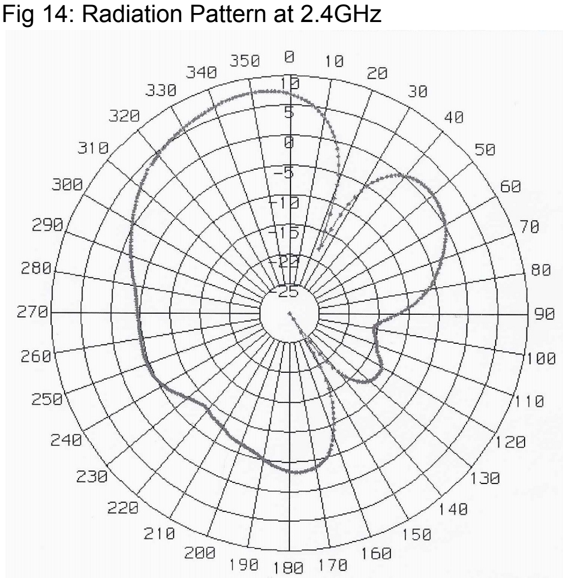

Fig 15: Radiation Pattern at 3.0GHz

antenna in a radar system, but based on the size of the sidelobes seen in the radiation patterns, that won't be achieved with these antennas.

To test isolation, a network analyzer was set up and the two ports were connected together through an RF barrel. S21 was measured and then normalized to zero level: with the two ports directly connected together, 100% of the power went from port 1 to port 2. Once normalized, anything less than 100% would show as negative decibels, and so isolation could be measured between the antennas. As can be seen in figure 16, a quick bench test was performed to see how much power was transferred from one antenna to the other, and the results can be seen in figure 17: approximately -30dB of isolation existed. This meant that 0.1% of the power exiting Antenna 1 was picked up by Antenna 2.

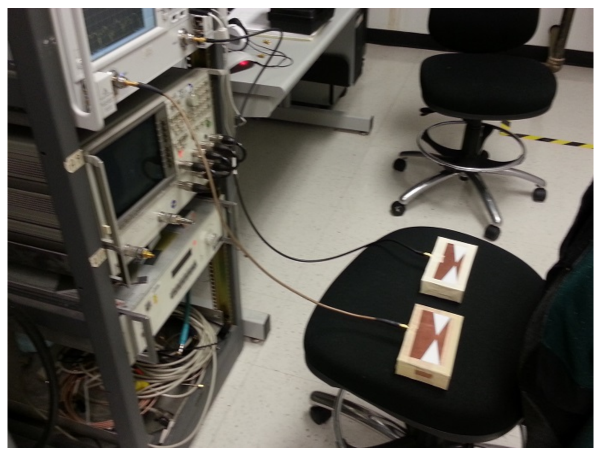

Fig. 16: Antenna Isolation Bench Test

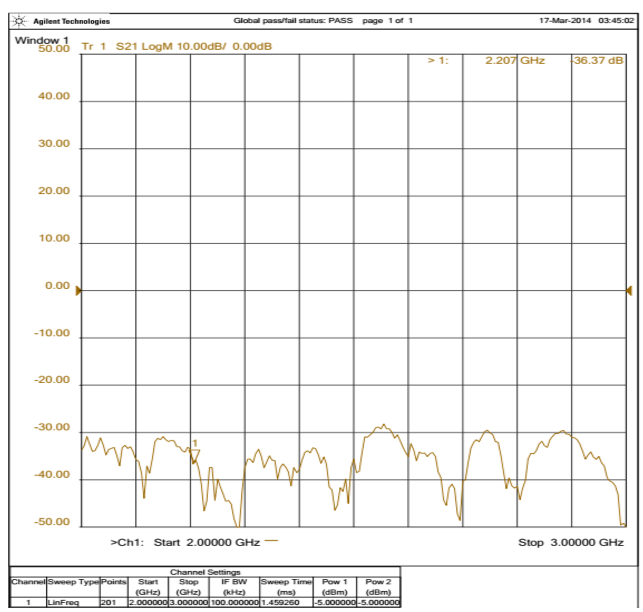

Fig 17: Isolation Measurement with Network Analyzer

Possible solutions to the isolation problem include putting absorbent materials between the antennas, or placing them further apart. It will take testing with the actual system to see just how negatively the crosstalk effects overall system performance.

III: Conclusion

The goal of this project was to design a low-cost, directive and broad-band antenna. To that end the project was a great success, as the antenna meets or exceeds all required specifications, and could be used as a real radar antenna. Lots of practical experience was gained by the author in design for test principles, computational simulations, and practical antenna testing. The most important thing was that the simulated results closely matched the experimental testing, which serves as both a sanity check and reinforces faith in software simulations.

Some problems included properly feeding the antenna, building a suitable cavity, and minimizing crosstalk between antennas. The feed problem will be addressed in the next iteration of the antenna, as a tapered transmission line could be designed that would be small enough for a standard SMA to span. Several different cavities were tried, but for rapid prototyping combined with cost and durability, stiff cardboard lined with conductive tape served perfectly well. A suitable microwave absorber was found and ordered to further reduce RF leakage between antennas, and this could also be implemented in a future system.

Acknowledgements

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