Frequency-Modulated Continuous-Wave Radar Rangefinder and Mapper

6.013 Class Project: Final Report

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***Abstract*—This report discusses the design and implementation of a continuous-wave radar design using ramped frequency modulation. The emphasis of the project is the analysis and design of microstrip transmission lines used for power coupling and impedance matching. The device contains both a microstrip directional coupler and Wilkinson power combiner.**

I. Introduction & Motivations

Electromagnetic waves are reflected to some degree by abrupt changes in index of refraction such as the surface of an object in air [1]. This reflection can be measured and used to determine many properties about the object. In a radar, the distance, velocity, size, and many other properties of the object can be determined. Several different modulation and measurement techniques exist for different purposes. This project will focus on the use of a sawtooth-modulated transmitter and a directional transmitter antenna. A reflected wave will be received, amplified, and mixed with a reference signal split off from the transmitter. A single-ended diode mixer is used to detect the envelope of the resulting beat frequency. The envelope is then low-passed to smooth it and can be detected with a scope or ADC on a microcontroller.

This approach has several benefits and drawbacks. One benefit of this design is that the beat frequency between the transmitted and received signals is much slower than the RF frequencies. This slow beat signal can be measured and interpreted using an inexpensive microcontroller. Another benefit of this approach is the simplicity. It requires few components, with no carefully-locked or precisely-phased fast signals. One drawback of this radar approach is that a moving object will cause a doppler shift of the returning signal. This frequency change will have the same effect as having a greater distance to the measured object. Another drawback of this approach is the difficulty of designing microstrips to split and mix RF signals.

II. Approach

The architecture of our radar is depicted in Figure 1.

The transmission stage consists of a VCO, power amp, splitter, and cantenna. The VCO receives a low frequency sawtooth which is used to modulate a 2.4GHz carrier frequency. The RF is fed through a power amplifier, and then split between the transmitting antenna and the mixer. The splitter is a directional coupler created by placing two microstrips close together so that their electric fields couple and EM radiation traveling along one microstrip couples into the other.

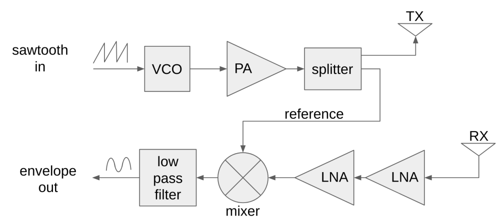


Fig. 1: Radar Architecture

The receive stage consists of a Yagi antenna, two cascaded LNAs, a mixer circuit, and a lowpass filter. The signal from the Yagi is amplified twice and then mixed with the reference signal split off from the transmit stage. Our mixer consists of a Wilkinson power combiner and a diode-RC envelope detector. The power combiner sums the RF reference and received signals. These signals only slightly differ in frequency, so their sum has a low-frequency beat tone, which is detected with the diode RC envelope detector. The beat frequency can then be directly measured with an ADC or oscilloscope.

Since the frequency is modulated, the speed of light delay of the round trip made by the transmitted signal will be different from the signal currently being transmitted. Mixing these two signals will create a beat tone envelope. Since the modulation signal is a sawtooth, the frequency of the envelope scales linearly in the distance the signal has to travel between the transmitter, the object, and the receiving antenna [2].

Assuming that the object the signal bounces off of is stationary, the beat frequency of the mixed signals divided by the rate of modulation (i.e. the slope of the sawtooth) gives the total round trip time of the transmitted wave. Using this round trip time, the distance to the object can be calculated.

III. Safety

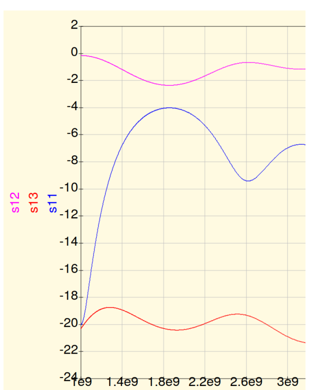
Since we are working at 2.4GHz, we need to comply with federal RF transmission regulations. 2.4 GHz is the standard frequency for wireless internet, so it is a fairly busy band. The limit for effective power transmission at 2.4 GHz is 4 watts and the limit for direct power to the antenna is 1 watt [6]. This level of power is not particularly dangerous, and we will not be using any line power.

IV. Results

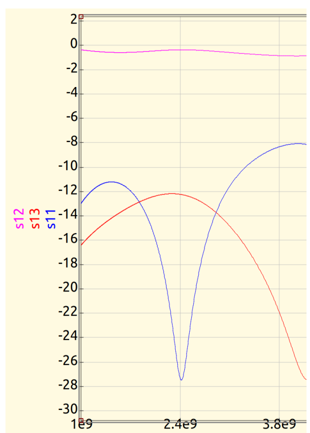
A. Design of Microstrip Directional Coupler

The design and simulation of the directional coupler was done in Qucs (Quite Universal Circuit Simulator). Qucs has a calculator for coupled microstrips, so in order to design the strip, all that was needed was the substrate parameters and the desired even and odd impedances of the coupler. In order to split off about 1/20th of the power (i.e. coupled power should be about -14dB), the required even and odd impedances are 61Ω and 40Ω (respectively) [4].

Our initial prototype of the coupler didn't take into account the input impedance of the terminations of the coupled strips, so the 50Ω microstrip connections to each port of the coupler were poorly matched and the coupler didn't couple power. After discovering this, simulated scattering parameters which confirmed the poor match (shown in Figure 2a).



(a) Poorly matched coupler



(b) Well matched coupler

Fig. 2: Magnitude (dB) of S11 (reflected), S12 (through), S13 (coupled) vs. Frequency (GHz)

After adjusting the widths and lengths of the microstrip connections to the coupler, we achieved much better performance, as shown in Figure 2b.

We created a milled prototype (shown in Figure 3) that had scattering parameter performance comparable to that of the simulation (at least for S12 and S13). We measured S12 and S13 to be -7dB and -17dB (compared to -1dB and -14dB simulated). We also measured an S11 of -10dB, which is not ideal but likely in part due to poor connection between our SMA cables and the prototype PCB.

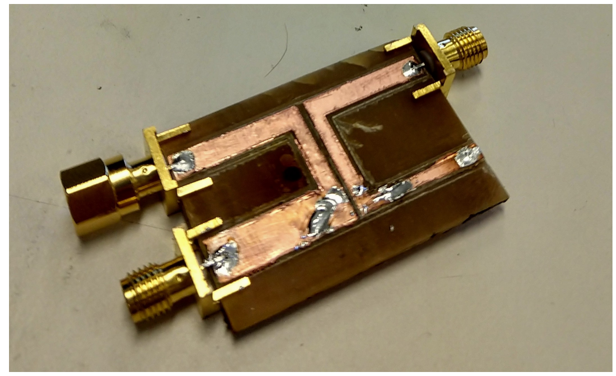


Fig. 3: Milled directional coupler prototype

Design of Wilkinson Power Combiner

Our mixer consists of a diode-RC envelope detector and a summing combiner constructed from a Wilkinson splitter/combiner.

The advantage of the Wilkinson combiner is that it is impedance matched at 50Ω and has good isolation between input ports. This isolation is achieved because of the half-wavelength long loop which shifts the phase of an input wave by 180 degrees. Combined with a resistor between the input ports, this architecture will dissipate all power that attempts to exit any port other than the output [5].

Our first milled prototype (shown in Figure 4) achieved 25dB isolation between the two inputs, with peak isolation around 35dB at around 3.5GHz, indicating that the half-wavelength section was a little too long for the substrate properties we had. It's transmission coefficient was -6dB, which is not spectacular given that the Wilkinson combiner architecture is reciprocal (so transmission should be -3dB) [5].

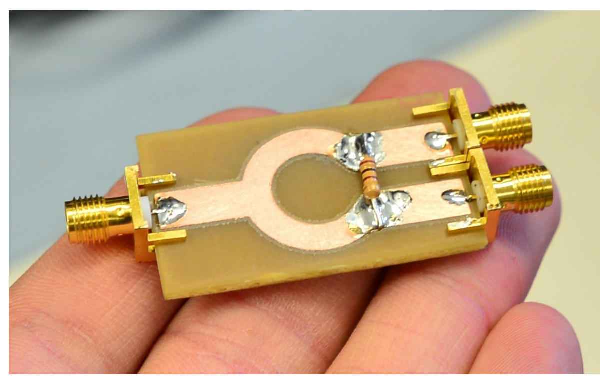


Fig. 4: Wilkinson combiner prototype

Design of Yagi Antenna

A Yagi-Uda antenna consists of a driven element, a reflector, and multiple director elements. The radiation from the driven element induces current in the directors which resonate and re-radiate in-phase radiation, which results in constructive interference along the axis of the antenna, creating a highly directional main-lobe. The reflector re-radiates out of phase, resulting in a null behind the driven element which increases the gain along the main-lobe [7].

We used the instructables guide in [8] to build our antenna. After some tuning of director placement and length, we achieved a reflection coefficient below -30dB.

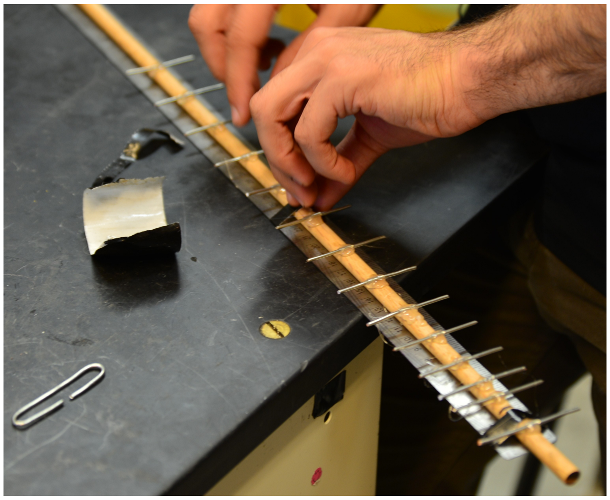


Fig. 5: Yagi antenna

Design of Cantenna

Our initial failed cantenna prototype placed a quarter-wavelength dipole antenna element about quarter-wavelength from the back of a normal-size soup can, which resulted in extremely low transmitted power at 2.4GHz.

Through testing, we found that almost the entirety of the RF power was reflected at 2.4GHz, and only at higher frequencies was power delivered to the antenna. This indicated that the can was too small to support the fundamental mode of the 2.4GHz wave. The next cantenna (Figure 6) consisted of a far larger cookie tin, with a diameter large enough to support a 2.4GHz wave. Additionally, placing the dipole a quarter-wavelength from the back of the can results in an optimal forward wave assuming the other direction is perfectly open. Since the open end of the can is not perfectly impedance-matched to free space, some power is reflected. When this additional reflected wave is taken into account, the optimal location for the driving dipole is longer than quarter-wavelength from the back of the can by around 40% [9].

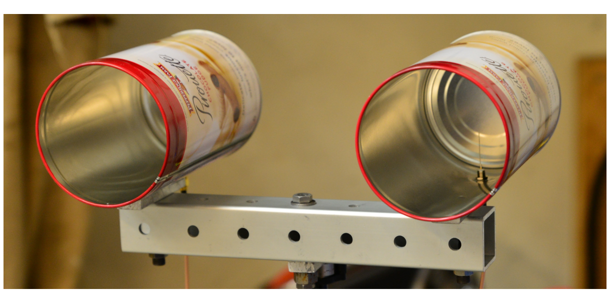


Fig. 6: Cantenna

Shifting the element slightly farther from the back of the larger can resulted in a reflection coefficient of -17dB, indicating that the cantenna was radiating most of the RF power. In order to couple even more power, a quarter-wave transformer could be used to match the 50 ohm amplifier to the 30 ohm cantenna impedance.

Integration and Testing

After mounting our components on a custom, etched PCB (Figure 7), we attatched the VCO tuning voltage to a function generator and the envelope detector output to an oscilloscope.

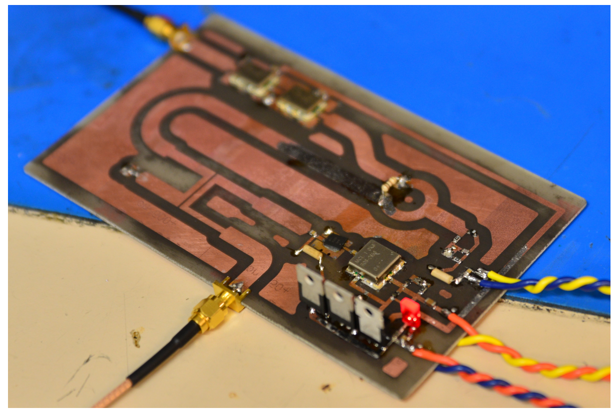


Fig. 7: Final board

We built a metallic foil corner-cube to use as a concentrating reflector to maximize the reflected power off of our target object and attempted to measure the beat tone at different distances of the cube.

Our initial plan to modulate our transmit frequency did not work — there was no detectable beat tone for a stationary corner-cube. However, our RF circuitry still worked; if we moved the corner cube we measured a beat tone that varied with the speed of movement. This means that the power coupler, combiner and envelope detector all function correctly. A scope readout of beat tone frequency is shown in Figure 8.

Most likely, our VCO did not produce RF frequency-modulation that was suitable for producing a measurable beat-tone.

Fig. 8: Beat frequency from moving corner-cube

References

[1] L. Daniel, K. P. O'Brien, K. Kolodziej, "6.013 Electromagnetics & Applications" MIT, Undergraduate Course, Spring 2019.

[2] W. Christian, "Frequency-Modulated Continuous-Wave Radar", radartutorial.eu.

[3] AFAR Comunications, "FCC Rules for Unlicensed Wireless Equipment operating in the ISM bands", afar.net.

[4] S. Jahn, "10dB Directional Coupler Design", qucs.sourceforge.net.

[5] L. Berens, "Design, Analysis, and Construction of an Equal Split Wilkinson Power Divider", Marquette University.

[6] FCC 1 C.F.R. §15.247 (2017).

[7] H. Yagi, S. Uda, "Projector of the Sharpest Beam of Electric Waves", Tohoku Imperial University, 1926.

[8] Biotele, "Easy to Build WIFI 2.4GHz Yagi Antenna", instructables.com.

[9] R. Karekare, "Building the Cylinder (Can) Waveguide", wikarekare.org.