Electromagnetic Fields and Waves
2 Meter Antenna Lab Project: Folded Dipole

Daniel J. B. Clarke
Gildart Haase School of
Computer Sciences & Engineering
Fairleigh Dickinson University
Email: danieljbclarke@gmail.com

I. Objective

The objective of this lab exercise is to become familiar with one type of antenna, the folded dipole, and with the design, construction, and outdoor pattern testing of the antenna. In an effort to understand the process of building an antenna as it is done in industry, real world standards and constraints are emphasized including cost, time, and other manufacturing constraints. In this lab, we design an antenna to work optimally on the Amateur Radio 2m band at a frequency of 146.5MHz. The antenna should have a gain of greater than 10 dB front to back ratio and a VSWR$< 2:1$. The antenna budget should not exceed $50.

II. Discussion

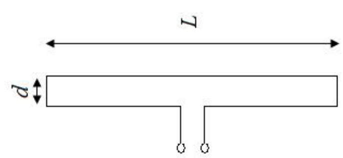

Fig. 1. Folded Dipole Antenna Theoretical Schematic [1]

The folded dipole antenna, illustrated in Fig. 1, typically has a $d << L$ and behaves like two parallel short circuited transmission lines of $l = \frac{L}{2}$, Z depends on the impedance of a transmission line of length $\frac{L}{2}$ [1].

$$\overbrace{Z_t}^{\text{Transmission Line}} = jZ_o \tan\frac{\beta L}{2}$$

$$\overbrace{Z_A}^{\text{Antenna Input}} = \frac{4Z_t \overbrace{Z_d}^{\frac{\lambda}{2}\text{ dipole}}}{Z_t + 2Z_d}$$

When fed from the center, the folded dipole resonates best at half-steps of wavelength ($0.5k\lambda, k \in \{1, 2, \dots\}$). According to [1], in the case where $L = \frac{\lambda}{2}$,

$$Z_A = 4Z_d = 4(70\Omega) = 280\Omega$$

A. Radiation Pattern

Because the antenna behaves as two parallel half-wave dipole antennas, the radiation pattern is evidently of the same form [1].

$$E_\theta = \frac{j\eta I_0 e^{-jkr}\cos\left(\frac{\pi\cos\theta}{2}\right)}{2\pi r\sin\theta}$$

$$H_\phi = \frac{E_\theta}{\eta}$$

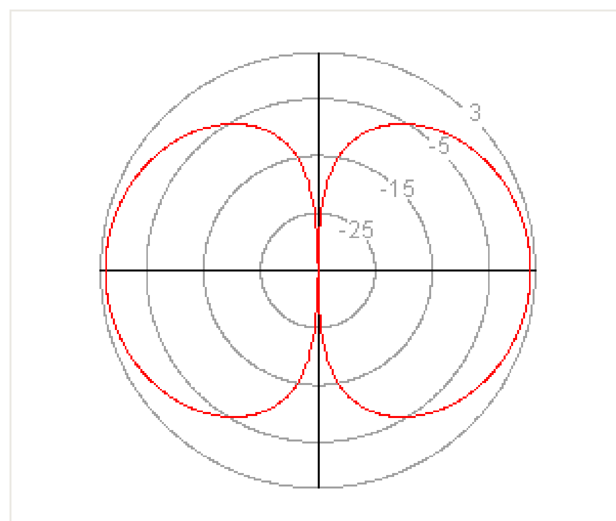

Fig. 2. Folded Dipole Antenna Radiation Pattern [2]

Shown in Fig. 3, the radiation pattern has a 2.15dB directivity where the Half Power Beamwidth (HPBW) is at 78°.

B. Balun

Because our antenna's impedance is mismatched with the feed line which is expected to be 75Ω, it is necessary to create a Balun (Balance Unbalance) that will match the two impedance for optimal resonance, one such simple Balun well known for the folded dipole is the 4:1 Coax balun [3].

$$Z_i = \frac{Z_A}{4} = \frac{280\Omega}{4} = 70\Omega \approx 75\Omega$$

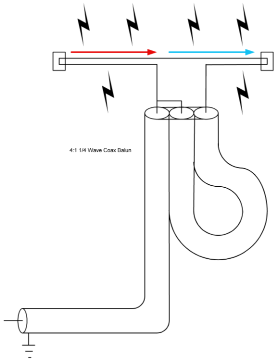

Fig. 3. 4:1 Dipole Half-Wave Balun Schematic [4]

In general, a Coax Balun can be constructed to satisfy the following equations: [3]

$$\overbrace{Z_c}^{\text{Balun}} = \sqrt{Z_o Z_i}$$

$$\overbrace{Z_o}^{\text{Antenna}} = \frac{Z_c^2}{Z_i}$$

$$\overbrace{Z_i}^{\text{Input}} = \frac{Z_c^2}{Z_o}$$

The impedance in the Balun is then used to construct one of the proper length. We'll use the well known 4:1 Balun as it is adequate. It calls for a $\frac{\lambda}{2}$ length cable of coax.

III. Design

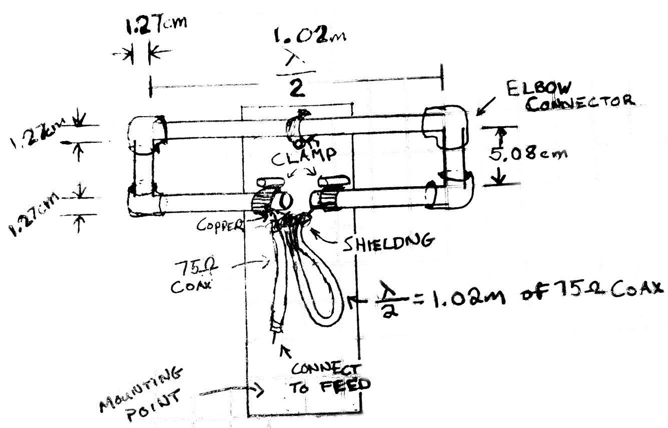

Fig. 4. Antenna Schematic

IV. Equipment

A. Tools and Devices

- Metal Cutting Saw
- Metal Sander
- Screwdrivers
- Wire Cutters
- Transmitter
- Antenna Analyzer
- Spectrum Analyzer

B. Materials

- Wood Nail
- 1.02m, 2 x 0.50m, 2 x 0.05m 0.5" EMT conduit (Home Depot Model # 101543), $2.55 for 10' (3.045 m)
- 4 x 0.5" EMT inside corner pull elbow (Home Depot Model # 14605), $4.95 ea, $19.80
- 1.02m, and transmitter feed Coax, 75Ω, (Home Depot Model # RG6-OPP-06W), $4.97 for 6' (1.829 m)
- 2"-by-4" 8' wood block (Home Depot Model # 161640), $2.95
- 0.5" EMT 1-Hole Strap (Home Depot Model # 96151), $0.86 for 4-pack
- 2 x 0.5" hose repair clamp (Home Depot Model # 6712595), $0.98 ea, $1.96
- Tape (Optional)

Total: **$33.09**

V. Procedure

A. Building

1) Buy the parts indicated in the list of equipment (Section IV).
2) Cut the 10' EMT into 1.02m, 2 x 0.5m, and 2 x 0.05m lengths of pipe.
3) Join the lengths of pipe with the corner pull elbows as indicated in the design (Section III).
4) Mount the $\frac{\lambda}{2}$ pipe to the top of the 2"-by-4" wood block using the EMT 1-Hole strap.
5) Cut the 6' Coax into 3 segments: 0.404m on each end (leaving the connectors) and 1.02m in the middle (no connectors).
6) Strip the 1.02m wire at the ends, exposing about 2" of the inner copper and shielding (separate from each other). Do the same to the exposed side of one of the 0.404m wires.
7) Connect all the shielding together and with an EMT hose repair clamp, strap the copper of one end of the 1.02m wire together with the copper of the 0.404m wire and one side of the open $\frac{\lambda}{4}$ pipe. Strap the other side of the 1.02m wire to the other pipe with the other hose repair clamp. See feed-point in the schematic for clarity (Section III).
8) The antenna is finished; tape the coax if necessary and proceed to test the antenna.

B. Testing

1) Mount the antenna onto a rotatable vertical mast, connecting a feed line coax to the connector on the coax on the antenna.
2) Begin transmitting a signal to the antenna.
3) Using the antenna analyzer, measure and record VSWR, R, and X at frequencies around your antenna. Measure at frequencies 143.5 to 148MHz in steps of 0.5MHz.
4) Using a spectrum analyzer, measure the received signal strength as the antenna is rotated 360°. Measure in intervals of 20°.

5) Using the results, generate plots of VSWR, R, and X vs frequency and of the power at different responses (see Section X-A).

VI. Results

TABLE I
VSWR, R, and X

f (MHz)	VSWR	R (Ω)	X
143.5	2	68	43
144	2.1	53	43
144.5	2	50	41
145	1.8	43	30
145.5	1.7	41	26
146	1.4	42	15
146.5	1.2	43	10
147	1.1	48	7
147.5	1.3	55	12
148	1.6	73	22

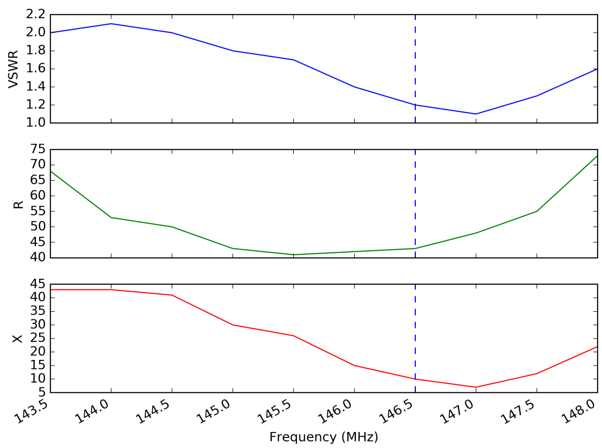

Fig. 5. Plot of VSWR, R, and X vs Frequency

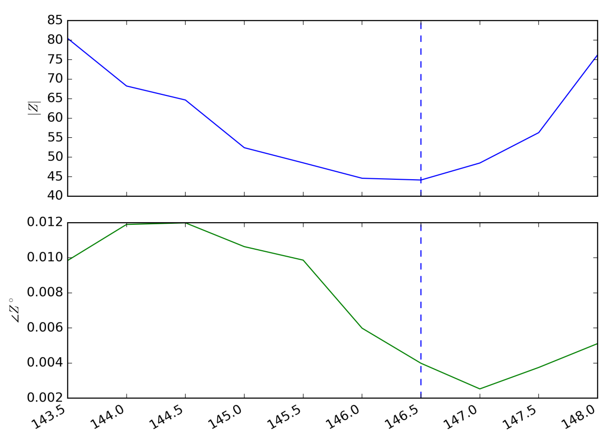

Fig. 6. Plot of VSWR, R, and X vs Frequency

TABLE II
Measured Power

Angle (°)	Power (dBm)	Power (dB)	Relative (dB)
180	-18	12	-3
160	-23	7	-8
140	-29	1	-14
120	-30	0	-15
100	-30	0	-15
80	-27	3	-12
60	-24	6	-9
40	-22	8	-7
20	-32	-2	-17
0	-32	-2	-17
-20	-30	0	-15
-40	-30	0	-15
-60	-24	6	-9
-80	-22	8	-7
-100	-25	5	-10
-120	-15	15	0
-140	-20	10	-5
-160	-22	8	-7
-180	-27	3	-12

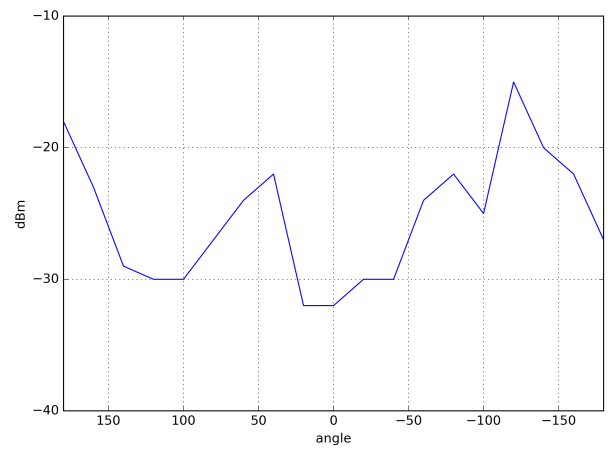

Fig. 7. Cartesian plot of measured power (dBm) vs Azimuth angle

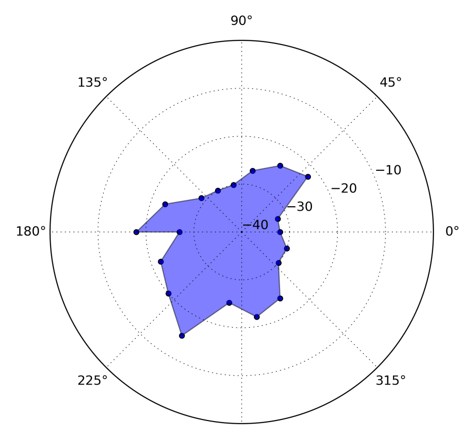

Fig. 8. Polar plot of measured power (dBm) vs Azimuth angle

VII. Analysis

A. VSWR, R, and X

The VSWR was expected to remain below 2:1, at 146.5MHz, our antenna achieved a VSWR of around 1.2 meeting the spec easily. While no spec was provided for the load impedance, at around 45Ω it

B. Power Output

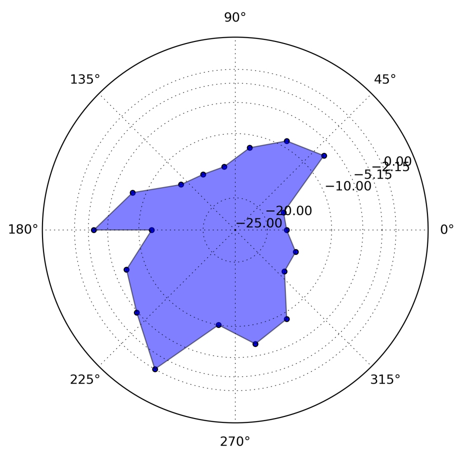

Fig. 9. Polar plot of measured power relative to max power received vs Azimuth angle

The front to back power ratio is quite a bit greater than 10dB front to back at about 15dB meeting the spec.

Subtracting the gains by the minimum (normalizing), the polar graph can be analyzed. Directivity was expected to be 2.15dB, so 0 (the highest reading) should be the max gain at 2.15dB. -3dB-2.15dB would be HPBW which should be located at 78°.

The antenna's peaks were at $44°$ and $240°$ rather than $90°, 270°$, $90° - 78° = \pm 12°$. At $\approx \pm 12°$ from the peaks, we do see that it goes down to the $-5.15dB$ line corresponding to the half power point at $240°$. While at $44°$, the peak is much smaller in that direction, and it seems to fall off way too fast in the clockwise direction.

During the testing, we experienced a signal close to our testing frequency, potentially contributing interference. The discrepancy seen at the two points measured at $180°$ further suggests that another signal was contributing to the excess or diminished gains over time (180 was measured first and last).

VIII. Future Directions

Given different constraints on the problem including more time and more money a number of improvements could have been made to the antenna to improve performance.

A. More Testing

With cross-talk during testing, more testing could have allowed us to eliminate data points caused by interference.

B. Antenna Direction

Because of the instability of the antenna, it was not feasible to position it properly (with the plane of the antenna perpendicular to the ground). Another block of wood would have been enough to position it properly for re-measurement.

C. Spacing optimization

The distance from the $\frac{\lambda}{2}$ element and the $\frac{\lambda}{4}$ elements was set at 2", one length of many that we planned to test. Given more time, we would try the antenna with both bigger and smaller lengths.

D. Adjustable Balun

A 4:1 Balun designed with a $\frac{\lambda}{2}$ length of 75Ω Coax line was used to get "close enough" to the 300Ω impedance expected on the antenna. A potentially better solution would be a Balun circuit with adjustable inductor and capacitors to best match the antenna with the line for optimal VSWR.

E. Pipe Diameter

While 0.5" EMT was used because of its availability, different diameters might prove to exhibit better results, given more money and time this path might be investigated.

IX. Conclusion

In this experiment we built and tested a folded dipole antenna for VSWR, load impedance, and directional power output at a frequency of 146.5MHz. With real world standards and constraints in cost, time, and manufacturability, we built the meter long antenna with $33.09 of purchased equipment, under $50 dollars, and ready tools achieving a VSWR of 1.2 at the desired frequency meeting the spec of $< 2 : 1$. With power output between -5dB and 10dB, the front to back ratio was 15dB meeting the spec of > 10dB.

References

[1] "The folded dipole antenna." http://www.antenna-theory.com/antennas/foldeddipole.php. Accessed: 2016-12-01.

[2] "Radiation pattern of vertical half-wave dipole; vertical section." https://en.wikipedia.org/wiki/Dipole_antenna#/media/File:RadPatt-dB.png. Accessed: 2016-12-01.

[3] "Coaxial balun by iϕqm." http://www.iw5edi.com/ham-radio/files/I0QM_BALUN.PDF. Accessed: 2016-12-01.

[4] "A folded dipole (300Ω) to coax (75Ω) 4:1 balun." https://en.wikipedia.org/wiki/Dipole_antenna#/media/File:Dipolehalfwavebalun.png. Accessed: 2016-12-01.

X. APPENDIX

A. Plot Scripts

Made in python, the following scripts generate plots to visualize the measurements attained in this experiment.

Fig. 10. Cartesian Angular Plot Script

```
df = pd.read_csv('azimuth_db.csv',
                 index_col=0)
ax = df.plot(legend=False)
plt.grid('on')
ax.set_yticks(list(range(-40,0,10)))
plt.ylabel(df.columns[0])
plt.show()
```

This script creates a Cartesian plot of the angular power measurements.

Fig. 11. Polar Plot Script

```
df = pd.read_csv('azimuth_db.csv',
                 index_col=0)
df.index *= np.pi / 180
ax = plt.subplot(111, projection='polar')
ax.scatter(df.index, df['dBm'])
ax.fill(df.index, df['dBm'], alpha=0.5)
ax.set_yticks(list(range(-40,0,10)))
plt.show()
```

This script plots the angular power measurements onto a polar plot.

Fig. 12. Relative Power Polar Plot Script

```
df = pd.read_csv('azimuth_db.csv',
                 index_col=0)
df.index *= np.pi / 180
df['dB']=df['dBm']+30
df['dBr']=df['dB']-df['dB'].max()
ax = plt.subplot(111, projection='polar')
ax.scatter(df.index, df['dBr'])
ax.fill(df.index, df['dBr'], alpha=0.5)
ax.set_yticks(list(range(-30,0,5)))
plt.show()
```

This script plots the angular relative power measurements onto a polar plot.

Fig. 13. VSWR, R, X Plot Script

```
df = pd.read_csv('vswr.csv', index_col=0)
ax = df.plot(subplots=True,
             sharex=True,
             legend=False)
for a,c in zip(ax, df.columns):
  a.set_ylabel(c)
  a.axvline(146.5, linestyle='--')
plt.xlabel('Frequency (MHz)')
plt.show()
```

This script plots VSWR, R, and X in relation to frequency; it includes an indicator for the frequency of interest in the lab 146.5MHz.

Fig. 14. Impedance Magnitude and Angle Script

```
df = pd.read_csv('vswr.csv', index_col=0)
df['$|Z|$']=(df['R']**2+df['X']**2)**(1/2)
df['$\\angle Z^\\circ$']=np.arctan2(df['X'], df['R
df = df[['$|Z|$','$\\angle Z^\\circ$']]
ax = df.plot(subplots=True,
             sharex=True,
             legend=False)
for a,c in zip(ax, df.columns):
  a.set_ylabel(c)
  a.axvline(146.5, linestyle='--')
plt.xlabel('Frequency (MHz)')
plt.show()
```

This script plots magnitude and angle of the impedance given that $Z = R + jX$.