Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

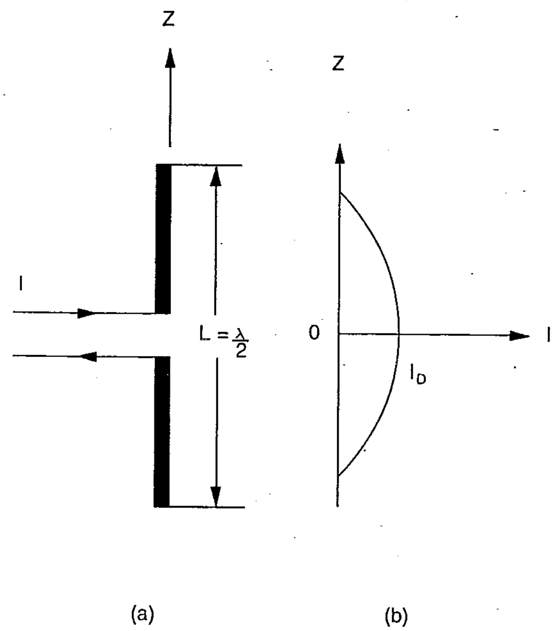
EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the characteristics of the half-wave folded dipole antenna and with the use of baluns for impedance transformation.

DISCUSSION

Description of the half-wave folded dipole

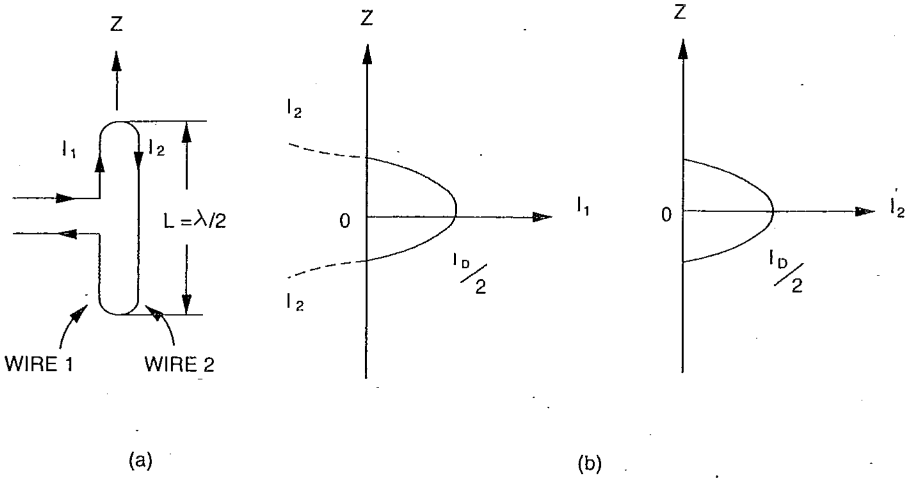
The **folded dipole** antenna consists of two parallel dipoles connected into a narrow wire loop. Figures 1-41 and 1-42 illustrate the differences between a half-wave dipole and a half-wave folded dipole.



(a) physical configuration, (b) current distribution

Figure 1-41. The half-wave dipole

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns



(a) physical configuration, (b) current distributions

Figure 1-42. The half-wave folded dipole

In the half-wave dipole of Figure 1-41, the current is forced to zero at both ends of the dipole. The current distribution is sinusoidal with a maximum of I_D at the centre.

The current distribution on a dipole can be expressed as

$$I(z) = I_D \sin\left[\frac{2\pi}{\lambda}\left(\frac{L}{2} - |z|\right)\right], \quad |z| < \frac{L}{2} \tag{1}$$

where z and L are as shown in Figure 1-41.

The half-wave folded dipole of Figure 1-42 has the same sinusoidal current distribution on wire 1, except that the maximum value at the centre is $I_D/2$ instead of I_D. The sinusoidal current falls to zero at both ends of wire 1, then increases again as wire 1 turns into wire 2. The current goes through another maximum at the centre of wire 2.

The two current distributions on wire 1 and wire 2 of the folded dipole, added together, are the same as the current distribution on the half-wave dipole. The radiating power is also the same:

$$P_D = \frac{1}{2} Z_D I_D^2 = P_F = \frac{1}{2} Z_F I_F^2 = \frac{1}{2} Z_F \left(\frac{I_D}{2}\right)^2 \tag{2}$$

where P_D, Z_D, I_D are the power, impedance and current of the dipole, respectively

P_F, Z_F, I_F are the power, impedance and current of the folded dipole, respectively.

Consequently, the input impedance of the folded dipole is four times larger than that of the half-wave dipole, which is 73 Ω.

$$Z_F = (4)Z_D = (4)(73) = 292\ \Omega \tag{3}$$

Note: *Different authors quote slightly different values for the input impedance of the half-wave dipole, for instance, 70, 72, or 73 Ω. Consequently, the input impedance of the folded dipole is also quoted at different values from 280 Ω to 300 Ω.*

Impedance matching

For optimum power transfer, the source impedance must be equal to the load impedance. This is illustrated in Figure 1-43 for a simple circuit with a voltage source V_S, a source resistance R_S, and a load resistance R_L. Maximum power transfer occurs when $R_S = R_L$.

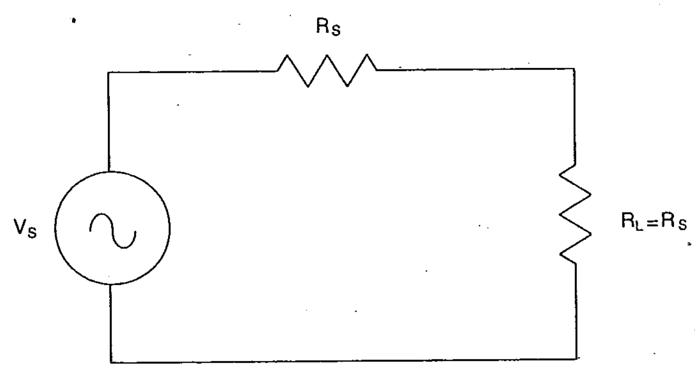


Figure 1-43. Matching source and load impedance for maximum power transfer.

For an antenna system, the same rule prevails. For optimum power transfer, the antenna impedance Z_{ant} must be equal to the transmission line or waveguide impedance Z_L, as shown in Figure 1-44.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

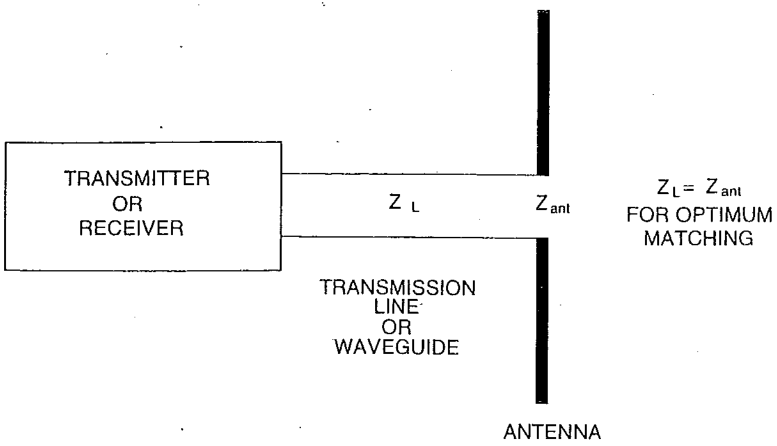


Figure 1-44. Impedance at transmission line and antenna junction

If the match between the transmission line and the antenna is not perfect, part of the power transmitted will be reflected back instead of being radiated by the antenna. In the case of a receiving antenna, part of the signal received by the antenna will not be forwarded to the receiver.

When there is an impedance mismatch, Equation (4) relates the power transmitted through the impedance junction to the power reflected.

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - \left|\frac{Z_{ant} - Z_L}{Z_{ant} + Z_L}\right|^2 \qquad (4)$$

where P_T is the power transmitted through the impedance junction
P_{Rfl} is the power reflected at the impedance junction
SWR is the voltage standing wave ratio (SWR = Z_{ant}/Z_L)

For instance, if there is a perfect match, $Z_{ant} = Z_L$ and there is no standing wave since SWR = $Z_{ant}/Z_L = 1$. In this case, there is no reflected power.

$$P_{Rfl} = \left|\frac{SWR - 1}{SWR + 1}\right|^2 = \left|\frac{0}{1}\right|^2 = 0 \qquad (5)$$

and all the power is transmitted.

In the case of a 73 Ω transmission line feeding into a half-wave folded dipole with four times the line impedance (4 × 73 = 292 Ω), a standing wave is produced and the SWR is

$$SWR = \frac{Z_{ant}}{Z_L} = \frac{4}{1} = 4 \qquad (6)$$

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - \left|\frac{3}{5}\right|^2 = 0.64 \qquad (7)$$

In this case, 64% of the power would be transmitted and 36% would be reflected.

This effect is not necessarily catastrophic (although it might be at high power levels), but it is undesirable. It would be preferable to obtain good impedance matching between the line and the antenna, as shown in Figure 1-45.

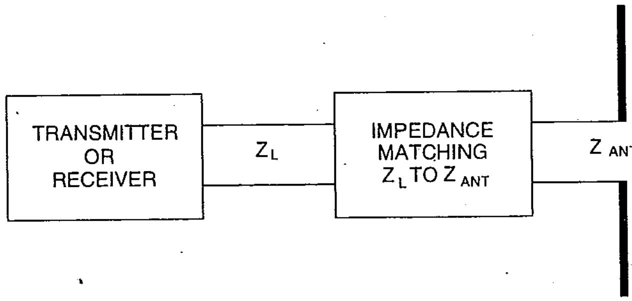


Figure 1-45. Impedance matching between transmission line and antenna

Connecting balanced to unbalanced transmission lines through a balun

A problem which is related to the problem of impedance matching is to connect a balanced antenna (such as a centre-fed dipole) to an unbalanced transmission line (such as a coaxial cable).

If the centre-fed dipole is connected to a balanced transmission line, such as a parallel-wire pair, the question of balanced to unbalanced connection does not arise.

If the centre-fed dipole is connected to a coaxial cable, however, the balance is upset. One side of the dipole is connected to the inner conductor while the other side is connected to the shield, and a current will flow on the outside of the shield. This current creates a field which cannot be cancelled by the fields from the current on the inner conductor, because of the shielding. Therefore there will be radiation from the current on the outside shield of the coaxial cable.

This problem can be resolved by using an extra length (λ/4) of coaxial cable as illustrated in Figure 1-46, connecting the outside shields together at a point λ/4 below the antenna terminals. A second current is then induced on the outside shield and the two currents cancel each other. This arrangement is called a **balun**, which is a contraction of "balanced to unbalanced."

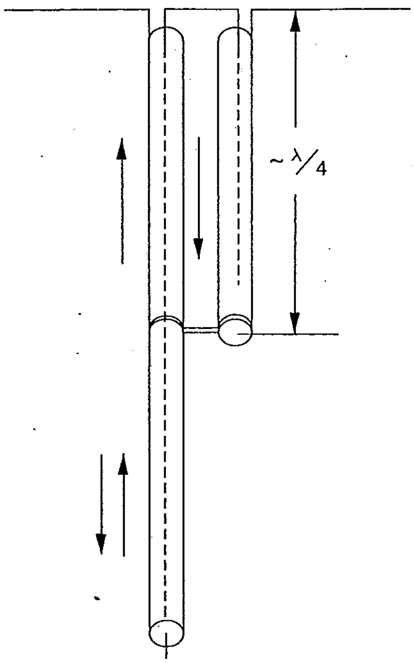


Figure 1-46. Balun for connecting a centre-fed dipole to a coaxial cable

The principle is that the λ/4 transmission line appears as an infinite impedance to the dipole and does not affect its operation. However, the current which flows on it balances the current which flows on the outside of the coaxial cable.

There are a number of types of baluns. The dipole connectors in the Antenna Training and Measuring System are equipped with baluns similar to that shown in Figure 1-46. There are also baluns which, in addition to a balanced-to-unbalanced connection, offer impedance transformation.

In the next section, you will study a half-wave folded dipole connected to a coaxial cable, in one case without a balun, and in the second case, through a balun which offers a 4-to-1 impedance transformation.

The Lab-Volt half-wave folded dipole

The Antenna Training and Measuring System includes a 1-GHz half-wave folded dipole. As shown previously, this type of dipole has an input impedance of 292 Ω.

The transmission lines used for connecting to the 1 GHz antennas in the Lab-Volt system are 50-Ω coaxial cables.

The Lab-Volt system offers two types of transitions from the 50-Ω coaxial cable to the 292-Ω folded dipole antenna, one without a balun and one with a "four-to-one" impedance transformation balun.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

Transition without a balun

Figure 1-47 illustrates a transition without a balun from a 50-Ω coaxial cable to a 300-Ω parallel wire pair balanced transmission line and then to the approximately 300-Ω half-wave folded dipole.

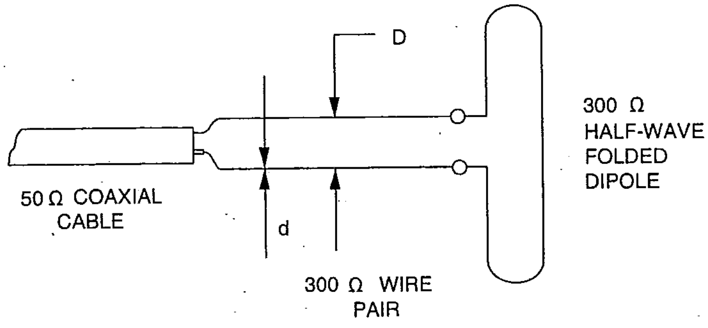


Figure 1-47. Transition without a balun from a 50-Ω unbalanced coaxial cable to a 300-Ω balanced wire pair and to a 300-Ω half-wave folded dipole

> **Note:** *The impedance of a parallel wire pair is a function of the ratio D/d, where D is the distance between the two wires and d is the diameter of each wire. For 300 Ω, D/d ≈ 6, for 75 Ω, D/d ≈ 1.25.*

In the case of Figure 1-47, due to the impedance mismatch between 50 Ω and 300 Ω, the SWR will be 300/50 = 6.

The relationship between the transmitted power P_T and the reflected power P_{Rfl} will be

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR-1}{SWR+1}\right|^2 = 1 - 0.51 = 0.49 \tag{8}$$

With perfect impedance matching, 100% of the power would be transmitted. In this case, however, only about 50% of the power will be transmitted. The other half will be reflected—a loss of 3 dB relative to the perfect impedance matching case.

Transition by a four-to-one impedance transformation balun

Figure 1-48 illustrates the transition from a 50-Ω coaxial cable to a 300-Ω half-wave folded dipole using a four-to-one impedance transformation balun. Folded dipole-balun assemblies may occasionally be connected to a 72 Ω coaxial cable such as RG-59U.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

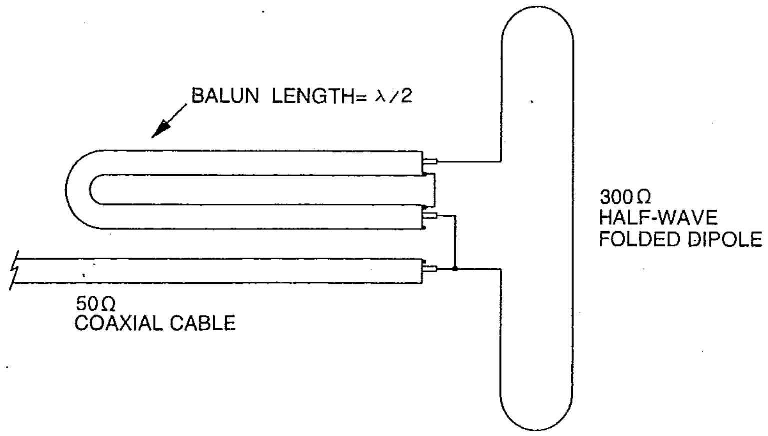


Figure 1-48. Transition from a 50-Ω coaxial cable to a 300-Ω half-wave folded dipole through a four-to-one impedance transformation balun.

Note that the four-to-one transformation is not quite ideal in this case. Ideally, a 6-to-1 impedance transformation would be required to go from 50 to 300 Ω.

Although imperfect, this four-to-one impedance transformation offers substantial improvement. The impedance transformer transforms the 300-Ω impedance into a 75-Ω impedance so that the impedance transition from the 50-Ω coaxial cable causes a SWR of 75/50 = 1.5

The relation between the transmitted and the reflected power is now

$$P_T = 1 - P_{Rfl} = 1 - \left|\frac{SWR - 1}{SWR + 1}\right|^2 = 1 - 0.04 = 0.96 \qquad (9)$$

Therefore, 96% of the power is transmitted and only 4% is reflected, which is not far from the ideal 100% transmission.

The half-wave folded dipole with balun is almost twice as efficient as the one without a balun. This will result in a difference of approximately 3 dB in measurements.

Operation of the four-to-one impedance transformation balun

The operation of the balun can be explained as follows.

Suppose that there is a voltage $V_1 = V_0 \cos(\omega t)$ between the centre connector of the coaxial cable and the grounded outside shield. This is in particular the case at the unbalanced end at point c of Figure 1-49.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

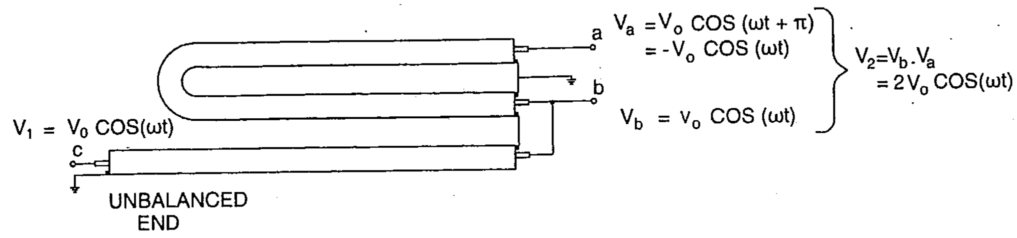


Figure 1-49. Operation of the four-to-one impedance transformation balun

Since there is no significant loss in the cable, the voltage between the centre conductor and the grounded shield will again be $V_b = V_o \cos(\omega t)$ at point b some distance away.

Between point b and point a, however, there is exactly a distance of $\lambda/2$. Between these two points a phase shift of π or 180° will occur and the voltage between the centre conductor and the grounded shield at point a will be

$$V_a = V_o \cos(\omega t + \pi) = -V_o \cos(\omega t) \tag{10}$$

Then

$$V_2 = V_b - V_a = 2V_o \cos(\omega t) \tag{11}$$

Since there is no significant loss in the coaxial cable, the radiated power P_2 measured at the balanced end (antenna end, i.e., points a and b) will be the same as the power P_1 measured at the unbalanced end (cable end, i.e., point c).

Using the relationship $P = \frac{V_{rms}^2}{Z}$, one can then write

$$P_1 = \frac{(V_{1\,rms})^2}{Z_1} = P_2 = \frac{(V_{2\,rms})^2}{Z_2} \tag{12}$$

or

$$\frac{Z_2}{Z_1} = \frac{(V_{2\,rms})^2}{(V_{1\,rms})^2} = 2^2 = 4 \tag{13}$$

Thus, $Z_2 = 4\,Z_1$.

Using a folded dipole antenna with a metal mast

In principle, the radiation pattern of the dipole and the folded dipole are both circular in the H plane. This is also the case in practice but the circular radiation pattern can be elongated by using a metal mast, as shown in Figure 1-50.

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

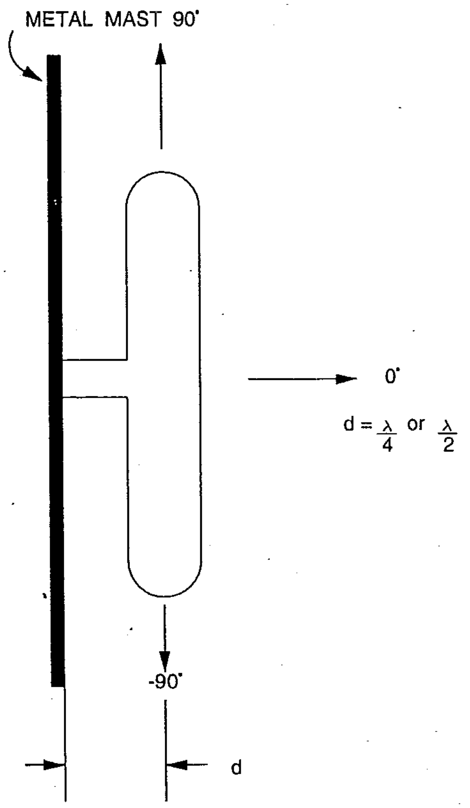


Figure 1-50. Folded dipole antenna on a metal mast

As shown in Figure 1-51, a quarter-wave spacing between the dipole and the mast will cause the radiation pattern to be elongated in the broadside direction (0°) whereas a half-wave spacing will cause the circular radiation pattern to elongated towards the sides (+90° and -90°). The gain in directivity can be 3 to 5 dB, which is quite appreciable.

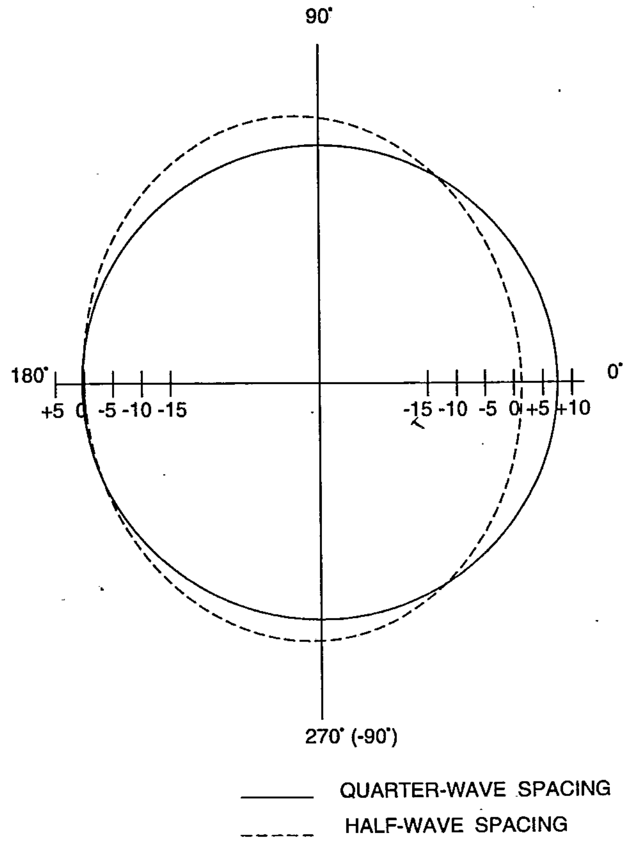


Figure 1-51. Effect of a metal mast on the radiation pattern of a folded dipole

Procedure Summary

In this exercise you will plot the radiation patterns of a folded dipole with and without a balun. You will then better understand the increase in gain resulting from the use of a 4:1 balun on an antenna having an input impedance of 300 Ω. You will learn the meaning of gain expressed in dBd and use this concept to evaluate the gain of the folded dipole. Finally, you will observe how a metal boom placed behind a dipole affects its directivity.

PROCEDURE

Setting up the equipment

☐ 1. The main elements of the Antenna Training and Measuring System, that is the Data Acquisition Interface/Power Supply, the RF Generator, the Antenna Positioner and the computer, must be properly set up before beginning this exercise. Refer to Section 4 of the User Manual for setting up the Antenna Training and Measuring System, if this has not already been done.

☐ 2. Place an antenna mast with horizontal clips on the transmission mast support. Clip the Yagi antenna on the mast, oriented for an acquisition in the E plane, and connect it to the 1 GHz OSCILLATOR OUTPUT of the RF Generator, using the long SMA cable.

☐ 3. Select the folded dipole connector **with** balun and the folded wire, then set up a folded dipole antenna, as shown in Figure 1-52.

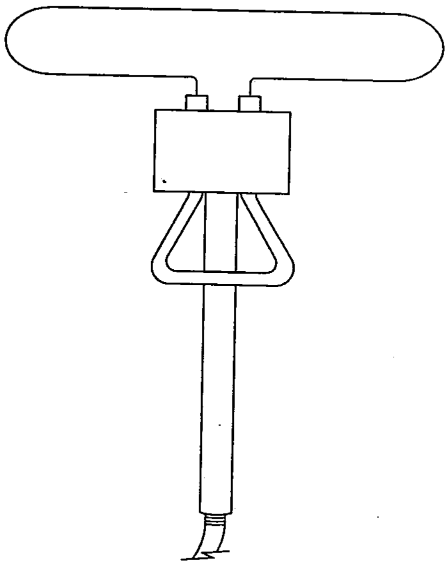


Figure 1-52. Set-up of a folded dipole antenna with balun

☐ 4. Place the antenna mast with vertical clips on the sliding support of the Antenna Positioner. Attach the folded dipole to the mast.

Using the sliding support, ensure that the antenna is in line with the rotation centre of the Antenna Positioner and oriented to rotate in the E plane (the folded dipole has the same polarization as that of the basic dipoles in Exercise 1-4).

Screw the 10 dB attenuator onto the RF input on top of the Antenna Positioner. Connect the antenna to the attenuator using the short SMA cable.

☐ 5. Position the antennas a distance of r = 1 m apart. Adjust them so that they are at the same height and directly facing each other.

☐ 6. Make the following adjustments:

On the RF Generator

1 GHz OSCILLATOR MODE . . . . 1 kHz
1 GHz OSCILLATOR RF POWER . . . . OFF
10 GHz OSCILLATOR RF POWER . . . . OFF

Power up the RF Generator and the Power Supply.

Turn on the computer and start the LVDAM-ANT software.

Radiation pattern

☐ 7. Set the 1 GHz OSCILLATOR RF POWER switch on the RF Generator to the ON position. Use the Attenuation control to optimize reception of the signal.

Start your acquisition and store the radiation pattern in the antenna1 data box, making sure you have selected the correct plane.

☐ 8. Rotate the Yagi antenna so that it is vertically polarized.

Remove the antenna mast with vertical clips from the sliding support and replace it with the other mast that uses horizontal clips. Making sure that it rotates in the H plane, install the folded dipole on this new mast and replace the short SMA cable with the intermediate one, as in Figure 1-53.

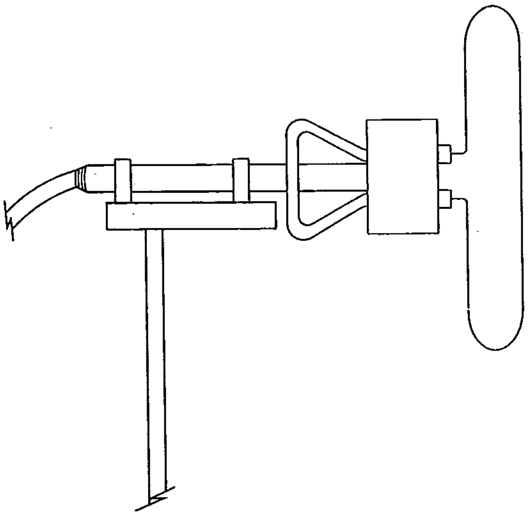


Figure 1-53. Set-up for a rotation in the H plane

Perform a new acquisition and store it as the H plane of antenna1. Plot the acquired patterns.

☐ 9. Remove the complete folded dipole assembly from the receiving mast. Use the folded wire of this antenna, and set up another antenna using the folded dipole connector **without** the balun. Clip this new antenna onto the mast.

> **Note:** *Make sure that the set-up here is the same as that in the preceding step - otherwise you won't be able to compare the two. This remark also applies to acquisitions made in the E plane.*

☐ 10. Do not modify the attenuation level; start an acquisition of the H-plane pattern.

Make the appropriate modifications (including the replacement of the receiving cable), then perform an acquisition of the E plane. Store these two patterns in the antenna2 data box.
Plot the acquired patterns.

☐ 11. Observe the patterns carefully. Which antenna gives the better gain and what is the difference (in dB) between them? To obtain a convenient graph for your comparison, print the H plane patterns of both antennas on the same sheet (remember to save the patterns stored in the antenna1 and antenna2 data boxes before printing).

Gain of a folded dipole

☐ 12. Set-up a λ/2 dipole to replace the folded dipole antenna. Without changing the attenuation level, perform an acquisition of the E plane. Store this pattern in the antenna3 data box. Plot the acquired E-plane pattern.

☐ 13. In Exercise 1-2, you saw that the antenna gain, which equals directivity multiplied by antenna efficiency, is a value expressed in dB relative to a hypothetical isotropic antenna. In antenna literature, you will often encounter antenna gain expressed in dBi, which is the gain relative to an isotropic radiator. Antenna gain can also be expressed relative to a half-wave dipole, thus gain in dBd, as shown in Figure 1-54. This figure shows the E-plane radiation patterns of a half-wave dipole (the 0-dB reference) and an example antenna, AntX. As can be seen from these patterns, the MSL of AntX is about 8.4 dB greater than the MSL of the dipole. Therefore, the gain of AntX is 8.4 dBd with respect to the 0-dB reference plot of the half-wave dipole.

If the gain in dBi of a half-wave dipole is known, then it is easy to convert from a gain in dBd to a gain in dBi. The typical, measured gain in dBi of the half-wave dipole in the Lab-Volt system is 1.9 dBi (the theoretical value for a half-wave dipole is 2.14 dBi). Therefore the gain of AntX expressed in dBi equals 8.4 + 1.9 = 10.3 dBi.

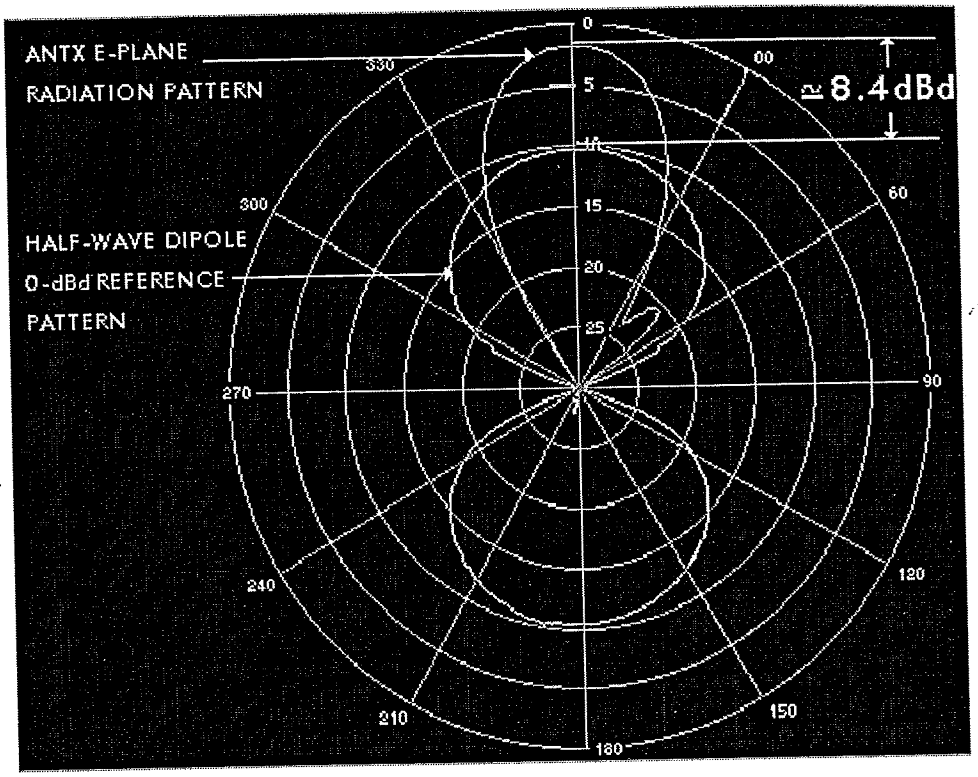


Figure 1-54. Gain expressed as a value over a dipole reference

In theory, the gain of the half-wave dipole and the folded dipole are supposed to be the same; in practice, however, differences sometimes occur. Using the typical dBi gain of the Lab-Volt half-wave dipole, express the gain of the folded dipole with balun in both dBd and dBi.

G = ______ dBd = ______ dBi

☐ 14. Print the 3-D representation of the radiation pattern of the folded dipole with balun and observe its similarity to that of the λ/2 dipole printed in Exercise 1-4.

Improving the directivity

> **Note:** *Be sure that the receiving antenna has the same orientation in Steps 16, 17 and 19, so that you can compare the different patterns you acquire.*

Improving the directivity

Note: *Be sure that the receiving antenna has the same orientation in Steps 16, 17 and 19, so that you can compare the different patterns you acquire.*

☐ 15. Save any patterns you expect to use in the future, then select the File, Close All command to make the antenna1, antenna2, antenna3 data boxes available again.

☐ 16. Remove the λ/2 dipole and the receiving mast. Set up the mast with horizontal clips on the sliding support and install the folded dipole with balun on this mast, polarized vertically. Orient the Yagi antenna in the H plane.

Adjust the attenuation level to get a maximum signal level of approximately -5 dB. Start an acquisition. Store the radiation pattern as the H plane of antenna1.

☐ 17. Add another sliding support onto the sliding support track. Insert the mast with vertical clips into this support and attach the aluminum mast included with the system to it. Position the support at a distance of λ/4 between the antenna and the mast. Refer to Figure 1-55.

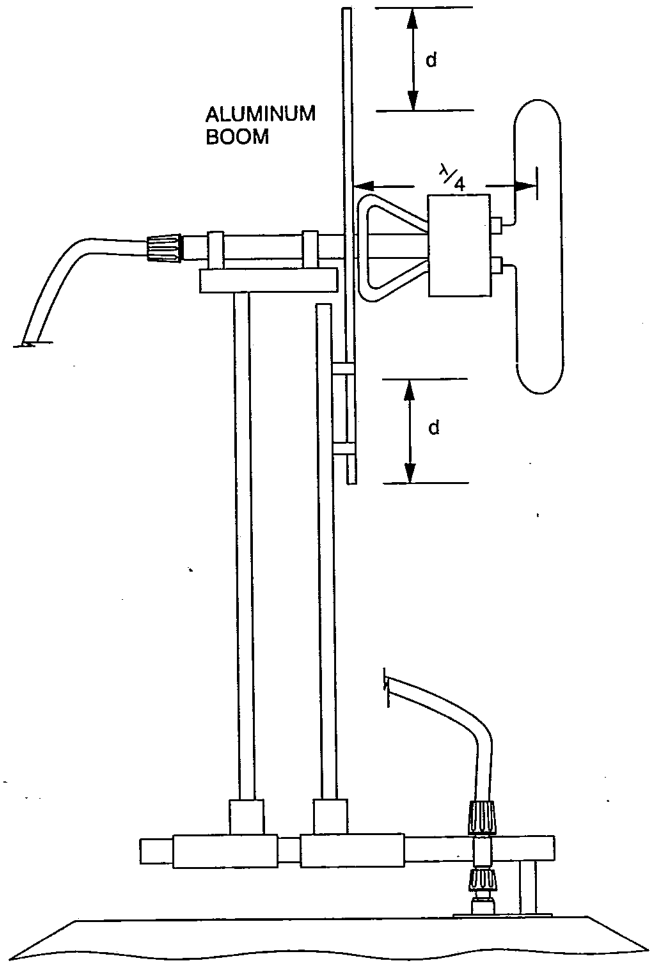


Figure 1-55. Set-up with an aluminum mast placed behind the antenna

Perform an acquisition WITHOUT changing the attenuation level. Store this H plane in antenna2.

Plot the two patterns acquired in Steps 16 and 17.

☐ 18. You should notice a difference between the two acquired patterns; the second set-up should have improved the directivity of the folded dipole. Give the value of this increase.

Increase of ______ dB

☐ 19. Modify your set-up to obtain a distance of λ/2 between the antenna and the mast, then plot the radiation pattern. You will probably have to rotate one of the sliding supports to perform this manipulation. Store your last acquisition as the H plane of antenna3 and compare this antenna pattern with that of the standard folded dipole. Does this correspond to the expected result? Plot the acquired pattern together with the previous two patterns.

☐ 20. Make sure you have saved your radiation patterns if you expect to use them in the future, then exit the LVDAM-ANT software. Place all power switches in the O (off) position, turn off the computer, disassemble the set-up, and return all components to their storage compartments.

CONCLUSION

In this exercise, you saw the radiation pattern of a folded dipole and observed the efficiency of a 4:1 balun used on an unmatched antenna. Using the gain of a $\lambda/2$ dipole antenna as a reference, you evaluated the gain of a folded dipole; you saw that these two gains are very similar. Finally, you improved the directivity of the folded dipole antenna by placing a metal boom behind it.

REVIEW QUESTIONS

1. Why is the impedance of the folded dipole four times greater than that of a $\lambda/2$ dipole?

2. What does the expression "perfect impedance match" mean? Why is it important for the antenna and the transmission line impedances to match, and what happens when a transmitting antenna is not correctly matched with the transmission line?

Half-Wave Folded Dipole Antennas and Impedance Transformation with Baluns

3. An antenna has a $HPBW_E = 28°$ and a $HPBW_H = 32°$. Calculate the gain of this antenna referenced to a theoretical half-wave dipole.

4. The use of a 4:1 balun improves the gain of a folded dipole fed by a 75 Ω transmission line. Explain why.

5. Is there any reason to attach a folded dipole to a metal mast? Does the distance between the antenna and the mast have any importance?