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Investigation of the Double-Y Balun for Feeding Pulsed Antennas

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ABSTRACT

The double-y balun, transitioning from an unbalanced coplanar waveguide (CPW) to a balanced coplanar strip (CPS), was originally developed for use with balanced mixers. In this paper, the feasibility of this balun for feeding pulsed antennas was investigated via time-domain pattern measurements of a resistively loaded V-dipole. The need for a balun when feeding a symmetric antenna is illustrated via time-domain pattern measurements of the resistively loaded V-dipole with and without the double-y balun.

Keywords: Balun, double-y balun, balanced, unbalanced, coplanar waveguide, coplanar strip

1. INTRODUCTION

Symmetric antennas such as the dipole, the complementary spiral, and the resistively loaded V-antenna require a balanced feed in order to radiate properly. Coaxial cables are often used to guide signals at RF and microwave frequencies. However, the coaxial cable is an unbalanced structure, and therefore cannot provide a balanced feed if connected directly to a symmetric antenna. In order to properly transition between balanced and unbalanced structures, a balun (*bal*anced - *un*balanced) is required.

The double-y balun, transitioning from an unbalanced coplanar waveguide (CPW) to a balanced coplanar strip (CPS), has been found to provide superior bandwidth performance compared to other baluns as well as other implementations of the double-y balun.[1–4] This implementation of the double-y balun can be manufactured precisely, offers little metal content, and is relatively small compared to other baluns; these features make this balun particularly attractive for use in landmine detection applications.

Double-y baluns have been investigated for use with balanced mixers.[1,2,4] In this paper, the feasibility of the double-y balun, implemented using CPW and CPS lines, is investigated for feeding a resistively loaded V-dipole. In Section 2, the concept of a balanced feed is developed and a general overview on baluns is given. In Section 3, design details as well as measured performance of the double-y balun of interest are presented. Finally, in Section 4, the need for a balun when feeding pulsed antennas requiring a balanced feed is investigated via time-domain pattern measurements of a resistively loaded V-dipole, with and without the double-y balun.

2. BALUN THEORY

Figure 1 illustrates a coaxial line with currents supported along its conductors. The skin effect causes balanced (equal in magnitude and opposite in phase) signal currents I_1 and I_2 to flow along the outside of the inner conductor and the inside of the outer conductor respectively. It is seen from Fig. 2a that the fields at a point P outside the coaxial line, due to the balanced signal currents inside the coax, are zero (fields due to I_1 and I_2 cancel outside the coax). Current is also supported by the coax along the outer surface of the outer conductor. This current is typically induced noise current and is shielded from the signal currents via the skin effect. The fields at a point P outside the coax, with the addition of this common-mode current along the outer surface of the coaxial line, are non-zero as illustrated in Fig. 2b. Thus, a coaxial line with a common-mode current along its outer surface radiates.

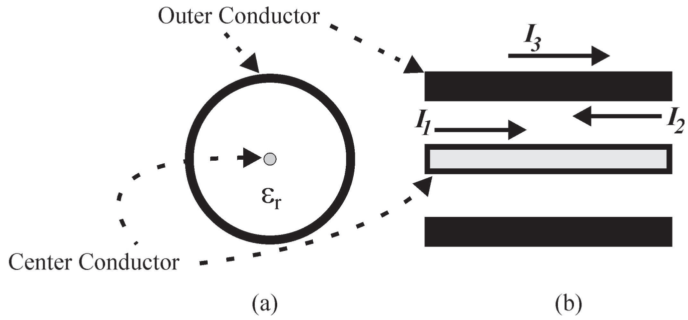

Figure 1. Illustration of (a) end-view and (b) cross-section view of coaxial line along with supported currents.

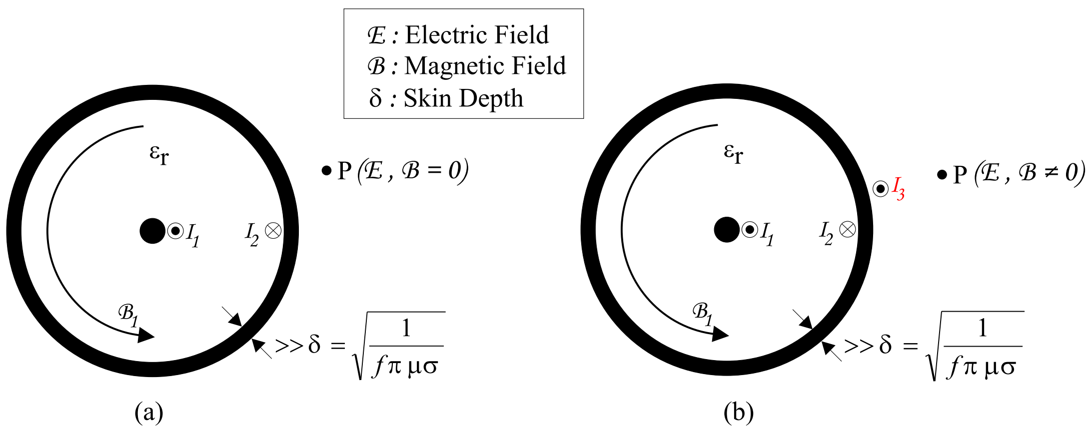

Figure 2. Illustration of (a) balanced signal currents and (b) common-mode current supported by coax. Fields at point P are zero in (a) but non-zero in (b).

A balanced feed can be defined as having only balanced or differential-mode currents along its conductors. Figure 3 illustrates a dipole fed directly by a coaxial line. It is seen that while only balanced currents I_1 and I_2 exist inside the coaxial line, a common-mode current (labeled I_3 in Fig. 3) is induced along the outer surface of the coaxial cable. The current is induced because of the asymmetrical coupling between the arms of the antenna and the outer conductor of the coax. This common-mode current causes the arms of the antenna to become unbalanced, resulting in radiation from the feed-line and distortion of the desired radiation pattern of the antenna. Distortion of the desired radiation pattern as well as radiation from the feed-line could adversely affect the operation of ground penetrating radars; feed-line radiation could couple antennas used in a bistatic ground penetrating radar, thereby significantly increasing clutter. The magnitude of I_3 is a function of the impedance between the outer surface of the coaxial cable and ground.[5–7]

In order to properly transition from an unbalanced structure (e.g. coax) to a balanced structure (e.g. symmetric antenna requiring balanced feed), a balun is required. It is seen from Fig. 3 that the fundamental operation of the balun is to prevent the common-mode current I_3 from flowing along the outer surface of the coaxial line, thus providing a balanced feed for a symmetric antenna. Choke baluns are designed to choke the common-mode current along the outer surface of the coaxial line. Examples of choke baluns include the sleeve balun, the Guanella balun, and the ferrite bead balun (ferrite beads placed around the coax near the feed-point).[5,7–10] Baluns are also designed to provide equal and opposite voltages at the balanced terminals (with respect to ground) irrespective of the load.[11] Examples of voltage baluns include the Ruthroff balun and the 180°

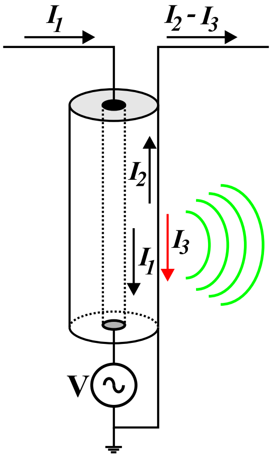

Figure 3. Illustration of dipole fed directly with a coaxial line.

phase shifting balun.[12,13] Some of the baluns are narrowband (e.g. sleeve balun) while others are broadband (e.g. Marchand balun[14]). In some cases there is an impedance mismatch between the unbalanced and balanced structures, and it is desirable for the balun to provide inherent impedance transformation capability (e.g. the 180° shifting balun provides 4:1 impedance tranformation[13]). If the balun cannot provide inherent impedance transformation, an external impedance taper is required to provide the necessary impedance transformation.

3. DOUBLE-Y BALUN

The double-y balun of interest is illustrated in Fig. 4. In order to obtain complete transmission from port 1 (unbalanced) to port 4 (balanced), ports 2 and 5 are shorted while ports 3 and 6 are open-circuited.[15] The CPW bridges maintain the outer ground conductors at the same potential, thus preserving the desired mode along the CPW lines. The input impedance of the double-y balun looking into the unbalanced section was determined by deriving the two port z-matrix (between port 1 and port 4 in Fig. 6b). The z-matrix components were derived to be

$$z_{11} = \frac{(z_6 + z_5)(z_2 + z_3)}{z_2 + z_3 + z_5 + z_6} \quad (1)$$

$$z_{14} = \frac{z_2(z_3 + z_5) - z_3(z_6 + z_2)}{z_2 + z_3 + z_5 + z_6} \quad (2)$$

$$z_{41} = \frac{z_5(z_2 + z_3) - z_3(z_5 + z_6)}{z_2 + z_3 + z_5 + z_6} \quad (3)$$

$$z_{44} = \frac{(z_6 + z_2)(z_5 + z_3)}{z_2 + z_3 + z_5 + z_6} \quad (4)$$

where

$$z_2 = jZ_{cps}tan(\beta_{cps}l_{cps}) \quad (5)$$

$$z_3 = -jZ_{cpw}cot(\beta_{cpw}l_{cpw}) \quad (6)$$

$$z_5 = jZ_{cpw}tan(\beta_{cpw}l_{cpw}) \quad (7)$$

$$z_6 = -jZ_{cps}cot(\beta_{cps}l_{cps}) \quad (8)$$

and Z_{cpw} and Z_{cps} are the characteristic impedances of the CPW and CPS sections respectively. The input impedance looking into the unbalanced section of the balun is then given by

$$Z_{in} = z_{11} - \frac{z_{14}z_{41}}{(z_{44} + Z_o)} \quad (9)$$

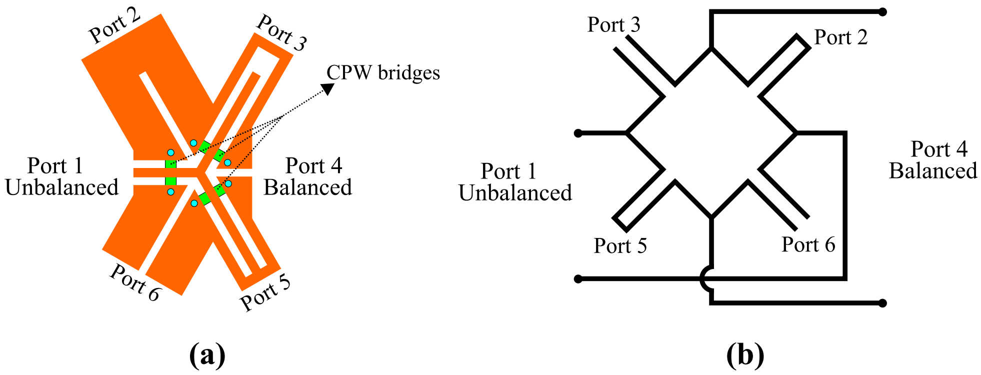

Figure 4. Illustration of (a) double-y balun (b) equivalent circuit model for impedance calculations.

where Z_o is the characteristic impedance at port 4 in Figure 6. If Z_{cpw}, Z_{cps} and Z_o are equal, then it is seen from (9) that the balun is matched at all frequencies. However, if Z_{cpw} and Z_{cps} differ at the balun junction, (9) limits the length of the open and short circuit stubs to be $\lambda/8$ at the highest frequency. This is illustrated in Fig. 5, where Z_{cps} and Z_o were set to 90Ω and Z_{cps} was varied between from 70-100Ω. It is seen that the all-pass behavior of the balun occurs only when the characteristic impedances of all the ports are identical. Therefore, in practice the length of the stubs should be chosen to be smaller than the $\lambda/8$ requirement.

A double-y balun, illustrated in Fig. 6, was designed to transition from an unbalanced 50Ω coaxial feed-line to a 188.5Ω balanced CPS antenna feed (initial project specifications required the balun to feed a complementary spiral antenna). The first step in the design of the balun was to establish specifications in order to reduce the number of variables in the design process. The widths of the gap between the conductors as well as the center conductor thickness at the balun were constrained to 8mil based on available manufacturing tolerances. The thickness of the substrate was chosen to be 39mil to provide sufficient mechanical rigidness. The gap between the CPS lines at the antenna feed-point was constrained to be approximately 40mil based on the antenna's dimensions at the feed-point. The lengths of the open and short circuited stubs were chosen to be 100mil to extend the high frequency operation up to 8GHz.

The CPW section of the balun was required to match a 50Ω coaxial cable, and the CPS section of the balun was required to match the 188.5Ω complementary spiral antenna. At the balun junction, the CPW and CPS sections are required to have the same characteristic impedance in order for the balun to operate properly. Impedance charts were generated for the CPW and CPS lines over FR4 substrate, and are illustrated in Figs. 7 and 8.[16,17] The CPW section of the balun was designed for a characteristic impedance of 94Ω and the CPS section of the balun was designed for a characteristic impedance of 107Ω. These were the maximum and minimum achievable impedances for the CPW and CPS lines respectively for the above specifications. Exponential impedance tapers were added to transition from the 50Ω coax to the 94Ω CPW section of the balun, and to transition from the 107Ω CPS section of the balun to the 188.5Ω feed-point of the antenna. The length of the entire taper was limited to 3200mil based on project specifications.

Figure 9 illustrates the impulse response of the balun (terminated with a 185.7Ω load) convolved with a Gaussian derivative pulse centered at 6GHz. The reflections due to the connector were present in the measurement because the network analyzer was calibrated with a 7mm calibration kit without the SMA connectors that were later attached for measurement purposes. These reflections were gated out in the time domain; the VSWR of the balun before and after time gating the reflections is illustrated in Fig. 10. The balun achieved a VSWR of less than 1.5 from 800MHz to 8GHz. Figure 11 illustrates the measured insertion loss of the balun. Parasitic resonances were removed by adding an additional CPW bridge near the junction.[18] The double-y balun achieved an insertion loss of less than 2.8dB from 800MHz to 8GHz.

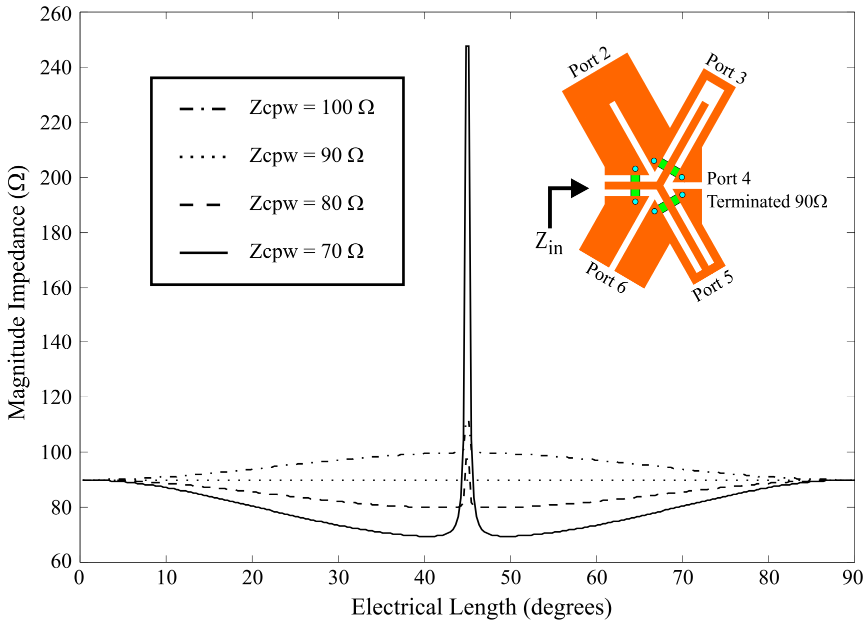

Figure 5. Input impedance looking into CPW section of balun junction.

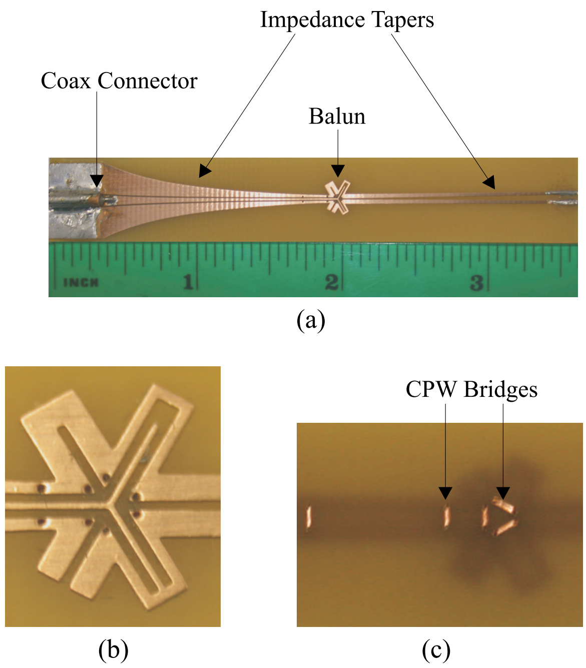

Figure 6. Top view of (a) double-y balun with impedance tapers, (b) expanded view of balun junction, and (c) bottom view of substrate with CPW bridges.

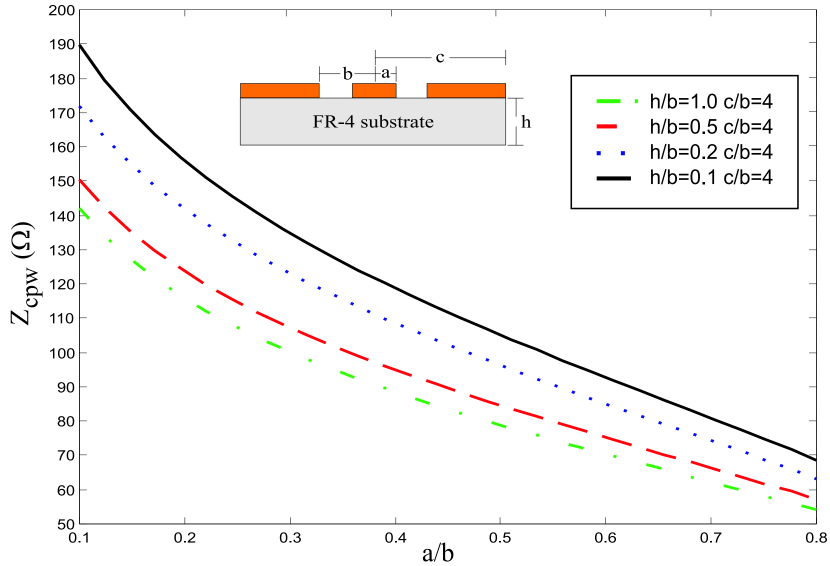

Figure 7. Impedance chart for CPW over FR4 substrate.

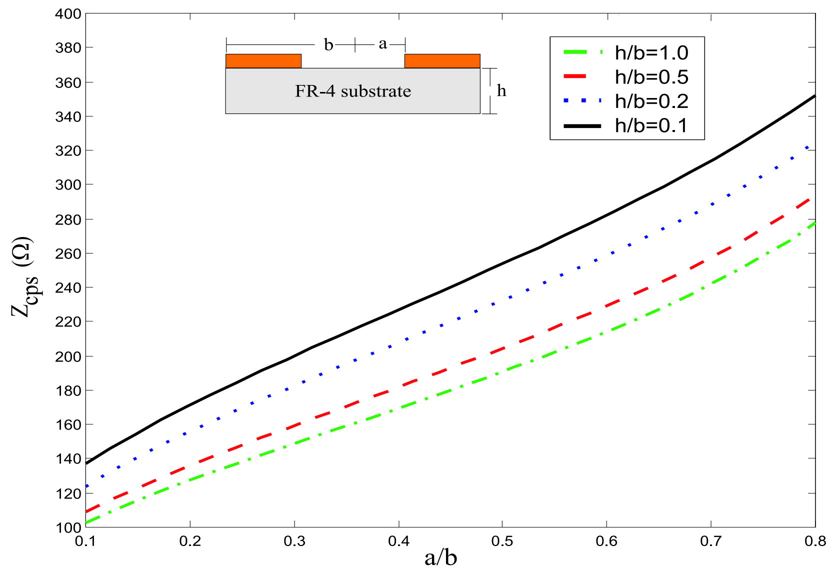

Figure 8. Impedance chart for CPS over FR4 substrate.

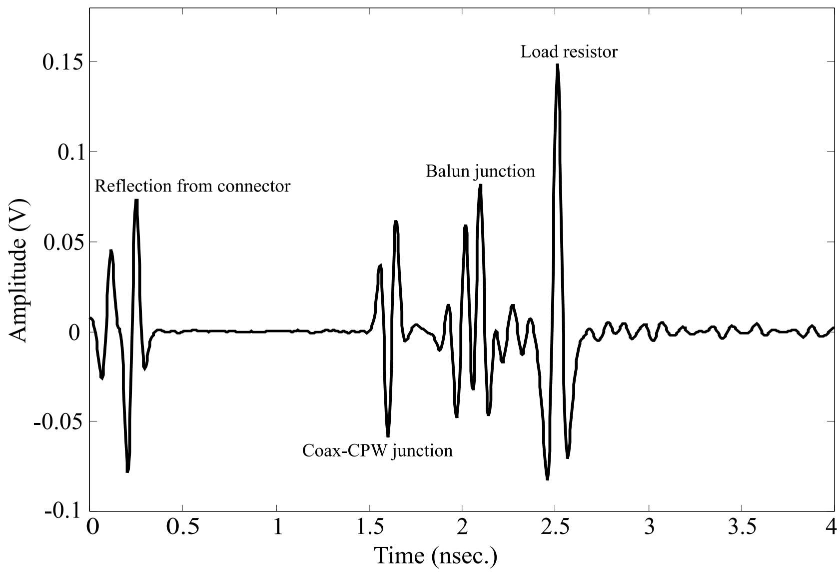

Figure 9. Impulse response of double-y balun convolved with Gaussian derivative pulse centered at 6GHz.

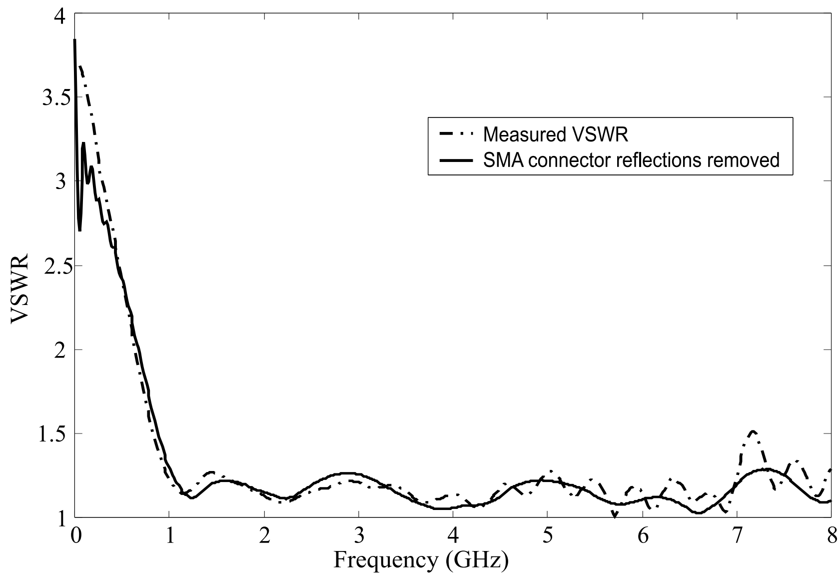

Figure 10. VSWR of double-y balun terminated with 185.7Ω load.

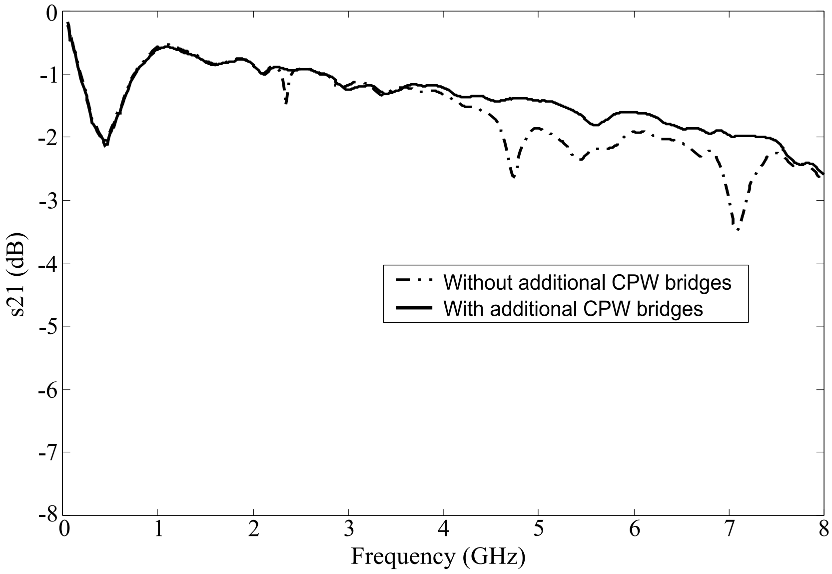

Figure 11. Insertion loss of double-y balun with and without additional CPW brige.

4. TIME-DOMAIN PATTERN MEASUREMENT

Time-domain patterns of a resistively loaded V-dipole[19] were measured with and without the double-y balun. The V-dipole is illustrated in Fig. 12 along with the double-y balun. Figure 13 illustrates the time-domain pattern measurement setup. A V-dipole with the double-y balun was oriented to transmit a wave that behaves as a vertically polarized plane wave in the region near the receiving antenna. The pattern of the receiving V-dipole, with and without the balun (a 50Ω coax was connected directly to the antenna), was measured by varying the antenna's pitch.

Figure 14 illustrates the time-domain pattern for the V-dipole (generated using Gaussian derivative pulse centered at 3GHz) with and without the double-y balun. It is seen that there is little difference between the received pulse amplitudes for both cases, even though there is a larger impedance mismatch when the V-dipole is fed directly with a 50Ω coax (V-dipole input impedance is around 200Ω at 3GHz). Since the electric field is the quantity being measured, only 64% of the power being transmitted still corresponds to 80% of the field being sensed.

It is seen from Fig. 14 that the pattern of the V-dipole loses symmetry without the balun for pitch angles greater than 5°. The loss in symmetry can be attributed to an unbalanced feed (magnitude of currents along arms of the antenna are not equal), as illustrated in Fig. 3. Figures 15 and 16 offer an expanded view of the time-domain patterns with antenna pitch angles of 10 and 20 degrees respectively. A DC offset was numerically added for the patterns measured with the balun for plotting purposes. It is seen that the pattern of the V-dipole attains much better symmetry when fed with the double-y balun than when fed without a balun. Thus, in order to obtain the desired radiation pattern of a symmetric antenna requiring a balanced feed, a balun is needed to properly transition from an unbalanced coax and provide a balanced antenna feed. The patterns for the case without the balun do not represent the worst case performance of the antenna when not fed balanced; it is difficult to predict the performance of the antenna when not fed balanced. Depending on the feed-line length or proximity of the antenna to a ground plane, the performance of the antenna without the balun could vary significantly. Additional reflections can be observed in Fig. 16 for the case without a balun. In order to analyze these reflections accurately, an improved measurement setup is currently being developed.

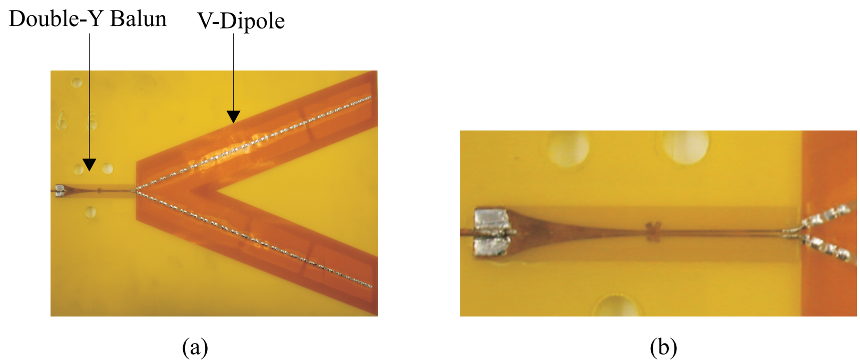

Figure 12. Illustration of (a) double-y feeding V-dipole and (b) expanded view of double-y balun and V-dipole feed-point.

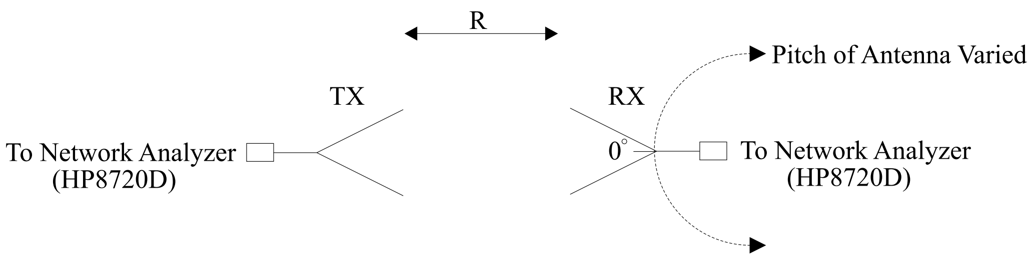

Figure 13. Setup for measurement of time-domain pattern of V-dipole.

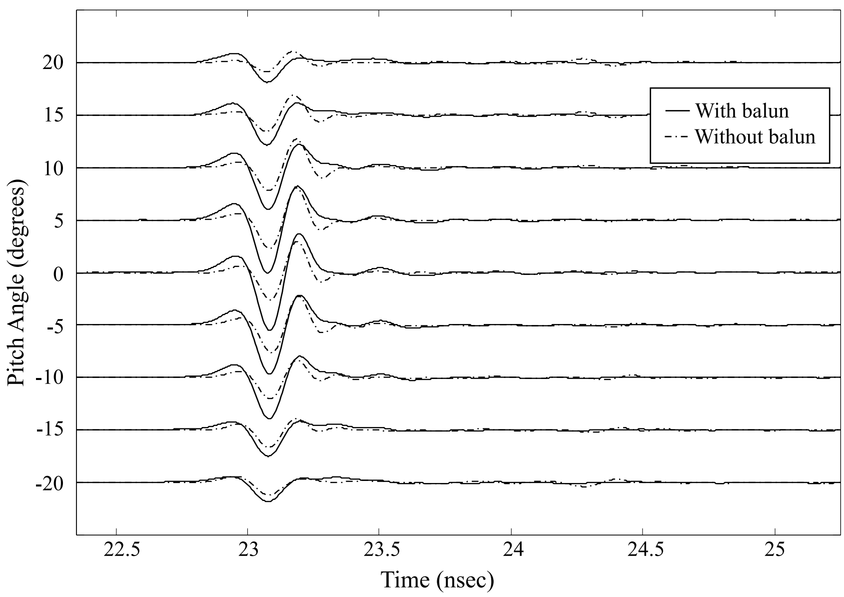

Figure 14. Time-domain pattern of V-dipole with and without the double-y balun.

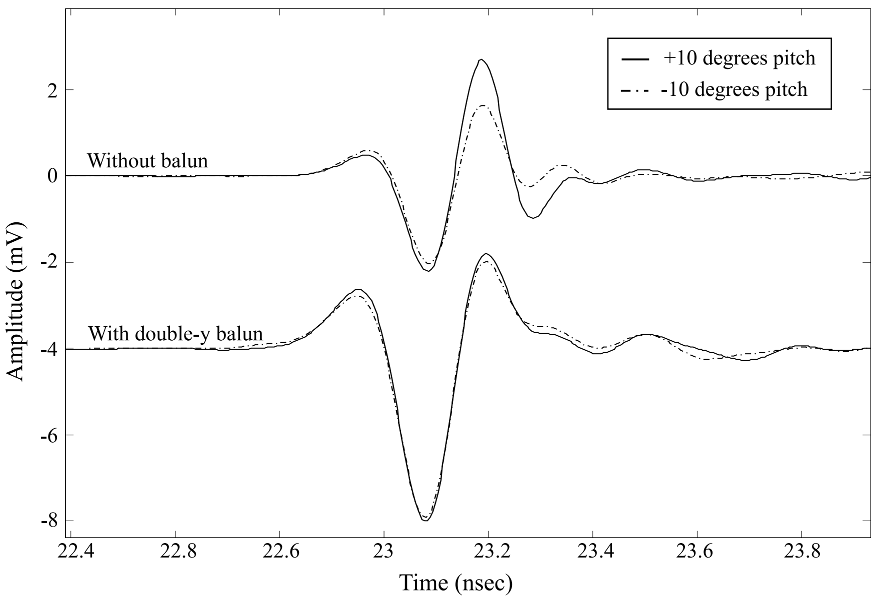

Figure 15. Time-domain pattern of V-dipole with and without the double-y balun at +/-10° pitch angle.

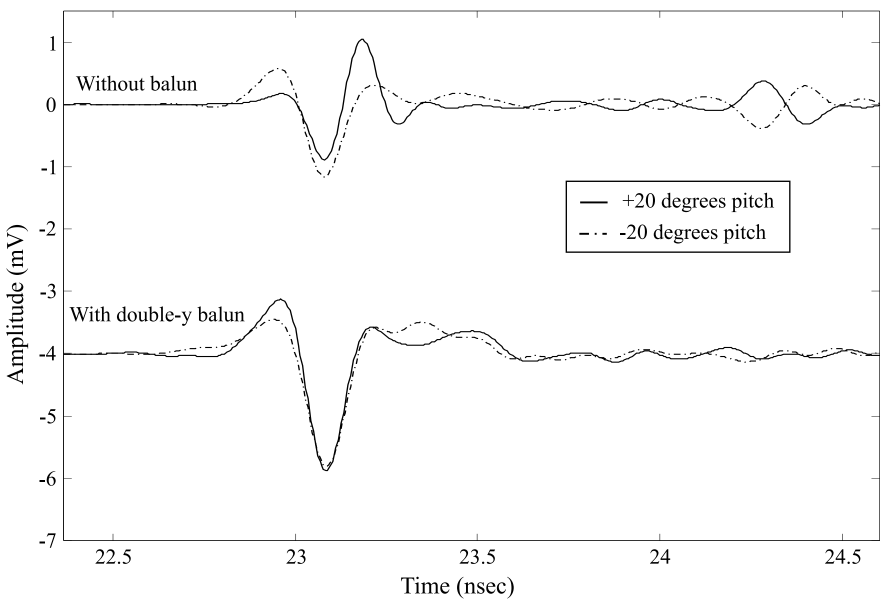

Figure 16. Time-domain pattern of V-dipole with and without the double-y balun at +/-20° pitch angle.

5. CONCLUSIONS

A double-y balun transitioning from an unbalanced CPW line to a balanced CPS line was originally designed to feed a complementary spiral antenna. The feasibility of using this balun for feeding pulsed antennas was investigated by using this balun in conjunction with a resistively loaded V-dipole. Symmetry was observed in the time-domain patterns of the antenna when fed with the balun. The need for a balun was illustrated via the asymmetry in the time-domain patterns of the antenna when fed directly with an unbalanced 50Ω coaxial cable. Currently, an improved measurement setup is being constructed in order to conduct accurate time-domain analysis of baluns.

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