Design of the Double-Y Balun for use in GPR Applications

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ABSTRACT

The double-y balun, transitioning from a coplanar waveguide (CPW) to a coplanar strip (CPS), was originally designed for use with balanced mixers. In this paper, numerical analysis of the double-y balun is conducted using two commercial electromagnetic simulators, Momentum and HFSS. Using these numerical solvers, the effect of substrate thickness on the performance of the double-y balun is investigated. A dipole, along with the outer conductor of a coaxial feedline is modeled in NEC to illustrate the effects of an unbalanced feed on the antenna pattern of a dipole. To accurately measure the amplitude pattern of a dipole, an automated measurement system is constructed. Using this measurement system, amplitude patterns of a 3.3 GHz dipole are measured with and without the double-y balun and compared with patterns obtained via NEC.

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

1. INTRODUCTION

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. 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. If the balun cannot provide inherent impedance transformation, an external impedance taper is required to provide the necessary impedance transformation.

The double-y balun, transitioning from a coplanar waveguide (CPW) to a 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.\textsuperscript{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.\textsuperscript{1,2,4} In this paper, numerical analysis is conducted on the double-y balun using two electromagnetic simulators, Momentum and HFSS. In Section 2, modeling of the double-y balun in Momentum and HFSS is discussed. Momentum is a method of moments code while HFSS is a finite element based code. Resonances limiting the bandwidth of the double-y balun are observed in the numerical results in Section 2. In Section 3, these parasitic resonances are studied, and the effect of substrate thickness on the balun’s performance is investigated in Section 4. In Section 5, a dipole and the outer conductor of a coaxial line are modeled in NEC to illustrate the effects of an unbalanced feed on the antenna’s radiation pattern. In addition, numerical results from the NEC model provide a basis to which experimental measurements can be compared with. To accurately measure the pattern of an antenna fed with and without a balun, an automated measurement system was constructed. Details of this measurement system are discussed in Section 6, along with preliminary amplitude patterns of a 3.3 GHz dipole fed with and without the double-y balun.
2. NUMERICAL ANALYSIS

The balun in this paper is intended to feed a resistively loaded V-dipole, whose input impedance is around 200 Ω. Therefore, the double-y balun is required to transition from a 50 Ω coaxial line to a 200 Ω V-dipole. The double-y balun cannot inherently transform impedances. Also, for the double-y balun to exhibit all-pass behavior, the impedances of the CPW and CPS lines must be equal. Furthermore, due to manufacturing tolerances, it is difficult to achieve 50 Ω CPS lines and 200 Ω CPW lines. Therefore, impedance tapers are used to transition from the 50 Ω coaxial line to the balun, and to transition from the balun to the 200 Ω V-dipole, as illustrated in Fig. 1.

![Figure 1](image)

**Figure 1.** Design approach to transition from coaxial feedline to double-y balun and resistively loaded V-dipole.

The double-y balun, implemented with CPW and CPS lines, was analyzed numerically using two commercial electromagnetic simulators, Momentum and HFSS. Momentum is a method of moments code, while HFSS is a finite element based code. Analyzing the balun using two different electromagnetic simulators allows better validation of simulated results. Figure 2 illustrates a double-y balun designed to transition from a 104 Ω CPW section to a 104 Ω CPS section over 58 mil thick FR4 substrate ($\varepsilon_r=4.4$, $\delta_{tan}=0.012$). The impedance tapers were omitted to reduce computational time.

![Figure 2](image)

**Figure 2.** Dimensions of double-y balun modeled in Momentum and HFSS.

In Momentum, the substrate was modeled as extending infinitely along the plane containing the double-y balun. The substrate characteristics were modeled as illustrated in Fig. 3. The CPW and CPS lines were drawn on the cond layer and mapped as strip. Mapping a layer as strip causes Momentum to assign conductive properties to the objects drawn on the layer (in this case objects on cond layer are treated as PEC). In contrast, mapping a layer to slot causes all objects drawn on the layer to be non-conductive and the surrounding layer to be conductive. The vias were drawn on the hole layer, which was mapped as via. Mapping a layer to via causes objects drawn on the layer to be conductive and cut vertically through one or more substrate layers. The jumpers connecting the vias were drawn on the cond2 layer and mapped as strip along the bottom of the substrate as illustrated in Fig. 3b. Dielectric loss was modeled in the substrate by adding a loss tangent value of 0.012 for the FR4 substrate.

The balun in Fig. 2 was also modeled in HFSS. The CPW and CPS sections were excited using lumped ports. Lumped ports excite a simplified, single-mode field excitation assuming a given reference impedance for s-parameter referencing. The reference impedances were chosen from impedance equations for CPW and CPS lines. All conductors were modeled as PEC, and the substrate was modeled with a dielectric loss of 0.012. Convergence criteria for the solution was established by setting a tolerance on the maximum change in the magnitude of the s-parameters between two consecutive passes. During each simulation pass, HFSS calculates the s-parameters and proceeds to refine the mesh if the convergence criteria is not met. A tolerance of 0.01 was
chosen as the maximum allowable change in the s-parameters between two passes. This tolerance was chosen to yield reasonable simulation times as well as memory consumption, with a tradeoff between accuracy and simulation times.

HFSS is a 3-D finite-element based code that solves for the field quantities within a bounded region. Therefore, unlike the FR4 substrate modeled in Momentum, the FR4 substrate modeled in HFSS has finite dimensions (in Momentum only the substrate thickness was finite). The balun was enclosed in an air bounded region, as illustrated in Fig. 4, and surrounded with perfectly matched layers (PMLs). The outer boundary of the PML was assigned a PEC boundary condition in order to minimize reflections from the interface. The perfectly matched layers act as absorbers that truncate the computational region while physically modeling unbounded space. Scattering parameters obtained for the double-y balun in Fig. 2 from Momentum and HFSS are illustrated in Figs. 5 and 6. It is seen from both figures that the resonant points agree very well with both simulators. The discrepancy in the $s_{11}$ curves could result from numerical error in both codes. Resonances limiting the bandwidth of operation are labeled in Fig. 6; these resonances are addressed in the following sections. Obtaining converging s-parameter data from two different simulators helps determine whether resonances that appear are due to the double-y balun or numerical error from the different codes (e.g. reflections from the PML, improper port excitations, etc.).
3. BALUN RESONANCES

The bandwidth of the double-y balun is limited by resonant modes, as seen in Figs. 5 and 6. Resonant modes in the double-y balun have been investigated when enclosed in a conductive enclosure. In this paper, these resonant modes are investigated for a double-y balun without conductive enclosures.

3.1. $\lambda/8$ Limitation

The bandwidth of the double-y balun has been reported to be limited by the lengths of the open and shorted coplanar waveguide (CPW) and coplanar strip (CPS) stubs. Due to junction parasitics and unequal dispersion between the CPW and CPS lines, the balun’s performance deteriorates as the lengths of the stubs ($L_s$ in Fig. 2) approach $\lambda/8$. Figure 7 illustrates a double-y balun implemented with CPW and CPS lines along with an equivalent lumped element model. Equations for the input impedance looking into the CPW section, to illustrate the $\lambda/8$ limitation, have been derived previously.

The lumped element model illustrated in Fig. 7b was modeled in HP Advanced Design System (ADS) using ideal transmission line components. Figure 8 illustrates a plot of $s_{21}$ comparing theoretical results obtained from with results obtained with ADS. Both cases model the double-y balun with 110 mil CPW and CPS stubs over FR4 substrate. The theoretical and schematic models agree very well for both, the matched and
Figure 7. Illustration of (a) double-y balun implemented with CPW and CPS lines and (b) equivalent lumped element model.

Figure 8. Plot of $s_{21}$ comparing theoretical results from with ADS model.

Mismatched cases. The resonance at $\lambda/8$ is seen with both models when $Z_{cpw} \neq Z_{cps}$. Figure 8 predicts the $\lambda/8$ resonance to occur near 8 GHz for stubs lengths of 110 mils, however, it is seen from Fig. 6 that with the full-wave model the resonance occurs near 6 GHz. This shift in the resonant frequency is addressed in Section 4.

3.2. CPW Resonance

A resonant mode along the ground conductors of the CPW input line has been reported. This mode is illustrated in Fig. 9 and is caused by differential-mode currents along the outer ground conductors. The outer ground conductors form a shorted transmission line, as illustrated in Fig. 9b, which resonates for lengths equal to multiples of a half-wavelength. Since the resonant frequency depends on the length of the input CPW section, this resonance can be pushed out of the balun’s passband by minimizing the length of the CPW line. However, since the double-y balun designed in this research requires an impedance taper to transition from a 50 Ω coaxial line to the balun, it is difficult to minimize the input CPW section and move the resonance out of the passband.

Another approach towards removing the CPW resonance in the balun’s passband is to add an additional CPW bridge along the input section, as illustrated in Fig. 10. The use of CPW bridges to eliminate the resonance along the outer CPW ground conductors is investigated in this section. Specifically, this section deals with two questions that arise when designing the additional CPW bridges: (1) how close to the balun junction...
should the additional CPW bridge be placed and (2) how many additional CPW bridges are needed along the CPW section.

In Section 2, the balun in Fig. 2 was analyzed numerically using Momentum and HFSS. Figure 11 illustrates the $s_{21}$ plot for this balun, obtained via Momentum, with the CPW resonance labeled. In addition, Figure 11 illustrates $s_{21}$ results for the double-y balun in Fig. 2 with and without an additional CPW bridge. It is seen from Fig. 11 that the additional CPW bridge cannot be placed arbitrarily close to the CPW bridge at the balun junction. Placing the additional CPW bridge 140 mils from CPW bridge at the balun junction yielded better results than placing the additional bridge 20 mils from the junction bridge.

The double-y balun designed in this research requires impedance tapers for both, the CPW and CPS sections. These tapers increase the overall length of the balun considerably, therefore, it is desirable to investigate the CPW resonance (this resonance is dependent on the input CPW line length) for the double-y balun with impedance tapers. However, modeling the balun with the impedance tapers requires significant computational time. Therefore, the balun in Fig. 2 was modeled in Momentum with extended CPW and CPS lines (length of each section was 1.6 inches), as illustrated in Fig. 12. These extended lines require a less complicated mesh, thereby decreasing computational time substantially. Figure 13 illustrates Momentum simulation results for the double-y balun in Fig. 12 with and without additional CPW bridges. It is seen that an additional CPW bridge is required to suppress the CPW resonances near 2.2 GHz and 4.4 GHz. Adding further CPW bridges, however, does offer little improvement as seen from Fig. 13.

### 3.3. Dipole Resonance

When enclosed in a conductive enclosure, a resonant mode was found to occur when the overall length of the balun was equal to odd multiples of a half-wavelength. The resonant mode was identified as being a ‘dipole’ resonance, as illustrated in Fig. 14: a resonance excited at the balun junction causing the CPW and CPS lines to act as dipole arms. The mode exists because the balun is not a perfect balun.

In this research work, the balun length is truncated when modeled numerically. Therefore, this resonance appears in the numerical simulations, as illustrated in Fig. 12. While the balun is truncated for numerical...
Figure 11. Momentum $s_{21}$ results for double-y balun in Fig. 2 with and without additional CPW bridge.

Figure 12. Illustration of double-y balun in Fig. 2 with extended CPW and CPS sections.

Figure 13. Momentum $s_{21}$ results for double-y balun in Fig. 12 with and without additional CPW bridges.
analysis, the balun in this research is not designed to be in a conductive enclosure. Practically, a long coaxial line is connected to the CPW section of the balun. Hence, it is difficult for this mode to exist. Therefore, although this resonance is observed in the numerical results, it is not expected to appear in measured results.

4. SUBSTRATE THICKNESS

The double-y balun in Fig. 2 was designed with 110 mil stubs over FR4 substrate. Results in Fig. 8 predict a $\lambda/8$ resonance to occur around 8 GHz for the double-y balun with 110 mil stubs over FR4. Numerical results for the double-y balun in Fig. 2 were illustrated in Section 2. It is seen that the resonance due to the $\lambda/8$ limitation occurs near 6 GHz, not 8 GHz as predicted by the lumped element model. To determine the cause of this shift in the resonance, the lumped element model in Fig. 7b was modified to include the effects of the CPW bridges, as illustrated in Fig. 18. As seen from Fig. 18a, two of the three bridges at the junction were added to the lumped element model.

The CPW bridges are necessary for the operation of the double-y balun. These bridges are to have negligible impedance (ideally should have zero impedance). The CPW bridges investigated in this paper are realized by jumpering via holes extending through the substrate, as illustrated in Fig. 3. The actual impedance of these bridges can be determined by calculating the input impedance looking into these bridges (bridges act as a transmission line extending through the substrate). The input impedance is given by

$$Z_{\text{inbridge}} = jZ_{\text{bridge}} \tan(\beta \cdot l_{\text{bridge}})$$

where $Z_{\text{bridge}}$ is the characteristic impedance of the bridge. To determine $Z_{\text{inbridge}}$, the CPW bridge was modeled in Momentum as illustrated in Fig. 15. The vias were modeled with a 6 mil diameter. Two cases were modeled.
in Momentum: one with a 58 mil substrate, the other with a 25 mil substrate. Figure 16 illustrates $Z_{inbridge}$ for both cases, obtained via Momentum. The plot clearly illustrates that the CPW bridge over 58 mil FR4 substrate has a fairly high impedance at high frequencies; at 8 GHz $Z_{inbridge}$ is around 100 $\Omega$. Reducing the substrate thickness to 25 mil reduces $Z_{inbridge}$ to around 45 $\Omega$. Figure 20 compares the $\lambda/8$ resonance frequency predicted by the ADS model and simulation results from Momentum for 80 mil balun stub lengths. Once again, the lumped element model agrees very well with results obtained from Momentum. To understand the effects of the CPW bridges on the performance of the balun, the bridges were modeled in the lumped element model, as illustrated in Fig. 18. The ADS model was modified to include the results in Fig. 16. Resulting $s_{21}$ from Momentum (double-y balun in Section 3.1 with reduced CPW and CPS transmission lines) and the modified ADS lumped element model are illustrated in Fig. 19. The shifted $\lambda/8$ resonance frequency from the ADS model agrees very well with the resonance frequency obtained from Momentum for 110 mil balun stub lengths. Hence, it is seen that the inductance due to the CPW bridges lowers the predicted resonance frequency (near 8 GHz in Fig. 8).

Figures 21 and 22 compare results from the ADS model and Momentum for the double-y balun with 110 and 80 mil stub lengths over 25 mil FR4 substrate, respectively. It is seen that the modified lumped element model simulated in ADS agrees better with the Momentum simulations for the baluns over 58 mil FR4 substrate than over 25 mil FR4 substrate. This can be attributed to additional parasitics not included in the modified lumped element model in Fig. 18. As the substrate becomes thinner, the height of the CPW bridges decreases, and a parasitic capacitance between the bridge and the conductors becomes significant. Nevertheless, the modified lumped element model illustrated in Fig. 18 provides insight into the shift of the predicted $\lambda/8$ resonance. Figure 17 illustrates simulation results obtained from Momentum by modeling the bridge as illustrated in Fig. 15 and varying the via diameter. The dimensions of all other components remained the same. It is seen from the Momentum results that increasing the diameter of the via hole lowers the impedance of the bridge.

Figure 23 compares $s_{21}$ results obtained via Momentum for the balun in Fig. 2 over 25 and 58 mil FR4 substrate. It is seen that the $\lambda/8$ resonance is shifted to a higher frequency for the double-y balun over 25 mil substrate. In addition, the ‘dipole’ resonance is significantly reduced for the balun over 25 mil substrate. Hence, reducing the substrate thickness improves the balancing of the double-y balun.

From the above results, it can be concluded that the substrate thickness should be minimized when designing the double-y balun, since the impedance of the CPW bridges increases with substrate thickness. It is seen from Fig. 16 that the impedance of the CPW bridge over 58 mil FR4 substrate is around 100 $\Omega$ at 8 GHz; at high frequencies the bridges act poorly as shorted jumpers. Also, increasing the hole size of the via (increasing the thickness of the wire for an air bridge) lowers the impedance of the CPW bridge. Modeling the inductive behavior of the CPW bridges provides insight as to why the shift in the $\lambda/8$ resonance occurs. Due to the CPW bridges, the actual upper frequency limit of the balun is lower than that predicted theoretically by the
Figure 17. Momentum simulation results illustrating effect of via diameter on CPW bridge impedance.

Figure 18. Modified lumped element model for double-y balun.

Figure 19. Illustration of shift in $\lambda/8$ resonance from Momentum and ADS simulations for 58 mil substrate and 110 mil stubs.
Figure 20. Illustration of shift in $\lambda/8$ resonance from Momentum and ADS simulations for 58 mil substrate and 80 mil stubs.

Figure 21. Illustration of shift in $\lambda/8$ resonance from Momentum and ADS simulations for 25 mil substrate and 110 mil stubs.

Figure 22. Illustration of shift in $\lambda/8$ resonance from Momentum and ADS simulations for 25 mil substrate and 80 mil stubs.
Figure 23. Momentum $s_{21}$ plot for double-$\gamma$ balun over 25 and 58 mil FR4 substrate.

$\lambda/8$ limitation.

5. MODELING UNBALANCED DIPOLE IN NEC

A dipole and the outer conductor of the coax have been modeled using Numerical Electromagnetic Code (NEC). The model is illustrated in Figure 24 along with its circuit equivalent. The model allows resistive loading to be placed near the feedpoint, as well as a Wu-King taper at the end of the feedline, however, neither one is used in the simulations detailed in this paper. Constructing a model in NEC serves two purposes: (1) provide a better understanding regarding the effects of an unbalanced feed on the performance of a dipole, and (2) provide a basis to which measured patterns can be compared with. The lengths of the segments were chosen to be $\lambda/20$ at the highest frequency. Voltage sources were placed on each arm of the dipole with values of $\alpha$ and $1-\alpha$; the degree of balance between the arms of the dipole was adjusted by varying $\alpha$ ($\alpha=0.5$ for balanced feed and $\alpha=0.1$ for unbalanced feed).

Figure 24. NEC model used to illustrate effects of unbalanced feed.

Amplitude patterns for the dipole were generated using NEC. The 2-D patterns were plotted by taking an azimuth cut (varying $\phi$ with $\theta = 90^\circ$) and an elevation cut (varying $\theta$ with $\phi = 0^\circ$), where $\theta$ and $\phi$ are as defined in spherical coordinates. As illustrated in Figs. 25 - 27, unbalancing the arms of a dipole has little effect on the normalized amplitude patterns along the azimuth cut at $\lambda/2$ resonance. However, as seen from Figs. 26 and 27, the normalized amplitude pattern is significantly affected along the elevation cut when the dipole is unbalanced. When the dipole is unbalanced, a standing wave is induced along the feedline. The current
distribution along the feedline varies according to the feedline length. Hence, the normalized amplitude pattern along the elevation plane for an unbalanced dipole, varies according to the length of the feedline as well.

Figure 25. Normalized amplitude patterns for balanced dipole at (a) \( \lambda/2 \) and (b) \( 3\lambda/2 \) computed using NEC.

Figure 26. Normalized amplitude patterns for unbalanced dipole with \( 15\lambda/4 \) feedline at (a) \( \lambda/2 \) and (b) \( 3\lambda/2 \) computed using NEC.

6. MEASURED DIPOLE PATTERNS

To accurately measure the antenna patterns of a dipole fed with and without a balun, an automated measurement system employing a rotary positioner was constructed, as illustrated in Fig. 28. Since the double-y balun is designed to feed a 200 \( \Omega \) resistively loaded V-antenna, feeding a dipole with this double-y balun would represent a stressful case for the balun. An HP8720D network analyzer and a Velmex VP9000 motor controller were connected to a PC using a GPIB and RS-232 interface, respectively. The motor controller was connected to a rotary positioner, onto which the antenna under test (AUT) was attached. The ports of the network analyzer were connected to the probe antenna and the AUT. The instruments were controlled using the PC via LabVIEW. Figure 29 illustrates the AUT attached to the rotary positioner. The positioner was covered with absorber during measurement to minimize clutter.

Normalized amplitude patterns along the azimuth plane for the dipole fed with and without a balun, are illustrated in Figs. 30 and 31. It is seen from both plots that the amplitude pattern is relatively unchanged at \( \lambda/2 \) for the dipole fed with and without the balun. This agrees with the results obtained from the NEC model illustrated in the previous section. Figure 30b illustrates the normalized amplitude pattern of the dipole...
Figure 27. Normalized amplitude patterns for unbalanced dipole with $25\lambda/4$ feedline at (a) $\lambda/2$ and (b) $3\lambda/2$ computed using NEC.

Figure 28. Block diagram illustrating automated measurement system.

Figure 29. Illustration of AUT attached to rotary positioner (a) without absorber and (b) with absorber covering the positioner during measurement.
fed without a balun at \(3\lambda/2\). This plot agrees closely with those obtained for the unbalanced dipole in NEC illustrated in Figs. 26b and 27b. Figure 31b illustrates the normalized amplitude pattern of the dipole fed with the double-y balun at \(3\lambda/2\). It is seen that this plot agrees closely with that obtained for the balanced dipole in NEC illustrated in Fig. 25b. Amplitude pattern measurements for the dipole along the elevation plane are currently being conducted using a new measurement setup. Antenna pattern measurements for a resistively loaded V-dipole are also being conducted.

![Figure 30](image1)

**Figure 30.** Measured normalized amplitude pattern for dipole fed without a balun at (a) \(\lambda/2\) and (b) \(3\lambda/2\).

![Figure 31](image2)

**Figure 31.** Measured normalized amplitude pattern for dipole fed with double-y balun at (a) \(\lambda/2\) and (b) \(3\lambda/2\).

### 7. CONCLUSIONS

In this paper, the double-y balun implemented with CPW and CPS lines was modeled numerically using two commercial electromagnetic simulators: Momentum and HFSS. The results obtained from both electromagnetic codes agreed very closely. Using the results from these simulators, parasitic resonances limiting the bandwidth of the double-y balun were investigated. The lumped element model for the double-y balun was modified to include the effects of the CPW bridges at the junction. Using the modified lumped element model, along with Momentum, it was shown that the inductive behavior of the CPW bridges lowers the predicted \(\lambda/8\) resonant frequency. To minimize the inductance of the bridges, the height of the bridges, and therefore the height of the substrate, needs to be minimized. Using simulation results from Momentum, the double-y balun over 25 mil FR4 was shown to achieve superior balancing behavior than the balun over 58 mil FR4 substrate.
A dipole along with the outer conductor of a coax, was modeled in NEC to illustrate the effects of an unbalanced feed. Numerical results obtained via NEC illustrated that an unbalanced feed had little effect on the pattern along the azimuth cut at $\lambda/2$. However, an unbalanced feed did alter the pattern along the elevation plane significantly. To accurately measure the amplitude patterns of a dipole fed with and without the double-y balun, an automated measurement system employing a rotary positioner was constructed. Resulting patterns for the dipole fed with and without the double-y balun were compared with those obtained via NEC. It was shown that the pattern for the dipole fed without the balun agreed with results obtained via NEC for an unbalanced dipole. The pattern for the dipole fed with the double-y balun agreed closely with results obtained via NEC for a balanced dipole. Antenna patterns for the dipole along the elevation plane and patterns for the resistively loaded V-dipole are currently being conducted.

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