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CHARACTERISATION AND PHASE COMPENSATION OF A COPLANAR WAVEGUIDE TO COPLANAR STRIP LINE BALUN

by

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SUMMARY

Characterisation and phase compensation of a coplanar waveguide to coplanar strip line balun

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Keywords: Balun; Coplanar waveguide; CPW; Coplanar strip line; CPS; Wideband; Uniplanar; Balance; Phase compensation; Test procedure.

A uniplanar balun that transforms unbalanced coplanar waveguide (CPW) to balanced coplanar strip line (CPS) is characterised through simulation and measurement. By illustrating the effect of many of the critical design parameters, the operation of this balun is discussed and a set of design criteria is defined. The parameter study discusses the size and shape of the radial open, the type and length of the CPW taper and the thickness and type of the bond wires. Newly developed etched bond wires are implemented to provide better manufacturing repeatability and reliability. A complete balun testing procedure is developed and described, consisting of three separate tests. The balun is tested in the normal back-to-back configuration, as a terminated single balun, and the magnitude and phase imbalance is also determined by using a three-port test circuit connected to the balun. The advantages of implementing this full test procedure, and thus fully characterising the balun under test, are emphasised throughout. Results obtained by using this procedure show that the basic balun works well over the full operating band, except for the phase imbalance, which is usable but not optimal. A simple technique to correct the phase imbalance of the balun is introduced, and validated through measurements of the balun connected to the three-port test circuit. As a final validation the balun is connected as feed for an etched dipole antenna for which good impedance matching and pattern results are shown.

OPSOMMING

Karakterisering en fase kompensasie van 'n enkelvlak golfgeleier na enkelvlak strooklyn balon

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Sleutelwoorde: Balon; Enkelvlak golfgeleier; CPW; Enkelvlak strooklyn; CPS; Wyeband; Enkelvlak; Balans; Fase korreksie; Toets prosedure.

'n Enkelvlak balon (BALans-na-ONbalans) wat van ongebalanseerde enkelvlak golfgeleier (CPW) na gebalanseerde enkelvlak strooklyn (CPS) transformeer, word gekarakteriseer deur simulasie en metings. Deur die effek van baie van die kritiese ontwerpsparameters te demonstreer, word die werking van die balon bespreek en 'n stel ontwerpskriteria opgestel. Die parameter studie bespreek die radiale ope struktuur se vorm en grote, die tipe en lengte van die CPW transformator and die dikte en tipe van die konneksie drade. Nuut ontwikkelde geëtste konneksie drade word geïmplementeer om beter vervaardigingsherhaalbaarheid en betroubaarheid te verseker. 'n Volledige balon toetsprosedure word ontwikkel en beskryf en bestaan uit drie aparte toetse. Die balon word getoets in die normale rug-aan-rug konfigurasie, as 'n enkel getermineerde balon en die grote asook fase van die wanbalans word bepaal deur die gebruik van 'n drie-poort toetsbaan wat aan die balon gekoppel word. Die voordele verbonde daaraan om hierdie volledige toetsprosedure toe te pas, en daardeur die balon volledig te karakteriseer, word deurlopend beklemtoon. Die resultate wat hierdie prosedure oplewer wys dat die basiese balon goed werk oor die volledige frekwensieband, behalwe vir die fase-wanbalans parameter, wat bruikbaar, maar nie ideaal is nie. 'n Eenvoudige tegniek om die fase-wanbalans van die balon te korrigeer word bekend gestel en getoets deur die drie-poort toetsbaan weer te gebruik. As 'n finale validasie word die balon aan 'n geëtste dipool gekoppel word, waarvan goeie impedansie aanpassings en patrone gewys word.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Over the past decade coplanar transmission lines have become accepted and are now regularly being used in many different applications. These transmission lines have several desirable characteristics, including ease of fabrication by using conventional photo etching techniques, small dispersion and easy integration to solid state devices and etched antennas. In many cases the most convenient type of coplanar line is coplanar strip line (CPS), which is inherently a balanced line and can thus be used to feed balanced devices and antennas. Coplanar waveguide (CPW), on the other hand, is unbalanced and can be directly connected to unbalanced coaxial cable. If this combination is to be used, a transition or balun from CPW to CPS should be implemented to accomplish the unbalanced to balanced transformation.

Several of these transitions have been suggested with various degrees of success. Probably the best known are the coplanar versions of the traditional Marchand balun which use quarter wavelength segments [1, 2]. An interesting alternative is to use an LC combination of lumped elements to replace the conventional quarter wave structure [3]. Both of these transitions have accurately predictable band pass characteristics with moderate bandwidths, limited by the resonant structures.

The double-Y balun [4] uses four resonant stubs to achieve a relatively wideband pass band with a compact design. However, for good bandwidth properties the design has to be done on a high permittivity substrate with very small gap sizes (in the order of 50 μm), which is not always achievable. Some other designs do not benefit from a finite open circuit structure [5-7], usually because only limited bandwidth is required. Larger bandwidths can be achieved but require very small etched gap sizes (of less than 100 μm) to operate effectively.

The basic balun structure that forms the topic of this dissertation was introduced by Tilley, Wu and Chang in [8], where it was tested in a back-to-back configuration and then implemented as a feed for an etched dipole. Since then this general structure has been improved on and successfully used as feed for other antenna applications such as spiral antennas [9].

Transitions between etched transmission lines, including these CPW to CPS transitions, are almost always characterised only in a back-to-back configuration [2-6, 9-14] (with the output from the first transition connected to the input of the second one). In this configuration the insertion and return loss of the combination of the two transitions can be readily measured. Although this basic test provides one with useful results, especially for comparative purposes, using it as the only test does have some disadvantages. The main problem is that it cannot provide one with a measure of the balance of a single transmission, which is necessary if the transition is to be used as a balun feed for a balanced device or antenna [15].

1.2 OBJECTIVES

The first objective of the study leading to this dissertation is to find and implement a topology capable of realising a CPW to CPS balun working over a minimum bandwidth of 0.5 to 2 GHz. The balun has to be implemented while keeping in mind some fundamental physical constraints including the type of substrate, which has to be FR4, and a minimum etchable gap size of 0.3 mm. The frequency band and limits are chosen so that the research outputs can be used for the international project called the Square Kilometer Array (SKA) [16], for which South Africa has a bid called the Karoo Array Telescope (KAT) [17]. This project aims to build the world's most sensitive radio telescope by combining the outputs from hundreds of individual reflector antennas; enough to cover a square kilometer of effective collecting area, thus the name. The original minimum required frequency band is 0.7 to 1.75 GHz. One of the options for the feed of the reflector antennas is to use a focal plane array of Vivaldi antennas, which can be electronically steered. The wideband balun designed here should be capable of feeding the Vivaldi antennas, but because literally thousands of these would have to built, it installs the need for inexpensive, but yet reliable manufacturing.

The main objective of this dissertation, however, is to develop a full procedure for testing, with which one can then test all the important characteristics of a balun, including its degree of balance. Although this test procedure is implemented on the CPW to CPS balun designed here, it must be usable on other types of etched baluns as well.

As a product of the other two objectives a third objective is formed. By implementing and fully testing this balun, it can be fully characterised for the first time. The important design considerations and the effect of the main design parameters, not previously published in the open literature, should be clearly shown. The results of the test procedure should illustrate the full characterisation of the balun including its return and insertion loss as well as the degree of magnitude and phase balance.

1.3 CONTRIBUTIONS OF THIS DISSERTATION

In this dissertation results of a more comprehensive characterisation of this balun type will be presented. There is no set of design equations to be found in the literature, and although a full analytic design is still not offered here, the effect of many of the relevant parameters and problems regarding the design are discussed. This gives much better insight into the working mechanisms of the balun, and thus enables one to design a more effective balun for a specific application.

Simulated as well as measured results are presented for a CPW to CPS balun on FR4 substrate with an operating bandwidth from 0.5 to 2 GHz and this implemented design is discussed in detail. An important characteristic of the newly designed balun is the implementation of etched bond wires, which is desirable for good manufacturing repeatability as well as reliability, in contrast to the traditional soldered-on bond wires.

A more complete test procedure is described and implemented. In addition to the back-to-back characterisation, the reflection coefficient of the balun as a single element terminated in a load is investigated. The magnitude and phase balance as a function of frequency is also determined using a test circuit, based on a characterisation technique described in [18] for a double-Y balun. This test methodology is presented as a general testing method for baluns. The importance of fully testing the balun, not just the basic parameters, is emphasised and the need for complete testing before final integration, including balance testing, clearly shown.

The design of a relatively simple phase compensation technique is shown and the resulting improvement in phase balance results is also presented, as implemented on this balun. As a validation of the balun, performance results of an etched dipole fed through the balun are discussed, with and without the additional phase compensation.

1.4 ORGANISATION OF THIS DISSERTATION

In Chapter 2 a broad overview of balun theory and standard designs are given, whereafter some of the more common etched transition designs are discussed, specifically those realisable in a uniplanar topology. These include the etched Marchand balun and the double-Y balun. The operation of the wideband single element type of CPW to CPS balun is then discussed in detail.

Chapter 3 illustrates the detailed design of the balun implemented here. The effects of the critical parameters and the main design considerations are shown using full wave simulation VSWR results of the single balun. Effects considered include those of the radial open, the CPW taper and the bond wires.

Chapter 4 then proposes the full testing procedure with special focus on the use of a balance testing circuit. This procedure is implemented on the balun designed in Chapter 3 and a full set of measured and simulated results is shown. The advantage, and importance, of using this full testing procedure is clearly demonstrated.

Following the complete testing procedure proposed in Chapter 4, Chapter 5 presents a phase compensating technique for improving any imbalance that may exist. Measured and simulated results for the phase compensated balun are presented by using the balance testing circuit of Chapter 4. As verification of this technique, and also to reiterate the importance of including the balance test in the balun characterisation, the balun is implemented as feed for a simple dipole antenna. This is done with and without the phase compensation, and the measured and predicted radiation pattern plots show a clear improvement.

Chapter 6 concludes the dissertation by summarising the work which was done and the main contributions of this study. The advantages and disadvantages of the designed balun as well as the testing procedure are also summarised. Finally some recommendations are made for future work to be conducted.

CHAPTER 2

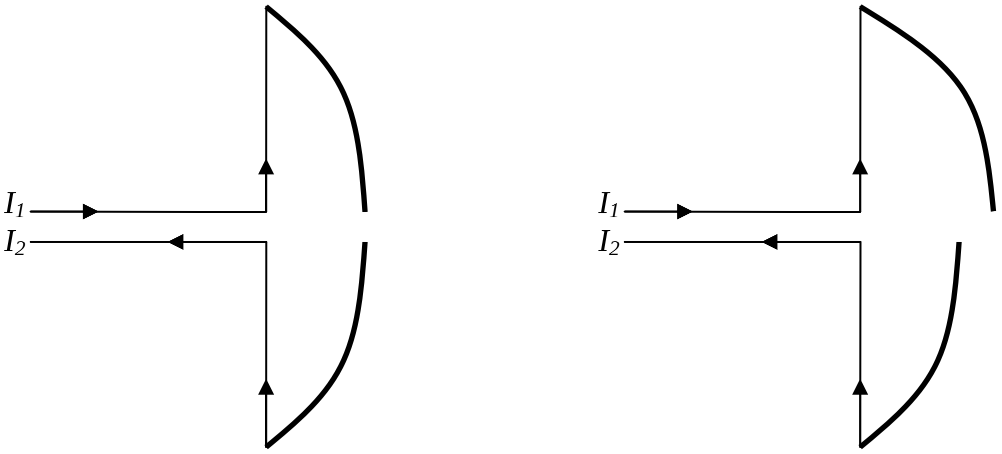
BACKGROUND ON GENERAL BALUN THEORY

This chapter provides a general background to the work discussed in the rest of the dissertation. The basic theory of baluns is discussed with special emphasis on etched baluns. Some examples of other types of CPW to CPS transitions are shown and discussed. The type of balun used for the purposes of this study is also discussed in detail.

2.1 GENERAL BALUN THEORY

Baluns form an integral part of many Electro Magnetic (EM) devices and circuits. They are used to transform an unbalanced form of transmission line (e.g. coaxial cable, microstripline and CPW) to a balanced form of transmission line (e.g. slotline, parallel stripline and CPS) - thus the word “balun”. This is necessary because many devices and antennas require balanced feeds; examples are mixers, hybrids, couplers, spiral antennas, dipole antennas and notch antennas. Apart from simply being a transition from one transmission line to another, a good balun also stops stray currents from propagating, which can cause squint in antennas, unwanted modes as well as measuring problems.

The best way of describing the problem is in terms of a parallel wire fed half-wave dipole antenna as shown in Figure 2.1 [19]. When currents I_1 and I_2 are equal in magnitude and opposite in direction, the feed is called balanced and does not radiate. If, however, the one current is larger than the other, and is thus unbalanced, this results in a net current flow on the transmission line. This uncontrolled current can cause radiation of the transmission line itself, which might not be in the direction required of the attached antenna or even have the correct polarisation. The secondary problem is that this unbalanced current on the antenna will cause its radiation pattern to change. Having an unbalanced transmission line feeding a symmetric antenna is thus clearly undesirable and highlights the need for a balun.



(a) ***I1 = I2*** **(b)** ***I1 > I2***

Figure 2.1. Half-wave dipole fed by balanced (a) and unbalanced (b) parallel transmission line, with (a) resulting in a symmetric current distribution and radiation pattern.

Parallel lines are an example of a balanced transmission line, but coaxial cable, which is very often used, is unbalanced. Although the waves travelling down the cable are considered balanced, as the current on the inner and outer conductors are equal and opposite, a current will flow on the outside of the outer conductor when it is connected to a symmetric antenna, making the transmission line and the antenna unbalanced. This happens because the inner and outer conductors of the coaxial line are connected to the antenna in different manners.

A simple type of balun, which is relatively easy to construct, is called the folded balun [19] or quarter-wave coaxial balun [20] of which a representation is shown in Figure 2.2. To construct this balun an extra piece of coaxial cable is connected between the feeding coaxial cable and the antenna side which is connected to the inner conductor of the feed. This extra cable should be a quarter of a wavelength long. This cable combines with the outer of the main transmission line to form another transmission line, but it is shorted at the connection point so that it transforms to an infinite parallel impedance at the antenna input. This means that this type of balun has no effect on the input impedance. The quarter-wavelength line induces another current on the outside of the outer conductor, which cancels the unbalanced currents, so that no current is present on the outside of the cable below the connection point.

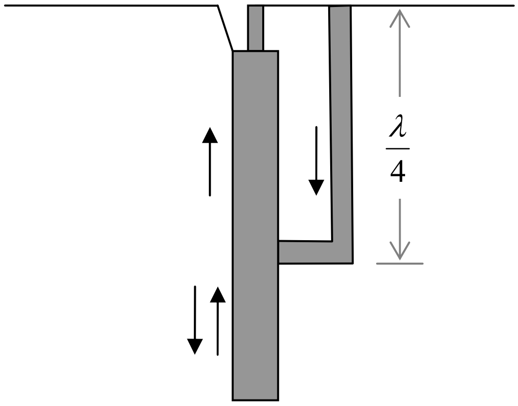


Figure 2.2. A representation of a folded balun.

Another, similar type of balun is the sleeve [19] or bazooka [20] balun, which uses a quarter-wave sleeve around the whole coax. These types of balun work well at relatively high frequencies (higher than 1 GHz), but at lower frequencies the finite length required tends to become limiting. Even at these higher frequencies studies have shown that this type of balun might not be as effective as generally accepted [21]. Also, these are obviously only narrow band solutions and can not be used for a larger bandwidth like the 0.5 to 2 GHz required for this application. At lower frequencies wound transformers are often used successfully, and with a ferrite core can obtain bandwidth of as much as 10:1 [20]. It has the additional advantage that it can simultaneously be used as an impedance transformer.

2.2 WIDEBAND BALUN CONFIGURATIONS

Applications requiring high frequency, broadband performance have to use other types of baluns. This subsection discusses some of the commonly used types in more detail, with specific emphasis on their etched implementations.

2.2.1 Tapered Balun

A relatively simple implementation of a wideband balun, is the tapered balun [19]. It is created by systematically tapering the unbalanced line to a balanced one over several wavelengths. This can be done in coaxial line by cutting the outer conductor on an angle, which then leaves the thin, cut end to form a parallel line transmission line with the extended centre conductor. It is also often implemented in microstrip line tapering to an etched parallel line as shown in Figure 2.3.

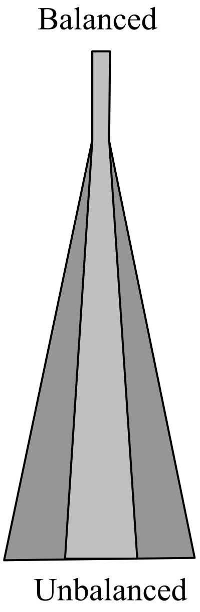


Figure 2.3. A tapered microstrip to etched parallel line balun.

The tapered coaxial balun has been used to feed a number of wideband antennas including TEM horns and Vivaldi antennas [22]. The etched version is often used to feed spiral antennas and uniplanar Vivaldi antennas [23-28]. The main disadvantage of this type of balun is that it has to be electrically long to achieve good balance results. For proper operation at 500 MHz the taper would have to be at least 1m long, obviously far too long to be of practical use. It must be stated that many applications have indeed used these tapered baluns where the total length was much less than one wavelength, but then the reduced squint and cross polarisation performance is acceptable. In general this type of balun, with manageable length, has considerably poorer balance performance than other types of commonly used baluns, e.g. the Marchand balun, which will be discussed next.

2.2.2 Marchand Balun

The Marchand balun, which was originally introduced in 1944 [29], is probably the most commonly used balun for wideband, high frequency applications in the antenna industry. The equivalent circuit is shown in Figure 2.4 [2], and exhibits a well defined band pass characteristic response. The full design procedure for a Chebychev passband characteristic is given in [30], or an approximate closed form solution is presented in [2].

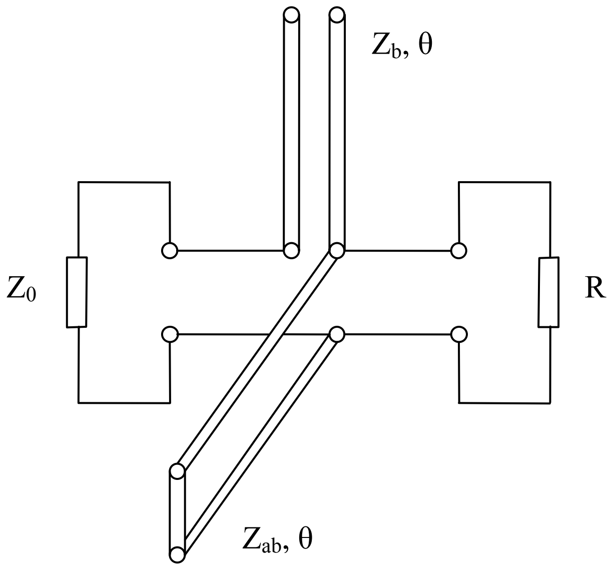


Figure 2.4. Equivalent circuit for a Marchand balun.

These baluns are regularly used as feeds for commercially available wideband spiral antennas, generally implemented in its second or third order form by using coaxial cable inside a metal cavity controlling the relative impedances and the centre frequency. Standard antennas with these Marchand baluns are capable of achieving more than a 9:1 bandwidth and have proven their good balance by the tight specifications attainable. Squint levels are well below 5° and axial ratio levels are generally below 1.5 dB at the radiation pattern peak over the full frequency range. This is noticeably better performance than those obtained by similar spirals with inline tapered baluns.

Marchand baluns have also been successfully implemented in etched form, mostly using microstrip line as input [1, 2]. An example from [2] is shown in Figure 2.5. The etched version has the advantage that it is inexpensive and less complex to realise some of the higher impedances needed in the design. In general, however, it is not possible to realise bandwidths as high as those of the coaxial versions. These etched baluns were introduced in 1960 [1] where it was used to feed a spiral antenna over an octave frequency band. This balun was fed in microstrip and the output was in slotline which rapidly tapered into co-planar stripline for easy connection to the spiral antenna.

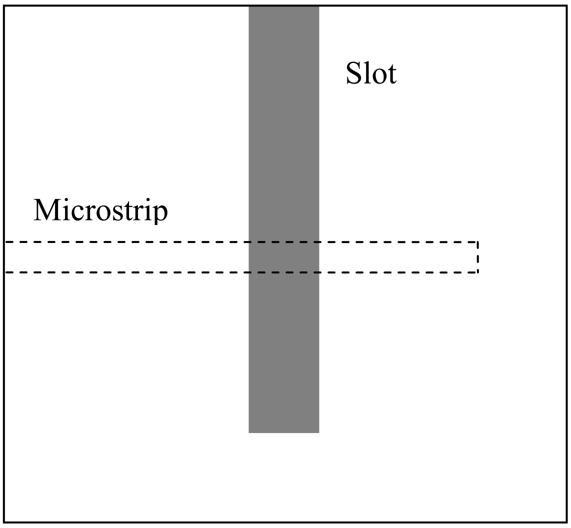


Figure 2.5. Microstrip to slotline etched Marchand balun.

Several variations of this basic etched balun have been seen over the last decades, with different types of terminating structures to improve the useable bandwidth of the balun. Specifically, many papers have been published for tapered slot (Vivaldi) antennas with stripline to slotline feeds. Square terminations were originally implemented and a full parameter study [31] showed a maximum usable bandwidth of about 4:1. Since then different combinations of square, circular and radial terminations have been studied [32, 33]. The most common combination now in use seems to be a radial stripline stub and a circular slotline cavity [34, 35] with a maximum bandwidth of about 6:1. Such an example is shown in Figure 2.6.

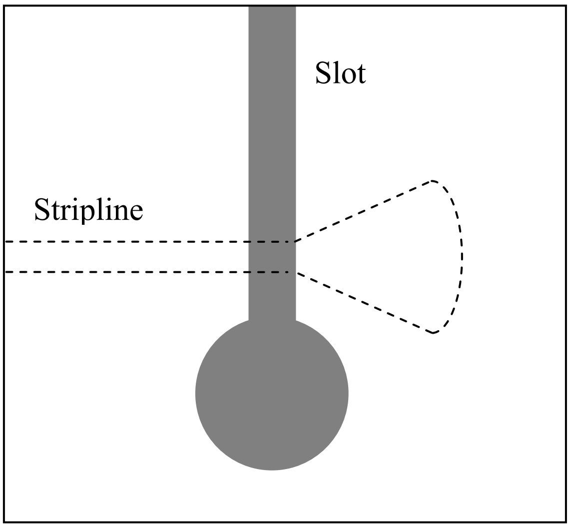


Figure 2.6. Stripline to slotline balun with radial stub and circular cavity.

Marchand baluns and their derivates have thus been regularly used successfully as feed for many different antenna applications. The traditional quarter-wave versions have a very precisely defined bandpass characteristic, with proven design techniques. The etched versions of these baluns are, however, limited to about a 3:1 usable bandwidth. By using other types of terminations the bandwidth can be increased to about 6:1. The balance of these baluns has not been pertinently tested, but has proven to be good over the full band by numerous successful implementations of different antenna types with good final radiation pattern performance. A CPW to CPS implementation is shown in the next section.

2.2.3 Double-Y Balun

The double-Y balun is another type of balun that can be used and is readily etchable. It is not nearly as widely used as the Marchand balun varieties, but a number of papers have been written about its design and performance. The basic theory describing the operation of the balun is given in [36] and the equivalent network is shown in Figure 2.7.

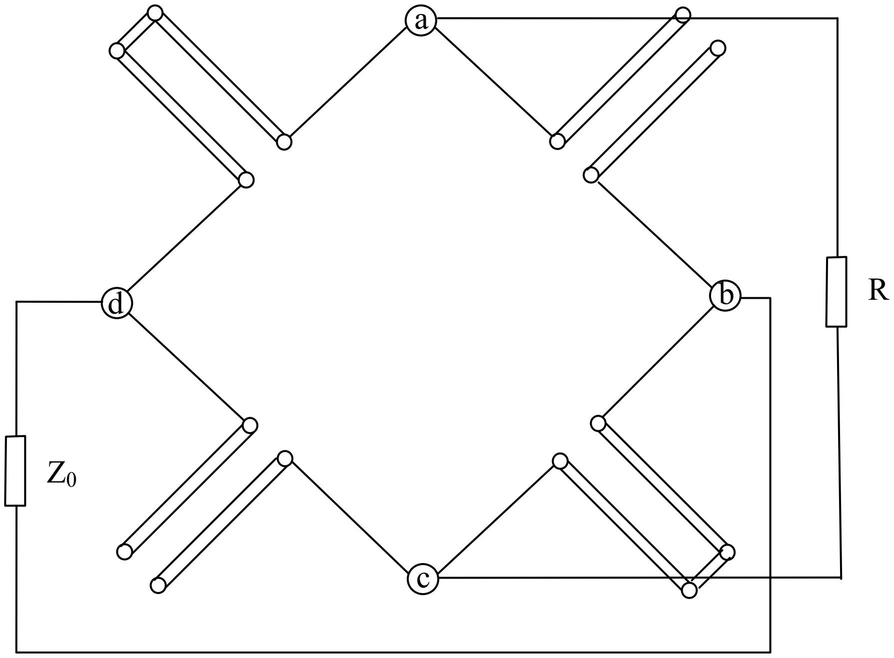


Figure 2.7. Equivalent circuit for a double-Y balun.

A double-Y balun consists of a 6-port double-Y junction, with three of the ports being balanced, and the other three ports being unbalanced, alternating around the centre of the structure. When junction effects are neglected each two opposite ports are uncoupled and the other four ports are matched. If opposite pairs of balanced and unbalanced lines are chosen so that they have opposite reflection coefficients (i.e. short and open circuits), the input signal on an unbalanced port is equally divided between the other four ports, and a balanced signal is obtained. From this basic theory the double-Y balun should exhibit an all-pass characteristic. In practical applications, however, the baluns tend to rather show a low-pass or even band-pass characteristic.

An example of this structure being implemented as a transition from microstrip to slotline [36] is shown in Figure 2.8. The high end frequency limit is set by the bandwidth of the slot line open circuit and the minimum gap size that can be accurately etched. The example in [36] uses a circular open and a minimum gap size of 0.1 mm on an alumina substrate (ε_r = 9.8) to achieve a bandwidth of 6:1. The next section also shows a CPW to CPS implementation, which is capable of wider bandwidths, with an upper frequency limit of 8.7 GHz.

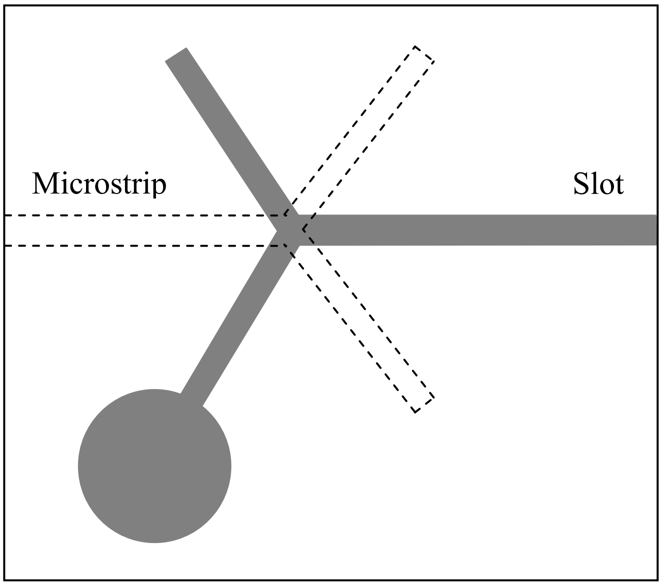


Figure 2.8. Microstrip to slotline double-Y balun.

In conclusion, the double-Y balun does have some advantages over the better known Marchand balun. Although it is more complex, it does not really pose a problem as it can be etched with good repeatability. Its inherent inline nature proved to be an advantage in many applications. It is possible to obtain bandwidths larger than 6:1, but its main disadvantage is that very small etching tolerances and high permittivity substrates are needed to achieve good high frequency performance. This makes it difficult to use in some applications, including the problem being dealt with in this dissertation.

2.3 WIDEBAND CPW TO CPS BALUNS

In the previous two sections some general examples of baluns were discussed. In this section three types of baluns which can be implemented in a CPW to CPS configuration are presented.

In the case where an etched antenna is to be fed, CPS is often the most useful form of transmission line to use. These antennas include etched dipoles [8], bow-ties [7] and notch or Vivaldi antennas [12-14]. CPS consists of two parallel metallic strips next to each other, with a small gap in between, which thus lends itself to easy connection to an antenna as specified above. The combination of the track and gap widths determines the characteristic impedance of the transmission line. The main advantage of the etched antenna and its feed structure to be uniplanar (on the same side of the dielectric board), is that the antenna is automatically more symmetric, which can result in better antenna radiation pattern parameters such as squint, axial ratio, cross polarisation and ripple. It is also easier and less expensive to manufacture.

CPW, on the other hand, can be seen as the uniplanar version of the microstrip transmission line type. It consists of a centre metallic strip, with a larger ground strip on each side of it, again on the same side of the dielectric structure. The combination of the strip width, together with the two gap widths (which is usually equal) defines the characteristic impedance of this type of transmission line. It automatically lends itself to easy integration with coaxial cable and connectors, but cannot directly be used to feed symmetric, etched antennas; thus the need for the CPW-CPS transition or balun.

2.3.1 CPW to CPS Marchand Balun

The Marchand balun in its general form was discussed in subsection 2.2.2. Here its implementation in the CPW to CPS form is considered. Figure 2.9 shows an example of such an implementation.

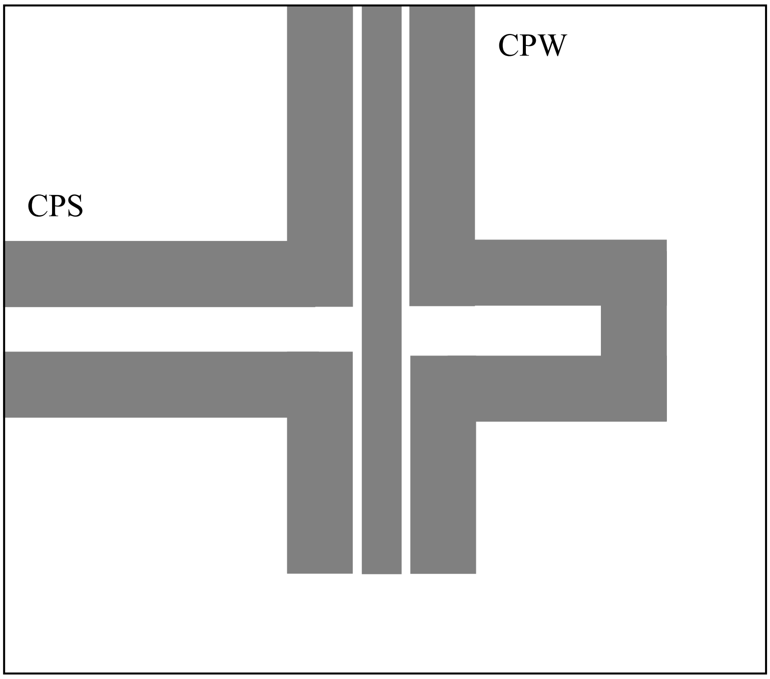


Figure 2.9. CPW to CPS Marchand balun.

The Marchand balun is relatively seldom implemented in this way, but it was done in [2]. The substrate used is 0.636 mm thick alumina with characteristic impedances of 50 Ω for the CPW and 70 Ω for the CPS. The bandwidth achieved in this case is 2.7:1, but the losses in the pass band seem to be rather high. This is because of the fact that transmission lines start to radiate when the open or short circuits are electrically longer than 45°. Co-planar transmission lines are particularly susceptible to this problem.

In general, these baluns tend to have smaller bandwidths than calculated, because of the radiation effects which can no longer be neglected. The CPW to CPS implementation also tends to have worse performance than its microstrip to slot line counterpart. Although very little information is available, it would seem as though the maximum achievable bandwidth is probably no more than 3:1, which makes this option unusable for the application at hand.

2.3.2 CPW to CPS Double-Y Balun

The basic configuration as well as the microstrip to slotline implementation was discussed in subsection 2.2.3. In [4] this balun is implemented as a transition from CPW to CPS and a representation is shown in Figure 2.10.

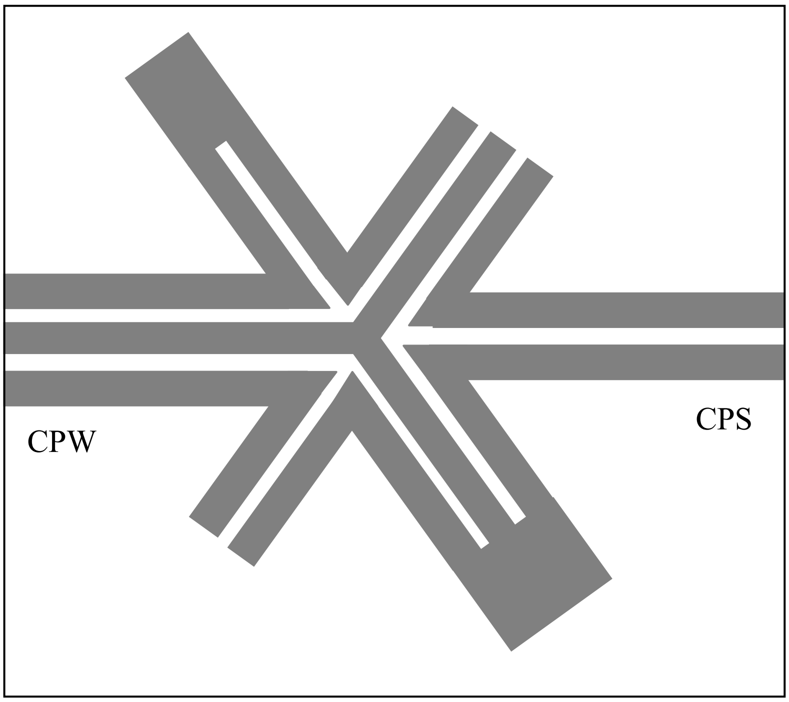


Figure 2.10. CPW to CPS double-Y balun.

It was shown that, although the double-Y balun is theoretically capable of all pass performance, the microstrip to slotline version showed band pass characteristics over a 6:1 bandwidth. As an improvement on this the CPW to CPS version was designed in [4]. This configuration has the advantage that it is possible to implement almost ideal open and short circuits, so the frequency range is not limited by the finite open as in the previous case. This implementation shows true low pass characteristics, with the upper frequency being limited by the minimum gap width that can be etched. In [2] and [4] such baluns are implemented on 0.635 mm thick alumina. The baluns are well matched from practically DC. Particularly good performance over a wide bandwidth is achievable. Using a minimum gap size of 50 µm the upper frequency limit is 6 GHz and with a gap size of 20 µm it goes up to as high as 13.5 GHz. This type of balun also suffers from the transmission line radiation problems like the Marchand balun, but apparently to a lesser degree.

The main disadvantage of this type of balun is described in a follow up paper in [18]. It was noticed that the balun did not perform as well at lower frequencies as its matching would indicate. A test circuit was designed to test the magnitude and phase balance of the balun over the full frequency range. It was shown that, although the balun is well matched from DC to 13.5 GHz, the imbalance turned out to be very large at the lower frequencies. The magnitude balance was measured to be less than 1.5 dB only from 2.5 GHz upwards, significantly reducing the usable frequency range of this balun.

It has been shown that the double-Y balun has the capability of achieving very wide bandwidths when implemented in CPW to CPS. Unfortunately very small etched gap sizes are required to achieve these bandwidths. When looking at the available data, it seems that the required upper frequency of 2 GHz would probably not be achievable with the available 0.3 mm minimum gap size. Even without this limitation, the doubly-Y balun’s imbalance in the required frequency range of 0.5 to 2 GHz precludes it from use for this application.

2.3.3 CPW to CPS Single Element Balun

Another type of balun, not yet discussed, uses a single open circuit element to accomplish the transformation and is inherently inline. Several of these transitions have been shown in the literature, with the first account being in [8], where it was tested in a back-to-back configuration and then used to feed an etched dipole antenna. Mostly, work on this type of balun does not explicitly name the balun, except for calling it a “wideband CPW to CPS balun”. For clarity’s sake it is here described as the “single element balun”, or later in the dissertation simply as the “wideband balun”. The basic layout of the single element inline CPW to CPS balun is shown in Figure 2.11.

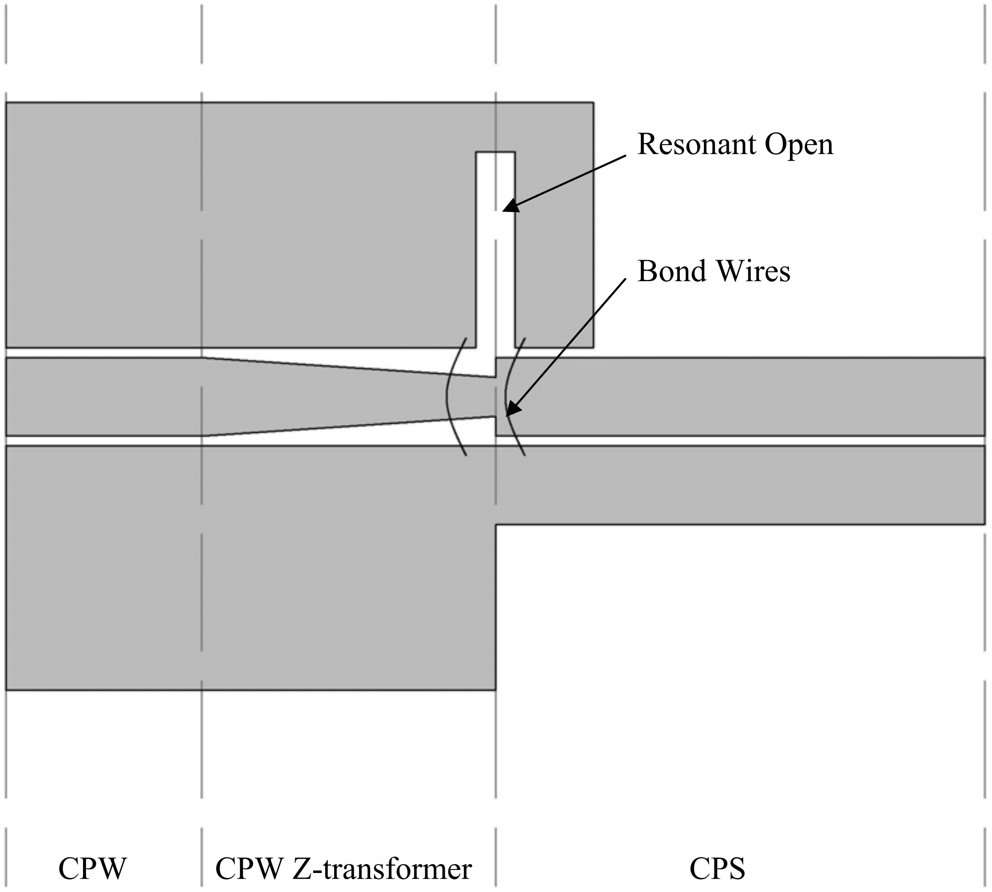


Figure 2.11. Basic layout of a single element CPW to CPS balun.

The first section of the balun is implemented in CPW and is fed directly from a coax cable. The impedance of this section is thus almost always chosen as 50 Ω for a good match. The last section of the balun is implemented in CPS, but its characteristic impedance is often not 50 Ω. This might be to match to the antenna to be fed, a dipole for example, but most of the time it is done because it is not easy to implement 50 Ω CPS without using very small gap sizes. This mismatch between input and output impedances forces the need for an impedance transformation section, which can readily be implemented in the CPW section. Linear tapers [37], single [7] and multiple [9, 38] quarter wave transformers have been used in the literature. Here, of course, the trade off between total length and a good impedance match has to be considered. To accomplish the actual CPW-CPS transformation some form of wide band open circuit structure is used to force the currents to flow between the two CPS conductors. In some specific applications a straight forward quarter wave stub can be used, but will only offer relatively narrow band performance. For wider bandwidth applications both circular [8] and radial [9, 38, 39] stubs have been implemented successfully.

Bond wires are used to suppress the generation of unwanted non-CPW modes and ensure that the potential on both ground planes are equal. These bond wires are usually soldered directly onto the substrate tracks. To achieve the best high frequency performance the wires must be very thin and be located as close as possible to the discontinuities.

Several of these baluns have been measured in a back-to-back configuration and published results are available for comparison [1, 9, 37 and 38]. Similar to the double-Y balun, this balun also shows typical low pass characteristics, with the upper frequency being limited by die minimum etchable gap size. In these examples upper frequency limits range from 3GHz to 5GHz, inversely proportional to the minimum gap size ranging from 0.1mm to 0.4mm. To achieve this performance, many of these baluns are built on relatively expensive high performance and high permittivity substrates, e.g. RT-Duroid with ε_r=10.2. Even though this balun has not yet displayed the very high bandwidths of the double-Y balun, it does in fact seem more capable of obtaining the required 2GHz upper frequency with realistic minimum gap sizes in the order of 0.3mm. The achievable bandwidths are still larger than those shown for the etched Marchand balun.

Apart from these advantages, there are some other properties that also make this balun more desirable than its competitors. Like the double-Y balun it is inherently inline, but is usually smaller. Unfortunately, none of the published articles have shown any degree of balance measurements for this type of balun, so it is unknown whether it suffers from the same low frequency imbalance problem as the double-Y balun. It is also less complicated to design and to do the lay-out. Its main disadvantage is that, unlike the Marchand balun and to a lesser degree the double-Y balun, it does not have an accurately predictable pass band, and the factors contributing to its final performance is not well documented. This means that designing this type of balun can be more time consuming, and require more iterations than the other types of balun. This problem is also addressed in this dissertation.

Looking at these three possibilities for CPW to CPS baluns, it is evident that only the single element balun is capable of achieving the required specifications within the set restraints. The rest of the dissertation thus focuses more on this type of balun and also uses it to implement the full test procedure for baluns.

CHAPTER 3

THE DESIGN AND PARAMETRIC STUDY OF SINGLE ELEMENT BALUNS

In this chapter the detailed design and operation of the single element balun is discussed, while investigating the effects of some of the important design parameters. The first subsection discusses the implementation of a single element CPW to CPS balun. The second subsection then shortly discusses the basic simulated balun performance as a point of reference for the rest of the chapter. The third section of the chapter uses simulated results to investigate the effects of the main parameters of the balun to highlight some of the necessary design considerations and to help improve future designs.

3.1 THE IMPLEMENTATION OF THE SINGLE ELEMENT BALUN

A single element wideband CPW to CPS balun as described in the previous chapter was designed and implemented and is shown in Figure 3.1 with its overall dimensions.

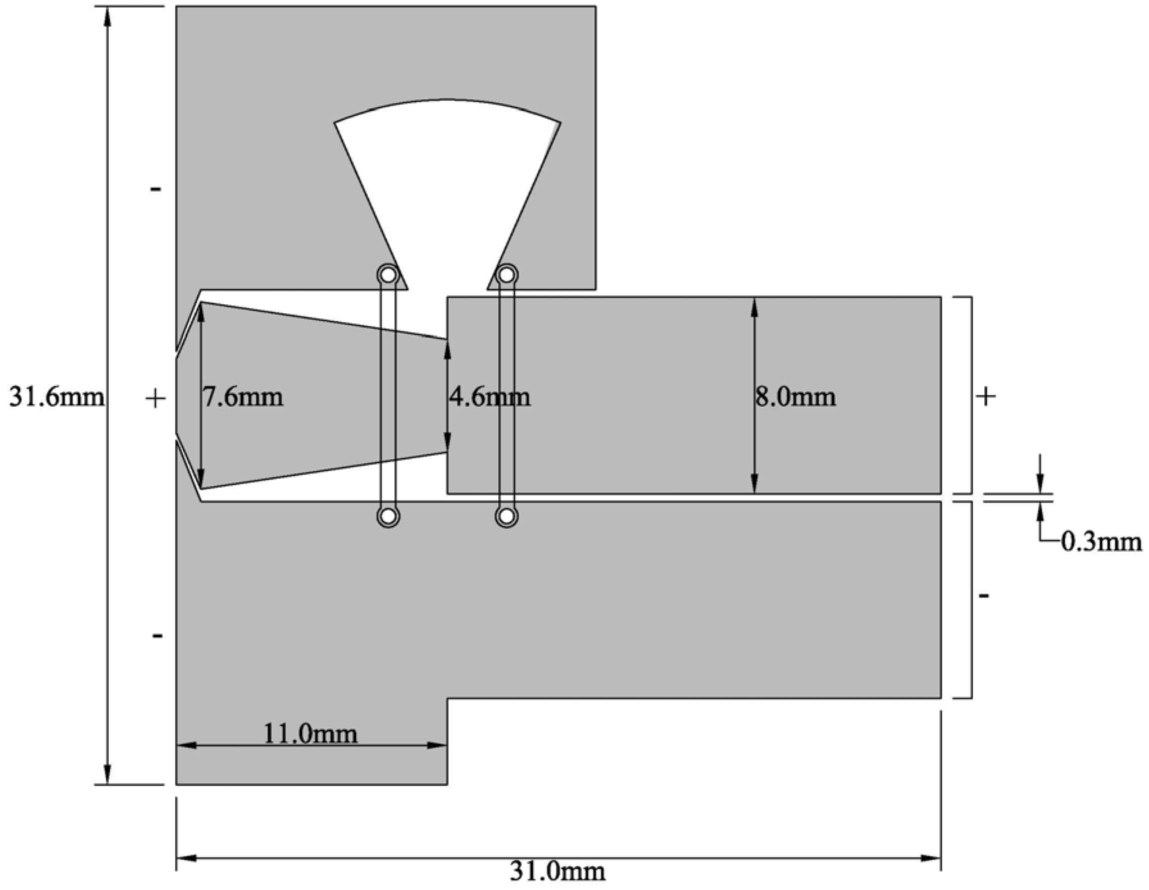


Figure 3.1. Detailed balun design layout.

The balun is designed for a specific application which needed an operating frequency band of at least 500 MHz to 2 GHz. The design was done for implementation on 0.8 mm thick FR4 substrate (ε_r = 4.4), which is readily available and relatively inexpensive, and thus especially suitable for low frequency applications with possible high production volumes. The balun is only 31 mm long and 31.6 mm wide. The available technology unfortunately limited the design to a minimum gap size of 0.3 mm, which, together with the FR4 substrate, does limit the upper usable frequency of the balun to a large extent.

The width between the two CPW ground planes can be designed to be the same as the corresponding width at the CPS output by taking great care in choosing the impedances and the different combinations that can result in the required values. This is done in order not to introduce one more discontinuity and to improve the symmetry of the whole structure. This can be accomplished by first finding a solution for the required CPS impedance where the minimum gap size usually has to be used. In this case the lowest impedance realistically realisable with a minimum gap size of 0.3 mm is 80 Ω, which corresponds to an 8 mm strip width on either side of the gap. To ensure the continuous width from the CPW input, the distance between the two ground planes is thus set to 8.6 mm. A 50 Ω CPW input line can be implemented with a strip width of 7.6 mm and gap sizes of 0.5 mm.

A linear taper is implemented in the CPW region for a 50 Ω to 80 Ω impedance transformation. The 80 Ω CPW is implemented with a 4.6 mm strip width and a 2 mm gap width. This relatively short transformation can be tolerated in this design because of the fact that 50 Ω and 80 Ω are relatively close to each other and that the total length had to be kept as short as possible.

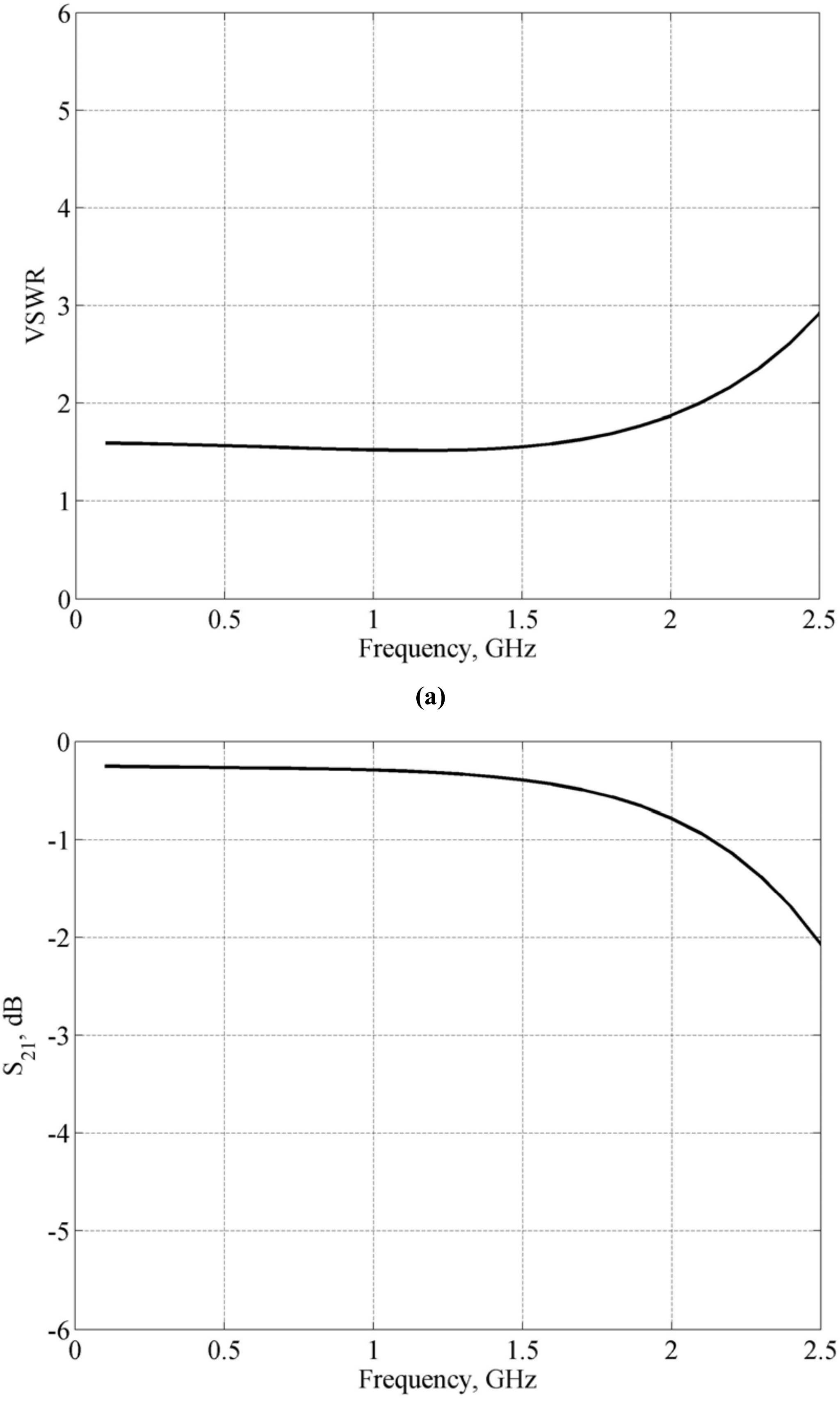
A radial stub was implemented as wideband open. Although there is some conflicting evidence in the literature on whether the radial or circular stub offers wider bandwidths, most authors do seem to lean towards the radial stub [38]. Both exhibit an inherently wide band match, more so than the narrow band quarter wave or even the rectangular stub. The implemented open has a radius of 12 mm and an angle of 45°.

As can be seen in Figure 3.1, the implemented bond wires are somewhat different from the usual soldered on bond wires. It was found that it is rather difficult to consistently solder these wires on to give repeatable results. It was found that even a small change in position, length or amount of solder used limited repeatable results, and ultimately inhibited accurately comparisons between measured and simulated results. As a way to improve this lack of consistency a new form of bond wire was implemented. This new bond wire is etched onto the bottom side of the same substrate and connected via through plated holes to the top surface. Due to the fact that this is now also done by using a photo etching technique, the performance of the bond wires is now precisely predictable and perfectly repeatable. It has a number of other advantages in that it also improves the reliability of the circuit while simplifying the production process, should larger quantities be needed. The bond wires need to be as thin as possible, but the available technology for the through hole plating limited this to a minimum of 0.6 mm.

3.2 THE PERFORMANCE OF THE SINGLE ELEMENT BALUN

This section will show the basic simulated performance and explain the operation of the designed balun. All simulations were done using the full-wave analysis software Zeland IE3D [40].

Figure 3.2 shows the simulated VSWR and Insertion Loss (S_{21}) of the designed balun. The output CPS is terminated in 80 Ω. If a VSWR of less than 2:1 is used as acceptable the theoretical performance of the balun is a frequency band of at least 100 MHz up to 2.1 GHz. This exceeds the required minimum frequency band of 0.5 to 2 GHz. In this frequency band the loss through the balun is also less than 1 dB (as shown in Figure 3.2(b)). The power is thus efficiently transmitted though the structure to the output port, without any undue radiation as is often a problem with uniplanar structures.



(a)

(b)

Figure 3.2. Simulated VSWR (a) and S_{21} (b) of the designed balun.

The basic operation of the balun was described in section 2.3.3. Figure 3.3 shows a graphical representation of the surface currents present on the balun, which helps to visualise and better understand the working of the balun. The figure shows where the high concentrations of currents are situated. It can be seen that in the CPW the currents are evenly distributed on each side of the centre conductor between this centre strip and the ground planes. What the stub, together with the bond wires accomplish is to transform these currents to the balanced CPS structure, where the currents are more or less evenly distributed on the edges between the two conducting strips of the transmission line.

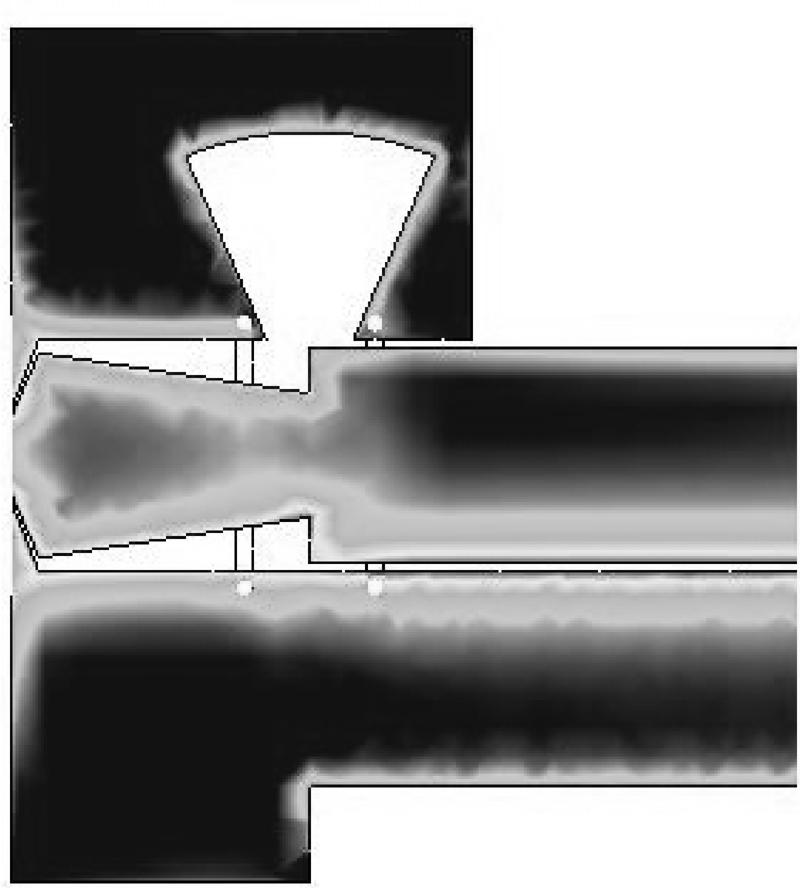


Figure 3.3. Graphical representation of the current distribution on the balun.

3.3 DETAIL PERFORMANCE AND PARAMETRIC STUDY OF SINGLE ELEMENT BALUN

In this section a detailed parametric study of the balun is presented. The aim is to develop a detailed set of design guidelines for the single element balun. All the published articles on this balun [7-9, 37], except [38], only briefly discussed the balun design and performance. The operation and performance of the balun is discussed in detail in [38] to highlight the operating principles of the balun, but no design guidelines or criteria are discussed or presented.

The initial design consists of specifying the port impedances, and thus the widths. A number of parameters which will influence the performance of the final circuit remain to be specified. This section investigates the effect of the key parameters in the design on the overall balun performance. The outcome is a better understanding of the detailed workings of the balun, to improve future designs as well as reduce the time needed for any similar balun designs. The balun parameters to be investigated are the radial open, the CPW taper and the bond wires.

3.3.1 The effect of the radial open on the performance of the balun

The first thing to investigate is the size of the wideband radial open. Figure 3.4 shows the VSWR of the balun with three different sizes ranging from 6 mm to 15 mm in length, with the final designed length being 12 mm, and a 0 mm configuration where the slot has been removed completely. The interesting observation to make here is not to find the differences between the finite sizes, but rather the fact that the size differences have a very small effect on the final VSWR. This is why some researchers are content to use the balun without any open circuit structure [7] or with an infinite open structure [5]. However, Figure 3.4 also clearly shows that the effect is not negligible. A smaller slot results in a 3% higher cutoff frequency than the 15 mm slot, but with a slightly worse VSWR around 1.5 GHz. Leaving the slot completely out, however, results in a much lower cutoff frequency below 2.0 GHz. The cutoff frequency of the balun can thus be tuned by changing the size of the open slot, but only to a very small degree. The actual inclusion of a finite slot is still important to obtain the high frequency performance.

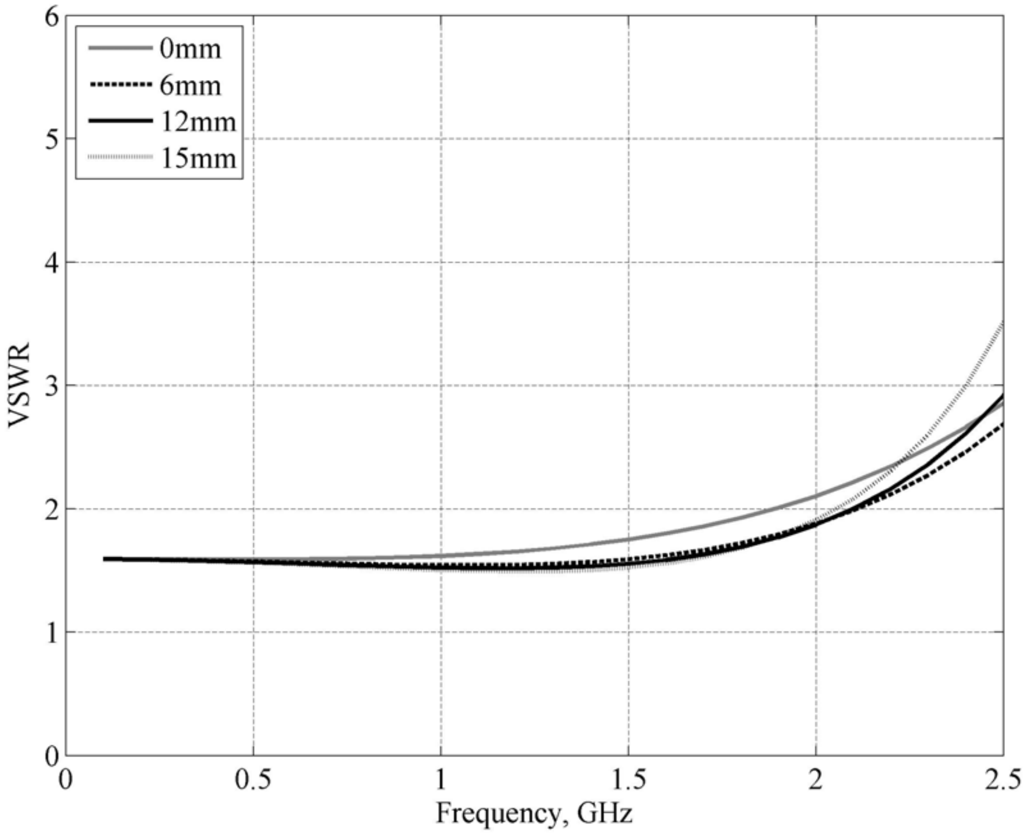


Figure 3.4. Effect of different size radial slots on the VSWR of the balun.

3.3.2 The effect of the CPW taper on the performance of the balun

A parameter that has a much larger impact on the overall performance of the balun is the length of the CPW taper. It has been stated in the literature that the total length of the balun is inversely proportional to the upper usable frequency of the balun [38], which does seem a bit counterintuitive. However, experiments run on this balun show exactly this same trend. These results are shown in Figure 3.5.

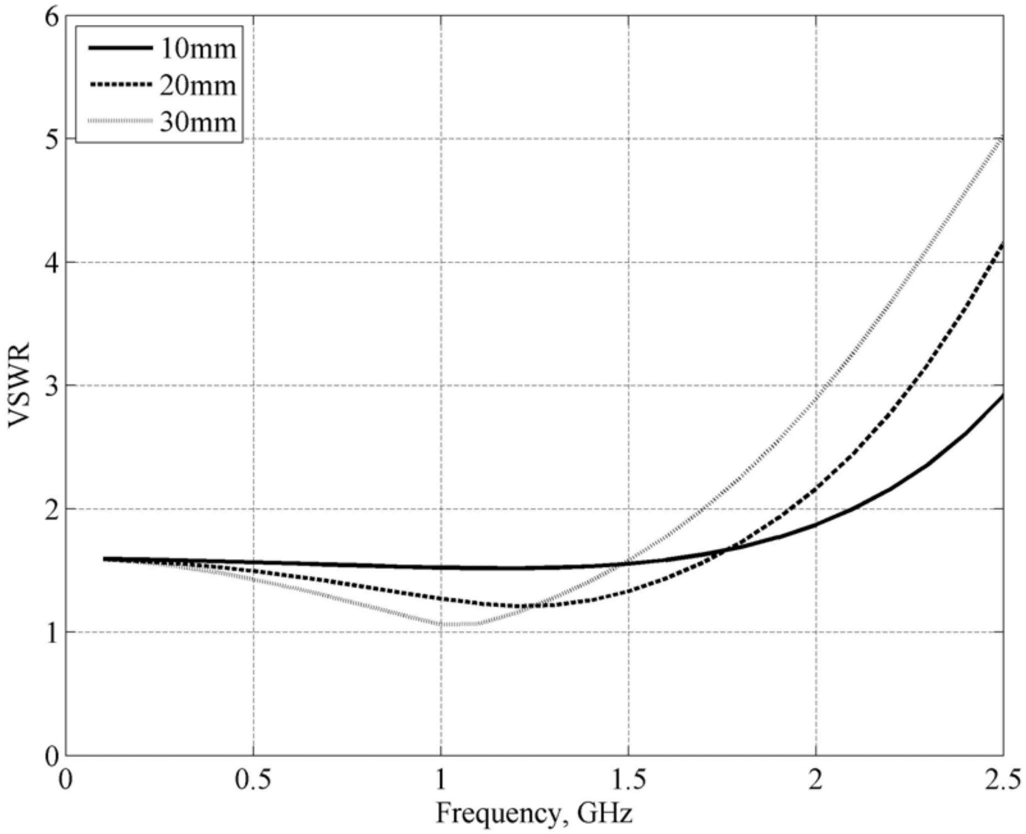


Figure 3.5. Effect of different length CPW impedance tapers on the VSWR of the balun.

It can clearly be seen that a balun with a longer taper will have a better general VSWR in the middle part of the band, but that it will then also have a lower upper cutoff frequency. The better VSWR is easily explained by the fact that the longer taper will be more effective at lower frequencies, and actually starts to perform as a proper impedance transformer. The longer the taper length, the lower the frequency where it starts to perform effectively. However, there is definitely a secondary effect which causes a balun with a longer taper to have a lower cutoff frequency. This effect is not caused purely by the longer taper, but is rather a function of the total balun length, which obviously also increases with a longer taper. This phenomenon has to do with the total length of the balun starting to be resonant at the higher end of the frequency band and causing the impedance match to degrade in the process. Naturally the longer the balun is, the lower the resonant frequency and the lower the resulting cutoff frequency becomes. This means that the final VSWR performance of the balun is a strong compromise between getting the VSWR as good as possible by making the taper as long as possible, but still keeping the high end cutoff frequency as high as possible by keeping the total balun length as short as possible. This turns out to be a very important design criteria and one which is worth carefully considering when designing a balun.

In this specific design the impedance transforming taper turned out to be extremely short (only 10 mm), and would seem to have no effect of the low frequency band. Figure 3.6 shows the difference between having this short taper and having no taper at all, thus going directly from 50 Ω CPW to 80 Ω CPS. It clearly shows that even this relatively short taper improves the impedance match of the balun over the entire frequency band and improves the upper usable frequency by more than 40%. The taper is thus an essential part of the total design and cannot be ignored.

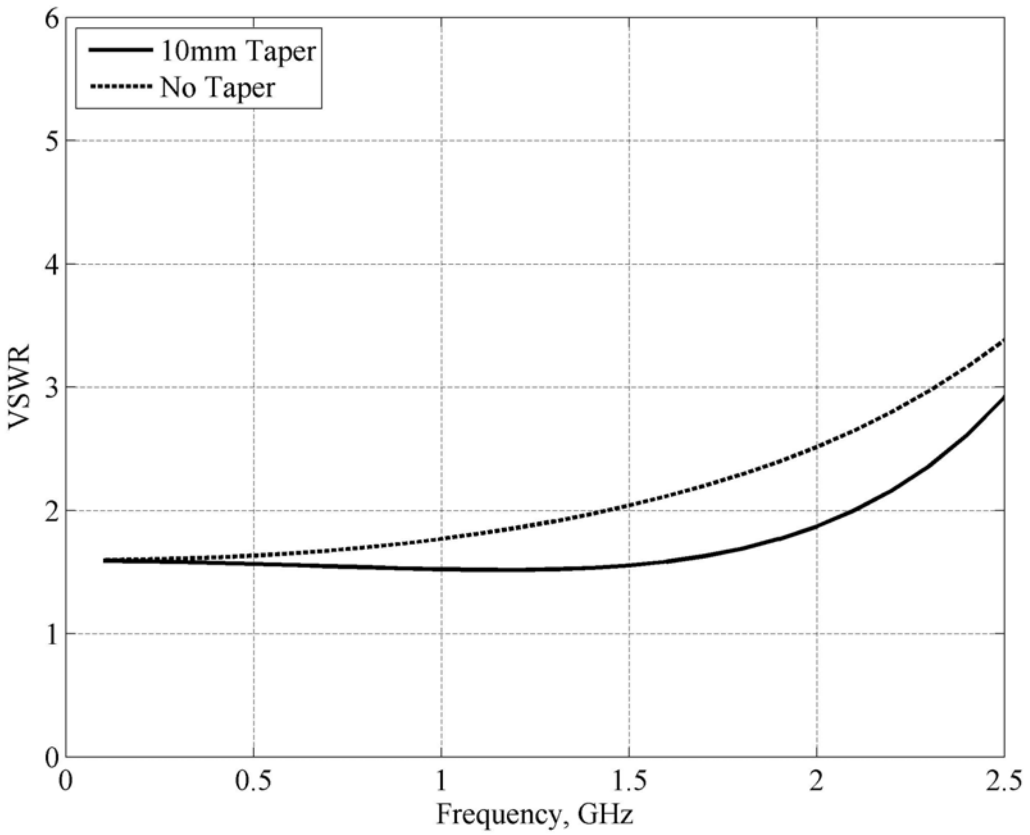


Figure 3.6. Difference between a short taper and no taper on the VSWR of the balun.

An interesting observation is that in all the plots, including those in Figures 3.5 and 3.6, the low end VSWR seems to converge to a value of 1.6:1. This is the region where the lengths of the taper and the total length of the balun actually have very little effect, as it is starting to become insignificantly small in terms of wavelength. One can compute the VSWR resulting from an impedance mismatch by using a simple formula [19]. The calculated VSWR mismatch between 50 Ω and 80 Ω works out to be 1.6:1, exactly the simulated values in the graphs, which shows that this convergence value is precisely predictable and can thus be designed for.

3.3.3 The effect of the bond wires on the performance of the balun

Bond wires are implemented to suppress unwanted modes in CPW transmission lines. Figure 3.7 shows the effect of bond wires on the VSWR of the balun and proves that the bond wires are an integral part of the balun design, although very few authors tend to discuss them or even mention or show their use.

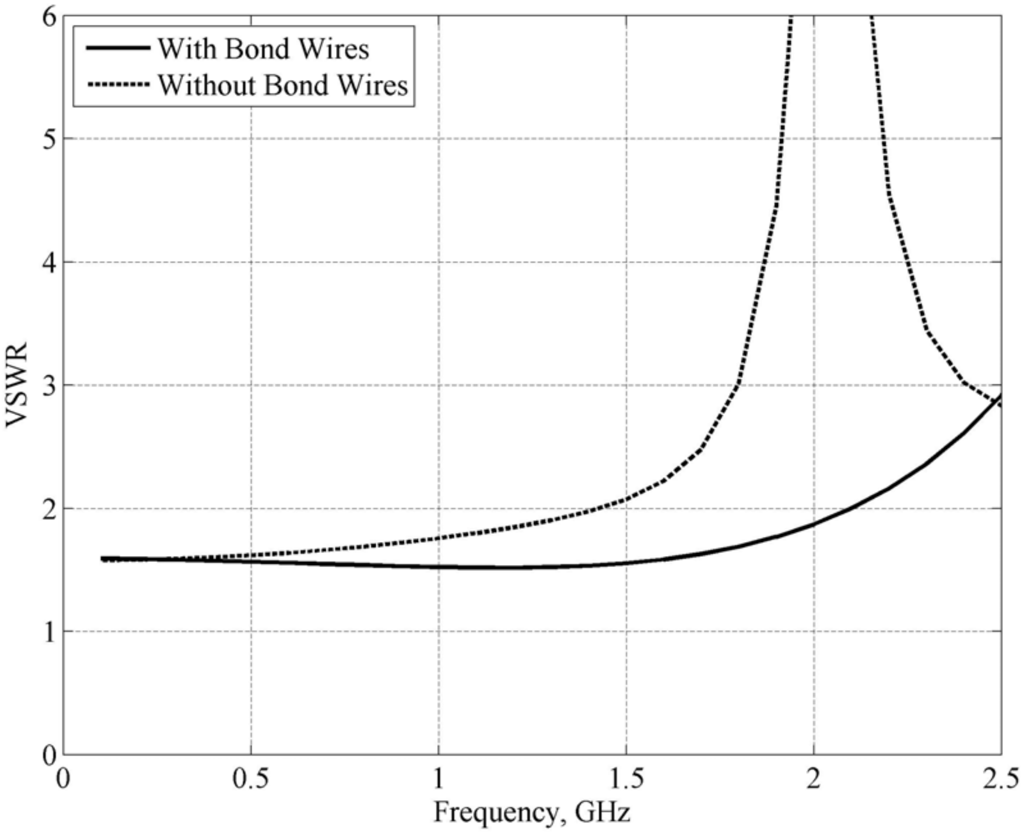


Figure 3.7. The effect of including the bond wires in the design on the balun VSWR.

The newly proposed etched bond wires were implemented and compared to the normal soldered bond wires. Simulations with the etched bond wires compared to 0.6 mm thick round wires are shown in Figure 3.8.

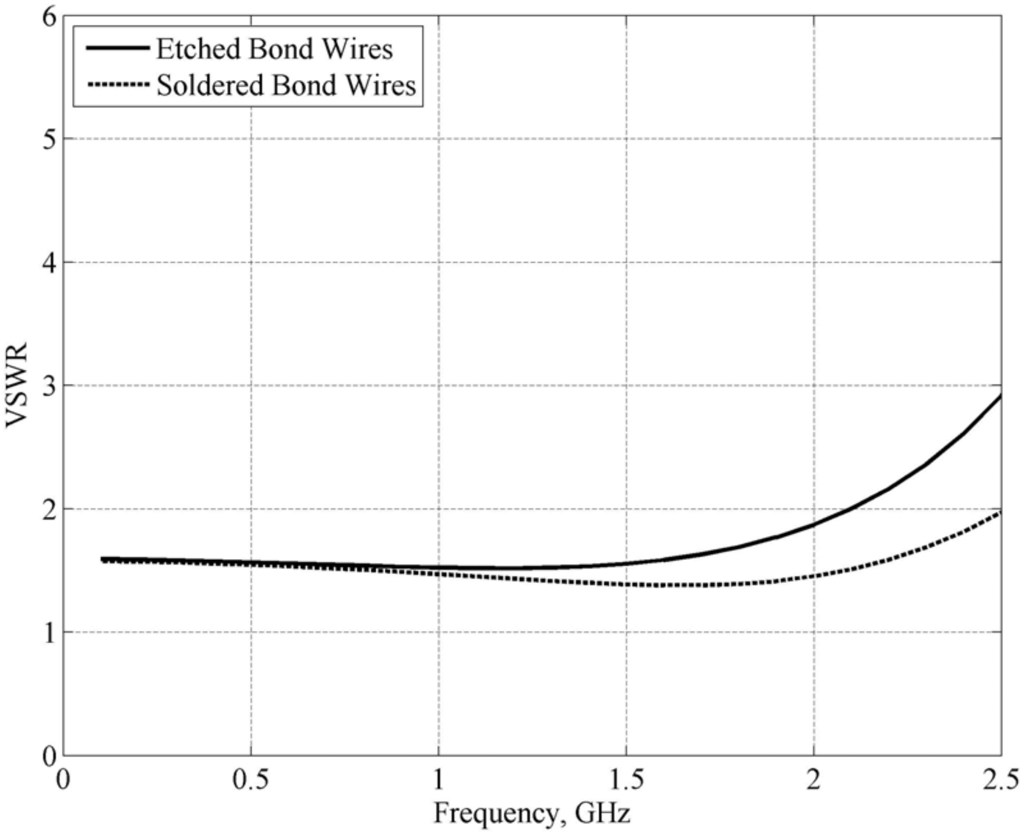


Figure 3.8. The effect of etching the bond wires on the VSWR of the balun compared to soldered-on bond wires.

It can be seen that the etched bond wires have a lower cut off compared to soldered wires with the same cross sectional thickness. This is because the coupling to the centre conducting strip is different. In this specific application the 16% reduction in high end cut off frequency can be tolerated, as it is still above the required 2 GHz, especially with the higher repeatability and reliability required. If the application requires a wider bandwidth then the soldered bond wires would have to be used, but that would mean compromising on the high repeatability and ease of manufacture of the etched bond wires.

The only real degree of freedom which is available to the designer when laying out these etched bond wires is the thickness of the strip, as they generally have to be situated as close as possible to the discontinuities. Figure 3.9 shows the simulated results with three different thicknesses of bond wires.

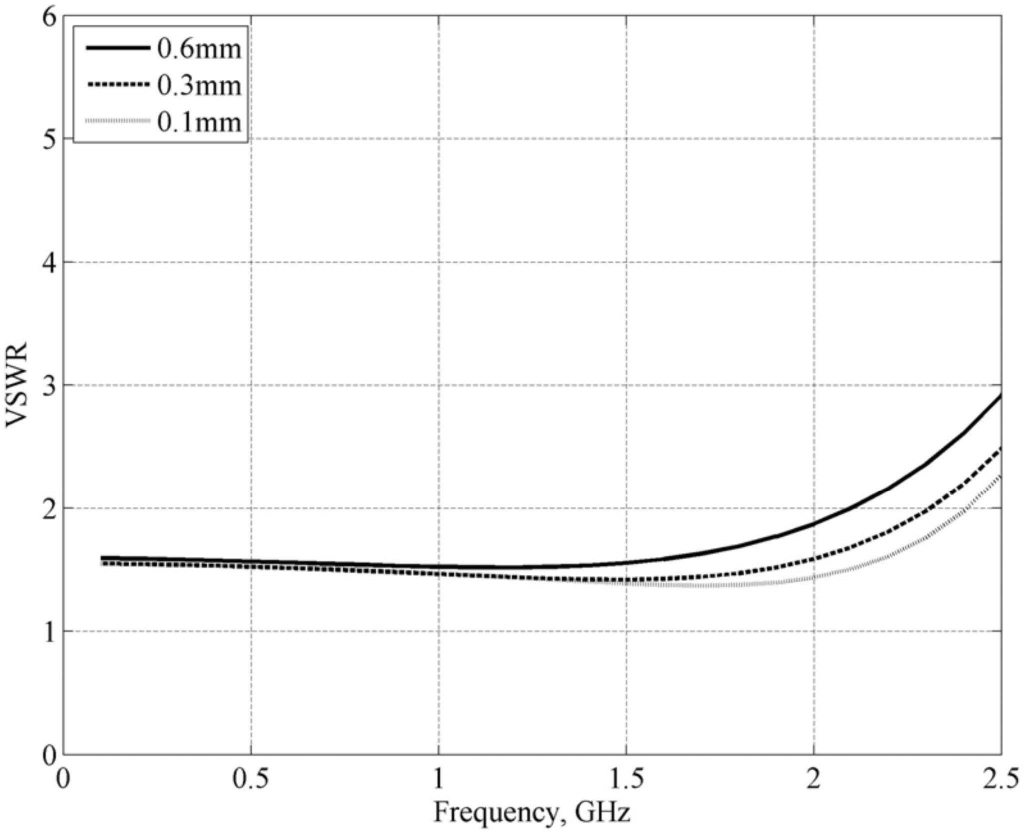


Figure 3.9. The effect of the bond wire thickness on the VSWR of the balun.

From these graphs it can be seen that the thinnest possible etched strip and through hole should be used as a thinner line give significantly better results. This is also true for the standard soldered bond wires. Unfortunately the available etching technology in this case limited the minimum thickness to 0.6 mm, which was then implemented.

3.4 CONCLUSION ON BALUN DESIGN AND PARAMETRIC STUDY

A successful implementation of a single element CPW to CPS balun was presented. Simulated results showed that the required bandwidth was achievable, even with the limitations on substrate and etching tolerances. The chapter also showed detailed examples of how the designed balun can be optimised for VSWR, given some physical restrictions and other design constraints. As part of the full characterisation of this type of balun all the crucial parameters that can be changed under the designer's control were investigated using a large number of simulations. The main parameters affecting performance are size of the radial slot and the length of the CPW taper as well as the effect of its inclusion. The idea of the etched bond wire was also introduced, showing the effect of its inclusion, comparing it to normal soldered bond wires and illustrating the effect of changing its thickness. As has been stated a number of times during this section there are always design decisions to be made regarding compromise between different design criteria like VSWR, cut off frequency, reliability et cetera. By demonstrating these effects of these different parameters this chapter should reduce development time of any similar balun designs.

In the next chapter the performance of the optimised balun, as developed in this chapter, is characterised using a new proposed test procedure. Although it is a general procedure, the results proposed aids to understand this specific balun better.

CHAPTER 4

A GENERAL TESTING PROCEDURE FOR PERFORMANCE CHARACTERISATION OF ETCHED BALUNS

This chapter will develop a test procedure to fully characterise CPW-CPS baluns. A series of tests are proposed and results presented to characterise the balun. The previous chapter focussed on simulations to optimise the design of the balun, while this chapter will focus on measured results to determine the actual performance of the balun and to compare it to the simulated results.

4.1 TESTING PROCEDURE FOR CHARACTERISING A BALUN

In general performance of etched baluns are almost always tested only in one specific configuration [2-6, 9-14] – the back-to-back test where two baluns are etched, with the output of the first balun connected to the input of the second, and the return and through losses of the combination measured. This method has proven to be very useful, especially for comparative tests, but does unfortunately not tell the full story of the balun’s performance. The through loss of a single balun is generally assumed to be half that of the combination, but this might not always be true due to a more complex interaction between the two baluns. For instance, if the transmission line impedance at the output of the balun differs from what was designed, or changes significantly over frequency, the back-to-back configuration will still show no discontinuity and thus good impedance matching, as the effect will be exactly the same on both baluns. Testing the single balun by physically terminating the output to the desired impedance would, however, show that there might be a problem with the balun design before the balun was actually connected to an antenna.

Even when a single element test is done, together with the normal back-to-back test, all the relevant information regarding the balun under test is still not obtained. The problem is that both these tests result in information regarding the wide band matching and losses of the structure, but no information on the actual degree of balance of the balun is tested. In other words – it is normally never tested if the balun successfully transforms the unbalanced input line to the balanced output line as it is designed to do. Without acceptable magnitude and phase balance results the balun is actually no more than a transition, and might result in performance degradation when used to feed an antenna, for example.

A full testing procedure is proposed for all baluns, especially etched baluns, to overcome the limitations on tests to characterise baluns as discussed above. The full set of tests consists of at least the following three experiments:

- Back-to-Back Test – This experiments tests two identical baluns connected in a back-to-back configuration. It is easier to implement than the other tests and can give a quick, but not always completely accurate measure of the balun's performance. It does, however, give an indication whether the insertion loss of the balun is good, unlike the single element test.
- Single Element Terminated Test – This experiment entails testing a single balun on its own by terminating its output port. This is easy to do in simulation, but care has to be taken when setting up the device for measurement. It gives a more accurate measure of the return loss performance, and thus the usable frequency band, than the back-to-back test.
- Magnitude and Phase Balance Test – This experiment utilises a symmetric splitter to measure the degree of magnitude and phase imbalance at the balun's output port. If these values are not relatively small, the balun may have a larger than expected influence on the antenna or device it is connected to.

Any one of these tests should only be ignored when the specific balun is very well known to the designer and has previously proven its full implemented performance.

In the remaining part of this chapter this testing procedure is implemented on the designed balun described in the previous chapter. The advantages of each of the tests are clearly shown, and in the end it is clear why this more rigorous test procedure is necessary for all new balun designs before final implementation.

4.2 BACK-TO-BACK CHARACTERISATION OF TWO BALUNS

The balun is first tested in a back-to-back configuration, which is the generally accepted way of characterising these devices through measurements. This implementation, as used here, is shown in Figure 4.1.

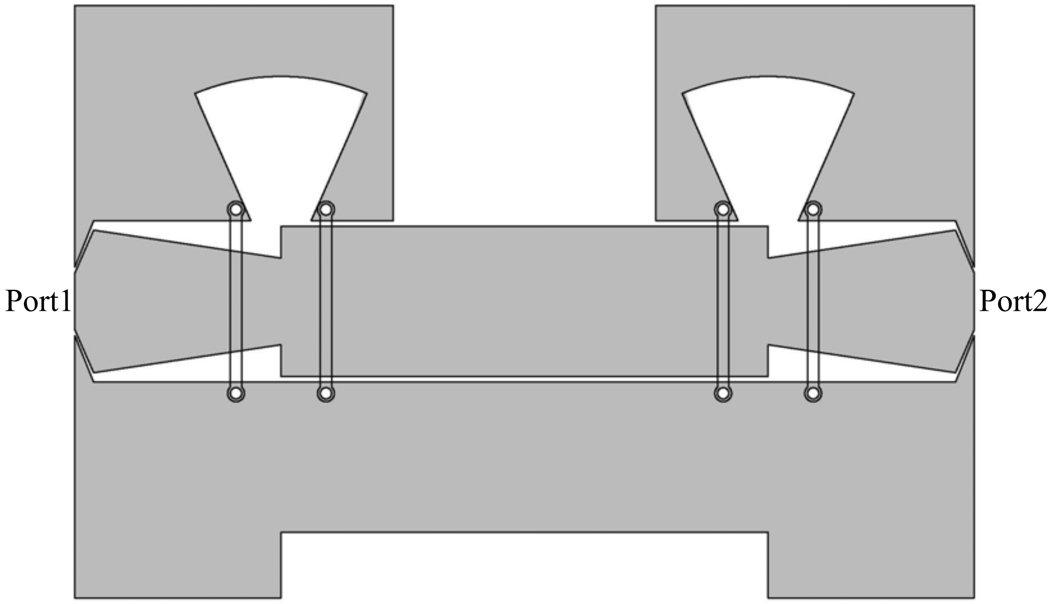
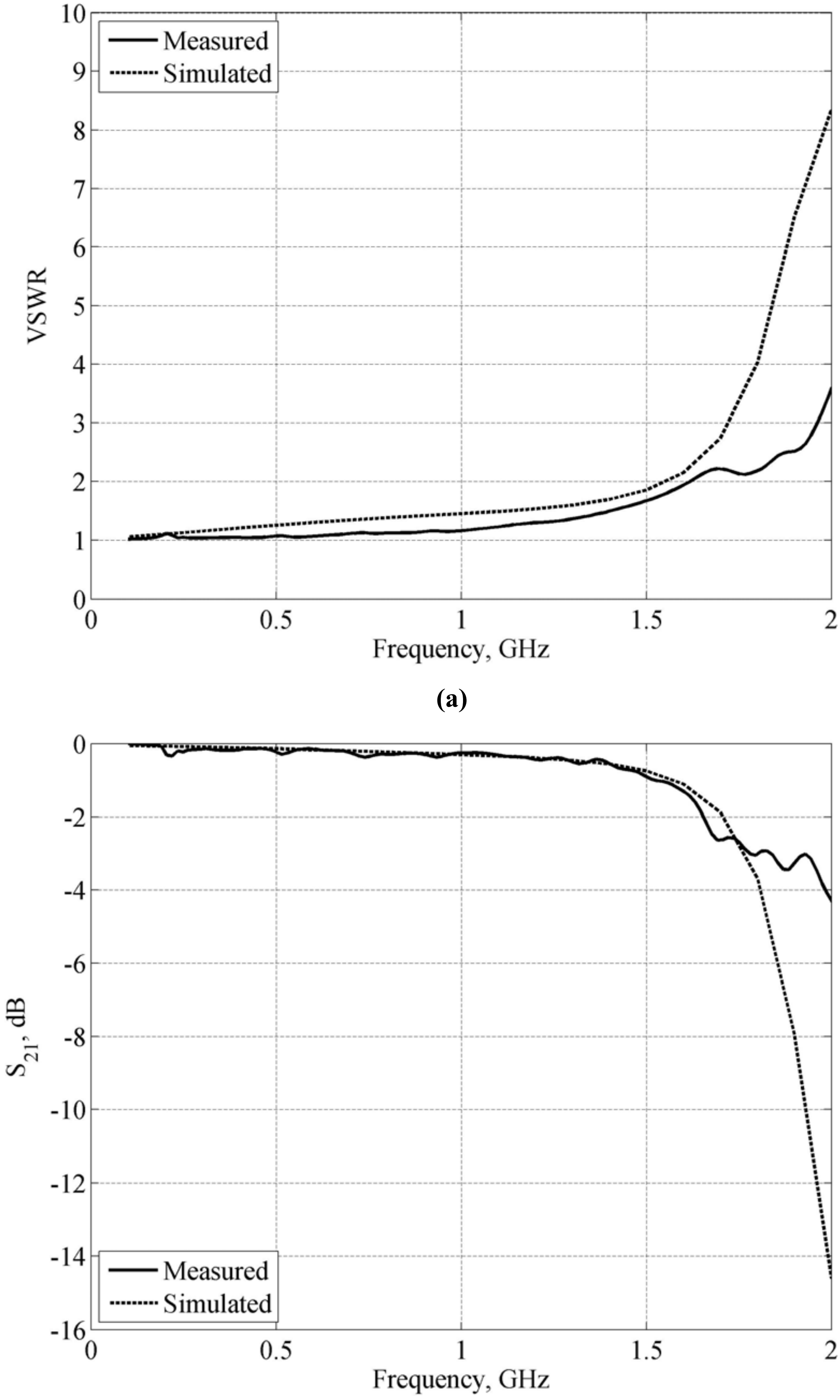


Figure 4.1. Back-to-back configuration layout.

The back-to-back configuration consist of two of the designed baluns being etched connected through there CPS ports. This means that there are two CPW ports available where connectors can readily be soldered on and measurements can easily be made. The main advantage of this type of test is that it lends itself to an easy measurement, with the disadvantage that the performance of two baluns are always tested together. The results are only an indication of the individual balun's performance. The test also assumes that there are no large interactions between the two baluns and that the two individual baluns are identical. In general, this is usually the only test to be conducted prior to balun implementation.

The full set of S-parameters were measured for a manufactured back-to-back connected configuration, and compared with simulated data. The VSWR and insertion loss (S_{21}) are shown in Figure 4.2.



(b)

Figure 4.2. Measured and simulated VSWR (a) and S21 (b) of the balun in a back-to-back configuration.

Good correlation can be observed between the two sets of data over the useable operating band. Up to 1.6 GHz the maximum insertion loss for a single balun was found to be less than 1 dB if one assumes that the baluns are identical. The VSWR is also less than 2:1 over this frequency band. An interesting observation is that above 1.8 GHz, in the out of band region, the simulated and measured results no longer track each other very well. This is caused by a resonance, which is a function of the physical overall length of the structure. This is not as evident in the measured results, because the measurement cables suppress this effect to a large degree. Similar results will be shown and discussed in more detail in a later chapter where the effects of the resonant length is clearer. The next subsection will show that the balun does indeed work up to 2 GHz, as specified, although it is not evident when looking at only these test results.

4.3 CHARACTERISATION OF A SINGLE BALUN

Although results of the back-to-back test for a balun give a fair indication of the useable bandwidth in terms of acceptable insertion loss and VSWR, a more accurate characterisation can be achieved if the VSWR is determined for a single balun terminated in a matched load. In simulation this can of course easily be done by terminating the CPS output port with a matched load to get a good single balun result [38], as was done in the previous chapter. To obtain an experimental result the CPS line of the single balun can be terminated by soldering a surface mount resistor onto the port. In this case a value of 82 Ω was used. Although still a relatively simple test, it is almost never performed in practice, but it will be shown that some useful information regarding the actual performance of the balun can be obtained from this test.

Figure 4.3 shows both the simulation and the measurement VSWR results. Again the correlation between the measured and simulated results is good, both predicting an upper limit of approximately 2.1 GHz, which is substantially higher than the 1.6 GHz when measured back-to-back. This discrepancy can be attributed to the interaction between the two baluns. A similar trend was seen with simulations in [38]. This shows that the actual upper usable frequency of such baluns can be up to 30% higher than is evident from measured results in a typical back-to-back configuration.

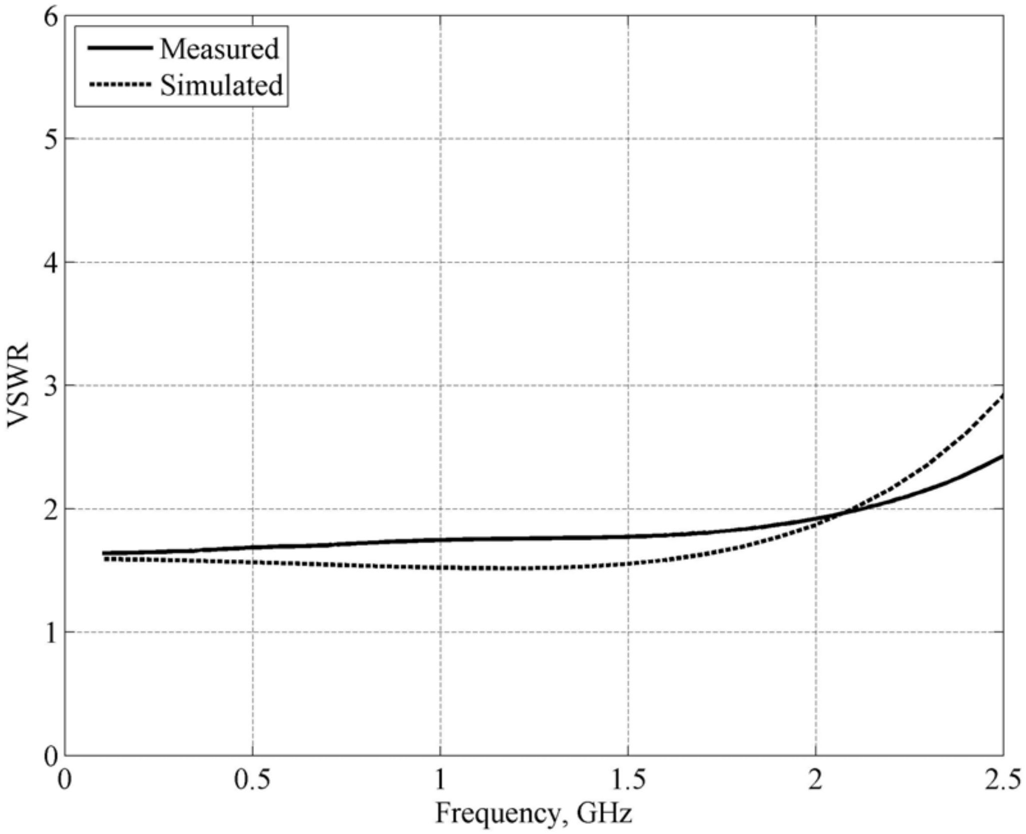


Figure 4.3. Simulated and measured VSWR of the singe balun terminated in an 82Ω load.

Another interesting observation when comparing the VSWR results from the single and the back-to-back results is that back-to-back baluns show a much better low end VSWR than the single balun. This can be explained by the fact that the single balun is terminated in the finite, fixed impedance of the resistor. On the other hand the back-to-back baluns are essentially terminated in their ideal CPS transmission line impedance. If the impedance of this CPS section varies significantly from 80Ω over the frequency range, which is in fact the case for most uniplanar transmission lines, then the single balun looses its matching at some frequencies, specifically at the low frequency end, whereas the back-to-back baluns will always be perfectly matched, as the effect will be exactly the same in both baluns. The back-to-back baluns show a very good low frequency VSWR, but might be misleading because it cannot actually be obtained in most practical applications.

4.4 MAGNITUDE AND PHASE BALANCE CHARACTERISATION OF A BALUN

Thus far the only results which were measured and shown were regarding the impedance match of the balun, and this is all that is usually tested when designing a balanced to unbalanced transition. However, one important parameter that has not been tested is the actual degree of balance, in magnitude and phase, between the two sides of the output port. This is why many authors refer to circuits of this type as transitions. A transition should only truly be called a balun when a measure of the degree of balance is known and acceptable. This information can be obtained by a number of different experiments. One way of getting a relative idea whether the balance on the output is acceptable, is by integrating it to an antenna and measuring the radiating patterns. A dipole, for example, will show excessive squint if fed from a line which is not well balanced. Even better is to use a spiral antenna and to measure the axial ratio, which will be significantly higher for an unbalanced feed than for a well balanced one.

In [18] a test circuit is shown where the output CPS is again systematically and symmetrically split into two CPW ports. It is used to test the balance of a double-Y balun where it proves that the actual useable frequency range of that balun is much smaller than was believed prior to the test. This type of test can also be implemented for the single element balun, and the circuit that was implemented for this application is shown in Figure 4.4. Again the use of bond wires at the discontinuities is critical.

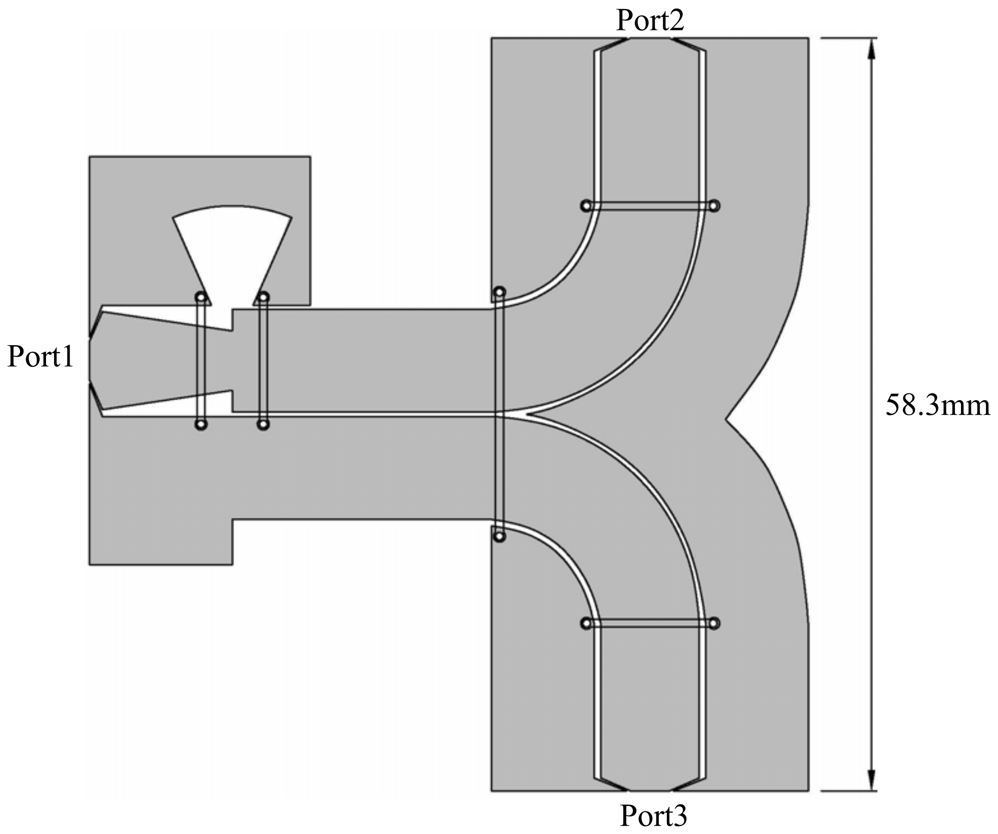


Figure 4.4. Layout of designed balance tester showing the port naming convention.

Bear in mind that the VSWR of the CPW input port does not have to be as good as that of the stand alone balun for the test still to be accurate and meaningful, as the main interest is in the amplitude and phase balance between the two output ports. This is why a plain taper from CPW to CPS can be tolerated. In this case the VSWR is actually still rather good as is shown in Figure 4.5 from the measured results.

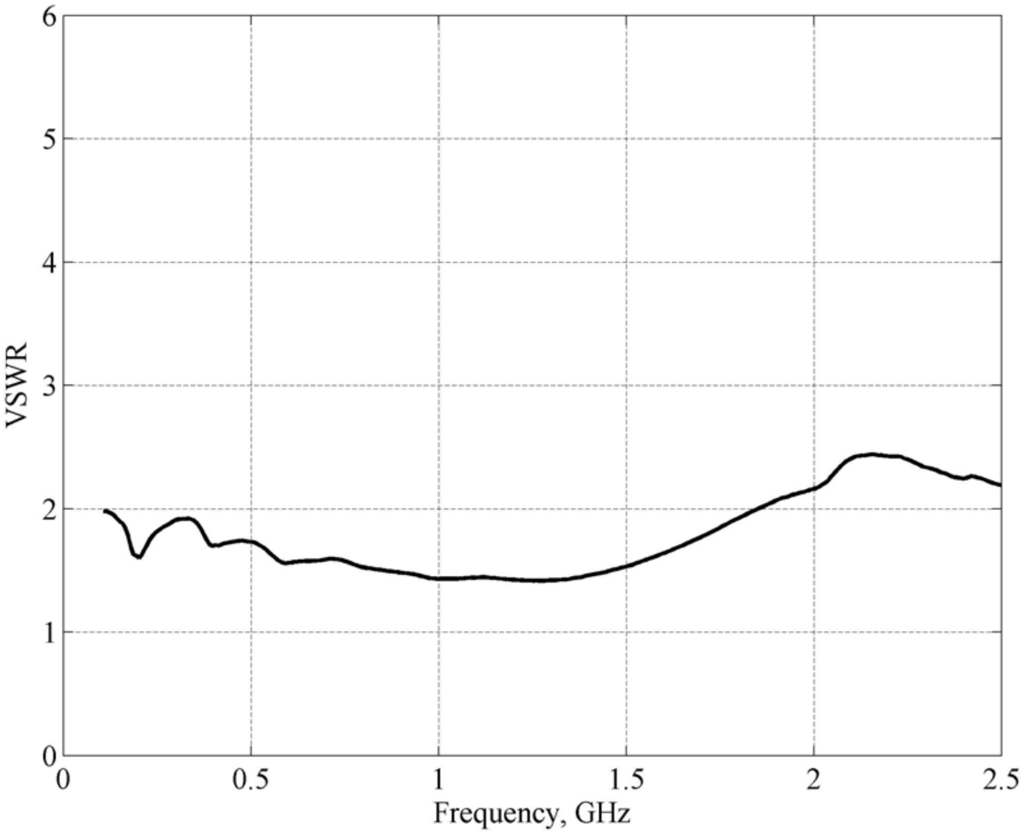
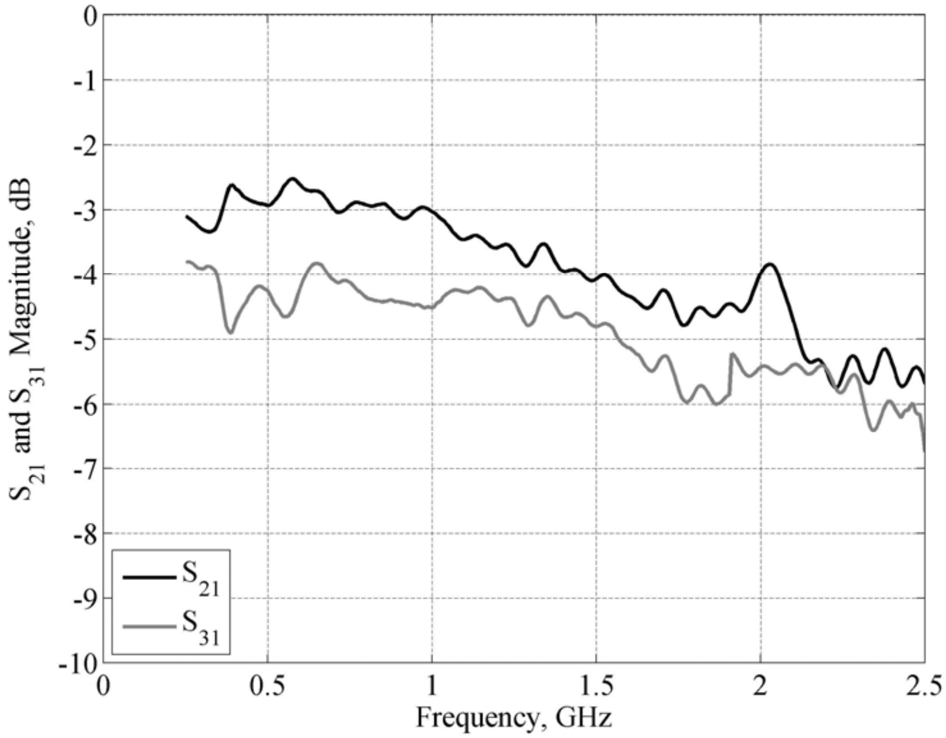
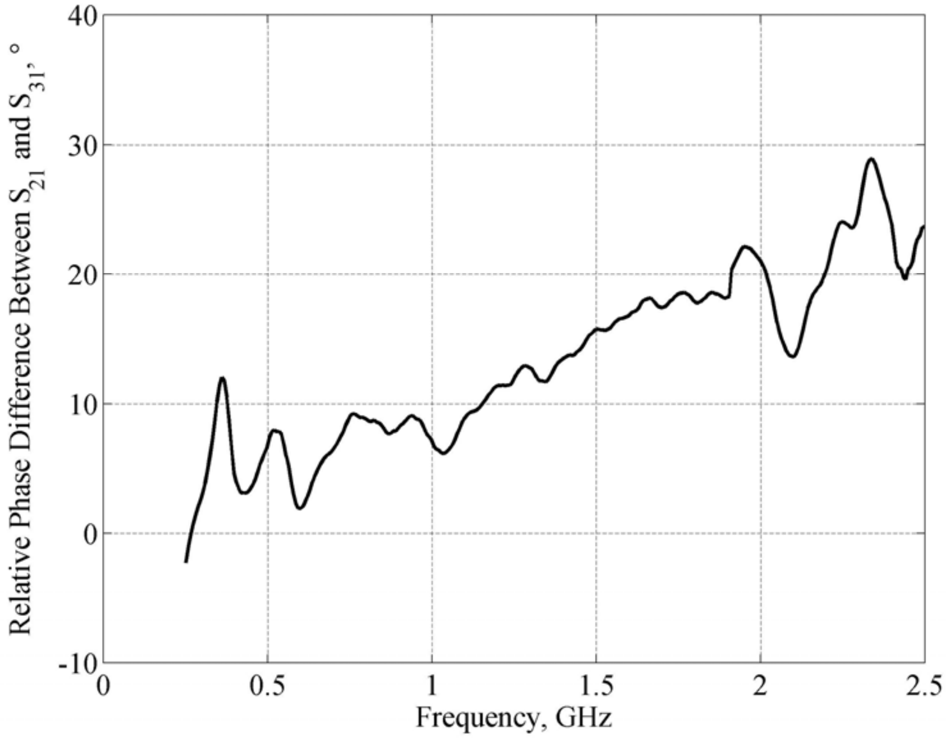


Figure 4.5. Measured VSWR of the balance tester.

Figure 4.6 shows the amplitude and phase of both the through channels. It can be seen that the amplitude tracking between the two channels is good over the full operating frequency band - it is suggested in [18] that an amplitude imbalance of less than 1.5 dB is quite acceptable, a value that is obtained over the entire band from 0.6 GHz upwards. The relative phase difference between the two channels is shown in Figure 4.6 (b). For perfect balance the difference between the two channels will be 180°, but for comparison purposes the graph shows the two sets of values subtracted from each other after 180° was added to one of the ports. The phase imbalance was found to be less than 22° for the full operating band up to 2.0 GHz. Considering that this phase results also intrinsically includes other added errors like the phase matching between the connectors and the soldering and etching tolerances, this result is acceptable.



(a)



(b)

Figure 4.6. Measured performance of the designed balun connected to the 3-port balance test circuit: (a) magnitude of S_{21} and S_{31}, and (b) phase difference.

An important observation is that the balance between the ports is good down to very low frequencies. This means that this wideband balun can be used across its full operating band as defined by its single element measurement. This is not the case for other baluns such as the double-Y balun [18] where the operating band is dramatically decreased by the imbalance of the output port at the low end, where the VSWR and insertion losses of the balun is still good, but it turns out that the magnitude at the two ports actual diverges. This is a good example why it is important to fully characterise the designed balun, including balance tests, before final implementation. It also shows an important advantage of this balun type.

4.4.1 Special considerations in the design of the balance tester

As mentioned previously, the simulated results of the balun tends to have a resonant effect related to the overall length of the balun. In this subsection this resonant effect will be discussed in more detail. Figure 4.7 shows a comparison between the measured and simulated phase results of the balance testing circuit.

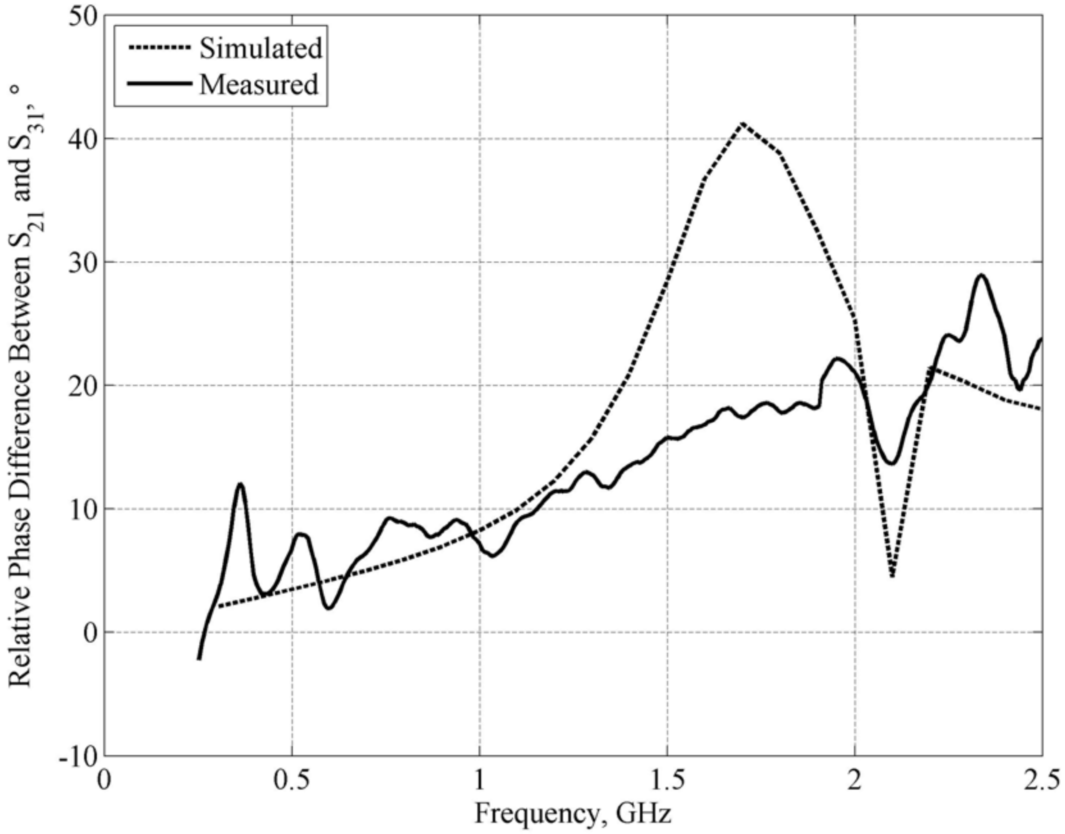


Figure 4.7. Measured and simulated performance of the balun connected to the 3-port balance test circuit.

It is clear that the two sets of results do not track particularly well above 1.3 GHz. What is strange, though, is the fact that the measured results are actually better, which is different from what is expected seeing that the measured results also include the imperfections of manufacture, which is not included in the simulated results. The measured results also have a generally smoother trend, not showing the peaks which are present in the simulated results. There are in fact two strange resonances in the simulated results that need some explanation – a peak at 1.7 GHz and a sharp minimum at 2.1 GHz.

These phenomena seem to be resonances that can be attributed to the overall physical lengths of the structure. Figure 4.8 shows results for the balance tester with four different CPS lengths between the balun and the splitter, each longer than the initial circuit.

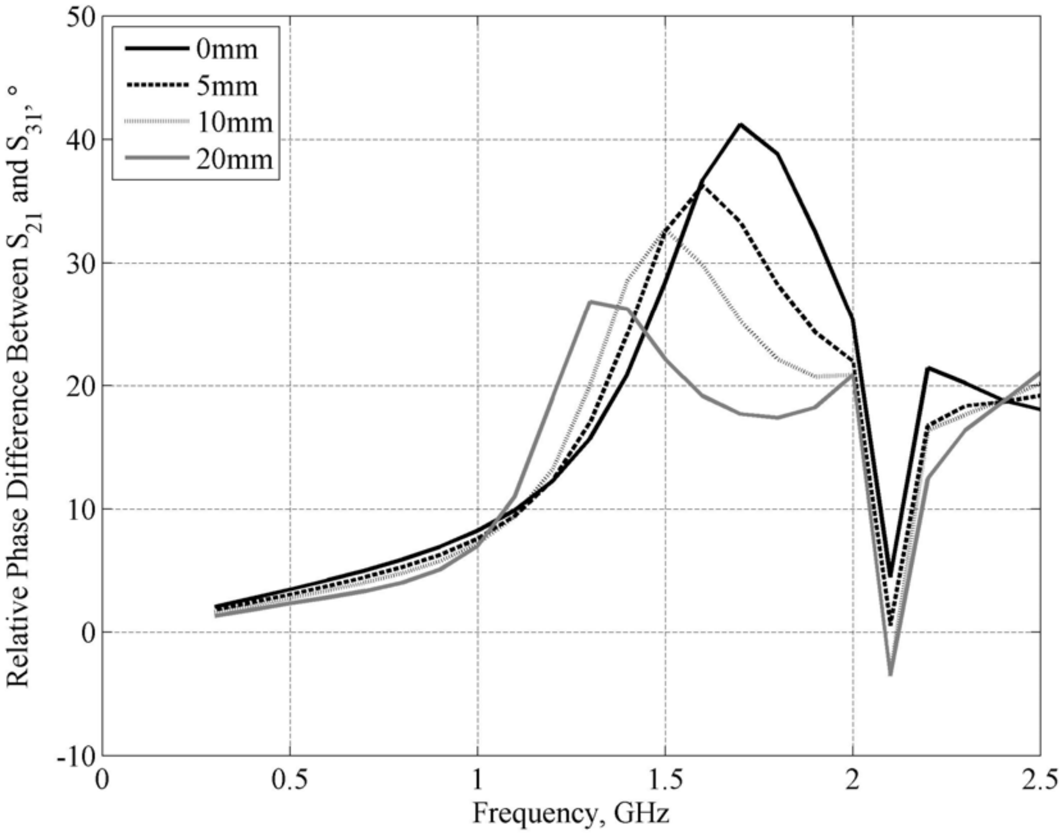


Figure 4.8. Simulated performance of the designed balun connected to the 3-port balance test circuit with different longer CPS lengths.

Unfortunately the CPS line on the balance tester cannot be made shorter, but to test the theory of the resonant length it can me made longer, as was done for Figure 4.8. It is clear that the first resonance peak is strictly frequency dependent, moving down lower in frequency as the total length is being made longer. At the same time the peak is also getting lower. This proves that the first resonance is being caused by the total length of the splitter circuit.

Interestingly, the second resonance does not move at all, and must thus be caused by another effect. Figure 4.9 illustrates this effect, where the output CPW lengths of the splitter outputs are made shorter.

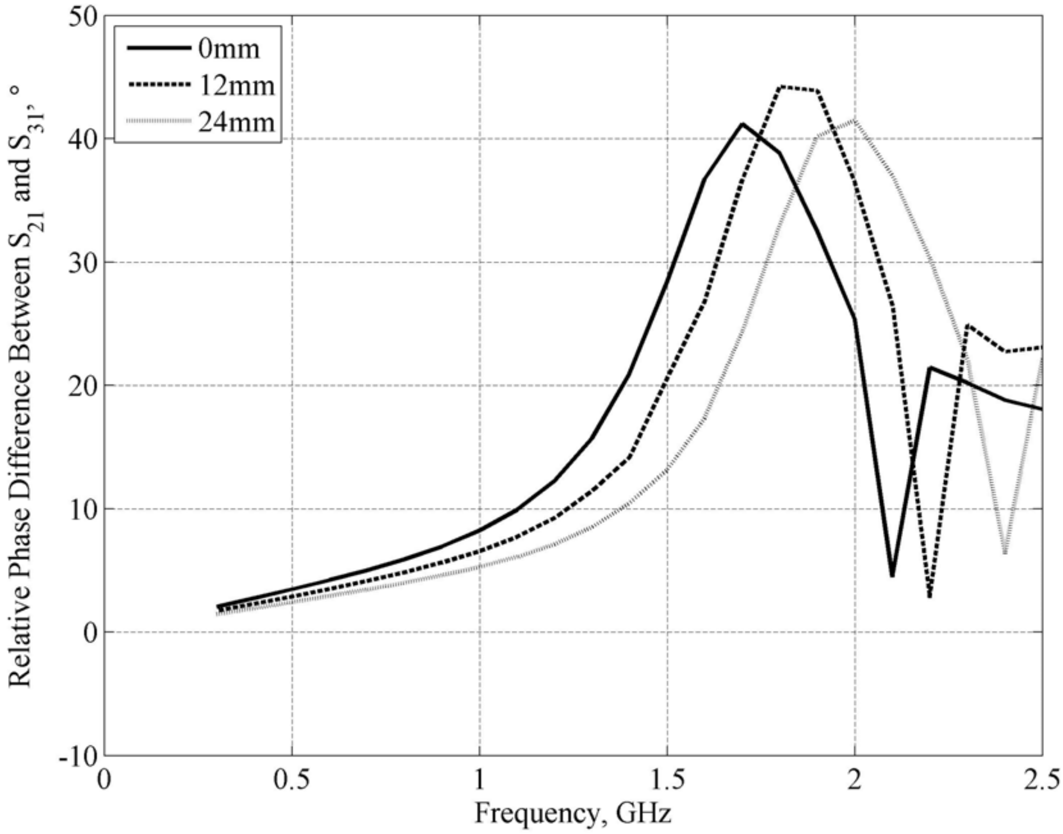


Figure 4.9. Simulated performance of the designed balun connected to the 3-port balance test circuit with different shorter output CPW lengths.

It is seen that the shorter the output lengths the higher in frequency both resonances, unlike the previous results where only the first resonance moved. Because the second resonance now also moves, it proves that it is related to the distance between the output ports. The fact that the first resonance also moves is explained by the fact that shortening the CPW lengths also shortens the total length of the splitter, and thus also changes that resonance frequency as well.

The causes of the two resonances are related to the physical lengths of the balance testing circuit, specifically the splitter part of it. These resonances are, however, not present, or greatly reduced in the measured results as shown in Figure 4.7. A trace of the second one can still be seen. When physically doing the measurement, coaxial cables are connected from each port to the relevant ports on the network analyser being used. In the simulation, this is obviously not the case, they stop abruptly at a point which is defined as a port and terminated in an impedance value, where the simulated S-parameters are computed. In the measurement the physical cables seem to make the structure look much longer and thus the resonant frequency moves much lower, actually to such a degree that it is no longer significantly present in the measured results.

All this means that the measurements are actually giving a more useful answer than the simulations. It is important to note that the simulation results are still actually correct, in a sense more so than the measurement results. The resonances are actually present in the physical structure but are suppressed by the measurement technique. This helps to produce better usable results.

Even after identifying the cause of this problem in the simulations, there is unfortunately not an easy way to correct it. The splitter circuit cannot be made much shorter, definitely not enough to completely move these effects out of the operating band. To obtain truly comparable simulation results to the measurements, a new type of splitter will have to be designed, one that does not have this inherent resonance problem. In the next chapter it will also be shown that the simulation results can still be useful, but only for relative comparisons between different designs.

4.5 CONCLUSION

In this chapter a complete balun characterisation technique was presented. It consists of three different tests to be performed on a balun. It clearly shows why the results of the back-to-back test should not be used as the only criteria, especially when the designer does not have lots of experience with a specific type of balun and does not know how these results will relate to the final implemented performance. The single element test gives one a much better idea of how the balun will actually perform when implemented as a feed for a device or an antenna. Even with these two tests successfully performed, it does however not necessarily prove the proper functionality of the balun. To test this, a degree of the balance of the balun also has to be known. A splitter was designed and implemented for this purpose.

The chapter also showed full test results of all these experiments, and proved that the designed balun does indeed achieve all the original design specifications and that it should be possible to successfully integrate this component to a balanced device or antenna. The measured results compared well to the simulated results. This new technique for complete characterisation can also be implemented on any other type of balun and can definitely help in finding potential problems with the design prior to final implementation.

CHAPTER 5

PHASE COMPENSATION TO IMPROVE BALANCE OF AN ETCHED BALUN

In an effort to improve the balance of the balun as tested in the previous chapter, this chapter introduces a technique that can be implemented to correct for any systematic phase imbalance. Measured results are given to show the resulting improvement. In the second section of the chapter an implementation of this balun as feed to a CPS dipole is shown, both with and without the additional phase compensation. This is done to verify the validity of the tests of the previous chapter and also to show the effect of improving the balance of the balun. It again shows why it is important to test the degree of balance of a specific balun.

5.1 PHASE COMPENSATION TECHNIQUE

Even though the phase balance of the designed balun is already relatively good, it seems that it can still be improved. Figure 4.6 (b) showed the relative phase difference between the two output ports has a definite upwards slope. This can only be caused when the one path from input to output port is longer than the other. Seeing that the splitter part of the balance testing circuit is perfectly symmetric, it means that this path length difference must lie in the balun itself. To be precise, it emanates from the currents on the top CPW conductor having to add to those on the bottom CPW conductor, and then going on to form the bottom CPS conducting strip. This combination is naturally longer than the centre CPW conducting strip which goes directly on to become the top CPS strip. This difference cannot be averted, as it is part of the intrinsic workings of the balun. If the minimum gap width could be made smaller (to around 0.1 mm rather than the current 0.3 mm) then the total distance between the two CPW ground planes could also be made significantly smaller, which will reduce this effect to a large extent. An alternative solution to reduce the path length differences between the input and the two output ports is proposed in Figure 5.1. An additional path length is introduced in the one path to compensate for the intrinsic path length difference that exists in the conventional design of the balun.

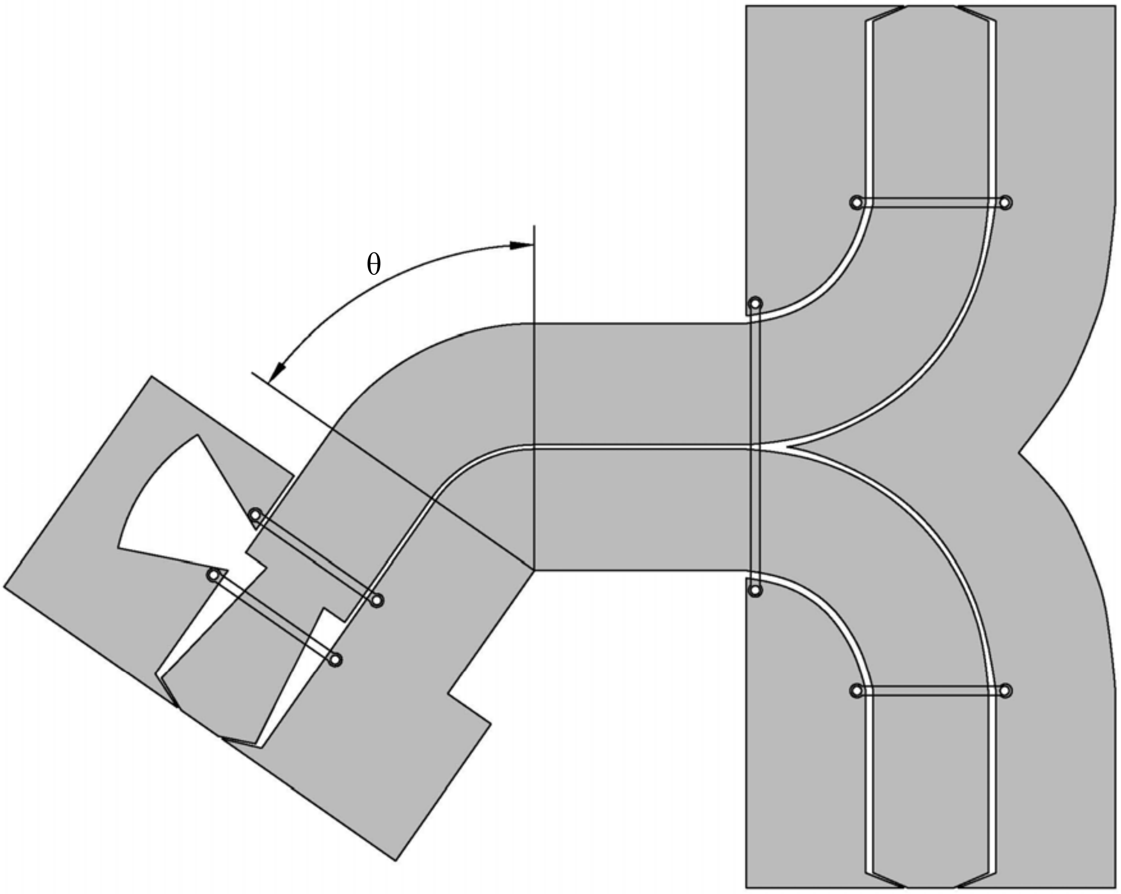


Figure 5.1. Layout of phase compensated balance tester.

The proposed solution is a new phased compensated version of the balance testing circuit. It accomplishes this phase compensation by introducing a variable angle bend in the CPS line part of the balun, before it is connected to the symmetric splitter. The bend introduces the ability to delay the currents on one CPS path relatively to the other strip, which has a smaller bend radius and thus a shorter path to travel. When the bend is chosen in the correct direction it compensates for the bottom path being longer and with the correct angle can significantly reduce the phase imbalance which would have been present at the output ports. Figure 5.2 shows results with three different angular values, with 0° being the straight balun.

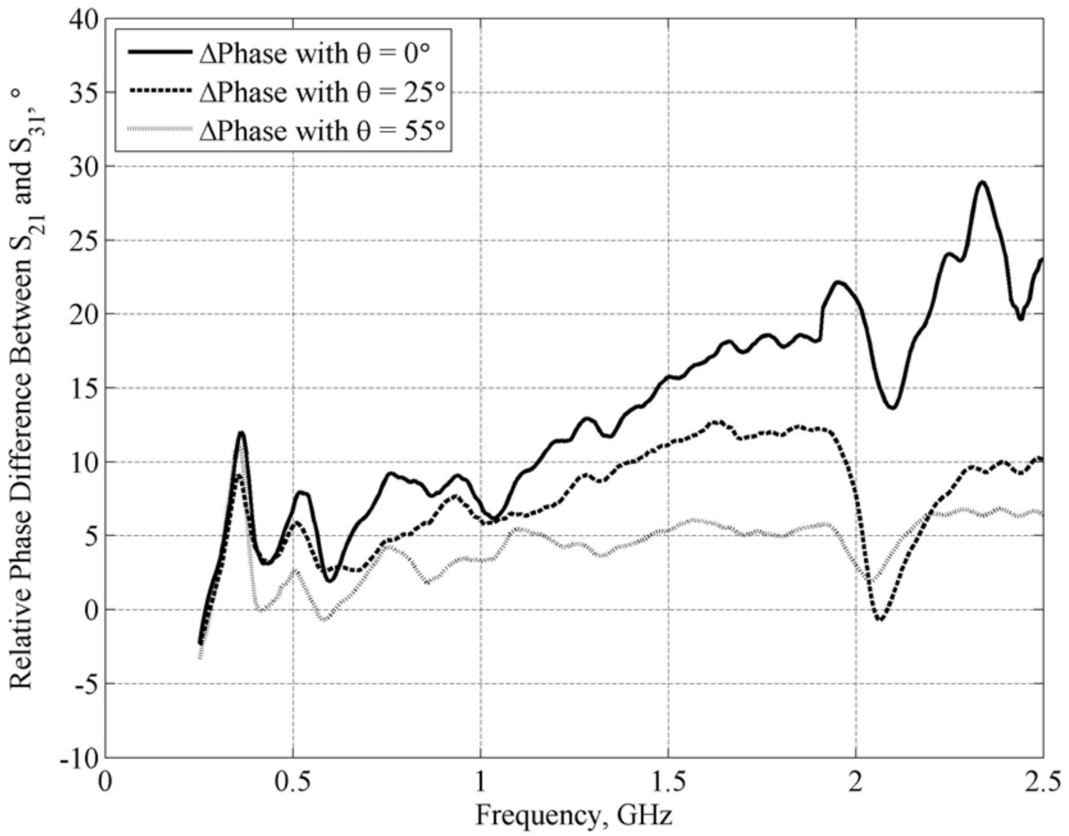


Figure 5.2. Measured phase performance of the designed balun connected to the 3-port balance test circuit with varying angle (θ).

The massive difference that the phase compensation makes on the final phase balance performance is evident. The larger the angle, the smaller the slope becomes and the smaller the maximum phase imbalance between the output ports. The circuit with a 55° bend has a maximum measured phase imbalance of only 6° in the operating band from 0.5 GHz to 2 GHz, an improvement of 16° on that of the uncompensated balun.

The phase compensation has little effect on the magnitude balance, as is shown in Figure 5.3. The 0° results are exactly those of Figure 4.6 (a), now just represented in a relative plot for easier comparison. The 55° circuit performs a little better near 2 GHz than the 0° circuit, but for the rest of the operating band the differences are relatively small.

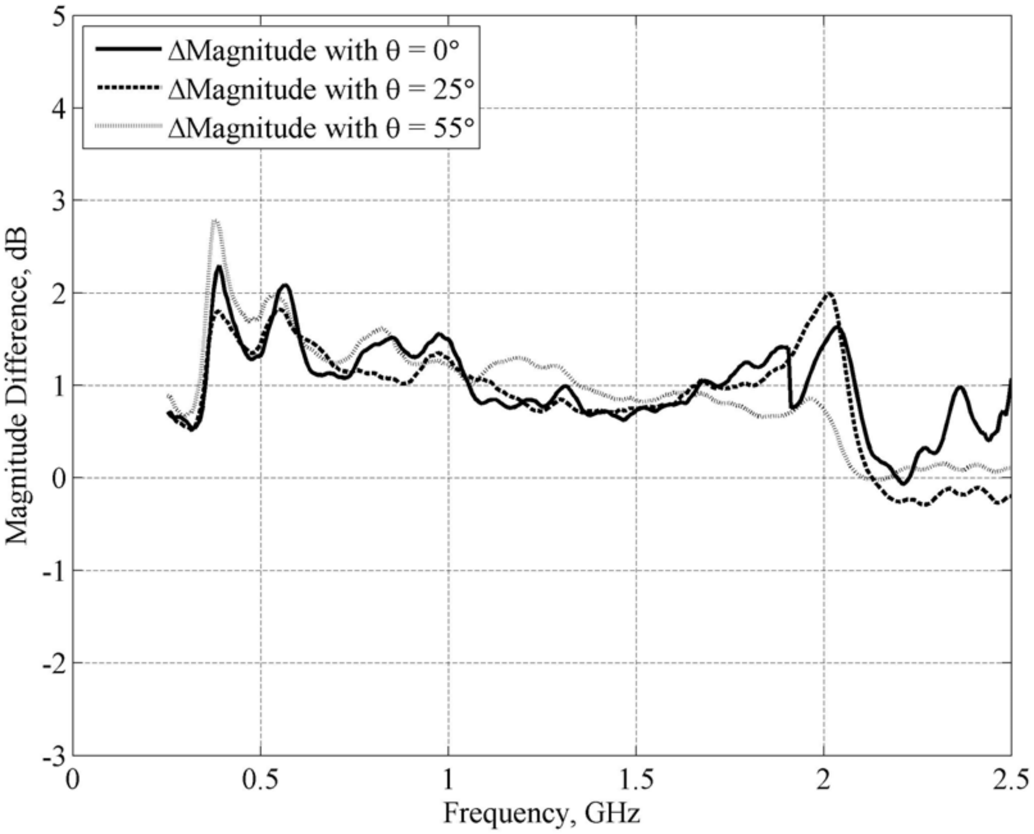


Figure 5.3. Measured magnitude performance of the designed balun connected to the 3-port balance test circuit with varying angle (θ).

As shown in subsection 4.4.1, the simulation results for the balance testing of the balun does not give as useful results as the measurements because of the resonance effect introduced into the simulations due to the length and size of the theoretical model. Figure 5.4 shows the simulation results for the phase compensated balance tester and even with this resonant effects correlates with the measured results shown in Figure 5.2.

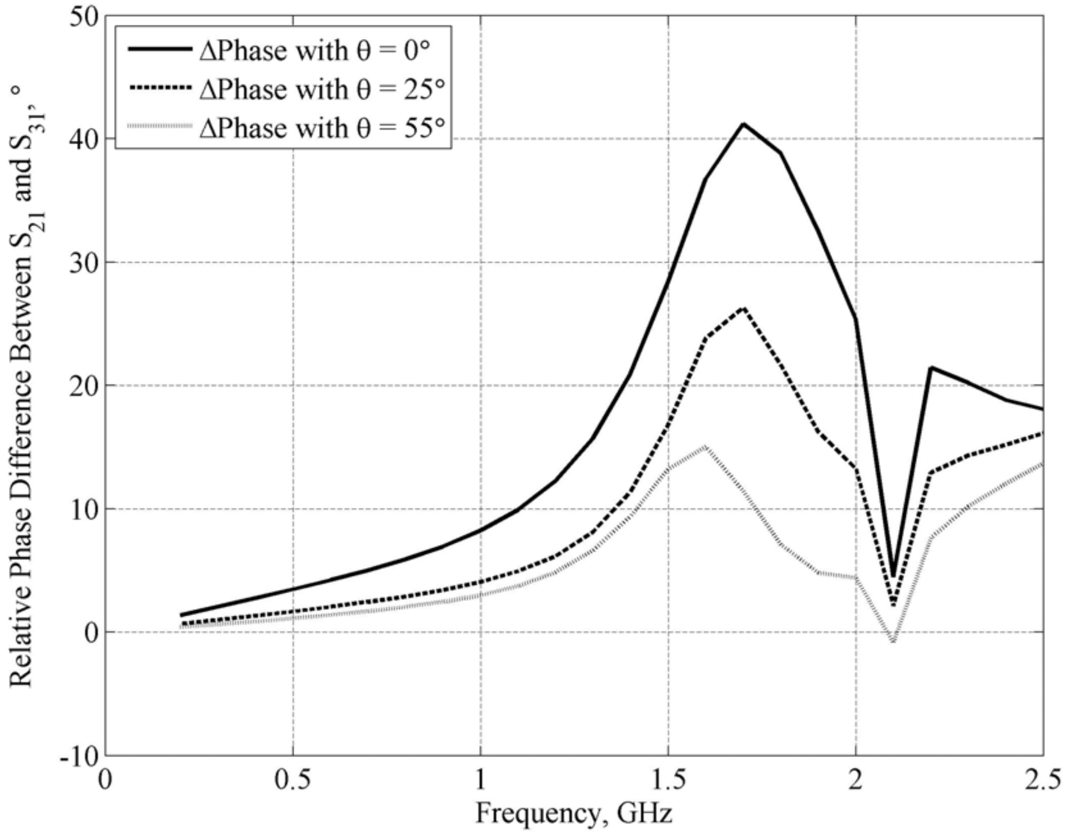


Figure 5.4. Simulated phase performance of the designed balun connected to the 3-port balance test circuit with varying angle (θ).

Although the comparison between the measured and simulated results is still not particularly good, the important fact to notice is that both sets of results show exactly the same trend of decreasing phase imbalance with larger compensation angles. This means that the simulations can still be used as a useful tool when comparing different sets of simulation results.

The final test to be performed as verification of this new phase compensation technique is to implement it on the single element balun and to observe the change in performance. This comparative VSWR graph is shown in Figure 5.5. It shows that there is nearly no effect to be attributed to the added phase adjustment, so all the other design criteria is still valid, and the phase compensating bend can be added as an extra implementation where and if it is needed, without compromising the rest of the functionality of the design.

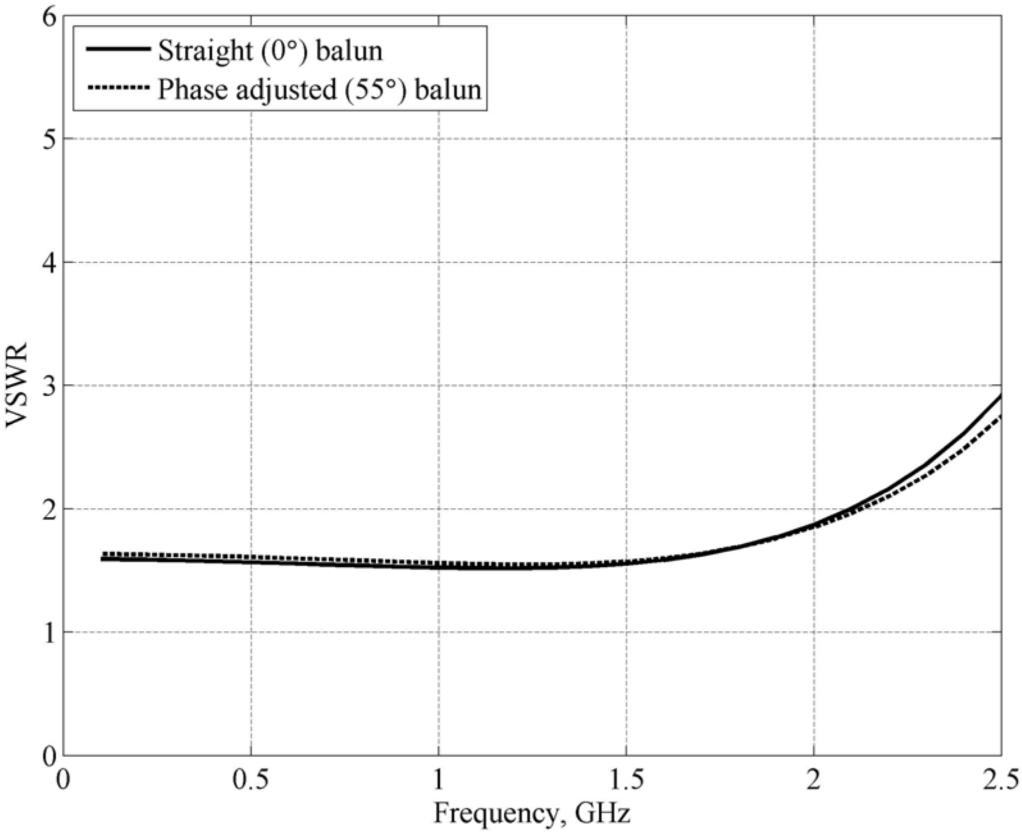


Figure 5.5. The effect of the phase adjustment on the balun VSWR.

The performance of the designed coplanar balun was improved by significantly reducing the phase imbalance between the output CPS ports, without changing the input characteristics. This was achieved by implementing a new phase compensation technique consisting of a variable angle bend in the CPS line, effectively compensating for any phase imbalances between the ports by making sure the path length difference between the two paths stays as small as possible. This technique was successfully implemented and tested. If the proposed full characterisation technique had not been followed, this imbalance would not even have been noticed, but now it can also be used to easily test for the optimum compensation angle. The advantages of implementing this phase compensating technique will be shown in the following section, where it is implemented as feed for a dipole antenna.

5.2 PHASE COMPENSATED BALUN AS FEED FOR DIPOLE ANTENNA

The balun is implemented as a feed for a simple etched dipole antenna to show how it can be used, and to verify that it actually performs as predicted. A dipole is simple to design, can easily be etched and is inherently a balanced antenna. Figure 5.6 shows this implementation, again with the variable phase adjustment for testing purposes.

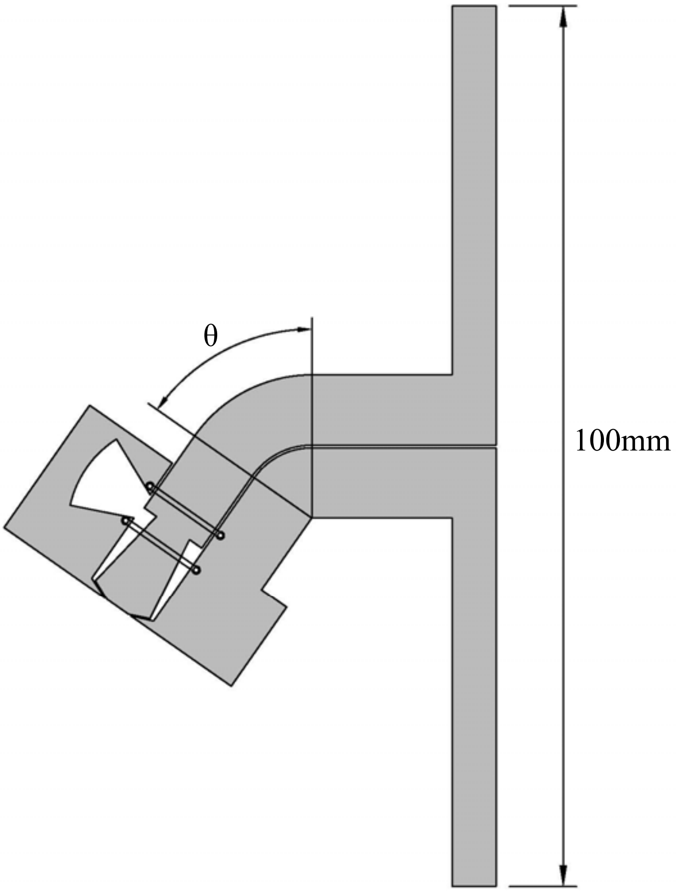


Figure 5.6. Layout of the implemented etched dipole with phase compensation.

The dipole is 100 mm long and 5 mm wide to result in a resonant frequency of about 1.3GHz, pretty close to the centre of the operating band of the designed balun. This dipole with its feed was simulated and measured with the three phase adjusting angles also mentioned in the previous chapter of 0°, 25° and 55°.

Firstly the measurements results are verified with simulations. Figure 5.7 shows a comparison between the measured and simulated reflection loss (S_{11}) results from the circuit as shown in Figure 5.6. In this case S_{11} is shown rather than VSWR for clarity.

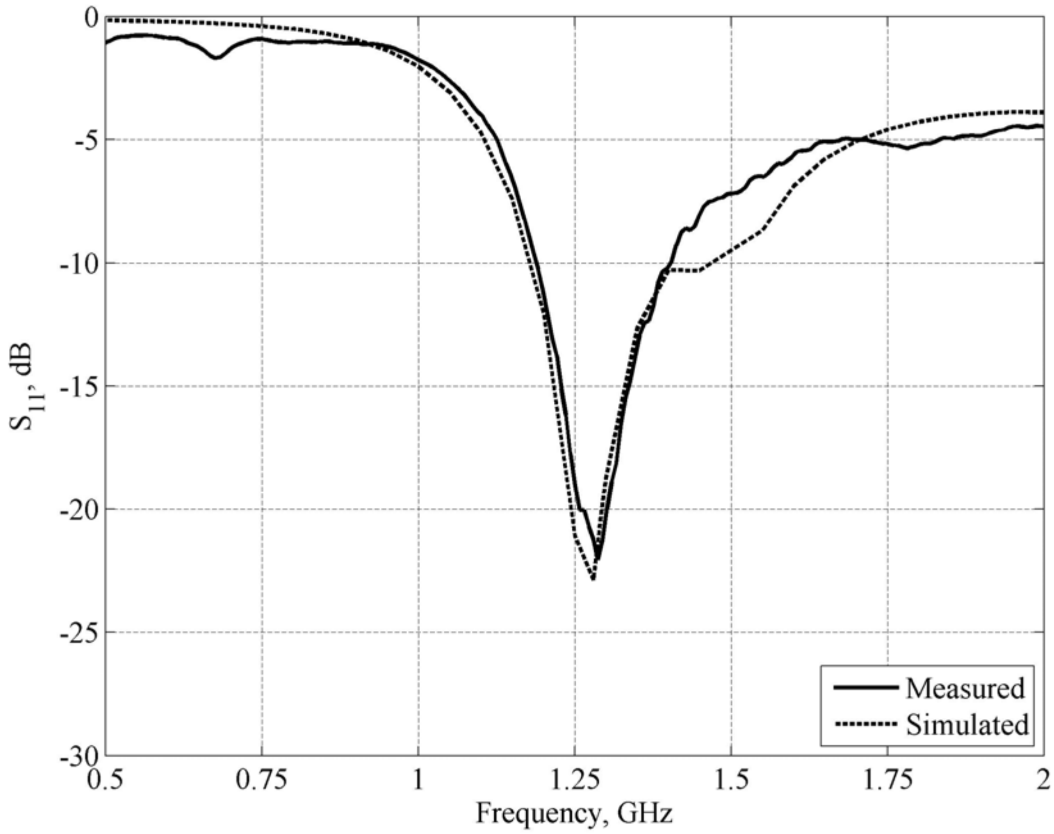


Figure 5.7. Simulated and measured reflection loss of the balun-dipole combination.

A sharp and deep resonant spike is seen, with a reflection loss of more than 20 dB, which can be considered as good. This shows that the balun does indeed not compromise the basic dipole structure as far as its matching is concerned. It is also nice to see that simulation and measurement results track each other particularly well in and near the resonant region.

Continuing the performance validation of the balun as feed, the far field radiation pattern of the antenna with 0° compensation was measured in an anechoic chamber. Figure 5.8 shows these measured H-plane radiation patterns.

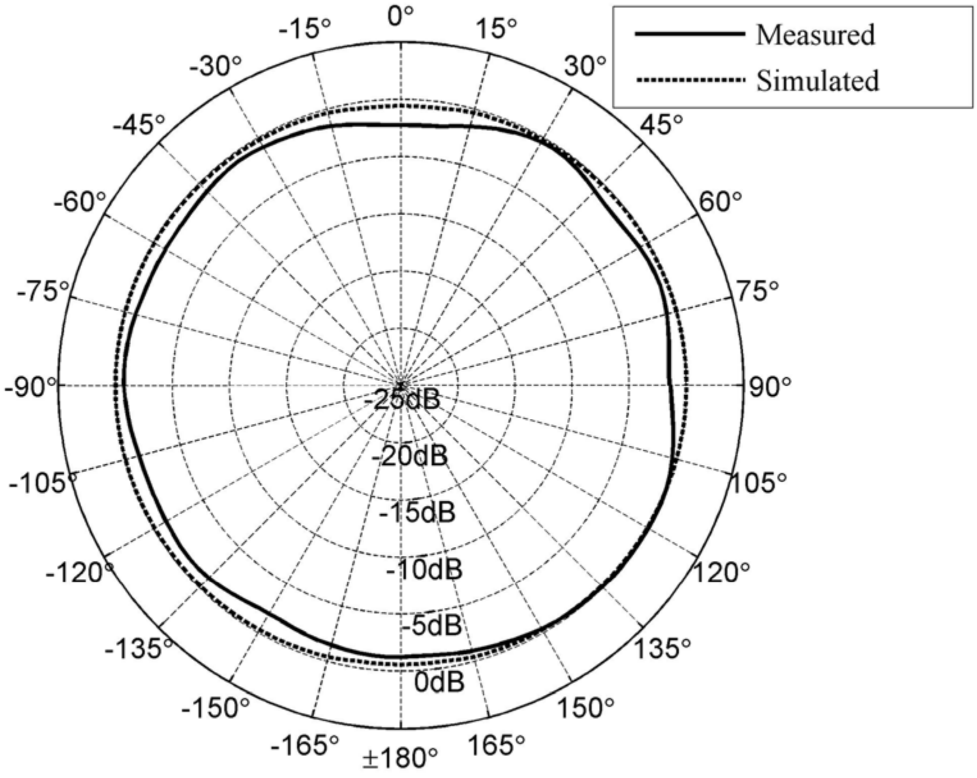


Figure 5.8. Simulated and measured normalised H-Plane pattern of the dipole at 1.3 GHz.

As expected the dipole has am almost perfectly omni-directional H-plane pattern. This can be seen particularly well in the simulation results, but even the measurements show a peak-to-peak ripple of only 2 dB, which is relatively little for a measurement of this nature. This shows that the presence of the balun does not significantly influence the omni directional nature of the dipole, which might have been possible considering the proximity of the added metal and the fact that the dipole is only printed on a single side of the substrate.

Figure 5.9 shows a similar comparison between the simulated and measured E-plane patterns of the dipole. The measured as well as simulated results show a definite asymmetry in the radiation pattern. In this case the balun does indeed negatively influence the radiation performance of the basic dipole, unlike in the reflection loss and H-plane parameters. The squint in the E-plane radiation patterns shown in Figure 5.9 can be attributed to the phase imbalance for the straight balun, shown in Figure 4.6. This shows that even a relatively small imbalance can have a negative effect in the final implementation, and reiterates the importance of testing this parameter.

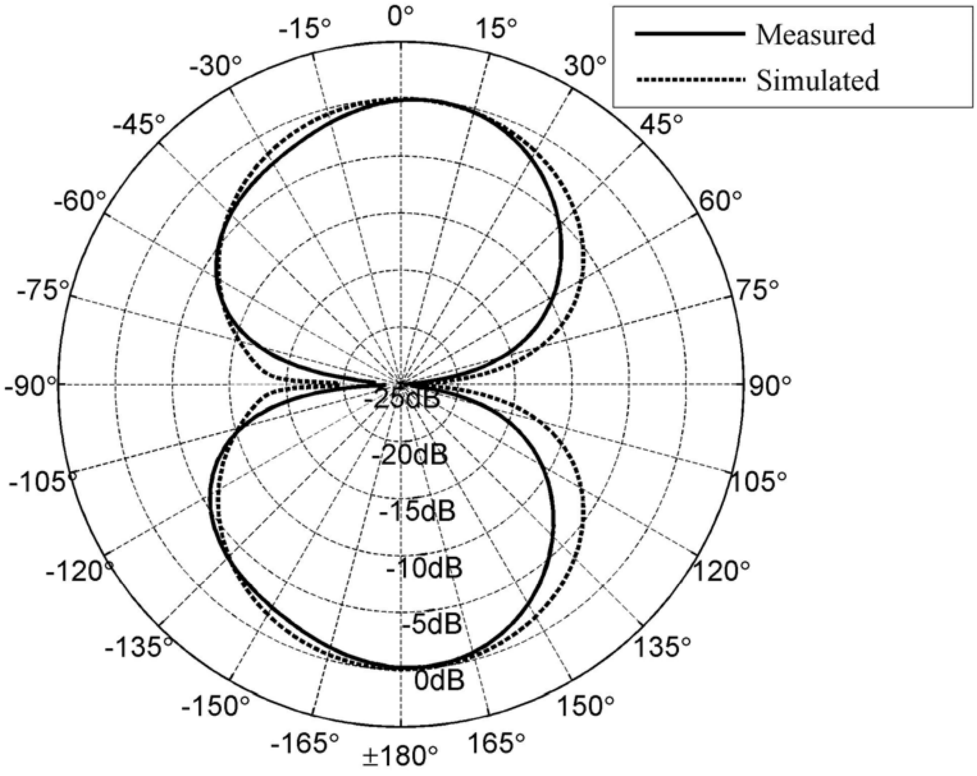


Figure 5.9. Simulated and measured normalised E-Plane pattern of the dipole at 1.3 GHz.

In the previous section the implementation of the new phase compensation technique was described in detail and the resulting improvement in phase balance demonstrated. This technique was employed in the balun feed for the dipole as shown in Figure 5.6. The measured E-plane results of two antennas are shown in Figure 5.10 - one without phase compensation (0°) and one with (55°).

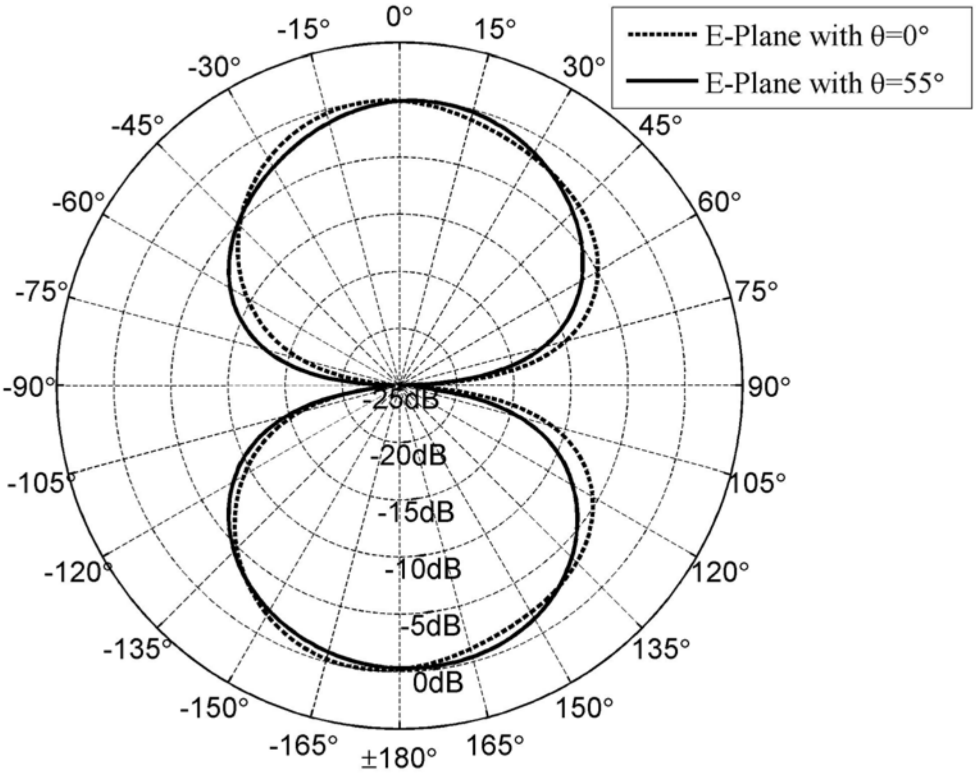


Figure 5.10. Measured normalised E-Plane patterns of the dipole at 1.3 GHz, with and without phase compensation

From this figure it is clear to see that the phase compensation corrects the asymmetry of the pattern to a large degree. In fact, it reduces the -6 dB squint value from 8° to only 3°, a significant improvement, which clearly shows that the phase compensation does in fact work well, and how it can be implemented to improve the performance of the final application. It might be noted that in the case of the dipole this squint improvement does not have many practical advantages, but in other application, such as spiral or notch antennas, it can well prove to be much more helpful. Nonetheless this simple example shows the desired effect very clearly.

A much larger improvement can be seen when one looks at the cross polarisation levels of the dipole with and without phase adjustment. This is shown in Figure 5.11. The phase compensated dipole with the better input balance shows a maximum cross-pol level of 28 dB, 17 dB better than when compared to the dipole without this adjustment. This is a significant improvement that can prove to very useful in some other applications.

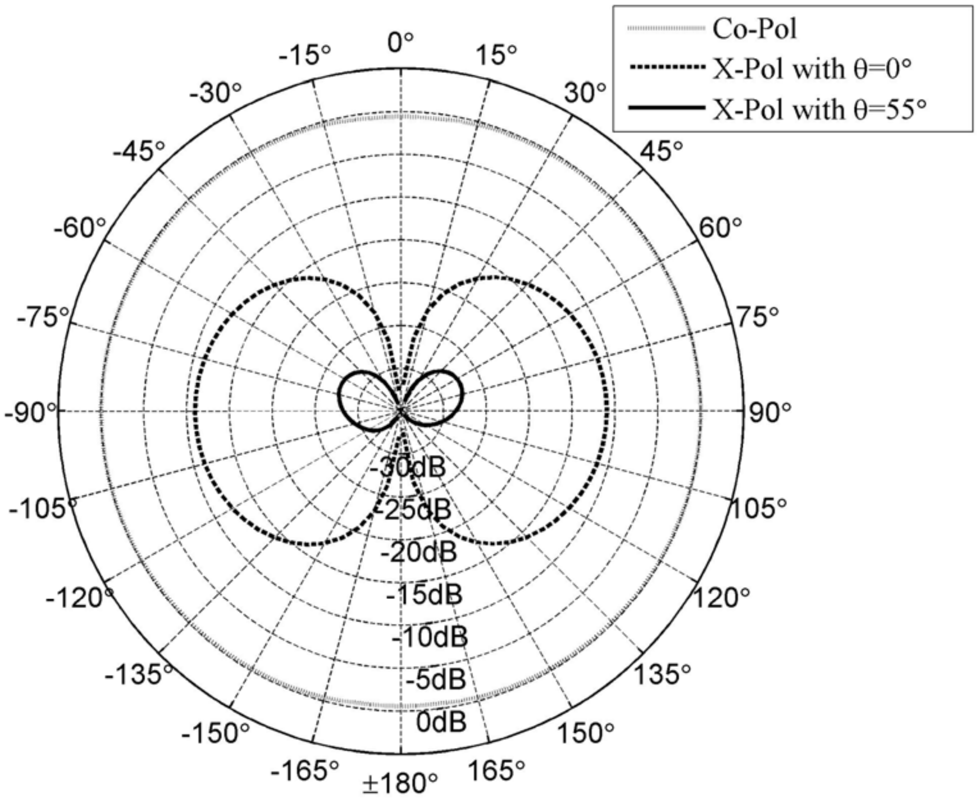


Figure 5.11. Simulated normalised H-Plane cross polarised patterns of the dipole at 1.3 GHz, with and without phase compensation

5.3 CONCLUSION

In this chapter it was shown that using the designed uniplanar balun as feed for a balanced antenna, in this case an etched dipole, does not negatively impact the basic antenna performance regarding either matching or H-plane patterns. However, because of the phase imbalance, although relatively small, it does influence the E-plane patterns by introducing extra squint as well as higher cross polarisation levels. It was shown that successful implementation of the phase compensation technique proposed in the previous chapter can significantly improve these parameters, to such an extent that the final results are again close to the ideal theoretical dipole results. Through this it was also shown why it is important to test the imbalance of the balun as part of the full testing procedure, before it is finally implemented.

CHAPTER 6

CONCLUSION

In this chapter the work described in the rest of the dissertation is shortly summarised while mentioning the main contributions of the study, the main advantages and disadvantages of the balun and the design techniques and then proposing some ideas for future work.

6.1 BACKGROUND AND SUMMARY

The aim of this study was to design and characterise a wideband CPW to CPS coplanar balun, and to develop and implement a complete balun testing procedure. Interest in these types of coplanar transmission lines and the devices and antennas that can be fed from them are definitely on the rise. Relatively few articles have been published in the open literature regarding the feeding mechanisms for these balanced structures. There are some examples of CPW-CPS baluns available, but most of them are either severely limited in bandwidth or requires specialised equipment and techniques for manufacture. The balun implemented for this study was one that uses a single wide band open circuit structure and bond wires to accomplish the transformation from unbalanced CPW to balanced CPS line. The frequency band and manufacturing limitations are chosen so that the balun can be used as a possible feed for a focal plane array of Vivaldi antennas in the SKA, or similar project, which requires a low cost, highly repeatable solution.

Although this type of balun has been used in the literature, there are no simple design criteria available to accomplish its design. In this dissertation all the main design options and parameters were discussed in detail as part of a parametric study. The logic behind, and effects of each change was clearly shown. Through this the operation of the balun can now be fully understood and future designers should be able to do so much more precisely and within a lot less time. Simulation as well as measurements results were used to characterise the balun.

As part of the testing and full characterisation of this balun, some new types of tests that can be performed on the balun were proposed. These include a technique for testing the actual balance performance of the balun and in the end formed a complete test procedure which can and should be used on a new balun design. The importance and the information that can be gained by each of these tests were clearly demonstrated. The good phase balance of the balun over the whole frequency band of the balun was highlighted as a major advantage of this balun.

The balance characterisation tests proved that the phase imbalance of the designed balun, although already rather good, still showed some room for improvement. To achieve this a new type of phase compensating section was designed and successfully implemented on the balun, significantly decreasing the phase imbalance of the balun. This proved to be a general technique that can also be implemented for other etched components and antennas which require high degrees of phase balance on their input ports.

This phase compensated balun was successfully implemented as feed for an etched dipole antenna. It was shown that the presence of the balun close to the dipole did not disturb the radiation patterns of the antenna. The effect and advantage of the phase compensation was clearly shown by the improvement in the squint and the cross polarization parameters.

6.2 CONTRIBUTIONS

By performing a detailed parametric study it was demonstrated how to design a balun of this type. This is the first time that such a detailed study was done to show how the balun works, which emerged as an important contribution in itself. The effect of design choices and parameters can now be much better understood and planned for from the beginning of the design.

It was shown that these baluns can successfully be implemented on a relatively low permittivity substrate, given some stringent etching constraints. The most interesting part of the balun design was, however, the use of newly designed etched bond wires. This new technique of etching the bond wires on the bottom of the substrate and connecting them to the main conducting strips via plated through holes, in stead of using the traditional soldered-on bond wires, significantly increases the reliability and repeatability of the balun, while still simplifying the production process.

The main contribution of this study emerged as the actual techniques being newly designed and used. A series of tests to fully characterise the balun was proposed and successfully implemented. This testing technique includes not only the usual back-to-back measurements, but also a single element test as well as a new implementation of a balance testing circuit. Interestingly, this new balance test showed for the first time that this type of balun has good balance right down to frequency values approaching DC. This is not the case for all baluns, e.g. the double-Y balun that shows good matching characteristics but suffers from phase imbalance at low frequencies. The actual degree of balance of this type of balun was also illustrated for the first time using the balance testing circuit.

The other new technique that was developed and successfully implemented is a phase compensation technique used to improve the output balance of the balun. The technique was shown to significantly improve the phase balance of the balun and by doing so improved the radiation performance of the balun-fed dipole antenna.

6.3 ADVANTAGES AND DISADVANTAGES

This section will list and discuss some of the main advantages and disadvantages of the designed balun and the techniques developed.

The designed CPW to CPS balun has the following advantages:

- It is a very small design in terms of wavelength.
- It is inherently an inline balun, unlike some other commonly used baluns like the etched Marchand varieties.
- The etched bond wires increases the manufacturing repeatability compared to traditional soldered bond wires.
- This balun is implemented on low cost, suitable for mass production substrate.
- As was shown it has a good balance right down to very low frequencies, which is not the case for all similar baluns, e.g. the double-Y balun.

The designed CPW to CPS balun has the following disadvantages:

- This type of balun has an inherent low-pass characteristic. This means that with careful design the balun can be used from very low frequencies, but very high frequency use is not possible. The design is thus not frequency scalable.
- This specific design has a lower cut-off frequency than some other balun designs. This constraint is mainly due to the type of substrate used and the restriction on a minimum etched gap size.
- No exact design equations exist for this type of balun, although many of the design criteria have been explained in this dissertation.
- The etched bond wires also have disadvantages in creating the need for double sided etching and through hole plating. They also decrease the upper cutoff frequency of the balun.

The main disadvantage of the full characterisation technique is that it takes more time than would usually be used to test a balun. An extra splitter has to be designed and etched to complete these tests. The importance of these tests has, however, clearly been shown and can actually save time during the integrated design phase. A disadvantage is that the splitter is not well suited to optimising the design using simulations and should thus be built as well. The main advantage of this technique is that the balun is completely tested and that all the characteristics of the balun are known before final implementation. If any possible problems are noted it can be addressed much earlier in the design phase.

The main advantage of the phase compensation technique is clear – It has the ability to easily correct for any systematic phase error that might exist. The advantage of this improved phase balance was clearly shown in the dipole implementation. However, because of its physical nature it can only provide a limited degree of phase compensation corresponding to the maximum bend angle that can be implemented. It will not be able to correct for a balun which has very poor phase balance to start of with, but is very useful if small corrections are needed for a specific application.

6.4 POSSIBILITIES FOR FUTURE WORK

This study has shown the basic workings of this balun and discussed a number of useful design criteria. However, a set of design equations, or even an equivalent network representation is still not available for this type of balun and future work with this goal in mind will be very useful.

More work could also be done on improving the splitter for the balance testing circuit to improve correlation between simulation and measurement.

Integrating the phase compensated balun to another antenna, e.g. a notch or Vivaldi antenna would be most useful as it will use the full wideband nature of the balun and would demonstrate its improved performance.

It would be interesting to see to where the upper cutoff frequency can be improved if the restraints which were set for this project are lifted. Making use of a substrate with better characteristics and an etched facility capable of smaller gap sizes should theoretically make it possible to build baluns with a significantly larger bandwidth. While improving the upper cut off frequency of the balun, changing these two parameters should also significantly improve the balance performance of the balun, as the two CPW ground planes will then be closer to each other.

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