MULTI-FUNCTION PATCH ELEMENT

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Abstract—Integration of multiple functions is for the first time achieved within a single patch circuit element. Firstly, out of phase equal power division and bandpass filter characteristics are combined within a patch element. The novelty of the proposed structure is to use simple asymmetric cross slots in the patch element to achieve this integration. A simplified equivalent circuit model to describe operation of this patch element is proposed. Coplanar waveguide/microstrip broadside coupling is then investigated to enhance the performance of the patch balun filter and eliminate narrow coupling gaps and microstrip lines. Subsequently, transition between microstrip and coplanar waveguide is then added to the patch element by using certain electromagnetic coupling methods for higher level integration without introducing additional loss. Different patch elements operating at 2.4 GHz are developed to validate the feasibility of the proposed structures. The circuits were designed, fabricated and measured. The measured results agree quite well with the simulation, exhibiting small amplitude and phase imbalance at the output ports throughout the desired passband, and good rejection levels elsewhere.

1. INTRODUCTION

With the rapid development of wireless communication technology, the miniaturization and performance improvement of wireless communication components have become increasingly necessary. In particular, the miniaturization of key components in radio frequency systems has become a very important issue. Miniaturization can be achieved either by compressing the sizes of the individual components, or by integrating different functions within a single component.

Baluns are components which transform an unbalanced signal to one that is balanced. They perform an important function in balanced circuit topologies such as balanced mixers, push pull amplifiers, antenna feeding network, and so on. In the past, various balun structures have been investigated for applications in microwave circuits [1–3]. Most of them can be easily realized using microstrip lines, but are not suited for very high frequency use due to significant and undesirable parasitic effects caused by junction discontinuities. This is because the junction widths become comparable to a quarter wavelength at very high frequencies. Thus a new structure is necessary that is more suited for high frequency applications that have a simple configuration which would allow for ease of fabrication.

A passive filter used to reject unwanted signals is another important circuit in wireless communication systems. Bandpass filters realized using microstrip line can be designed using single or dual mode resonators. The concept behind dual mode band-pass structures has been widely investigated and implemented in the past. Microstrip dual mode filters using a rectangular ring resonator have been investigated in theory and by experiment [4]. Patch resonators using square and triangular patch can also be utilized to design an alternative dual mode filter [5, 6]. They usually suffer from high radiation loss and are large in size when compared with their microstrip ring counterparts. Crossed slots have been successfully implemented for size reduction [5].

For commercial applications, it is advantageous to combine different components together such as the antenna, balun, filter and transition. An integrated component will reduce the number of parts required, compress the size of the RF front end whilst keeping the cost low. This integration should not be a direct connection of different components with matching networks in between as the resulting circuit would occupy a larger size and have much higher insertion loss. In [7], the bandpass filter is employed under the patch antenna using multilayered ceramic/foam architecture. This topology does save space but is still a direct connection of different components and not a true integration. Recently, several designs have been proposed to combine the balun and filter functions. The integrated device is able to convert an unbalanced signal to a filtered balanced one, which consists of two signals of the same magnitude but with 180° phase difference. L. K. Yeung and K.-L. Wu derived the integrated balun filter based on the center-tapped transformer circuit [8]. A balun filter was also designed using a dual-mode ring resonator which also achieved this integration [9].

Featuring simple patch element structures which results in ease of fabrication will be the main focus of the work presented here. The

rectangular patch element is an interesting element, and so far only single function applications have previously been reported. Thus, the rectangular patch is investigated here for the implementation of integrated multi-functionality. In this paper, we propose structures with integral multiple functions and include out of phase power dividing, bandpass filtering and transition between different interfaces, all within a single common patch. The equivalent circuit to describe the operating principle and subsequent parametric analysis are also provided. Several designs based on the patch are investigated, designed, fabricated and measured to validate the proposed structures.

2. COMPACT PATCH BALUN FILTER

Compared to conventional microstrip line elements, microstrip patch resonators have many attractive features. The main advantages are their simple structure, ease of design and fabrication. The performance of microstrip line components becomes poorer with increasing frequency due to junction parasitic effects. In addition, at higher frequencies such as at millimeter waves, microstrip line sections become difficult to control accurately, but this is much less of a problem for patch elements. Use of patch elements makes fabrication much easier because it does not rely on narrow microstrip lines. Microstrip patch resonators can usually be expressed by an equivalent shunt inductance capacitance conductance circuit, where inductance indicates the effect of currents flowing on the surface of the patch resonator, capacitance represents the capacitor formed between the patch and the ground plane, and the conductance represents the radiation loss of the patch. Three ports should be defined as the most basic requirement for a power division structure. If the input port is placed on the left side of the square patch, the two output ports will appear on the top and bottom side of the patch respectively, as shown in Fig. 1. The patch structure with symmetric slots described in [5] cannot be employed in the proposed three port network. This is because the resulting circuit can only give equal power division with in phase characteristics, which does not meet the requirements of a balun.

The analysis will start from the patch element lumped equivalent circuit. To investigate the structure of this three port patch element, the simplified lumped element equivalent circuit as shown in Fig. 2 is used. The inductance between the ports can be treated as inductors (L_1, L_2, L_3, L_4, L_5, and L_6). While the capacitors (C_1, C_2, C_3, and C_4) represent the capacitances between the conductor and ground plane. Capacitors (C_{in} and C_{out}) represent the capacitances resulting from
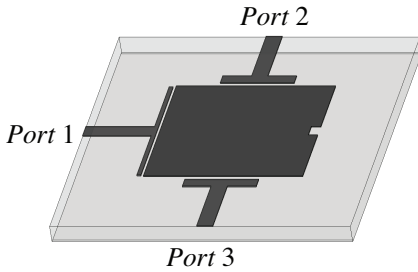
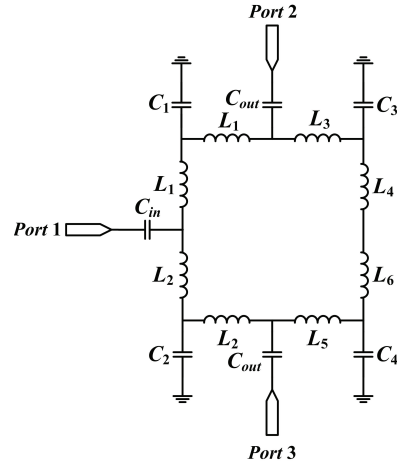**Figure 1.** Configuration of the three ports patch device.

Figure 2. The lumped element equivalent circuit of three ports patch device.

the edge coupling between the input/output ports and patch. The capacitors (C_{in} and C_{out}) were used to provide excellent bandpass characteristics, which ensure the high level suppression within the desired stop bands. Asymmetric values for the inductors (L_1 and L_2, L_3 and L_5, L_4 and L_6) and capacitors (C_1 and C_2, C_3 and C_4) were found to result in both an out of phase power division and a bandpass filter characteristics. Simulation was performed using Agilent Technologies' Advanced Design System (ADS) and the resulting frequency response of the equivalent circuit is shown in Fig. 3. The values of circuit parameters can be extracted using Agilent ADS according to the desired requirements such as operating frequency, bandwidth, positions of transmission zeroes, etc..

Slots are widely used in patch elements including patch antennas and patch filters for various purposes. Use of slots have been reported to aid in size reduction and bandwidth enhancement of patch antennas [10, 11]. This technique has also been applied to patch filters for size reduction and dual band operation [12, 13]. Similar techniques such as defected ground structures are also popular methods to design passive circuits based on microstrip line [14]. However, the applications are limited within the stopband effect and slow wave effect. Different from previous works, the asymmetric slots are employed to integrate multiple functions within a simple patch circuit element. Introduction of slots will change the current distribution within the patch and

characteristics of the conductors between the different ports. Thus the realization for the values of inductors (L_1, L_2, L_3, L_4, L_5, and L_6) and capacitors (C_1, C_2, C_3 and C_4) in the equivalent lumped circuit is possible. Asymmetry of the etched slots within the patch is used to realize the requirements for a balun filter. At the same time, all the equivalent inductance (L_1, L_2, L_3, L_4, L_5, and L_6) of the microstrip conductor increases with the introduction of the slots, implying a decrease in the operating frequency. Therefore, the asymmetric slots not only provide the desired electrical behavior between the input and output ports, which will ensure the bandpass behavior and equal out of phase power division. It also realizes a size reduction when compared to a conventional single function patch resonator.

The patch element eliminates the narrow line width required in the microstrip ring resonators. This is important especially when the required operating frequency of the balun filter is high, resulting in fabrication difficulties. To maintain a simple design procedure, the equal length cross slot is introduced into the rectangular patch according to the desired operating frequency, after that, different T shape slots are used to terminate the ends to achieve the required electrical behavior between the three ports according to the required performance. The design procedure for the proposed patch balun filter may be summarized as follows.

1) Specify the patch element passband response, center frequency, and fractional bandwidth.

2) Obtain the corresponding element values L_1, L_2, L_3, L_4, C_1, C_2, C_3, C_4, C_{in}, and C_{out} of the equivalent circuit model in accordance with the balun filter specification.

3) Adjust the dimensions of patch element particular to the substrate to provide the required lumped-element values. The center frequency is principally determined by w, l, w_s, and l_s for the patch resonator. In addition, the asymmetric dimensions of w_{s1}, l_{s1}, w_{s2}, l_{s2}, w_{s3}, l_{s3}, w_4, l_4 controls the out of phase power division characteristic. The input/output coupling to the patch element will ensure good matching within the passband.

All the circuits described in this paper are designed using Rogers RO3010 with dielectric constant $\varepsilon_r = 10.2$ and thickness of $h = 1.27\,\mathrm{mm}$.

2.1. Compact Patch Balun Filter

The element that represents the main building block of the proposed structure is a rectangular patch with four asymmetric slots as shown in
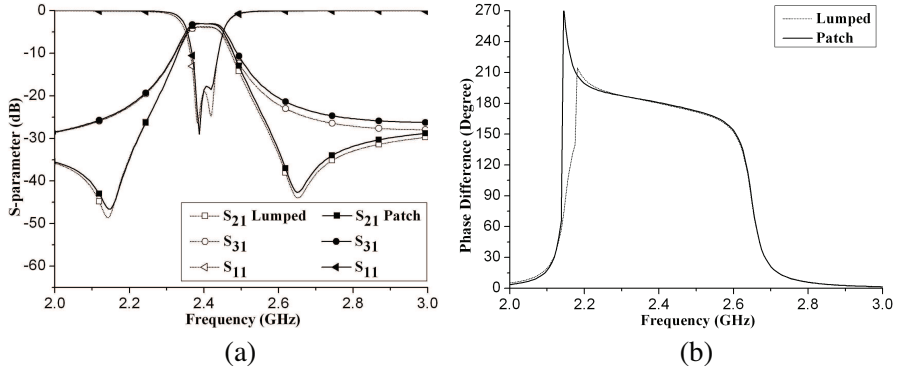
Figure 3. The simulated frequency responses of lumped element equivalent circuit and patch element.
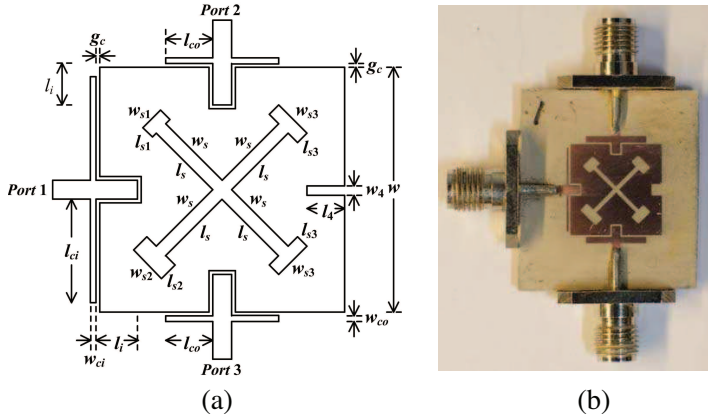

Figure 4. Structure of proposed patch balun filter. $w = 11.7$ mm, $l = 11.7$ mm, $w_{ci} = 0.3$ mm, $l_{ci} = 5.1$ mm, $w_{co} = 0.9$ mm, $l_{co} = 1.9$ mm, $g_c = 0.2$ mm, $l_i = 2.0$ mm, $w_s = 1$ mm, $l_s = 4$ mm, $w_{s1} = 1.5$ mm, $l_{s1} = 1.3$ mm, $w_{s2} = 2.4$ mm, $l_{s2} = 1.3$ mm, $w_{s3} = 2.0$ mm, $l_{s3} = 1.3$ mm, $l_4 = 1.6$ mm, $w_4 = 1.2$ mm.

Fig. 4. To increase the feeder to resonator coupling, the feeding lines are inserted into the rectangular patch at both input and output ports. To the author's knowledge, there is no established design formula for this type of patch resonator even for the simple patch filter. Therefore, the patch element was designed using a commercial method-of-moment (Mom)-based software Zeland IE3D. For demonstration purposes, the design and experimental results for the compact patch balun filter

described earlier are presented. The detailed dimensioning of the patch element is given in Fig. 4. It can be found that the designed patch element has a size of approximately a quarter wavelength by a quarter wavelength at the center frequency, while a conventional rat race coupler based on microstrip line occupies a area of a quarter wavelength by a half wavelength at the center frequency. In order to verify the validity of the lumped equivalent circuit, the results of the equivalent circuit analysis and full wave simulation of the patch element are compared and shown in Fig. 3. It can be observed that the simulated response matches very well with that of its equivalent lumped circuit. This verifies that the proposed equivalent circuit is a good representation of the actual physical behavior of the patch structure.

To study the effects of the etched asymmetric slots, the two dimensional current density is viewed at the center operating frequency and can be seen in Fig. 5. This was obtained via simulation using IE3D and it can be observed that the current density is concentrated around the slots, and more significantly toward the ends of the slots. The current is rerouted by the slots, which results in the shift of resonant frequency. On the other hand, the current densities at the output ports are found to be approximately the same at the operating frequency, indicating that equal power division is also achieved using the etched asymmetric slots.

For a simple design procedure, the design of this patch balun filter is investigated by studying the effect of the slot length l_s and slot width w_s on the passband frequency range and power division behavior compared with the optimum design described in Fig. 4. Fig. 6 shows a group of simulated curves including the return loss and insertion loss with different slot lengths l_s. It is found that, as l_s increases,
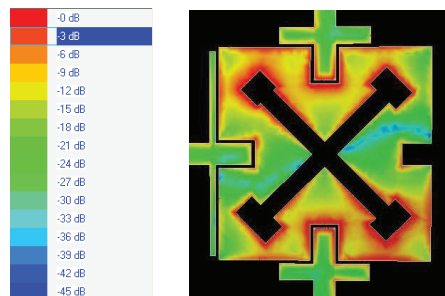

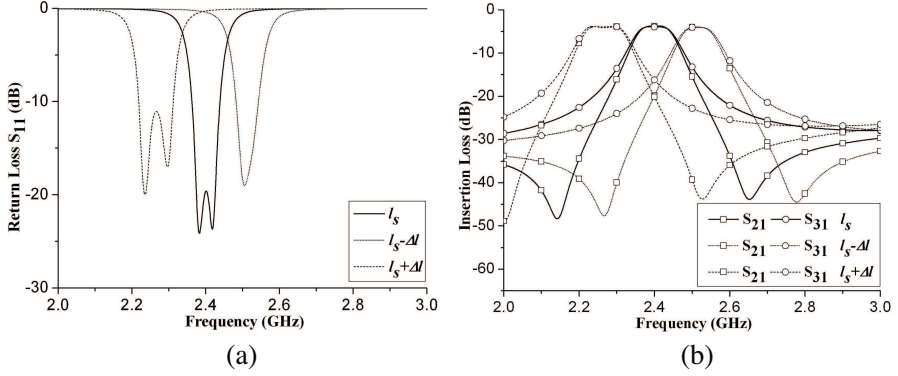**Figure 5.** Current distribution within the square patch at the operating frequency.

Figure 6. Simulated frequency responses of patch balun filter with different slot lengths. $\Delta l = 0.5\,\text{mm}$. (a) Return loss. (b) Insertion loss.
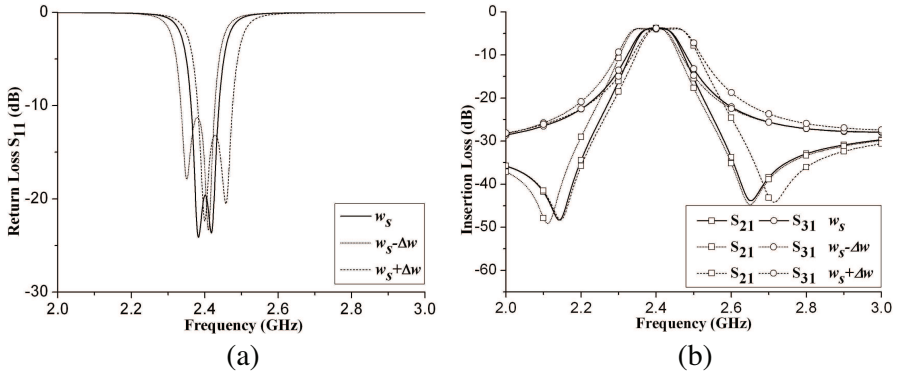

Figure 7. Simulated frequency responses of patch balun filter with different slot widths. $\Delta w = 0.3\,\text{mm}$. (a) Return loss. (b) Insertion loss.

the bandpass frequency shifts from 2.4 GHz to a lower frequency of 2.27 GHz, the bandwidth becomes wider, and the equal power division behavior also shifts to a lower frequency at the same time maintaining a good matching. Similar observations can be made from Fig. 7 which shows the effect of the slot width w_s on the behavior for $l_s = 4.5\,\text{mm}$. When w_s decreases, the bandpass frequency range shifts to a lower frequency of 2.35 GHz, the equal power division behavior also shifts to a lower frequency. Similarly the transmission zeros also shift to lower frequencies. However, slot width w_s does not have significant effects

on the operating frequency, but greatly affects the position for one of the transmission zeros. These results indicate that the behaviors can be controlled by adjusting Δl and Δw. It can be also found that the matching is not always good for all dimensions, so in some cases, other parameters should be modified in the design of the patch element.

To verify an optimum design, a patch balun filter operating at 2.4 GHz was fabricated and measured. For the same operating frequency, a conventional 23.7 mm × 23.7 mm square patch without slots is needed to implement a patch element for single function of bandpass filtering. While the patch area occupied by the proposed structure is only about 24.3% of the conventional patch filter, this indicates a compact size for this novel structure based on a patch element.

In Fig. 8, the dotted and solid lines represent the simulated and measured frequency response of the compact patch balun filter described above, respectively. Results were measured using an HP 8753ES network analyzer. Good agreement between simulated and experimental results is observed, which validates our proposed design. The measured insertion loss at output ports $|S_{21}|$ and $|S_{31}|$ are 5.63 dB and 5.56 dB respectively at the center frequency of 2.395 GHz. The measured insertion loss introduced by the proposed structure is 2.6 dB compared to the ideal 3 dB power division. It is better than the insertion loss caused by the direct connection of filters and balun, which will be much larger than 3 dB. The measured $|S_{11}|$ is less than −10 dB across a 50 MHz frequency range. Within this band the measured maximum magnitude imbalance between the two output ports is 0.35 dB. While the measured phase difference between the two
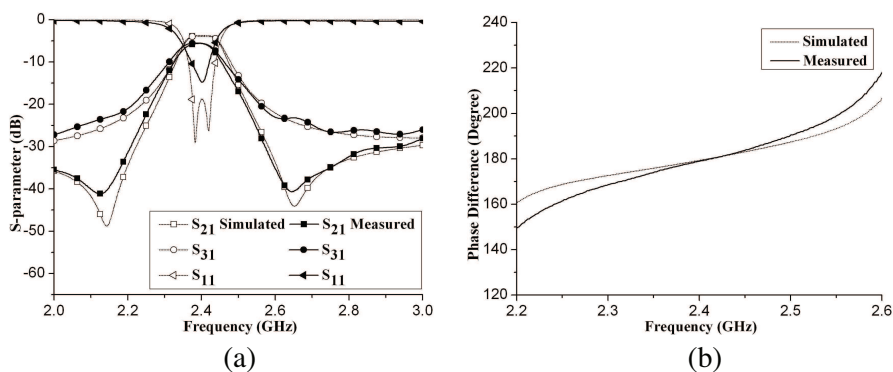

Figure 8. Simulated and measured responses of proposed compact patch balun filter.

ports is $180° \pm 3.8°$ for the same bandwidth. Two transmission zeros are observed at 2.13 GHz and 2.65 GHz at port 2 of the patch balun filter. The transmission zeros can also be designed to appear in port 3 of the patch element by adjusting the dimensions of the terminating T shape slots according to the specific requirements.

2.2. Coplanar Waveguide Feed Patch Balun Filter with Enhanced Performance

The patch balun filter design using a microstrip structure has been demonstrated to exhibit good performance in the previous section. Because of the advantages of a coplanar waveguide structure over a conventional microstrip structure, the implementation of our proposed patch balun filter using CPW feed structure is also considered. CPW structures have been widely used as feeding lines in microstrip antennas. Reasons include low radiation loss and the practical use of shunt and series connections on the same side of the planar substrate, thus avoiding the use of costly and inductive via holes. The CPW feed method is introduced here to extend the applications of the proposed patch balun filter structure. The performance of the circuit is therefore found to be sensitive to fabrication error. Thus the CPW feed method is considered as a new coupling method for our proposed balun filter structure. The possibility for performance improvement both in bandwidth and ease of fabrication will be investigated.

The CPW feed patch balun filter which consists of two layers are illustrated in Fig. 9. For the top layer, the rectangular patch with asymmetric slots acts as the resonator. For the bottom layer, three T-shaped CPW feed lines are used to provide the required coupling to the patch resonator. The CPW feed line consists of a 50 Ω line and two symmetric branches. The CPW 50 Ω line is constructed using a metal strip of a fixed width and gaps of spacing from the ground plane on both sides. The CPW structure can be used to realize wider impedance ranges than that of traditional microstrip using low cost fabrication techniques. As indicated in Fig. 9, the width of the 50 Ω CPW line is given by w_0, and the spacing by g_0. This broadside coupling method provides tighter coupling than the conventional edge coupling method. Coupling between the feed lines and resonator are determined by the lengths (l_{ci}, l_{co}), widths (w_{ci}, w_{co}), gaps (g_{ci}, g_{co}) and coupling region within the patch.

Obviously, the effects of the length l_s and width w_s of the slots on the filtering and power division behavior are similar to the microstrip structure because of the same operating principle behind the patch element with asymmetric slots.

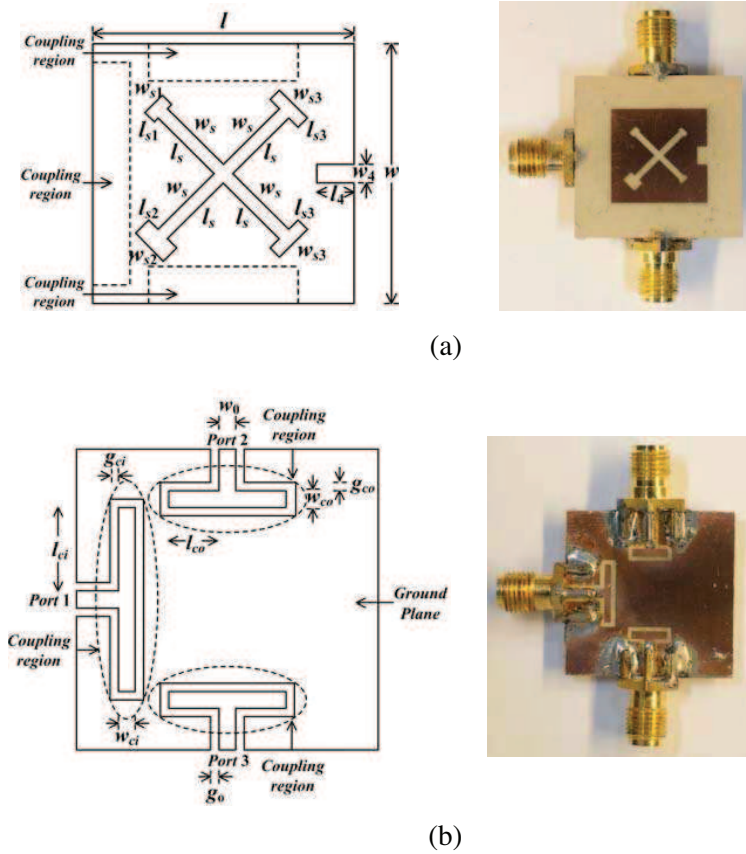According to the description given above, a CPW feed patch balun

(a)

(b)

Figure 9. Structure of proposed CPW feed patch balun filter. (a) Top layer. (b) Bottom layer.

filter operating at 2.4 GHz was also designed and fabricated. The physical dimensions of the circuit are $w = 14.9$ mm, $l = 14.9$ mm, $w_{ci} = 0.9$ mm, $l_{ci} = 3.84$ mm, $w_{co} = 1.1$ mm, $l_{co} = 2.34$ mm, $g_{ci} = 1.0$ mm, $g_{co} = 0.7$ mm, $w_s = 0.5$ mm, $l_s = 5.2$ mm, $w_{s1} = 1.2$ mm, $l_{s1} = 0.5$ mm, $w_{s2} = 2.6$ mm, $l_{s2} = 1.3$ mm, $w_{s3} = 0.9$ mm, $l_{s3} = 0.5$ mm, $w_4 = 2.7$ mm, $l_4 = 1.5$ mm. The size of the resulting balun filter is a bit larger than the microstrip one to avoid the overlap of the coupling regions and slots. As mentioned earlier, the microstrip form of the patch balun filter requires narrow microstrip line and coupling gap to ensure good performance. From the dimensions of the CPW feed patch balun filter describe above, it can be concluded that the required narrow line width and coupling gap are eliminated, which
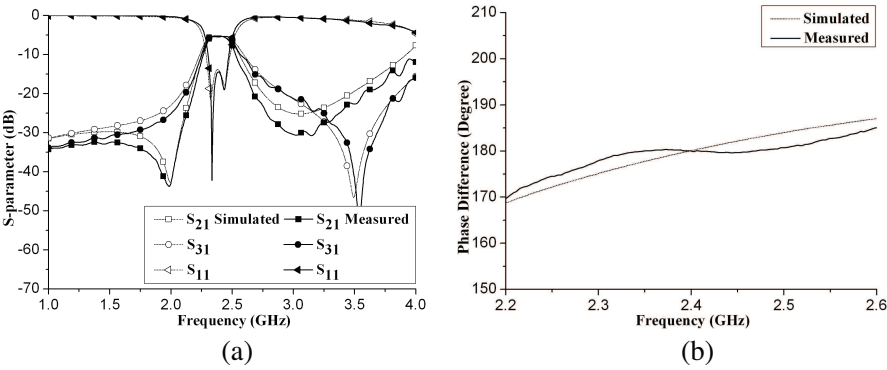
Figure 10. Simulated and measured responses of proposed CPW feed patch balun filter.
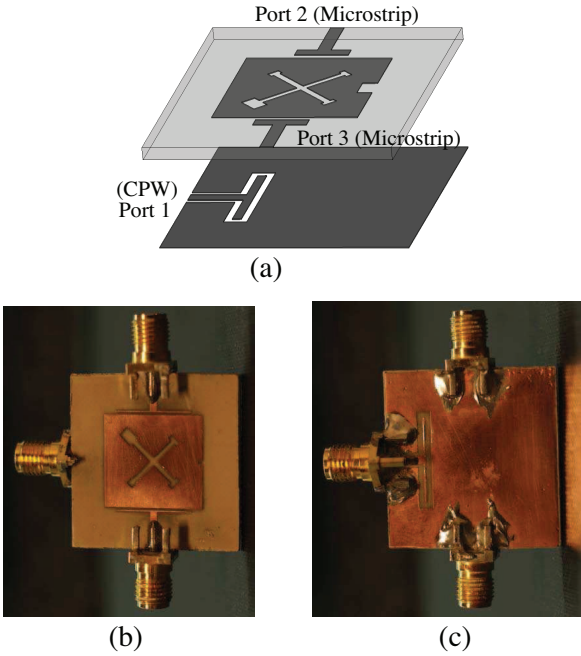

Figure 11. Structure of proposed patch balun filter with integrated CPW to microstrip transition.

will relax the stringent fabrication requirement, and consequently will result in an easier fabrication process.

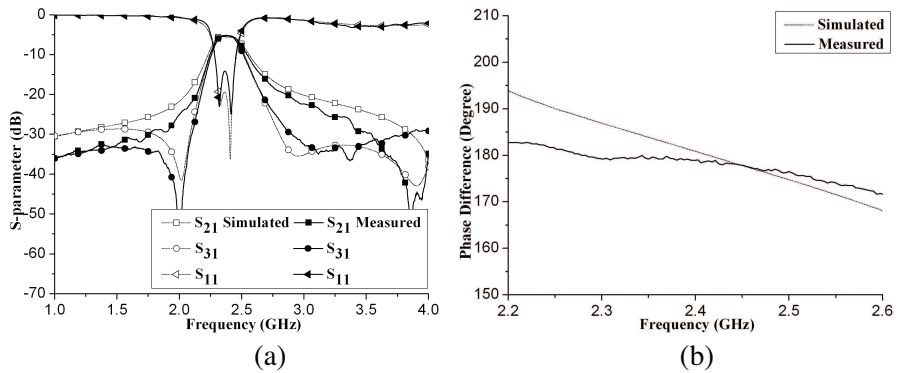The proposed circuit was designed and simulated using Ansoft's

Figure 12. Simulated and measured responses of proposed patch balun filter with integrated CPW to microstrip transition.

full-wave commercial package High Frequency Structure Simulator (HFSS). Fig. 10 shows the simulated and experimental results of the CPW feed patch balun filter. It can be seen that the agreement between simulated and measured results are good. Fractional bandwidth obtained for return loss better than 10 dB is 6.9% centered at 2.39 GHz, which is much wider than the one implemented using a microstrip structure. The insertion losses in the pass band at the two output ports ($|S_{21}|$ and $|S_{31}|$) are both better than -5.7 dB from 2.35 GHz to 2.45 GHz. Meanwhile, the measured maximum magnitude imbalance between the two output ports is 0.4 dB and the measured phase difference between the two ports is $180° \pm 0.4°$ over the same frequency band. Two transmission zeros with more than 30 dB attenuation are observed at about 2 GHz and 3 GHz in port 2 of the balun filter. One additional transmission zero of 55 dB can be found at 3.55 GHz at port 3 of the circuit.

3. PATCH BALUN FILTER WITH INTEGRATED TRANSITION

The increasing system complexity leads to the combined use of different types of transmission lines, in order for these transmission line circuits to achieve their optimum performance. There are two main techniques for the transition between microstrip and CPW. One is by electrical contact, and the other is electromagnetic coupling. Transitions by electrical contact usually call for via holes or/and bonding wires. These transitions provide compact size and wide bandwidth, but they also involve a higher mechanical complexity. Transitions by electromagnetic

coupling require no wire bonds or via holes, most of them suffer from narrow bandwidth and larger size. These transitions can easily be implemented at the desired ports in the transformation between different interfaces.

The need for microstrip/CPW transition is also required for the patch balun filter, as different transmission lines can be used for different feeding networks and antennas for optimum performance. Electromagnetic coupling between the input/output ports and the patch can be used in the patch element as described in Section 2. It provides the required electromagnetic coupling mechanism for a transition. Thus the transition between microstrip and CPW will be considered here, integrated within the structure without any other additional components.

To realize the integration of microstrip to CPW transition, for the input electromagnetic coupling, microstrip edge coupling is chosen, while for the output coupling CPW/microstrip broadside coupling is used. Similarly, the CPW to microstrip transition can be integrated within the proposed structure as well. The CPW-fed broadside coupling is used at the input, while the microstrip edge coupling is employed at the output. The detailed microstrip layout is shown in Fig. 11. It can be observed that the input port is located on the bottom layer, while the two microstrip lines for the output ports and slotted patch element are configured for edge coupling on the top layer.

Based on the above proposed structures, an integrated patch balun filter with CPW to microstrip transition is designed to operate at 2.4 GHz as an example. The definition of dimensional parameters is the same as that described in Fig. 4 and Fig. 9. The optimum physical dimensions obtained are $w = 16.3$ mm, $l = 15.4$ mm, $w_{ci} = 0.4$ mm, $l_{ci} = 6.24$ mm, $w_{co} = 0.3$ mm, $l_{co} = 5.7$ mm, $g_{ci} = 0.9$ mm, $g_{co} = 0.3$ mm, $w_s = 0.8$ mm, $l_s = 4.1$ mm, $w_{s1} = 1.8$ mm, $l_{s1} = 2.5$ mm, $w_{s2} = 1.1$ mm, $l_{s2} = 1.1$ mm, $w_{s3} = 1.9$ mm, $l_{s3} = 0.8$ mm, $w_4 = 0.5$ mm, $l_4 = 0.7$ mm.

Both the EM simulation and measurement results are shown and compared in Fig. 12. The fractional bandwidth obtained for a return loss better than 10 dB is 6.9% centered at 2.37 GHz, which is comparable to the CPW fed patch balun filter. Fig. 12 shows the magnitude and phase response of the proposed circuit. The measured magnitude and phase imbalances in the passband from 2.31 GHz to 2.44 GHz are less than 0.4 dB and 2.1°, respectively. The insertion losses in the pass band at the two output ports are both better than 6 dB, indicating the successful integration of transition without additional loss. Transmission zeroes of S_{21} at 2 GHz and 3.1 GHz were measured, and agree with that predicated by the EM simulation.

Therefore, it can be concluded that the integration of transitions do not result in performance degradation for bandwidth or insertion loss.

4. CONCLUSION

In this paper, a new class of patch topologies integrated with multiple functions is proposed. For the first time, the patch balun filter structures that are interchangeable between microstrip and CPW interfaces have been proposed. A simplified equivalent circuit has been synthesized and verified for modeling this type of patch element. We have also demonstrated, for the first time, patch balun filters integrated with transitions between microstrip and coplanar waveguide. The characteristics of these patch elements have been described and verified by measurements. These patch elements offer not only an alternative design of microstrip line based balun filters, but also a simple structure, ease of fabrication and a higher level of integration. It is expected that these patch elements will be very attractive for developing planar components with multiple functions, simple structure and high power handling especially for high frequency applications such in millimeter waves.

ACKNOWLEDGMENT

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