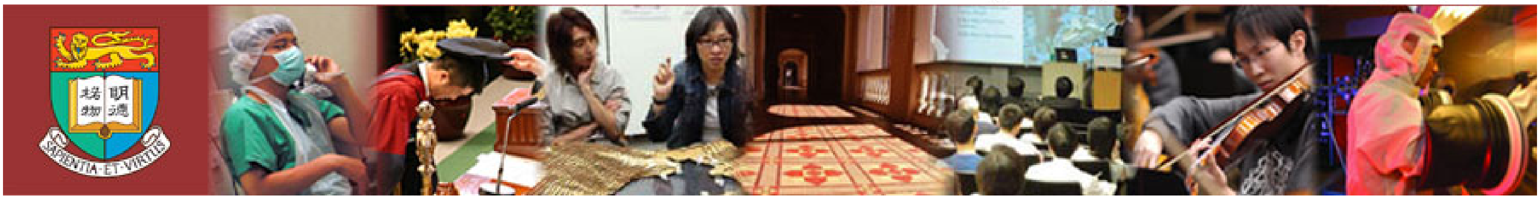

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Novel Dual-Mode Balun Bandpass Filters Using Single Cross-Slotted Patch Resonator

Sheng Sun, *Member, IEEE*, and Wolfgang Menzel, *Fellow, IEEE*

***Abstract*—In this letter, a novel dual-mode bandpass balun filter is presented using a miniaturized cross-slotted patch resonator. This balun filter consists of a single slit-loaded patch etched by a pair of cross slots and a stepped-impedance open stub. An unbalanced input port is orthogonally arranged in-between two balanced output ports along the patch, and each feed line is connected to an additional stub for enhanced coupling. Due to the dual-mode characteristic of the patch resonator, two transmission poles can be easily constructed at both balanced passbands. Asymmetrical width and length of the cross-loaded slots perturb the field of the patch and excite two degenerate modes simultaneously, while the attached open-circuited stub provides an additional degree of freedom for performance tuning. Finally, two prototype balun filters are designed and fabricated at 3.48 and 1.80 GHz, respectively. Measured results achieve good filtering and balun performance and agree well with those from simulations.**

***Index Terms*—Balun bandpass filter (BPF), balanced filter, cross-slotted patch, dual-mode resonator.**

I. INTRODUCTION

TODAY, integration, compact size, and low cost are highly desirable for RF and microwave integrated circuits in modern wireless systems. As two key components, both balun and filter play important roles in the design of RF front-end modules. Directly cascading a balun and a filter offers an intuitive solution for the balanced-to-unbalanced signal conversion with filtering selection. However, this proposal always suffers from high insertion loss and large size due to the linear sum of two separate circuit topologies.

To overcome these problems, an idea of integrating these two devices has been proposed to reduce the loss and circuit size [1], [2]. That means an integrated device can provide not only a frequency-band selection as a filter, but also a balanced-to-unbalanced conversion as a balun. By using low-temperature co-fired ceramic (LTCC) technology, a balun and a filter were connected in series and considered as a chip-type multi-functional device [1]. Because of multilayer configurations, these LTCC-based balun filters have compact sizes, but the structure and design procedure is very complicated. Based on the traditional Marchand balun, the filtering function can also be introduced by involving lumped capacitors [2]. However, the circuit has large size and requires many via holes due to the multiple use of short-circuited coupled lines. In [3], smaller size can be achieved by implementing shorter multi-coupled lines on LTCC substrate. Nevertheless, more shunt lumped capacitors have to be added into the multilayer structure and make the design more complicated. On the other hand, a symmetrical four-port balanced-to-balanced bandpass filter (BPF) can be converted to a three-port balun filter with one of the ports being opened [4].

In this letter, we present a dual-mode balun BPF using a cross-slotted patch resonator. The concept of dual-mode balun filter was initially proposed in [5] and modified in [6] using a single ring resonator. Due to the excitation of two degenerate modes, two-pole transmission characteristic can be realized on both of two balanced outputs. To reduce the size and radiation loss, dual-mode filters using cross-slotted patch resonators were developed in [7], [8]. As the slot length is increased, the route of the electric current on the patch is bent and extended. Then, the resonant frequency can be shifted down, and the size can be reduced accordingly. In [9], two such patch resonators have been stacked to make a balun filter, where each resonator produced two modes for each balanced passband. However, an additional conductor plane was inserted between two patch resonators and increased the design complexity and cost accordingly. Therefore, the objective of this work is to design a balun filter using a single patch resonator. By etching the patch with asymmetrical-cross slots, two degenerate modes can be excited and coupled to each other at both balanced output ports. Finally, two patch balun filters with and without shielding box are designed and verified experimentally.

II. PROPOSED BALUN FILTERS

Fig. 1 depicts the schematic of this proposed balun BPF. A pair of asymmetrical-crossed slots, ended with a stepped-impedance-shape and T-shape slots, is formed on a square patch resonator with four slits at its four sides. An open-circuited stepped-impedance shaped stub is installed at the enlarged slit and provides an additional degree of freedom for performance adjustment by controlling the transmission zeros. Compared to the two-port dual-mode BPF with only port 1 and 2, a third port (port 3) is added to another side of the patch. Since both port 2 and 3 are placed face-to-face at the orthogonal plane with respect to port 1, a half-wavelength electrical length is naturally formed between them and offers an 180° phase difference for the two balanced outputs. Each feed line is connected to a coupling stub inserted into slits in order to provide an enhanced coupling degree. Fig. 2 shows the size-vectored current densities on the conducting surface of the patches at 3.48 GHz. The current

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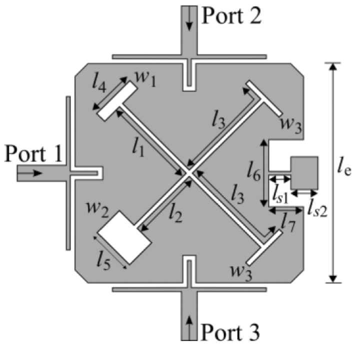


Fig. 1. Physical layout of the designed balun BPF.

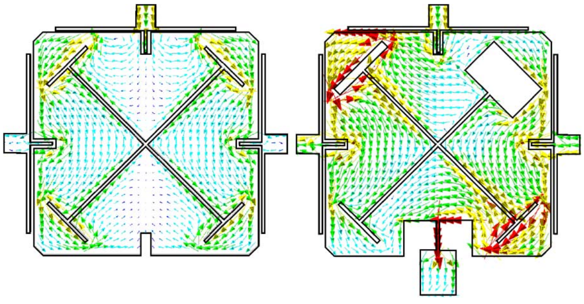

(a) (b)

Fig. 2. Current distributions of the (a) symmetrical and (b) asymmetrical cross-slotted patches.

flow path on the patch is significantly distorted and extended by the pair of symmetrical-crossed slots, where the electrically extended and oppositely oriented current densities along the slots lead to a reduction of the size and radiation loss. In particular, the current distributions around port 2 and 3 are also symmetrical, which implies that the two degenerate modes at two output ports can be excited by sharing the asymmetrical perturbations, as shown in Fig. 2(b).

Similar to the operation principle of the inner corner-cut perturbation along a ring resonator [10], the effective inductive loading between input port 1 and output port 3 is larger than the other one between port 1 and 2, due to wider etching at the end of the stepped-impedance-shape slot. That means two transmission zeros can be only observed at the transmission path between input port 1 and output port 2. Fig. 3 displays the frequency responses with varied slot and stub sizes. By adjusting these perturbation elements, the dual-mode behavior with two transmission zeros can be well controlled to obtain both balanced in-band and out-band responses. In order to provide an insight of the quality of a balun filter, the associated mixed-mode parameters, e.g., differential and common modes, can be determined from the standard three-port S-parameters as [11]

$$S_{21d} = (S_{21} - S_{31})/\sqrt{2} \tag{1}$$

$$S_{21c} = (S_{21} + S_{31})/\sqrt{2}. \tag{2}$$

The simulated transmission responses of the differential (S_{21d}) and common (S_{21c}) modes are shown in Fig. 4, where a bandpass performance is observed in differential excitation. According to the definitions in (1) and (2), the intersection points between S_{21d} and S_{21c} are corresponding to the transmission zeros in S_{21} as appeared in Fig. 3. On the other hand, 20 dB suppression of the common mode has been achieved over the whole simulated frequency range.

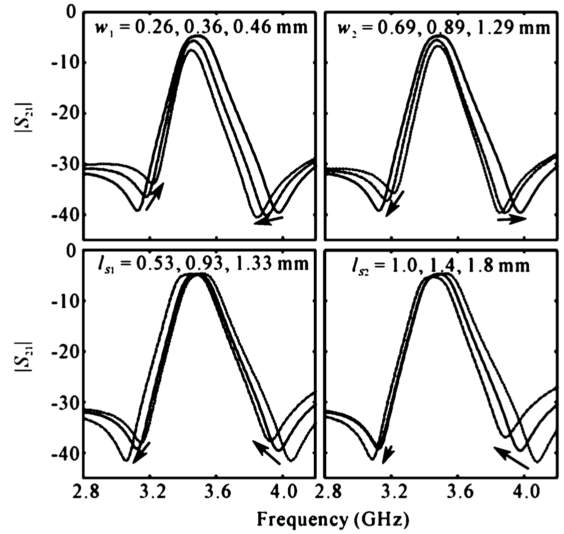


Fig. 3. Frequency responses with varied slot sizes (w_1 and w_2) and stub lengths (l_{s1} and l_{s2}).

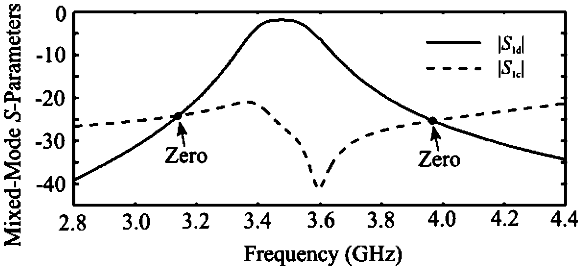
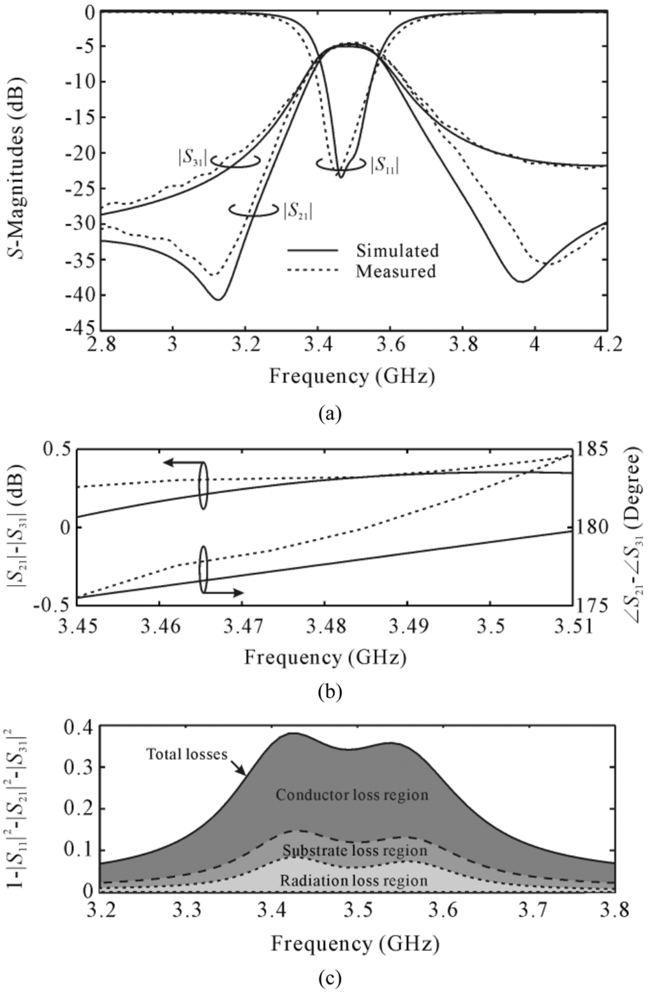


Fig. 4. Transmission responses of differential and common modes.

III. Implementation and Measurement

To verify the performance of the aforementioned balun filters, a balun filter, namely, balun-filter A, has been designed at 3.48 GHz. Fig. 5(a) shows the frequency responses of the proposed balun-filter A and Fig. 5(b) shows the amplitude and phase differences of the two balanced ports. The measured minimum insertion and maximum return losses are $(3 + 1.9)$ dB and 23.1 dB, respectively. The measured amplitude imbalance and phase difference between the two balanced ports are within 0.5 dB and $180 \pm 5^\circ$, respectively, over the passband from 3.45 to 3.51 GHz. Fig. 5(c) shows the simulated loss factors against frequency. We can note that the main loss is mainly contributed from the metallic conductor, while the substrate loss is comparable with the radiation loss. In order to further reduce the conductor and radiation losses, the balun-filter B is designed with wider strip width at 1.8 GHz, and shielded within an aluminum box. The inset of Fig. 6 illustrates the photograph of this fabricated circuit. A good agreement between the simulated and measured mixed-mode S-parameters is achieved and shown in Fig. 6. The obtained insertion loss of the differential mode is about 1.45 dB, while the suppression of the common mode is better than 20 dB. Table I compares measured 3-dB bandwidths



(a)

(b)

(c)

Fig. 5. Simulated and measured results of the designed balun-filter A. (a) S-Magnitudes. (b) Amplitude imbalance and phase balance. Dimensions: $l_c = 7.0, l_1 = 3.24, l_2 = 2.16, l_3 = 4.15, l_4 = l_5 = 2.10, l_6 = 2.12, l_7 = 1.13, w_1 = 0.26, w_2 = 1.29, w_3 = 0.10, l_{s1} = 0.93, l_{s2} = 1.40$. All are in mm. Material: $\varepsilon_r = 10.8$ and thickness $h = 0.635$ mm, $\tan\delta = 0.0023, \sigma_{\text{Copper}} = 5.8 \times 10^7$ S/m. (c) Simulated loss factors against frequency. EM simulator: Advanced Design System 2009.

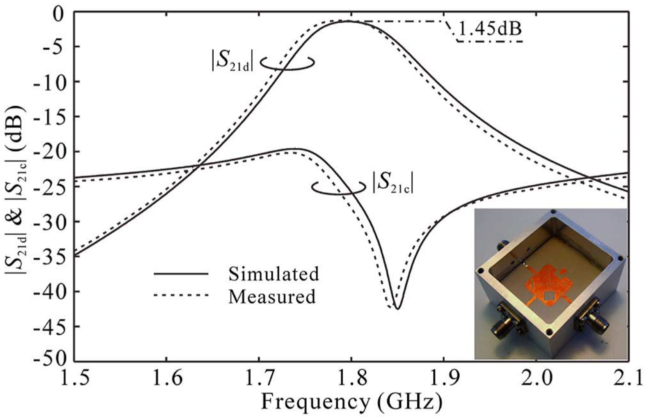


Fig. 6. Transmission responses of differential and common modes for balun-filter B with shielding box ($\sigma_{\text{Aluminum}} = 3.8 \times 10^7$ S/m). Inset: Photograph of the fabricated shielded balun BPF. Dimensions: $l_c = 14.0, l_1 = 6.18, l_2 = 2.98, l_3 = 8.30, l_4 = l_5 = 4.20, l_6 = 4.24, l_7 = 2.26, w_1 = 0.72, w_2 = 3.92, w_3 = 0.20, l_{s1} = 1.86, l_{s2} = 2.85$. All are in mm. Material: $\varepsilon_r = 10.8$ and thickness $h = 1.27$ mm, $\tan\delta = 0.0023$.

TABLE I
COMPARISONS AMONG PUBLISHED AND OUR PROTOTYPE BALUN FILTERS

Techniques	Measured 3-dB Bandwidths	Measured minimum insertion losses (dB)
Multilayer LTCC [1]	12.4%	2.0 @ 2.43 GHz
Multilayer LTCC [2]	35.7%	2.5 @ 5.34 GHz
Multilayer LTCC [3]	30.6%	1.3 @ 1..58 GHz
Stepped-impedance resonators [4]	10.1%	2.28 @ 990 MHz
Ring resonators [5]	18.7%	2.5 @ 2.57GHz
Ring resonators [6]	3.5%	3.4 @ 2.55 GHz
Stacked patches [9]	7.0%	1.5 @ 985 MHz
Balun-Filter A	5.5%	1.9 @ 3.48 GHz
Balun-Filter B	5.8%	1.45 @ 1.79 GHz

and minimum insertion losses for published and our prototype balun filters.

IV. CONCLUSION

In this letter, we present a dual-mode balun BPF using only a single cross-slotted patch resonator. By adjusting the sizes of the asymmetrical-crossed slots and the embedded stub, a two-pole filtering responses can be easily obtained in the passbands at two balanced outputs. Moreover, the losses are further reduced with the help of the shielding metal box and the wider strip width.

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