A COMPACT BALUN BASED ON MICROSTRIP EBG CELL AND INTERDIGITAL CAPACITOR

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Abstract—A novel compact balun (balanced-to-unbalanced) that consists of a low-pass network served by a microstrip electromagnetic bandgap (EBG) cell and a high-pass π-network formed with an interdigital capacitor is presented. This proposed approach can effectively operate the compact balun without the use of $\lambda/4$ microstrip lines to reduce the circuit area over 50% compared to the conventional Marchand balun. The core dimension of the compact balun is $0.74\,\mathrm{cm} \times 0.7\,\mathrm{cm}$. The planar structure enables an efficient circuit design in printed circuit boards (PCB) without using any bonding wires, defected ground structures (DGS), or surface mounted devices (SMD). A compact balun operating in the 3 GHz band has been implemented in a FR-4 PCB. From the measured results, the return loss of the input port is better than 15 dB over the band from 2.6 to 4 GHz. The amplitude and phase imbalances are less than 1.4 dB and 3° with the 20% operational bandwidth ranging from 2.7 to 3.3 GHz, respectively.

1. INTRODUCTION

Baluns are important components and generally used in many wireless applications such as push-pull amplifiers, balanced mixers, antenna feed networks [1], frequency multipliers [2] among others. For planar applications, the most popular one is the Marchand balun [3]. It has been acknowledged that the even-mode impedance of the Marchand balun is too extreme to be implemented in typical PCB manufacturing processes due to its tightly coupled structure. In order to overcome this problem, a collateral coupled-line balun consisting of two-pair identical couplers with two-pair symmetric coupled-line sections has

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been proposed [4]. The collateral method is used to increase the spacing between the coupled-line sections due to the increase of mutual capacitance. However, the physical dimension of the balun is proportional to the wavelength of the center frequency and larger than conventional Marchand balun.

Through the years, several variations and improvements of the balun have been proposed. Reduced-size lumped-element uniplanar transitions that can be found in [5], using the planar parallel and series inductor–capacitor circuits to realize the effective open and short circuits respectively, have been proposed. However, the structure needs extra bonding wires to generate the uncertain factors of the balun caused by the PCB manufacturing processes. Furthermore, an additional process is needed with either lower yield or higher cost. A novel balun with vertically periodic DGS has been demonstrated [6]. In actuality, as the ground plane is perforated, the substrate must be suspended so that the circuits cannot be fixed on a metal base for mechanic robustness. Consequently, this structure cannot be easily integrated with other microwave components.

In this paper, a novel planar balun is implemented in an FR-4 PCB. The proposed balun consists of a low-pass network served by the EBG cell and a high-pass π-network formed with an interdigital capacitor without using any bonding wires, DGS configurations, and SMD components. It eliminates the above-mentioned drawbacks and has the significant advantages of planar circuit design and compact circuit size.

2. DESIGN OF THE COMPACT BALUN

The configuration of the proposed balun is shown in Fig. 1, which consists of a high-pass π-network and a low-pass network. Both networks not only provide a function of phase shift but also can be
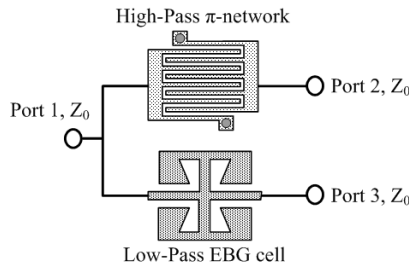

Figure 1. Schematic diagram of the proposed balun.

manufactured by a milling machine on a signal-layer PCB substrate. Port 1 is the unbalanced port, and ports 2 and 3 are the balanced ports. The characteristic impedance of Z_0 is $50\,\Omega$. The architecture of the high-pass π-network is depicted in Fig. 2(a). The high-pass π-network is, in essence, designed with a series capacitor and two shunt inductors. The series capacitor and shunt inductors are realized utilizing the interdigital capacitor [7] and short microstrip stub, respectively. The corresponding lossless L-C equivalent circuit is presented in Fig. 2(b), where the inductors L_p correspond to the short stubs. The capacitance C_p is the parasitic element associated with the shunt capacitance of the rectangular and interdigital sections. The capacitance C_s is the series capacitance of the interdigital section. Specifically, C_s is predominately related to the dimensions s_1, s_2 and x_1, where n is the number of fingers. The total C_s can also be calculated approximately by utilizing [8]

$$C_s = \frac{\varepsilon_{\mathit{eff}}\,10^{-3}}{18\pi}\frac{K\left(k\right)}{K'\left(k\right)}\left(n-1\right)x_1\,\mathrm{pF} \tag{1}$$

where $\varepsilon_{\mathit{eff}}$ is the effective dielectric constant of the microstrip line of width s_1, and

$$\frac{K\left(k\right)}{K'\left(k\right)} = \frac{1}{\pi}\ell n\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right)\ \text{for}\ 0.707 \le k \le 1 \tag{2}$$

$$= \frac{\pi}{\ell n\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right)}\ \text{for}\ 0 \le k \le 0.707 \tag{3}$$
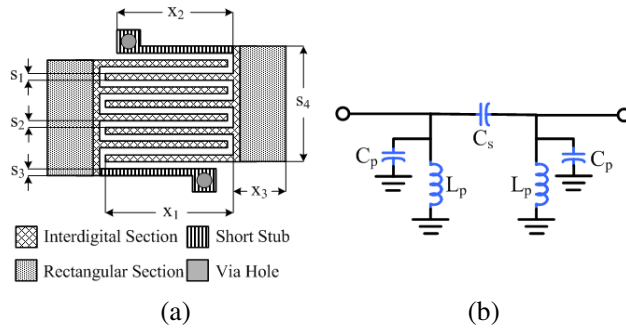

(a)   (b)

Figure 2. (a) The proposed high-pass π-network. (b) Lossless L-C equivalent circuit.

The modulus are

$$k = \tan^2\left(\frac{s_1\pi}{4\left(s_1 + s_2\right)}\right) \qquad (4)$$

$$k' = \sqrt{1 - k^2} \qquad (5)$$

As depicted in Fig. 3(a), the configuration of the low-pass network primarily relies on the unit cell of the EBG structure [9, 10]. Microstrip transmission lines incorporating the EBG structure exhibit band-stop and slow-wave characteristics which can be utilized to generate phase shift and reduce the dimensions of the microstrip structure. The corresponding lossless L-C equivalent circuit of the EBG cell is shown in Fig. 3(b). In essence, the transverse and longitudinal narrow connecting strips shown in Fig. 3(a) are modeled as the inductors L_1, L_2, L_3, and L_4, and the shunt capacitance of the triangular patch corresponds to the capacitance C_2. The capacitance C_1 is the gap capacitance between the triangular patch and the narrow connecting line. Furthermore, the high-pass π-network and EBG cell are directly combined to accomplish the proposed planar balun shown in Fig. 1. The high-pass π-network is of dimensions $x_1 = 4.35\,\text{mm}$, $x_2 = 3.7\,\text{mm}$, $x_3 = 0.6\,\text{mm}$, $s_1 = 0.15\,\text{mm}$, $s_2 = 0.1\,\text{mm}$, $s_3 = 0.15\,\text{mm}$, $s_4 = 2.2\,\text{mm}$ and $n = 8$. The designed dimensions of the EBG structure, as shown in Fig. 3(a), are $w_1 = 0.15\,\text{mm}$, $w_2 = 1.8\,\text{mm}$, $w_3 = 2.8\,\text{mm}$, $w_4 = 5.4\,\text{mm}$, $w_5 = 4.1\,\text{mm}$, $a_1 = 0.15\,\text{mm}$, $a_2 = 2.6\,\text{mm}$, $a_3 = 2.9\,\text{mm}$, $a_4 = 0.35\,\text{mm}$. In this design, Agilent ADS momentum is used in the full-wave electromagnetic (EM) simulation to calculate the S-parameters. By optimizing the EM simulation, the proposed characteristic can be achieved without any degradation compared to the conventional baluns.
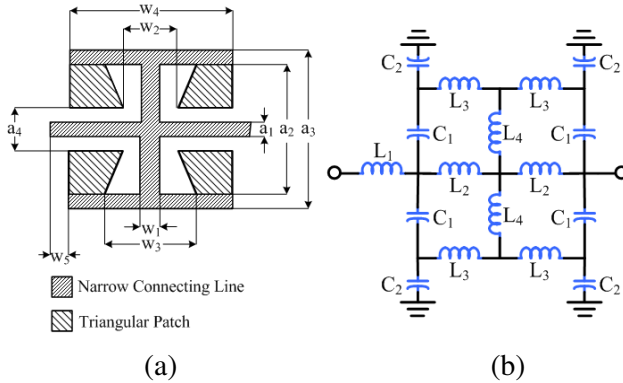

Figure 3. (a) The proposed microstrip EBG cell. (b) Lossless L-C equivalent circuit.

In addition, the corresponding values of the lossless L-C equivalent circuit obtained by curve fitting the EM simulation results are $C_s = 1.84\,\mathrm{pF}$, $C_p = 1.76\,\mathrm{pF}$, $L_p = 3.68\,\mathrm{nH}$, $C_1 = 0.01\,\mathrm{nH}$, $C_2 = 0.56\,\mathrm{pF}$, $L_1 = 1.92\,\mathrm{nH}$, $L_2 = 0.4\,\mathrm{nH}$, $L_3 = 0.4\,\mathrm{nH}$, and $L_4 = 0.4\,\mathrm{nH}$. The equivalent circuit simulation was performed by employing Agilent ADS. Consequently, the proposed approach appears to be simple and an uncomplicated means for the realization of the compact planar balun. Indeed, the planar structure enables an efficient circuit design in printed circuit boards without any bonding wires, DGS configurations, and SMD components.

3. IMPLEMENTATION AND RESULTS

To verify and demonstrate the proposed circuit, a compact planar balun with a center frequency fixed at 3 GHz was designed and implemented, as shown in Fig. 4. A low-cost FR-4 PCB with the relative permittivity of 4.3, loss tangent 0.023, and a 0.8 mm-thick substrate was used. The overall dimension of the circuit is about 1.7 cm × 1.6 cm. The core circuit dimension is 0.74 cm × 0.7 cm not including the 50 Ω microstrip lines. The hybrid occupies only 50% of the area of a conventionally Marchand balun at the center frequency of 3 GHz. This is more effective in reducing the circuit size. In order to obtain the exact design, the SMA connecters are de-embedded. Finally, the fabricated balun is measured and characterized by using an Agilent PNA E8364A network analyzer.

The measured and simulated scattering parameters as a function of frequency are shown in Fig. 5. Due to the fabricated variation, the measured results slightly deviate from the simulated curves. However,
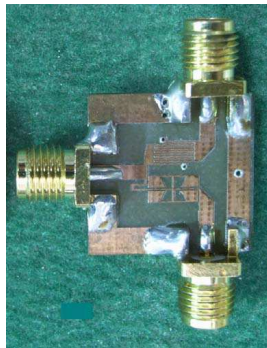

Figure 4. Photograph of the fabricated balun. The dimension of the circuit is about 1.7 cm × 1.6 cm.

the measured response was quite close to the predicted performance. With the 20% operational bandwidth ranging from 2.7 to 3.3 GHz, the measured S_{21} and S_{31} show a power split of 3.8 ± 0.5 dB. This outcome indicates that the compact balun can successfully separate an incoming signal into two equivalent amplitude outputs. The measured return loss of S_{11} is better than 15 dB over the same frequency range.

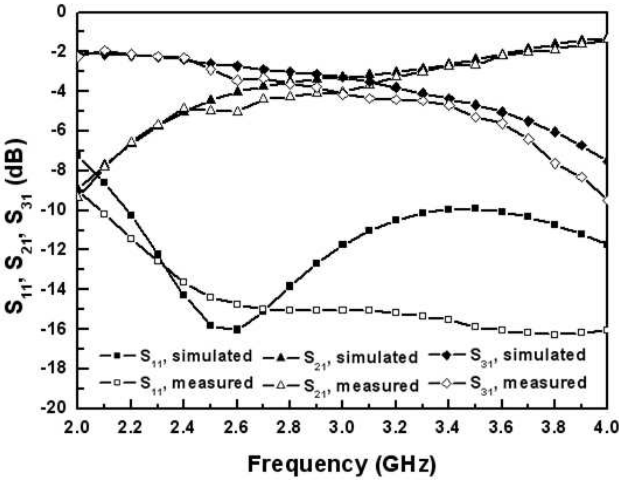From the measured amplitude and phase imbalances between

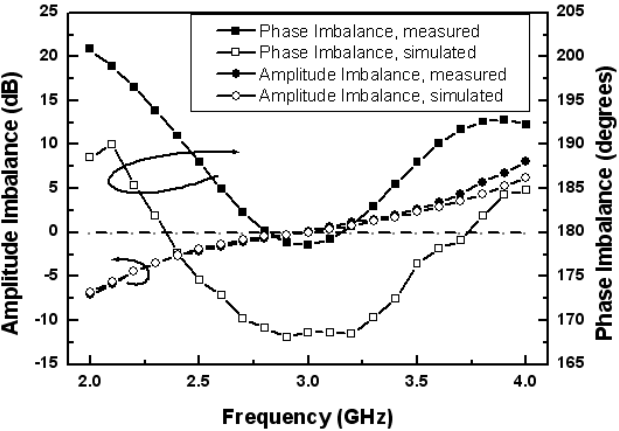**Figure 5.** The measured and the simulated scattering parameters as a function of frequency.

Figure 6. The simulated and measured amplitude and phase imbalances between two balanced signals of the proposed balun.

Table 1. Comparison of reported baluns.

Ref.	[4]	[6]	[11]	This Work
Center frequency	1.8 GHz	2 GHz	2.5 GHz	3 GHz
Technology	Coupled line	DGS	Phase shifter	EBG & interdigital cap.
Bandwidth (GHz)	1.5–2.1	–	1.7–3.3	2.7–3.3
Bonding Wire	yes	no	no	no
Planar circuit	yes	no	yes	yes
Size	$4 \times 2\,\text{cm}^2$	$9 \times 4.5\,\text{cm}^2$	$7 \times 6\,\text{cm}^2$	$1.7 \times 1.6\,\text{cm}^2$

two balanced signals of the fabricated balun, as shown in Fig. 6, the amplitude and phase imbalances are less than 1.4 dB and 3° within the bandwidth of 2.7 to 3.3 GHz, respectively. The measured results demonstrate that the proposed topology is applicable to the compact planar balun. Table 1 shows the comparison of the proposed balun with the previously reported ones implemented by using various topologies. These results demonstrate that this design presents a significant dimension decrease without any additional procedure for the process.

4. CONCLUSION

A novel configuration consisting of the high-pass π-network and microstrip EBG cell has been demonstrated to achieve a good-performance planar balun with smaller circuit dimensions. The measurements indicate that the amplitude and phase imbalances are less than 1.4 dB and 3° with the 20% operational bandwidth ranging from 2.7 to 3.3 GHz, respectively. Compared with the conventional Marchand balun and the other types of balun, the proposed topology exhibits potentially significant advantages; one of which is that the physical dimension of the balun is not proportional to the wavelength of the center frequency. Additionally, it can be easily designed on a single-layer printed circuit without using a multilayer substrate and DGS configuration. Without the use of any bonding wires, the circuit design is uncomplicated and more stable. This is indeed highly conducive for the further application of the RF circuit design.

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