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Research Article

Compact Two-Section Half-Wave Balun Based on Planar Artificial Transmission Lines

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Artificial transmission lines are realized by a series of meandered-line inductors, parallel-plate capacitors, and interdigital capacitors, which belong to metamaterial transmission lines. An ameliorated artificial transmission line is proposed to realize a low characteristic impedance transmission line. A two-section half-wave balun at 900 MHz is designed, fabricated, and measured in this paper. The compact balun is based on conventional and ameliorated planar artificial transmission lines instead of microstrip transmission lines. The main advantage of the proposed balun is its size reduction, which occupies only about 10% of a conventional one. Measured results match well with theory and simulation. The balun features excellent amplitude and phase balance in microwave power combining and a reasonable bandwidth of the return loss as well.

1. Introduction

A balun is a device to act as a transformer to match an unbalanced circuit to a balanced one, or vice versa, which was first proposed by Marchand in 1944. Owing to the output balanced amplitude characteristic with its phase difference of 180 degrees, it is a key component in balanced circuit topologies, such as balanced antennas and balanced mixers. Various balun configurations have been reported for applications in microwave circuits, such as coupled-line baluns, composite right/left-handed (CRLH) transmission line baluns, Wilkinson power divider baluns, three-line baluns, microstrip taper baluns, and lumped baluns [1–5].

Recently, with the rapid development of modern communication systems, the increasing demands for miniaturized components have been imposed on microwave circuits, as the size reduction in radio frequency (RF) circuit is an important part of the miniaturization and cost reduction of wireless communication systems. The balun as an important passive component was required to be designed to reach the requirement.

In this paper, we proposed a compact two-section half-wave balun at 900 MHz, which was designed with artificial transmission lines. In recent years, artificial transmission lines [6] have been proposed, and some microwave components with artificial transmission lines have been realized, such as branch-line couplers [7], power dividers [8], and antennas [9, 10]. We proposed modified artificial transmission lines to realize the transmission lines with low characteristic impedance. The proposed design method adopts seven transmission line sections composed of the artificial transmission lines to replace the conventional transmission lines so as to miniaturize the circuit size of the balun as far as possible. The proposed balun demonstrates a very compact dimension of 28.9 mm × 26.8 mm, which is about 10% of the area of a conventional balun of this same topology without folded lines. The overall dimension of the proposed realization is approximately $0.13\lambda_g \times 0.12\lambda_g$.

2. Theoretical Analysis of N-Section Half-Wave Balun

The realization of a three-port balun is based on the forms of a symmetrical four-port network as shown in Figure 1, in which one specified port is terminated with a short or open circuit,

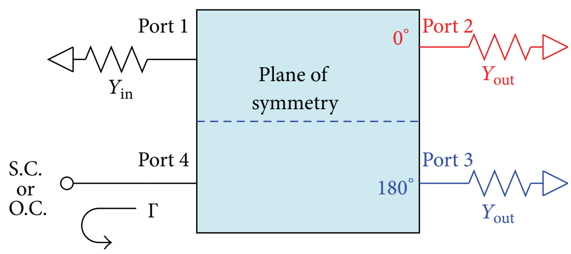

FIGURE 1: Balun topology as a symmetric four-port network.

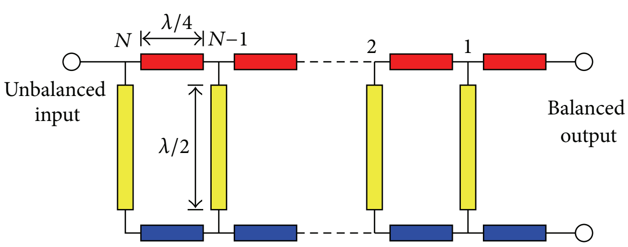

FIGURE 2: N-section half-wave balun.

such as a coupled-line Marchand balun or an N-section half-wave balun.

In this approach, the open- or short-circuit terminal is replaced by a load Y_{in} to form a fully symmetrical network. Γ is the reflection coefficient of port 4. For synthesizing this kind of three-port balun, the following relationships are required [11].

For the short-circuit case where $\Gamma = -1$,

$$Y_{even} + Y_{odd} = 2Y_{in}. \quad (1)$$

For the open-circuit case where $\Gamma = 1$,

$$\frac{1}{Y_{even}} + \frac{1}{Y_{odd}} = \frac{2}{Y_{in}}. \quad (2)$$

An N-section half-wave balun [12, 13], which consists of several half-wavelength transmission lines connected in parallel by quarter-wavelength sections as illustrated in Figure 2, can be synthesized directly. It is noted that an N-section half-wave balun is realized with a port of open-termination with the theory of symmetrical four-port network. The quarter-wavelength series lines can be used for impedance transformation, while the half-wavelength branches achieve phase shift of 180 degrees required for balun operation and compensate each other for broadband performance. Actually, it is an inherently narrow band design since the half-wave transmission line holds only at the center frequency. This kind of balun is designed by properly choosing the line impedance of the half-wave and quarter-wave line to achieve impedance matching and thereby to obtain the best performance.

For simplicity, we focus on analyzing the two-section balun in detail, whose structure is illustrated in Figure 3. The even-mode circuit is shown in Figure 4(a) even-mode, while the odd-mode circuit is shown in Figure 4(b) odd-mode.

Figure 4(a) is naturally a transmission stop network at the operating frequency due to the short circuit formed by the quarter-wavelength open-ended transmission line.

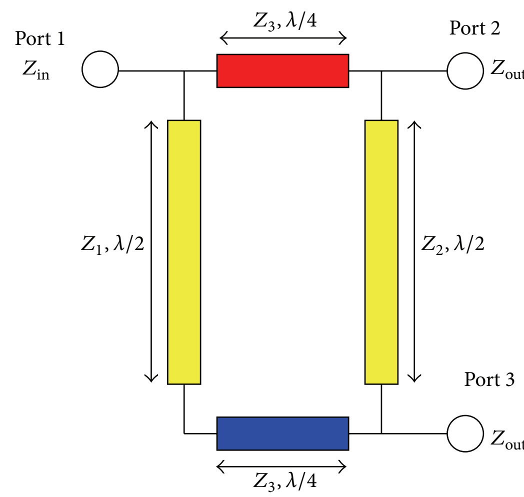

FIGURE 3: Topology of the optimized two-section half-wave balun.

In Figure 4(b), the circuit is equivalent to a quarter-wavelength transmission line for power transmission. The input impedances of the even- and odd-mode circuits are a short circuit for even excitation and an impedance transformer for odd excitation, respectively. Considering the condition of the two-section half-wave balun working at its operating frequency, we have $Z_{even} = 0$ and $Z_{odd} = Z_3^2/Z_{out}$. Then, the relation of Z_3, Z_{in}, and Z_{out} obtained from (2) is

$$Z_3^2 = 2Z_{in}Z_{out}. \quad (3)$$

To design a balun at 900 MHz, the final optimized impedances are $Z_1 = 23.5\,\Omega$, $Z_2 = 32.8\,\Omega$, and $Z_3 = 59.7\,\Omega$. Then by (3) we obtain $Z_{in} = 35.6\,\Omega$. Meanwhile, an impedance transformer of quarter-wave line is inserted at the input port for matching with the standard port impedance $50\,\Omega$, of which the characteristic impedance is $42.2\,\Omega$.

3. Implementations of Artificial Transmission Lines

3.1. Theory of Conventional Artificial Transmission Lines. The concept of conventional artificial transmission lines [6] was proposed by Wang et al., which were composed of microstrip structures of interdigital capacitors, meandered-line inductors, and parallel-plate capacitors. The layout and equivalent circuit of a unit of conventional artificial transmission line are shown in Figure 5, respectively. The design and methodology of such kind of conventional artificial transmission lines have been presented in detail in [6].

A unit of artificial transmission line can be equivalent to the circuit of Figure 5(b) and its characteristic impedance Z_{ATL} and guided wavenumber $\beta_{g,ATL}$ of each unit of artificial transmission line are determined by

$$Z_{ATL} = \sqrt{\frac{L_{tot}}{C_{tot}}},$$
$$\beta_{g,ATL} = \omega\sqrt{L_{tot} \cdot C_{tot}}, \quad (4)$$

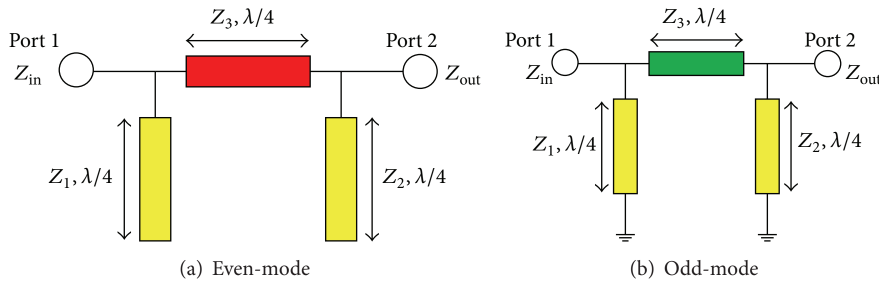

Figure 4: Even- and odd-mode analysis of two-section half-wave balun.

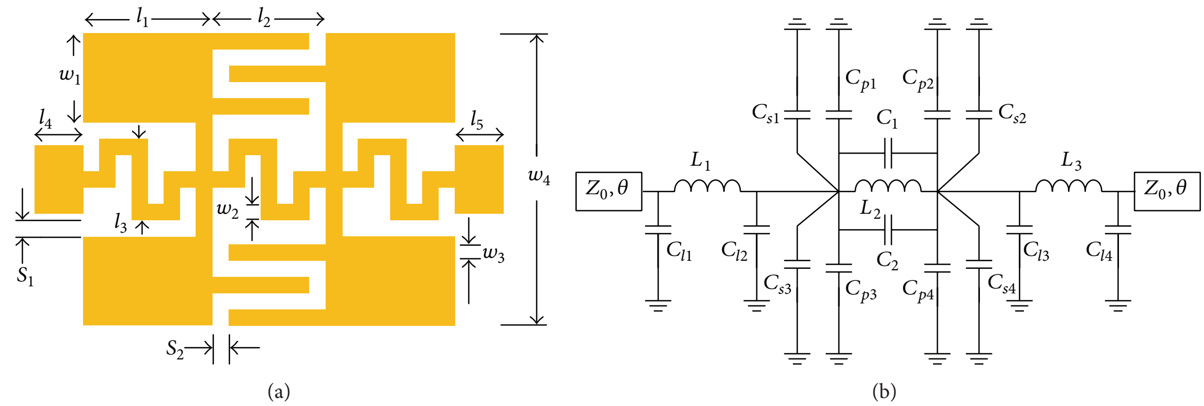

Figure 5: A unit of artificial transmission line and its equivalent circuit.

where L_{tot} and C_{tot} are equivalent total inductance and capacitance for a unit of artificial transmission line, respectively, and ω is the working angle frequency.

As compared with conventional structures of microstrip transmission lines, the required physical dimensions of artificial transmission lines are substantially reduced especially at low frequencies, whereas their electrical properties remain the same. Therefore, the artificial transmission lines have found more and more applications to miniaturizing microwave components and devices.

The design of two-section half-wave balun is performed by full-wave EM simulation software IE3D. The lines of $Z_3 = 59.7\,\Omega$ with 90-degree phase shift are realized by conventional artificial transmission lines. The total capacitance and inductance can be calculated out, which are 4.65 pF and 16.58 nH. Finally, the optimized specific parameters of artificial transmission line of Z_3 are shown in Table 1. Besides, all parameters are defined by the notations in Figure 5(a).

The input impedance matching microstrip line with characteristic impedance $Z_{trans} = 42.2\,\Omega$ is not realized by a structure of conventional symmetric artificial transmission line but by modified artificial transmission lines as shown in Figure 6 to further reduce the total size of the balun. As a result, the optimized specific parameters of artificial transmission lines of Z_{trans} are shown in Table 2 with the notations marked in Figure 6.

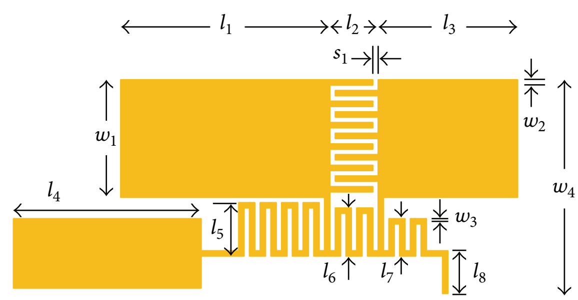

Figure 6: Modified asymmetric artificial transmission line.

3.2. Realization of Low Characteristic Impedance Line. The conventional artificial transmission lines mentioned above are usually suitable for lines with characteristic impedance between 30 and 100 Ω. If the characteristic impedance is too low or too high, the conventional artificial transmission line meets its limitation in the dimensions of corresponding inductors or capacitors with either too high capacitance or inductance. Therefore, in order to design low characteristic impedance line, the artificial transmission line can be ameliorated by applying chip capacitors in place of distributed parallel-plate microstrip capacitors.

The ameliorated artificial transmission lines can be applied to low characteristic impedance lines which are hardly realized by conventional artificial transmission lines, such as the line with characteristic impedance of $Z_1 = 23.5\,\Omega$ or $Z_2 = 32.8\,\Omega$. In this ameliorated structure, chip capacitors are applied to substitute the parallel-plate capacitors. As shown in Figure 7, there are neither microstrip

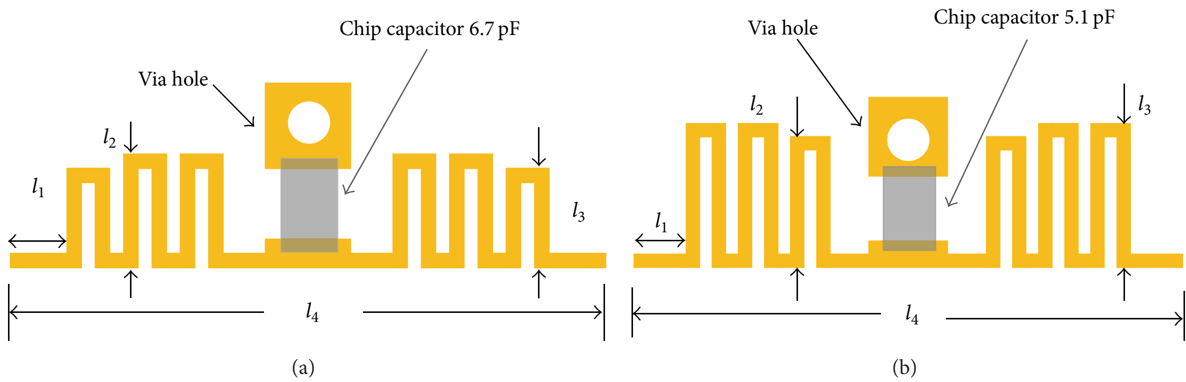

Figure 7: Ameliorated artificial transmission line of characteristic impedances 23.5 Ω and 32.8 Ω.

Table 1: Dimensions of artificial transmission lines of Z_3 (unit: mm).

Impedance	l_1	l_2	l_3	l_4	l_5	w_1	w_2	w_3	w_4	s_1	s_2
Z_3	4.4	1.8	4.4	0	5	4.3	0.2	0.3	11.6	0.3	0.2

Table 2: Dimensions of artificial transmission lines of Z_{trans} (unit: mm).

Impedance	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	w_1	w_2	w_3	w_4	s_1
Z_{trans}	11.8	1.8	7.6	12.2	1.7	1.5	1.1	4.6	5.8	0.2	0.2	12.1	0.2

interdigital capacitors nor parallel-plate capacitors to realize the ameliorated artificial transmission lines. Two chip capacitors of 6.7 pF and 5.1 pF are applied to realize lines with characteristic impedances of 23.5 Ω and 32.8 Ω and electrical length of 1/4. The capacitances of chip capacitors are also approximately calculated, in fact, which equals the value taken away from the parasitic capacitance of meandered-line inductors from the calculated total capacitance. Chip capacitors and via holes just metalized on the edges with radius 0.3 mm replace the corresponding microstrip parallel-plate capacitors. Furthermore, the detailed parameters of ameliorated artificial transmission lines of Z_1, Z_2 with 90-degree phase shift are shown in Table 3 with the notations signed in Figure 7.

We realize transmission lines of the characteristic impedances $Z_1 = 23.5\,\Omega$ and $Z_2 = 32.8\,\Omega$ with the ameliorated artificial transmission lines and fabricate a balun with them. The ameliorated artificial transmission lines are applied to realize the transmission lines with low characteristic impedance.

4. Simulation and Measurements

To verify the performance of the proposed two-section half-wave balun based on artificial transmission lines, the balun in Section 2 at 0.9 GHz was designed, simulated, and fabricated on F4B-2 substrate with thickness of 1 mm, dielectric constant of 2.65, and loss tangent of 0.001. In the balun, the transmission lines with characteristic impedances of $Z_1 = 23.5\,\Omega$ and $Z_2 = 32.8\,\Omega$ are achieved by adopting the ameliorated artificial transmission lines with chip capacitors (size code: 0603) and the $Z_3 = 59.7\,\Omega$ by conventional

Table 3: Dimensions of ameliorated artificial transmission lines of Z_1, Z_2 (unit: mm).

Impedance	l_1	l_2	l_3	l_4
Z_1	0.4	1.3	1.2	7
Z_2	0.3	1.8	1.9	7

artificial transmission lines and the $Z_{trans} = 42.2\,\Omega$ by the modified asymmetric artificial transmission line. The layout and photo of the fabricated balun are shown in Figure 8 with a total size of $0.13\lambda_g \times 0.12\lambda_g$, where λ_g is the guided wavelength on the substrate at 0.9 GHz. We have marked the seven sections of artificial transmission lines with different background in Figure 8(a). Figure 8(b) shows the fabricated balun, which is 28.9 mm × 26.8 mm. The proposed balun is about 11% of a balun realized by conventional microstrip lines.

Figures 9 and 10 illustrate the simulated and measured frequency responses of the proposed balun. The simulations have been completed by IE3D, while the measurements are performed with a PNA8362B vector network analyzer. The measured −10 dB bandwidth of voltage reflection at its input port is from 0.82 GHz to 1 GHz, which presents a relative bandwidth of about 20%. The measured results show that the return loss at the input port at 0.9 GHz is 23 dB, and the insertion losses of the output ports 2 and 3 at 0.9 GHz are both 3.7 dB. The difference between the simulated and measured $|S_{11}|$ is due to ignored effect of cable and connector in simulations. The measured output amplitude imbalance calculated by $(|S_{21}| - |S_{31}|)$ and phase imbalance calculated by $(\text{Phase}(S_{21}) - \text{Phase}(S_{31}))$ between the two output ports are

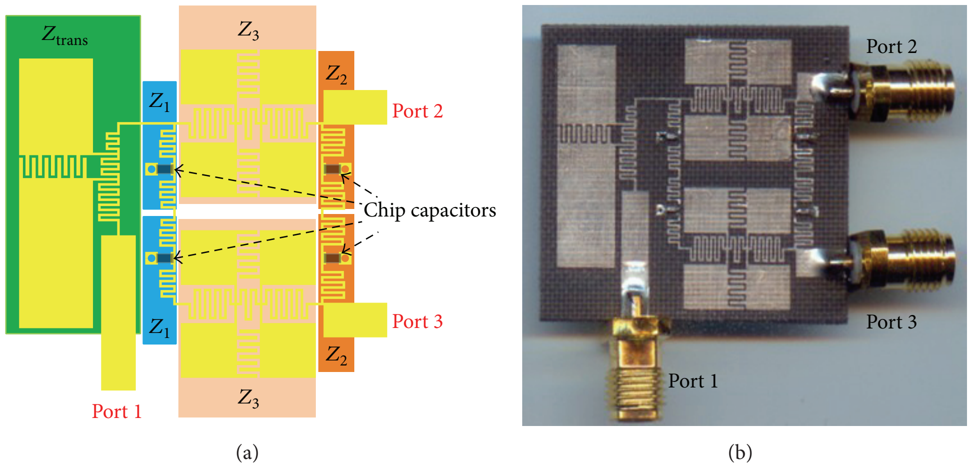

FIGURE 8: Layout and photo of the proposed two-section half-wave balun.

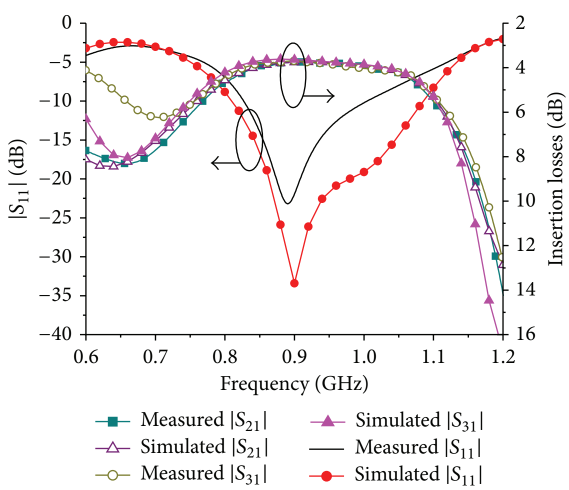

FIGURE 9: Measured and simulated return losses and insertion losses.

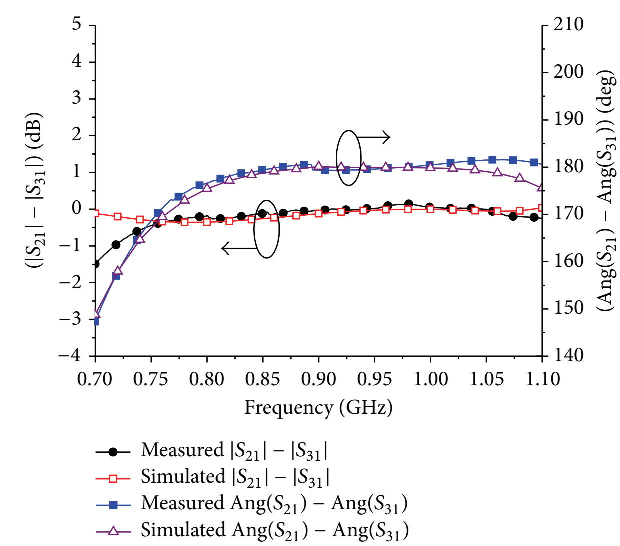

FIGURE 10: Measured and simulated phase differences and magnitude differences of output ports.

illustrated in Figure 10. In the 10 dB return loss bandwidth, the phase imbalance is within 2 degrees, and the amplitude imbalance is within 0.3 dB. Figure 10 demonstrates that the equal amplitude and 180-degree phase shift are well matched (within 0.3 dB and 2 degrees) over the frequency band of 180 MHz from 0.82 GHz to 1 GHz.

The superiority of the proposed design is clearly verified. Not only is the proposed balun compact but it also features excellent in-band amplitude and phase balance and a comparable 10 dB return loss bandwidth. The proposed design is suitable for low frequency applications, in which it demonstrates a significant size reduction. There are two limitations of the proposed balun in system applications. One is the insertion loss mainly due to its complicated structure. The total insertion loss is 0.6 dB in the proposed balun. The other is the power capacitance due to thin microstrip lines. The proposed design will find applications in low and medium power systems.

5. Conclusions

A novel two-section half-wave balun has been designed, fabricated, and measured in this paper, which is realized by utilizing seven sections of artificial transmission lines. The design method and procedure are presented in detail. Ameliorated asymmetric artificial transmission lines are proposed to realize transmission lines with low characteristic impedance. A balun at 900 MHz has been implemented and shows excellent frequency responses from measured results. The balun is compact at low frequency band, which is only about 10% of a conventional microstrip balun of the same configuration. The proposed balun is attractive for practical applications of microwave system in L and/or P band.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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