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Research Article

Compact and Broadband-Balanced Amplifier for a Monolithic Microwave Integrated Circuit Using Lumped Elements Only

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A flat phase difference across a broad bandwidth is achieved by appropriately combining the positive and negative phase propagation of right-handed (RH) and left-handed (LH) transmission lines (TLs), respectively. Employment of lumped elements provides easy realization of both TLs with the desired frequency passband, characteristic impedance, and phase propagation. The proposed quadrature power divider (QPD) was fabricated in a compact size by only using lumped elements instead of general TLs with a large area and a narrow bandwidth. The fabricated QPD maintains a flat phase difference of $90^\circ \pm 8.7^\circ$ over a frequency range of 1.19–2.96 GHz while its circuit size is 0.036 λ_g^2. Owing to drastic size reduction of the QPD, the proposed balanced amplifier (BA) also could be realized with an extremely compact size of 0.044 λ_g^2 and broad bandwidth unlike in other BAs reported in the literature and maintains a return loss of less than −10 dB at each port over the bandwidth of the QPD.

1. Introduction

Compactness and broadbandness are essential in modern radio-frequency and microwave components. However, conventional transmission line (TL)-type circuits for impedance matching, power splitting/combining, or feeding networks occupy a large area on the circuit board or have a narrow bandwidth [1–5]. To overcome such limitations, several compact and broadband microwave components have been introduced in [6–10], where compactness in size was achieved by replacing conventional TLs with lumped elements.

A left-handed (LH) TL, which is well known as one-dimensional metamaterials, has a negative phase constant, opposite to a right-handed (RH) TL. Recently, various applications of LH metamaterials have been demonstrated for microwave components. Some previous studies achieved an improvement of a wide bandwidth or size reduction using an advantageous property of composite right- and left-handed (CRLH) structures such as the phase propagation, resonance, and filtering. In [11–16], the authors suggested power dividers with in-phase or quadrature phase differences, and the authors in [9] introduced a balun with a 180° phase difference for a broadband frequency. Moreover, the authors in [17] realized a compact filtering antenna using a LH property.

A quadrature power divider (QPD) splits an input signal into two equal-magnitude outputs with a 90° phase difference. In [11, 12], conventional 90° hybrid couplers were substituted by a QPD, indicating that QPDs can be used in balanced amplifiers (BAs). The main purpose of BAs is to minimize the input and output reflections by incorporating two identical amplifiers with a 90° hybrid coupler at the input and output, respectively. As a result, both the couplers cancel the reflections at the input and output of the two amplifiers by combining them with a phase difference of 180° [18]. However, because of the narrow bandwidth of the hybrid coupler, the bandwidth of the general BA is narrow. Furthermore, because the hybrid coupler occupies a large area, the size of the whole BA circuit must be very large. In [11], the authors demonstrated a broadband BA using composite right- and left-handed (CRLH) TLs; however, it still occupies a large area and is not appropriate for a modern microwave system where a compact IC style module is required.

Our main idea in this study is a considerable size reduction and broadband impedance matching of BA by replacing 90° hybrid couplers with compact QPDs integrating RHTLs and LHTLs with lumped elements only. The QPDs in many articles consist of complicated patterns or TLs with a large area on their circuit boards although some studies employ lumped elements for the LH structures. As lumped elements can be easily implemented with a standard monolithic microwave integrated circuit (MMIC) process, the whole circuit can be further minimized. In this paper, we demonstrate our main idea by presenting the theories and experimental results of the fabricated BA. Particularly, for a low-frequency band, our work can contribute to an extreme size reduction.

2. Broadband and Constant Phase Difference between an RHTL and an LHTL

Because there are numerous studies discussing the structures and analysis of an RHTL and an LHTL, we will provide a brief overview of the theories used to explain the broadband 90° phase difference.

Figure 1(a) depicts an RHTL equivalent unit cell which is a low-pass filter structure comprising two series inductors and a shunt capacitor. Conversely, an LHTL unit cell (Figure 1(b)) works as a high-pass filter, which consists of two series capacitors and a shunt inductor. By cascading several identical unit cells of each TL, a periodic cutoff frequency (Bragg cutoff frequency) emerges, and each cutoff frequency can be computed using the following equations [9]:

$$f^{R}_{\text{Bragg}} = \frac{1}{\pi\sqrt{L_R C_R}},$$
$$f^{L}_{\text{Bragg}} = \frac{1}{4\pi\sqrt{L_L C_L}}, \quad (1)$$

where the superscripts R and L denote the RHTL and LHTL, respectively.

For the passbands of both TLs, the characteristic impedances can be approximated using equations (2) and (3) , respectively [9].

$$Z_{0R} = \sqrt{\frac{L_R}{C_R}}, \quad (2)$$

$$Z_{0L} = \sqrt{\frac{L_L}{C_L}}. \quad (3)$$

Also, the phase constants of an RHTL and an LHTL are given by equations (4) and (5), respectively [9].

$$\beta_R = \omega\sqrt{L_R C_R}, \quad (4)$$

$$\beta_L = -\frac{1}{\omega\sqrt{L_L C_L}}. \quad (5)$$

Unlike that of an RHTL, the phase constant of an LHTL is negative, indicating that the phase propagation is in the direction opposite to that of the Poynting vector. Figure 2 illustrates the theoretical phase propagation of each TL with one section and their phase difference based on equations (4) and (5) when $L_R = 1$ nH, $C_R = 2.5$ pF, $L_L = 2$ nH, and $C_L = 5$ pF. Therefore, the calculated cutoff frequencies of both the TLs, f^{R}_{Bragg} and f^{L}_{Bragg}, are 6.37 and 0.79 GHz, respectively. As shown in Figure 2, the bandwidth maintaining a phase difference of 90° ± 5° is broad from 1.26 to 4.02 GHz. These theoretical results are based on simple calculations using the constant values of the lumped elements without considering the tolerance and self-resonant frequency of each element and any parameters from a realization. By carefully selecting the appropriate element values of the RHTL and LHTL after considering their characteristic impedances, cutoff frequencies, and phase constants, the desired flat phase difference can be achieved for the broad bandwidth (Figure 2).

3. Realization and Measurement of the Compact and Broadband BA

Figure 3 illustrates the TL model of the proposed BA. Two QPDs are connected at the input and output ports. The QPD at the input port equally splits the input power with a 90° phase difference, while the QPD at the output port combines the two amplified signals in phases. Thus, the two QPDs effectively cancel the reflected signals at the input and output of the amplifier by combining them with a 180° phase difference. As explained in the previous section and shown in Figure 3, an RHTL and an LHTL are used after a Wilkinson power divider to have a broadband 90° phase difference for the QPD at the input. As the Wilkinson power divider and both the TLs in the QPD can be realized with lumped elements, the whole circuit can be made compact, facilitating drastic size reduction when the circuit is an IC type.

Figure 4 shows the compact and broadband BA fabricated on an RO4003 board whose thickness is 0.5 mm and relative permittivity is 2.3. Each QPD consists of a synthetic LHTL and RHTL to have a wideband 90° phase differentiation and a Wilkinson power divider with a synthetic RHTL. For the broadband amplifier, NLB-300 from RF Micro Devices, Inc., was used. Because the QPD employs only chip lumped elements (1608 size in mm), its occupied area on the circuit board is 0.07×0.11 λ_g^2, making the size of the whole fabricated BA very compact. To design the Wilkinson divider using lumped elements, a synthetic RHTL with a phase propagation of a quarter wavelength with a characteristic impedance of $\sqrt{2}Z_0$ is required as shown in equations (2) and (4).

We implemented EM simulation using ANSYS HFSS. Each lumped element on the RH and LH TLs is assigned by

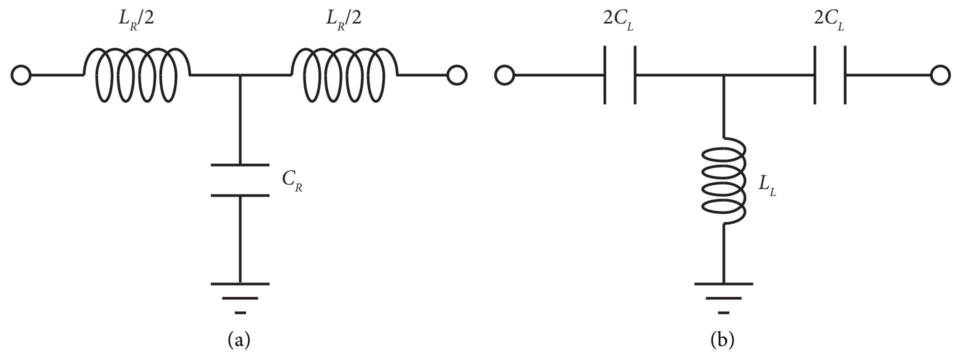

FIGURE 1: Lumped element unit cell structures of an (a) RHTL and (b) LHTL.

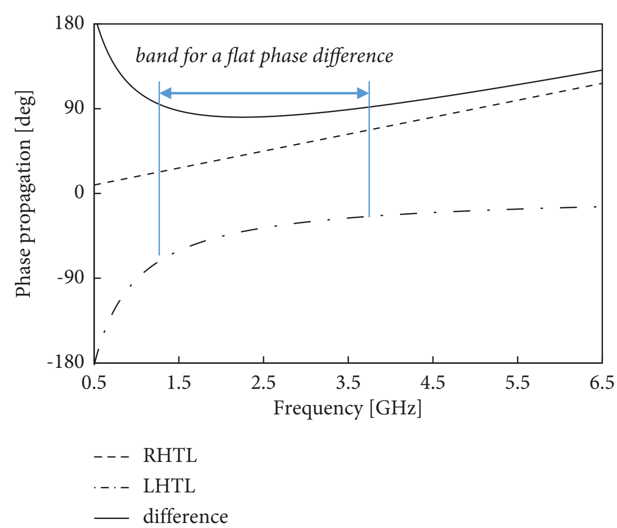

FIGURE 2: Flat phase difference between the phase constants of an RHTL and an LHTL.

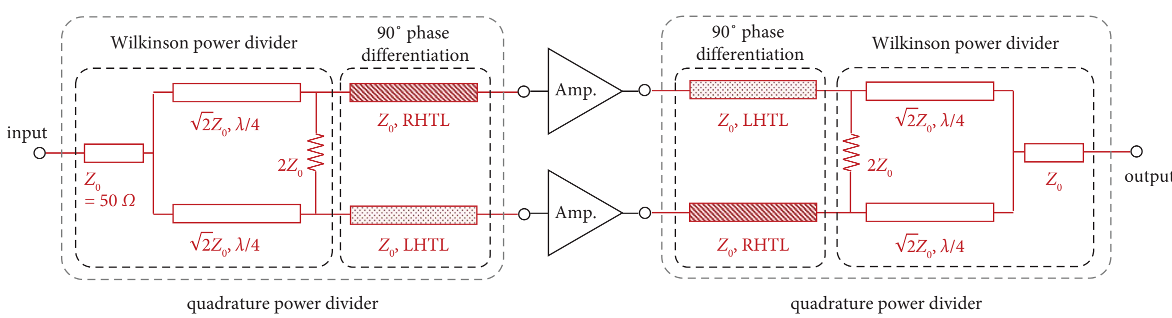

FIGURE 3: BA structure using QPDs with an RHTL and an LHTL.

the boundary condition, and input/output ports are connected to each TL through the microstrip lines. The simulation and measurement results of the proposed QPD are shown in Figure 5. The measurement results of the fabricated QPD show a good agreement with the simulation as can be seen in both results. From the measured results, we set the bandwidth at 1.77 GHz (between 1.19 and 2.96 GHz) so that the return losses at all the ports (S_{11}, S_{22}, and S_{33}) and the isolation between the output ports (S_{23}) are over 10 dB. For the same frequency range, the insertion losses of S_{21} and S_{31} vary from 3.33 to 4.14 dB and from 3.4 to 3.94 dB, respectively. Moreover, the absolute values of the magnitude imbalance ($|S_{21} - S_{31}|$) are less than 0.32 dB. In addition, the QPD maintains a phase difference of $90^\circ \pm 8.7^\circ$ within the bandwidth. Table 1 shows the comparison of the proposed QPD and other quadrature power-dividing components in some literatures. The size of our QPD in Table 1 is the whole board size ($0.24 \times 0.15\ \lambda_g^2$) including the microstrip lines at the input/output ports for measurement. The authors in [20, 22] have excellent characteristics with a very wide

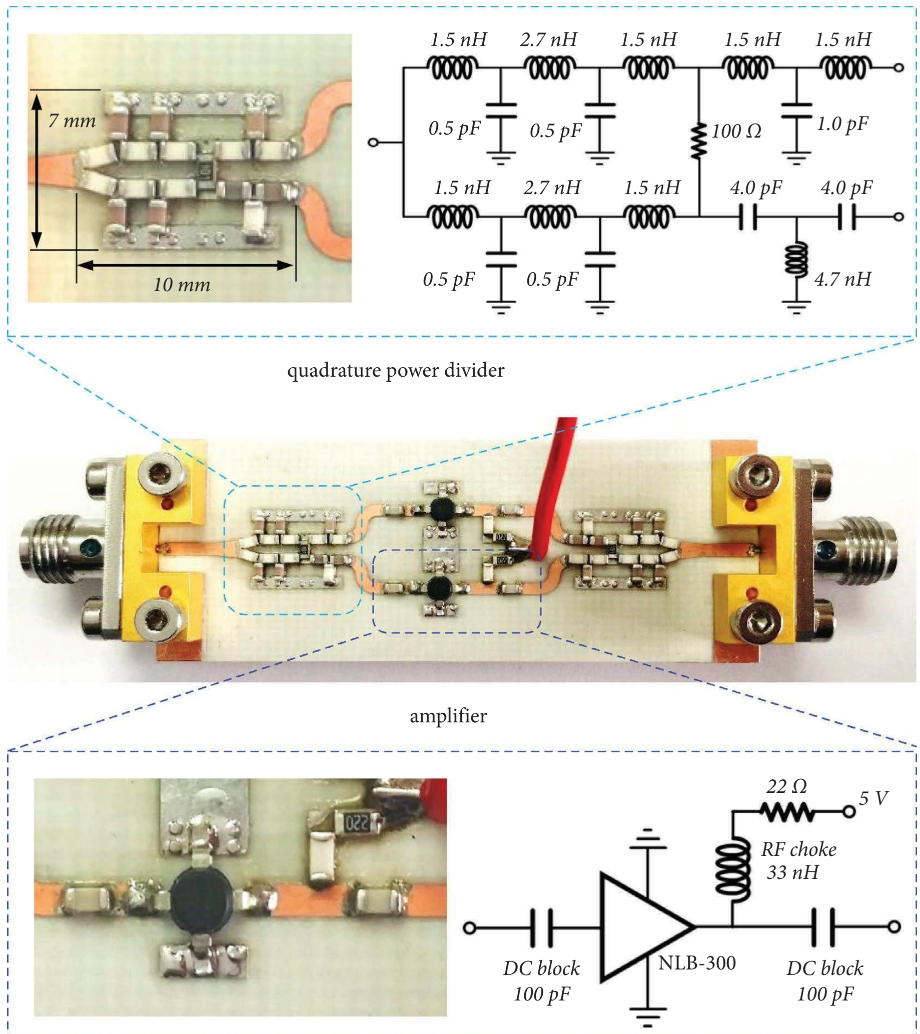

Figure 4: Fabricated BA with the lumped elements.

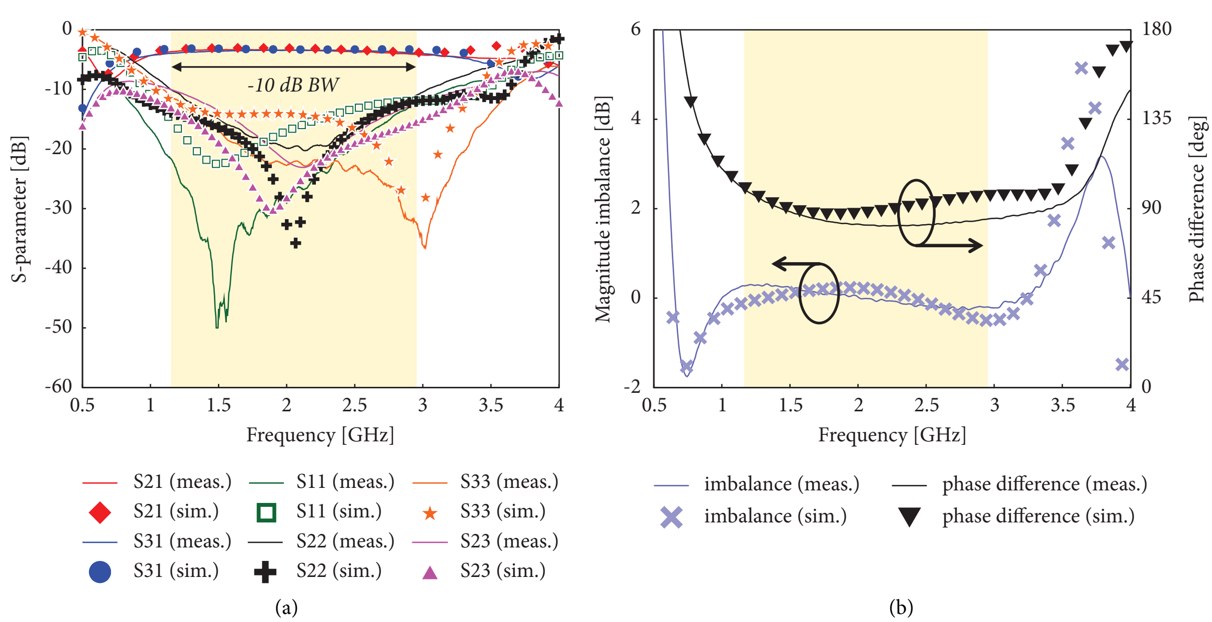

Figure 5: Simulation and measurement results of the QPD: (a) magnitude and (b) insertion loss imbalance and phase difference at the output.

Table 1: Comparison between the proposed QPD and previous works.

References	Frequency (GHz)	Relative bandwidth (%)	Phase error (deg)	Magnitude imbalance (dB)	Size (λ_g^2)
[16]	1.1–3.5	104	±5	<0.9	0.44
[19]	3–8	90.9	±5	—	1.5
[20]	0.71–2.74	117.7	±4.5	<0.5	0.17
[21]	2.3–5.48	81.7	±10	<1.5	0.05
[22]	3.1–11.1	112.7	±5	<0.3	0.08
[23]	3.8–8	71.1	±3	<1	0.34
This work	1.19–2.96	85.3	±8.7	<0.32	0.036

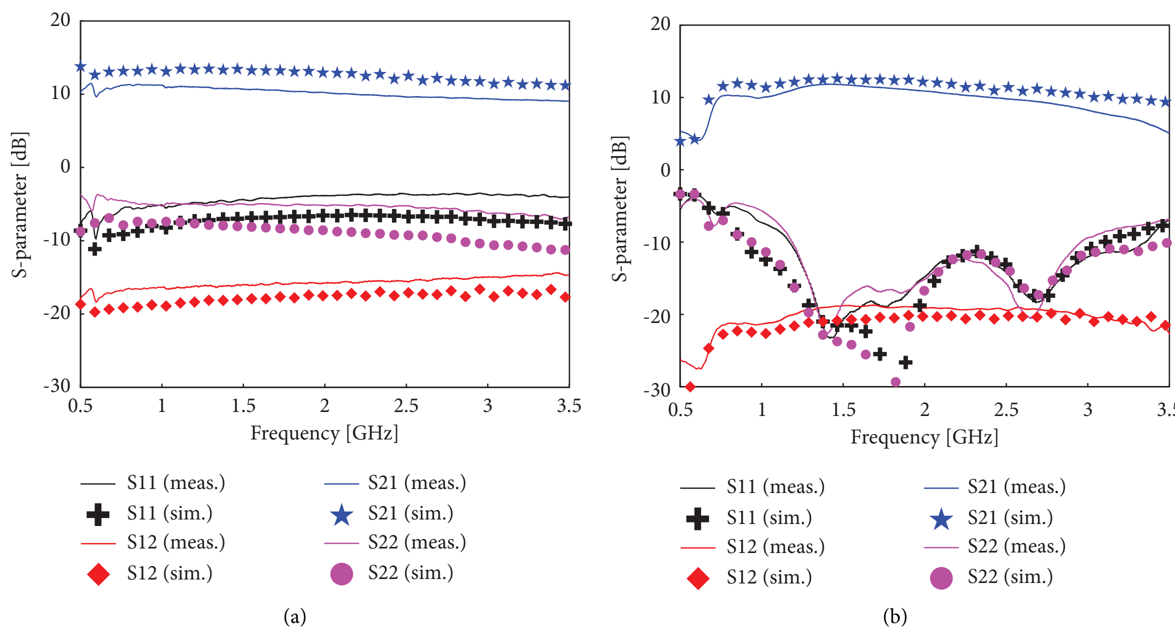

Figure 6: Comparison of the simulated and measured S-parameters of (a) a single amplifier and (b) the fabricated BA.

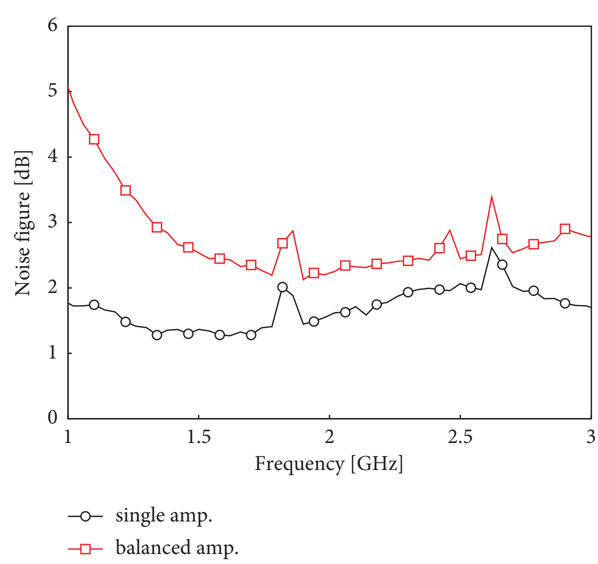

Figure 7: Measured noise figures of a single amplifier and the fabricated BA.

Table 2: Comparison between the proposed BA and previous works.

References	Frequency range (GHz)	Relative bandwidth (%)	Return loss (dB)	Gain (dB)	Size (λ_g^2)
[11]	1.2–3.5	97.9	>10	—	>0.88
[24]*	2.4–2.5	4.1	>15	>16	5.38
[25]	8–11.5	35.9	>10	>16	>7.18
[26]	8–10	22.2	>10	12.5–14.2	5.27
[27]	1.5–2.1	33.3	>10	>7	12.95
PCB BA in [28]	1	—	21	19.5	0.11
This work	1.19–2.96	85.3	>10	8.44–11.84	0.044

*simulation results.

bandwidth (the relative bandwidth is over 100%), but each circuit size is much larger than our work.

To verify the return loss improvement, we compared the fabricated BA with a single amplifier without any impedance matching, as can be seen in Figure 6. The gain of the BA varies from 8.44 to 11.84 dB for the −10 dB bandwidth between 1.19 and 2.96 GHz. The small decrease in the gain of the BA compared to the single amplifier is mainly due to the insertion loss, magnitude imbalance, and phase error of the QPD fabricated with the lumped elements only. The proposed compact BA could noticeably enhance the indistinct return loss of a single amplifier. The measured noise figures of the single amplifier and the BA are shown in Figure 7. The noise figure of the compact BA is from 2.13 to 3.76 dB within the bandwidth which is slightly higher than the single amplifier. Nevertheless, the size of the whole BA circuit is $0.37 \times 0.12\ \lambda_g^2$. This is possible by replacing all the general TLs required to construct the BA with lumped elements based on synthetic RHTLs and LHTLs. Table 2 shows a comparison of the fabricated BA and other previous works. It is appropriate to mention here that the written sizes of [11, 25] are deduced from the size of both used QPDs in each BA because the precise sizes are not provided in each paper. The BA in [11] suggests that its design method is very similar with our work using LH materials. However, the circuit size of [11] is significantly larger than ours although the relative bandwidth is 12.6% wider than ours.

4. Conclusions

Herein, we present a broadband BA that uses a compact and broadband QPD based on synthetic RHTLs and LHTLs. The use of the phase propagation difference between the RHTL and LHTL enables achieving a flat phase difference over a broad bandwidth. The compact design of the QPD, which employs only chip-lumped elements, results in a compact size for the fabricated BA. By using the proposed theories, a desired phase difference, not limited to 90°, can be achieved for a broadband range. For example, a broadband balun can also be made compact. Particularly, for a lower frequency band with a long wavelength, our main idea can lead to an extremely compact realization. By incorporating the presented theories and results, the circuit can be made MMIC, which can further minimize the losses and size, and extended to promise modern microwave applications that require compactness and broadbandness.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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