suppresses higher-order harmonics effectively. This novel BPF is shown in Figure 2. The dimension of this BPF is reduced from 1.1 × 7.95 cm² to 1.1 × 2.45 cm², with a reduced factor up to 70%. The simulated and measured results are shown in Figure 7. Good agreement between the measured and simulated results is observed.

5. CONCLUSION

We have presented a class of novel compact-size filters with a quasi-hairpin structure using SIRs at 2.45 GHz. This structure exhibits improved TB and suppression of harmonic response in the stopband for the LPF and BPF. It also retains the dimensions of the circuit by more than 70% for the BPF, and by 60% to 74% for the LPFs, as compared to the conventional ones. By providing an efficient method for the filter design, this structure is attractive in MIC/MMIC applications.

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ABSTRACT: A broadband left-handed parallel-line microstrip coupler is implemented by both electromagnetic simulation and actual fabrication. The circuit dimensions are smaller and more compact than those in previous studies and a thinner Duroid substrate of thickness h = 0.635 mm is used. Parametric studies were performed using IE3D, and fabrication was done via a Quick Circuit 7000 prototyping machine. The network-analyser measurements indicate broad bandwidth coupling in the 6.5–7.7-GHz region. © 2005 Wiley Periodicals, Inc. Microwave Opt Technol Lett 45: 255–258, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20788

Key words: left-handed transmission line; microstrip coupler; coupling effect; S-parameters

1. INTRODUCTION

In 1968, Veselago theoretically postulated [1] the existence of a new class of materials with simultaneously negative electric permittivity (e < 0) and magnetic permeability (μ < 0). These materials were named left-handed materials (LHMs) because within them, the vectors \( \vec{E} \), \( \vec{H} \), and \( \vec{k} \) form a left-handed triad. In LHMs, the direction of the Poynting vector \( S \) is antiparallel to the phase velocity \( \vec{k} \) and this gives rise to a backward-propagating wave [2], plus several other interesting effects [1]. Potential applications in the form of a perfectly flat slab of the material have been suggested [3], which focuses light beyond the resolution limit of a conventional lens [4]. Experimental observations of LHMs based on the split-ring resonator and wire structures have already been reported by several groups [5–7]. The above structures however, suffer from large leakage losses in the microwave regime and are inherently bulky constructions. The working bandwidth is also narrow due to the reliance on split-ring resonance. To overcome these problems, a different approach to realising LHMs based on transmission-line networks has been independently proposed by two groups [8, 9]. In [9], the LH coupling transmission line is built entirely of microstrip components, such as interdigital capacitors and shorted stub inductors.

In this paper, we report that our simulation and experimental results confirm the presence of the backward-coupling behaviour reported in [9]. Further, our results also verify the claim that this implementation presents moderate insertion loss and broad bandwidth. The primary differences between our present work and the previous investigation in [9] are (i) a substrate of different thickness was used, (ii) parametric studies of the circuit via simulation were carried out, (ii) the LH transmission line was built from an entirely new set of circuit parameters, and (iii) a different approach to fabrication was undertaken.

2. DESIGN

The principle of realisation of an LH transmission line involves interchanging the capacitor \( C \) and inductor \( L \) of a conventional transmission line [see Fig. 1(a)], hence resulting in a unit cell of dual configuration [see Fig. 1(b)]. By cascading these dual-unit
cells, an LH transmission line which supports backward waves is achieved [8, 9].

A photograph of our version of a LH microstrip coupler is shown in Figure 2. Our coupler was fabricated on RT Duroid 5880 substrate, chosen for its low-loss tangent at microwave frequencies. Our substrate has a relative dielectric constant \( \varepsilon_r = 2.2 \) and a thickness \( h = 0.635 \) mm, which is less than half the thickness of the original substrate in [9]. Due to the difference in substrate thicknesses, an entirely new set of circuit dimensions was determined for the desired LH coupling behaviour. In order to arrive at this optimised set of dimensions, parametric studies on the relationship between circuit geometry and coupling performance were carried out via simulation. The results of these parametric studies are discussed in the next section.

A schematic layout of our coupler is presented in Figure 3. Note that the capacitor length \( l_c = 4.5 \) mm and inductor length \( l_i = 4.0 \) mm are less than half of the original in [9, 10]. The number of interdigital teeth \( n_t \) is deliberately kept small (that is, 4) in order to reduce the number of processing steps during fabrication. The planar line width (2.25 mm) was chosen such that the overall line impedance [11] is as close to the standard impedance of 50\( \Omega \) as possible. However, this is limited by having to accommodate an exact number of interdigital teeth with spacings of 0.15 mm in between, and hence the closest value obtained was 42.3\( \Omega \), which is nevertheless reasonably close to the standard value. The via hole is of a large enough size (that is, 0.80 mm) to allow a wire to be inserted for shorting to the ground plane.

Finally, two identically symmetric segments of LH transmission line were placed side-by-side in a parallel configuration to achieve the desired coupling effect. The line separation \( s \) between our two transmission lines is 0.2 mm. Additional leg extensions (see Fig. 2) were added for the purpose of attaching SMA connectors, which are used for the network-analyser measurements. The total length of our eight-unit cell coupler, including the leg extensions, is 8.835 cm.

3. PARAMETRIC STUDIES

The optimised set of parameters presented above was obtained through electromagnetic simulation using the commercial software IE3D. An initial set of circuit dimensions was first obtained by proportionally scaling down the dimensions in [9], according to the simple relation in Eq. (1), which is based on the ratio of substrate thicknesses, given by

\[
\text{scale factor} = \frac{h_{\text{current}}}{h_{\text{original}}}. \tag{1}
\]

where \( h_{\text{current}} \) is the thickness of the substrate used in our present study, and \( h_{\text{original}} \) is the thickness of the original substrate in [9]. Here we assume all other parameters of both substrates to be identical. This scale factor was then multiplied to the circuit dimensions in [9]. Through simulation, it was determined that although such a scaled down set of dimensions did yield some coupling effect, it was not ideal. As seen from Figure 4(a), the coupling is initially very weak in the 5.5–6.5-GHz region. \( S_{31} \) is below \(-3\) dB and \( S_{21} \) and \( S_{41} \) are both close to \(-10\) dB, thus indicating that transfer of energy from port 1 into port 3 is not complete.

To improve the characteristics, these initial dimensions were then used as a starting point and the parameters were individually varied in order to obtain an optimised set. The parameters varied were: (i) line separation \( s \), (ii) capacitor length \( l_c \), (iii) inductor length \( l_i \), (iv) number of unit cells \( n_u \), and (v) number of interdigital teeth \( n_t \).

(i) Variation of line separation \( s \) was done by simulating the circuit at different values of \( s \). It was determined that the coupling effect is strongest at the closest line separation. At \( s = 0.1 \) mm, the coupled port \( S_{31} \) is very nearly \( 0 \) dB and the other three ports are below \(-15\) dB (see Fig. 5). As \( s \) increases, the energy transfer into the coupled port decreases almost linearly and weakens until the effect is completely destroyed. In the above cases, energy is coupled from port 1 into port 3, with port 4 being isolated. These

Figure 1 Transmission-line schematic: (a) circuit model for conventional RH (right-handed) transmission line; (b) dual-configuration LH transmission line with capacitor and inductor interchanged. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 2 Photo of LH microstrip coupler with an eight-unit cell cascade. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 3 Unit cell with optimised set of dimensions. \( l_c \) = capacitor length, \( l_i \) = inductor length, \( n_t \) = number of interdigital teeth, \( n_u \) = number of unit cells.
are characteristics of a backward coupler. Therefore, to achieve tight coupling, the LH transmission lines should be laid as close to each other as possible. However, this will be limited by the minimum resolution of the chosen fabrication technique.

(ii), (iii) Variations of capacitor length \( l_c \) and inductor length \( l_i \) yield qualitatively similar results. Initially, at low values of \( l_c \) and \( l_i \), the coupling between the input port 1 and the other three ports is weak. As \( l_c \) and \( l_i \) increases, an ideal coupling level is observed at a certain optimal value of \( l_c \) and \( l_i \). As the lengths are increased above these optimal values, however, the coupling effect once again weakens and the incident energy becomes reflected from the input port 1.

(iv) The number of unit cells \( n_u \) were varied in single steps from 2 to 12 (see Fig. 6). Forward transmission to the output port (that is, \( S_{21} \)) is reduced by increasing the number of cells, due to moderate losses through the circuit. However, better isolation (that is, \( S_{41} \)) is also achieved by longer line lengths. The working region for backward coupling is unchanged at 7.2–8.2 GHz.

(v) The number of interdigital teeth \( n_t \) was also varied in single steps from 2 to 7. Backward coupling was found to be present for \( n_t \) in the range of 2 to 5. At \( n_t = 2 \) [see Fig. 7(a)], a very strong isolation of nearly \(-30\) dB is achieved in ports 2 and 4. The working region for backward coupling is fairly wideband in the frequency range of 7.5–9.0 GHz. However, this is not ideal as \( S_{11} \) remains close to \( 0\) dB, indicating that much energy is reflected from port 1. For \( n_t = 7 \) [see Fig. 7(b)], there is very poor energy coupling between port 1 and the other three ports. If we are to disregard issues of idealised circuit performance and impedance matching, it is possible to construct an LH microstrip coupler with only two interdigital teeth. This gives extremely small line widths and reduces the number of fabrication steps.

The simulated S-parameters for our optimised set of dimensions are shown in Figure 4(b). As seen from the diagram, this optimised circuit will give a strong coupling effect in the 7.5–8.5-GHz region, with \( S_{31} \) near \(-30\) dB and \( S_{21} \) and \( S_{41} \) both close to \(-20\) dB. This demonstrates that complete coupling of energy from port 1 to port 3 is achieved within this frequency range. The 5-GHz cutoff frequency indicates the high-pass nature of this structure. Overall, our optimised dimensions have been scaled down considerably from those in [9, 10], thus achieving a more compact circuit that is easier to fabricate and saves physical space.

4. FABRICATION

In our research, a different approach to fabrication was undertaken using the Quick Circuit 7000 prototyping machine. The prototyping machine allows the direct drilling of via holes into the strip inductors, which is not available via the wet-etching technique used in [9, 10].

The prototyping machine works by moving a high-speed rotating carbide drill bit over the substrate surface. Via holes are drilled to the opposite side of the substrate simply by changing the vertical displacement of the drill bit. Because the drill is mechanically restricted to movement in the \( x \)-, \( y \)-, and \( z \)-directions only, this avoids the problem of photoresist undercutting found in wet etch-
ing. However, one tradeoff is the coarser machine resolution at 0.15 mm, which is dependent on the minimum size of the drill bit used. In the course of our fabrication, it was determined that finer drill bits are easily breakable, and this will factor significantly higher costs into the process.

5. RESULTS
A Hewlett-Packard 8722D Vector Network Analyser was used to measure the $S$-parameters of our completed coupler. Measurements indicate that there is good qualitative agreement between the simulated results [see Fig. 4(b)] and measured results (see Fig. 8). In Figure 8, the coupling parameter $S_{31}$ is close to 0 dB (that is, $-1.767 \, \text{dB}$) at about $f_0 = 7 \, \text{GHz}$. At this frequency, $S_{21}$, $S_{41}$, and $S_{41}$ are all close to $-20 \, \text{dB}$ and almost all the power is transferred between port 1 and port 3. The coupling level is typically smaller than $-4 \, \text{dB}$ in the frequency range from 6.46 to 7.68 GHz, which corresponds to a fractional bandwidth of 17.4%. The isolation is better than 10 dB is this same frequency range. Overall, attenuation losses through the device are moderate. The 4-GHz cutoff frequency shows the high-pass nature of the structure, which indicates that our LH microstrip coupler is essentially a high-pass filter. In short, the measurements indicate that our coupler is essentially broadband and has a bandwidth of nearly 1.22 GHz, which is noticeably larger than those of split-ring resonator structures.

6. CONCLUSION
In this paper, a broadband LH parallel-line backward coupler with moderate loss was realised on a thinner RT Duroid 5880 substrate of thickness $h = 0.635 \, \text{m}$. The circuit dimensions of our microstrip coupler are smaller and more compact than previous studies, hence demonstrating that LH microstrip couplers are downscalable. Fabrication was achieved using a Quick Circuit 7000 machine, suggesting that the instrument can be considered as a workable alternative to wet etching. Parametric studies performed on the circuit parameters led to a better qualitative understanding, which will be useful for future LH coupler designs.

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