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## Design Feature

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# Building a Zero-Order BPF with CRLH Transmission Lines

Metamaterials and unconventional CRLH transmission lines combine to create RF/microwave bandpass filters with miniature dimensions for wireless applications such as WiMAX.

**M**iniaturization of RF/microwave filters helps pave the way to developing smaller wireless devices for internet access. Using metamaterials and circuit structures such as composite-right-left-handed (CRLH) resonators has proven effective in shrinking RF/microwave filter circuits and was demonstrated in the design of a compact bandpass filter (BPF) well-suited for WiMAX wireless applications.

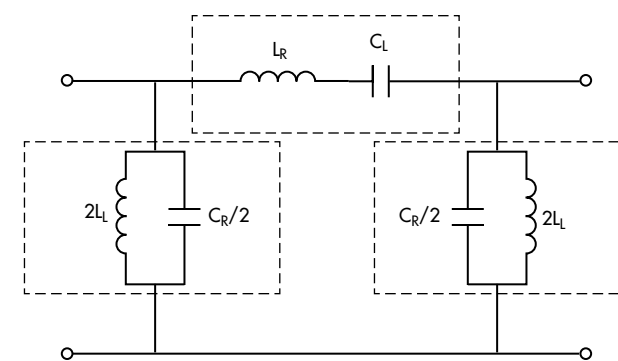
Leveraging third-order coupled CRLH resonators, the filter achieves a center frequency of 5.9 GHz with transmission zero at 6.4 GHz. Measuring just  $16 \times 24 \text{ mm}^2$ , or about 40% the size of BPFs based on conventional resonators, the filter has a passband insertion loss of just 1.5 dB.

Metamaterials have shown great promise for the fabrication of compact, high-frequency RF/microwave circuits.<sup>1-4</sup> First proposed in 2002, CRLH transmission lines (CRLH-TLs) are forms of high-frequency transmission lines that exhibit backward-wave transmission behavior capable of unusual electromagnetic (EM) wave propagation. Metamaterial approaches to microwave circuit design are typically based on CRLH or negative-refractive-index transmission lines in planar struc-

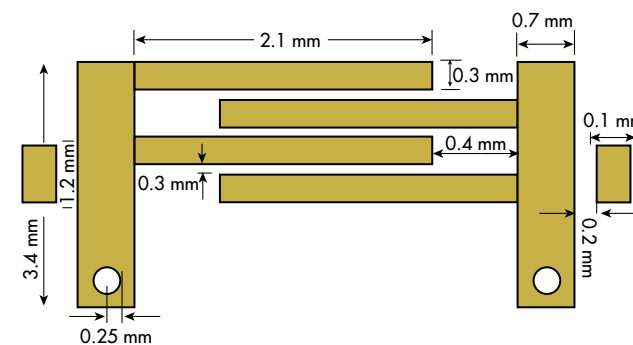
tures by loading a host transmission line with series capacitor and shunt inductive load.

Use of metamaterials and CRLH-TLs enables the design of RF/microwave BPFs with small size, low passband loss, and even low cost. The small sizes supported by metamaterials make possible multiple-band filters that are a fraction of the size of BPFs formed with conventional transmission lines.<sup>5-10</sup> Coupled metamaterial resonators have formed compact BPFs.<sup>8,10</sup> In addition, compact microwave CRLH gap resonators with high quality factors (Qs) show great promise for forming miniature BPFs.<sup>11,12</sup>

To demonstrate, by combining high-Q CRLH gap resonators with third-order zeroth-order-resonator (ZOR) coupled resonators, a microwave BPF with extremely compact dimensions was designed and fabricated for WiMAX applications with standard, low-cost circuit materials. The filter was constructed on RT/duroid 6010 circuit material from Rogers Corp. ([www.rogerscorp.com](http://www.rogerscorp.com)). The 1.27-mm-thick circuit material has dielectric constant of 10.8 at 10 GHz in the z-axis (thickness). Commercial electromagnetic (EM) simulation software helped optimize the design, which was



1. Shown is an equivalent-circuit representation of a composite-right-left-handed (CRLH) unit cell resonator.



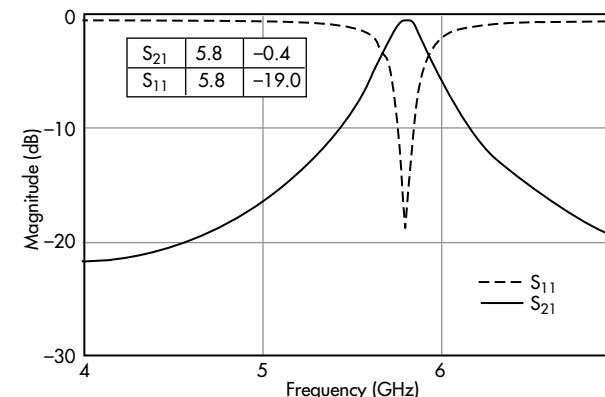
2. This layout was used in the fabrication of a CRLH unit cell on commercial PCB material.

characterized using a 50- $\Omega$  microstrip feed line and commercial test equipment, notably an RF/microwave vector network analyzer (VNA).

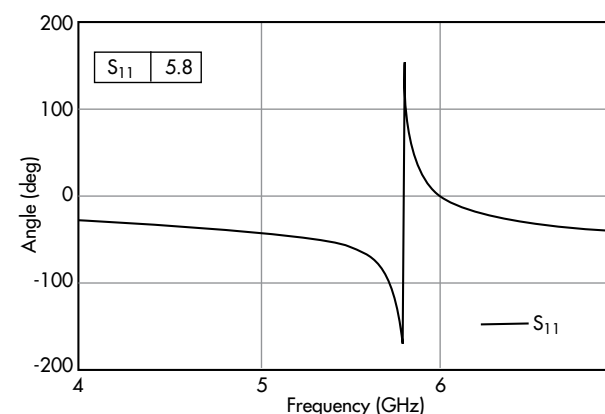
Figure 1 shows an equivalent-circuit model of the CRLH-TL that consists of right-handed inductance ( $L_R$ ), right-handed capacitance ( $C_R$ ), left-handed inductance ( $L_L$ ), and left-handed capacitance ( $C_L$ ). In a practical circuit design,  $C_L$  is fabricated as a four-finger interdigital capacitor,  $L_L$  is a viahole in the printed-circuit-board (PCB) material, and capacitance  $C_R$  and inductance  $L_R$  are parasitic circuit elements essentially invisible in size.

Mathematical analysis of the CRLH structure can be performed by applying transmission-line theory to the equivalent circuit of a CRLH cell. In this case, the CRLH cell is coupled to a short 50- $\Omega$  ( $Z_0$ ) feed line for impedance matching to 50- $\Omega$  environments and measurements with an RF/microwave VNA.

The frequency of a ZOR is independent of the order of the unit cell. This property can be parlayed into the design of a novel filter in which the center frequency is independent of the physical length of the transmission lines. In turn, the



3. These simulated scattering parameters depict the insertion loss ( $S_{21}$ ) and return loss ( $S_{11}$ ) of the CRLH unit cell.



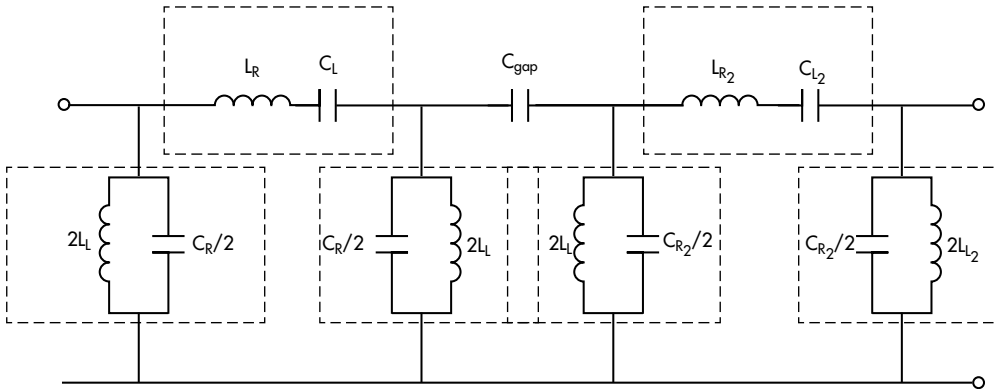
4. The plot shows the simulated  $S_{21}$  phase angle (in deg.) of the CRLH unit cell.

filter's size can be dramatically reduced, since the resonator frequency does not rely on the half-wavelength size of the transmission lines.<sup>5-8</sup>

The phase of the transmission lines can be found by applying Eq. 1, as a super-position of right- and left-banded phases from the CRLH transmission lines. By controlling the circuit loading elements ( $C_L$  and  $L_L$ ), a zero-phase condition ( $\varphi_{\text{CRLH}} = 0$ ) is achievable:

$$\varphi_{\text{CRLH}} = -\beta l = [1/\omega(C_L L_L)^{0.5} - \omega(C_R L_R)^{0.5}] \quad (1)$$

Figure 2 provides a layout of the CRLH unit cell used in the design of the compact BPF. Figure 3 shows the computer-simulated full-wave scattering (S) parameters of the CRLH cell. The curves indicate a sharp resonance at 5.9 GHz, where the value of  $S_{21}$  (insertion loss) is almost -1 dB and the value of  $S_{11}$  (return loss) is less than -20 dB. Figure 4 shows the computer-simulated phase of the CRLH resonator cell, where



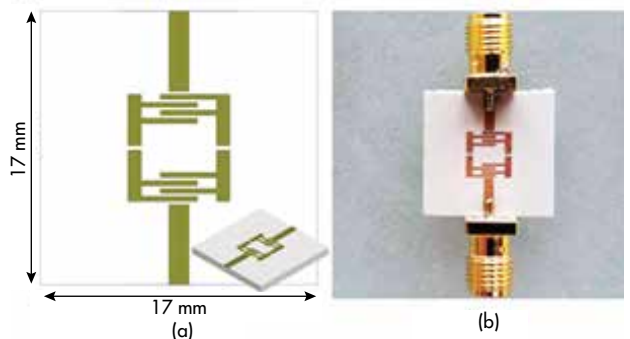
5. This CRLH resonator equivalent-circuit diagram was used to construct a two-pole CRLH filter.

the phase at 5.9 GHz is almost equal to 0. This is the justification for claiming that a zeroth-order coupled resonator has been created.

**CRLH CONSTRUCTION**

A microstrip configuration was used to fabricate a two-pole filter using equivalent circuits of the CRLH unit cell resonators (Fig. 5) as building blocks along with a capacitive gap, with the design aided by full-wave EM simulations in the ANSYS HFSS software to find computer-simulated S-parameters. The filter was constructed on commercial PCB material (including low-loss viaholes). The circuit material was Rogers Corp.'s RT/duroid 6010.2, with dielectric constant of 10.8 and dissipation factor of 0.0023, both at 10 GHz. Substrate thickness was 1.27 mm, with 0.35- $\mu$ m-thick copper cladding for forming the circuit traces.

These parameters were duplicated in the HFSS EM simulation software from ANSYS ([www.ansys.com](http://www.ansys.com)). The lumped-element circuit parameters for the equivalent-circuit model of a two-pole filter, which were also developed with the aid of the Advanced Design System (ADS) simulation software from Keysight Technologies, include  $C_R$  of 0.2 pF,  $L_R$  of 0.21 nH,  $C_L$  of 5.0 pF,  $L_L$  of 5.2 nH, center frequency ( $f_0$ ) of 5.9 GHz, and feed-line impedance ( $Z_0$ ) of 50  $\Omega$ .



6. The layout of a two-pole CRLH-based bandpass filter (a) is shown next to a fabricated prototype of the filter (b).

Figure 6a shows the layout of the two-pole symmetrical BPF using coupled CRLH transmission-line resonators, where the overall size of the filter is 17  $\times$  17 mm<sup>2</sup>. And Figure 6b shows a prototype of the fabricated CRLH filter. Figure 7 contains the simulated S-parameter magnitudes, where it should be clear that the passband surrounds a center frequency of 5.9 GHz with magnitude values of  $S_{21} = -2$  dB and  $S_{11} = -25$  dB. By comparing full-wave HFSS EM simulations with S-parameters measured with a VNA on the fabricated prototype, values of  $S_{21} = -2.5$  dB and  $S_{11}$  approaching  $-10$  dB were found for the experimental CRLH BPF design.

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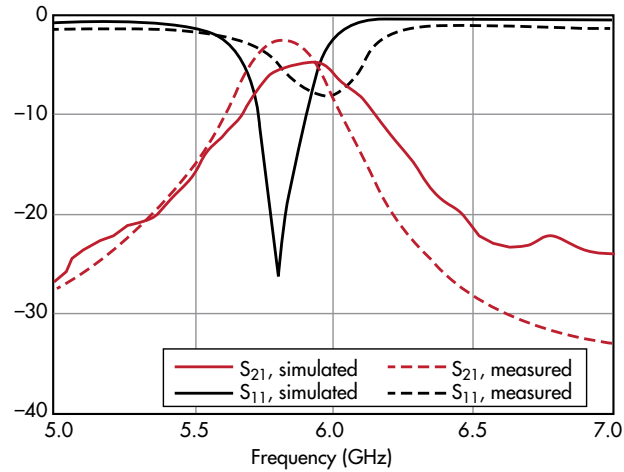
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7. Two-pole filter scattering parameters and fabrication measurements are provided in this plot.

**THIRD-ORDER RESULTS**

Figure 8a shows the layout of the BPF designed with third-order coupled CRLH-TL resonators, where the overall size of the BPF formed with these resonators is  $16 \times 24 \text{ mm}^2$ . The simulated (HFSS) scattering parameters for the filter (Fig. 9) indicate that it provides excellent performance through the passband surrounding its center frequency at 5.9 GHz, with passband insertion loss,  $S_{21}$ , of just 1.5 dB, and passband return loss,  $S_{11}$ , close to 30 dB. The filter has a transmission zero at 6.3 GHz, which equips it with an advantage in smaller dimensions compared to a conventional two-pole filter design.

The single transmission zero also yields much improvement in skirt selectivity; the order number of the transmission zero is equal to  $N - 2$ , with  $N$  the number of resonators in the design. Fig. 9 shows good agreement between design theory and the EM simulation results, indicating that a lower trans-

mission zero can be added to the design by increasing the filter order.

In fact, the compact filter has a frequency and passband characteristics that make it well-suited for WiMAX applications. It takes full advantage of the zeroth-order resonance of third-order coupled CRLH resonators to achieve good passband loss characteristics in a small size. The zeroth-order resonance at 6.3 GHz improves the passband skirt selectivity in a filter size of only  $16 \times 24 \text{ mm}^2$ . By following a design procedure that achieved good agreement among theory, computer simulations, and measurements, a 5.9-GHz BPF was created with CRLH resonators that's about 40% smaller than BPFs designed with conventional microstrip transmission-line resonators. [mmw](#)

**B**y following a design procedure that achieved good agreement among theory, computer simulations, and measurements, a 5.9-GHz BPF was created with CRLH resonators that's about 40% smaller than BPFs designed with conventional microstrip transmission-line resonators.

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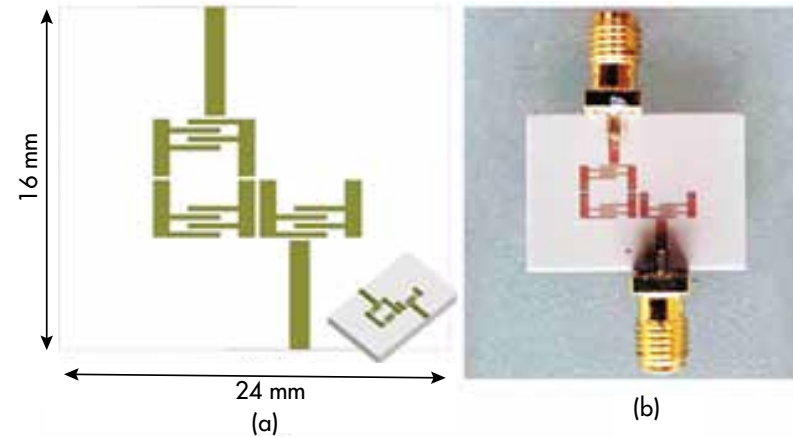
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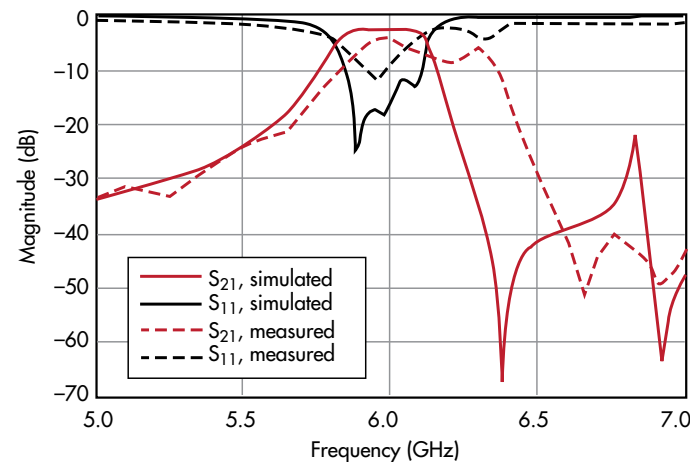
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8. The layout of the ZOR BPF formed with third-order CRLH resonators (a) is shown next to the fabricated prototype (b).



9. These measured results reveal the performance of the BPF fabricated with third-order CRLH resonators.

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