6. CONCLUSIONS
This article presents the design and uncertainty analysis of two-layer dicroic employing rectangular slot lattice for a two-channel QON. The discrepancy between the simulated and measured insertion losses can be partly attributed to the fabrication errors, i.e., the ISD variation and the UAE. It is shown that the effect of UAE on the transmission performance is much greater than that of ISD variation, and the transmission performance is more prone to the UAE in the X direction rather than that in the Y direction. Therefore, more attention should be paid to the control of UAE of the two-layer dicroic configuration in the X direction during the fabrication process.

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Key words: metamaterials; composite right/left-handed (CRLH) transmission lines; dual-band components

1. INTRODUCTION
Metamaterial transmission lines are artificial lines consisting of a host line loaded with reactive elements. The first metamaterial transmission lines were presented in 2002, as one-dimensional metamaterials based on nonresonant elements and consist of a host line loaded with series capacitances and shunt inductances [1–3]. The first resonant-type metamaterial transmission line was presented in 2003 [4]. Such line consisted on a coplanar waveguide periodically loaded with shunt connected strips and split-ring resonators, previously introduced by Pendry et al. [5]. In 2004, the complementary split-ring resonator (CSR) was introduced for the first time [6] and subsequently applied to the design of a metamaterial transmission line in microstrip technology [7]. All these artificial lines exhibit a composite right/left handed (CRLH) behavior (a concept introduced for the first time in [8]), namely, left-handed wave propagation at low frequencies and right-handed wave transmission at frequencies higher than the resonance, typically separated by a forbidden frequency band. It has been demonstrated that by balancing these lines such gap can be collapsed and the two passbands degenerate on a single band exhibiting a wide bandwidth, and roughly frequency independent characteristic impedance in the vicinity of the transition frequency [9].

In capacitive and inductive-loaded lines, the loading elements are dominant at low frequencies. Thus, the series reactance of the T-or π-circuit model of the loop cell of these lines is capacitive at low frequencies, whereas the shunt reactance is inductive, and this provides backward (or left-handed) wave propagation at low frequencies [9–11]. At higher frequencies, the parameters of the line (series inductance and shunt capacitance) dominate over the loading elements, and wave propagation is forward. In resonant-type metamaterial transmission lines, the circuit models exhibit an additional element (as compared to capacitive and inductive-loaded lines), responsible for the presence of a transmission zero at the left of the left-handed band, but such lines exhibit a CRLH behavior, which is interpreted as in capacitive and inductive-loaded lines.

In [12], the dual CRLH transmission line concept was introduced in the first time. The model of the unit cell of this line consists of a parallel resonator placed in the series branch and a shunt connected series resonator. This structure exhibits a stop band behavior, with forward wave propagation at low frequencies and left-handed wave propagation at high frequencies. As compared to the previous CRLH artificial transmission lines, dual CRLH transmission lines can be considered to exhibit unconventional dispersion, but the fact to exhibit a stop band behavior and the impossibility to achieve a continuous transition between the forward and backward transmission band may limit
their applications. In this article, CRLH transmission lines exhibiting forward and backward wave propagation at low and high frequencies, respectively, and exhibiting bandpass-type (rather than stop band) characteristics are presented and applied for the design of dual-band microwave components that cannot be easily implemented by simply using conventional (capacitive and inductive-loaded or resonant-type) CRLH metamaterial transmission lines.

2. TOPOLOGY OF THE NOVEL CRLH TRANSMISSION LINES WITH UNCONVENTIONAL DISPERSION

The novel CRLH transmission lines exhibiting forward and backward wave propagation at low and high frequencies, respectively, consist of an a parallel connection of two unit cell lines: one of them is an artificial line exhibiting forward wave propagation and implemented by loading a line with a CSRR (etched in the ground plane) and a shunt connected stub (such artificial right-handed lines were introduced for the first time in [13]); the other one is an artificial line implemented by loading a line with a series gap and a CSRR. The forward wave unit cell line must by properly tuned to provide the transmission band and required characteristics (phase shift and characteristic impedance) at the required (lower) frequency. The left-handed unit cell, must be tuned to provide backward wave propagation (as well as the required phase shift and characteristic impedance) at the required (upper) frequency (these lines loaded with a gap and a CSRR do also provide forward wave propagation at higher frequencies [14], but this band is not of interest for our purposes).

A typical topology of these novel artificial lines is depicted in Figure 1. The principle of operation of these lines is based on the diplexer action of the two parallel connected unit cell lines. Namely, at the lower frequency, where the right-handed line is tuned, the left-handed unit cell is in the evanescent mode, and hence the injected power is transmitted through the right-handed unit cell. At the upper frequency, the situation is reversed, and the signal is transmitted through the left-handed unit cell. The reason of using an artificial unit cell line for the implementation of the forward wave transmission line is simply because we need further degrees of freedom for design (as compared to conventional lines) and also to prevent signal propagation at the upper frequency (the diplexer action is not possible with conventional lines because filtering is required). One important aspect to achieve the required diplexer action in the proposed configuration is to achieve a return loss for the right/left handed unit cell closer to 1 (i.e., $|S_{11}| = 1, S_{31} = 0^\circ$) at the upper/lower operating frequencies. This is achieved by tuning the length of...
the access lines of the two unit cell lines and must be done by means of an optimization procedure.

The CRLH unit cell of Figure 1 has been designed to provide an electrical length of +90° and -90° at \( f_1 = 0.8 \) and \( f_2 = 1.6 \) GHz, respectively, with a characteristic impedance of 70.71 Ω at both frequencies. The simulated (through the Agilent Momentum commercial software) phase response of this structure is depicted in Figure 2. The dependence of the characteristic impedance with frequency of this structure, inferred from the simulated S-parameters through well known formulas [15], is also depicted in Figure 2. The required characteristics (phase shift and characteristic impedance) at the two design frequencies are achieved. The procedure to determine the layout of each individual unit cell line is based on reported electrical models [16–18] and optimization, and it has been previously published by the authors [19] (hence it is out of the scope of this article). However, as has been mentioned, caution must be taken to achieve total reflection (with zero phase shift) of the lines operating in the evanescent mode at the two design frequencies.

3. APPLICATION TO THE DESIGN OF DUAL-BAND MICROWAVE COMPONENTS

Dual-band microwave components have been designed by means of metamaterial transmission lines following different strategies [20, 21]. With resonant-type CRLH transmission lines, several microwave components based on dual-band admittance inverters have been designed [21, 22]. The principle of operation of such dual-band microwave components is very simple: The inverters are implemented by means of CRLH transmission lines providing -90° and +90° at the lower and upper frequency bands, respectively, and the required characteristic impedance. Thus, the lower operating band of the device lies within the left-handed band of the CRLH line, whereas the upper frequency band lies within the right-handed band. Several components such as branch line hybrid couplers, Y-junction power dividers, or Wilkinson power dividers, among others, use impedance inverters with identical phase characteristics. But there are other microwave components based on impedance inverters with reversed phase characteristics; namely based on impedance inverters that must provide -90° and +90° at the same frequency. In these cases, we cannot apply the strategy given in [21]. However, we can combine conventional CRLH CSRR-based lines with those proposed in this article (Fig. 1). The conventional CRLH lines can be used to implement the inverters requiring -90° and +90° phase shift at the lower and upper operating frequencies, respectively. The artificial lines with
unconventional dispersion can be used for the synthesis of the admittance inverters with reversed phase shift, namely, $+90^\circ/C\nn$ and $-90^\circ/C\nn$ at the lower and upper frequencies, respectively.

### 3.1. Dual-Band Rat-Race Hybrid Coupler

Let us now apply the proposed artificial lines to the design of a dual-band rat race hybrid coupler. This microwave device is used in many applications, such as mixers, modulators, and detectors, among others. The topology of the conventional (mono-band) device is depicted in Figure 3. It is a four-port device consisting on a ring structure of $1.5\ k$ (where $k$ is the signal wavelength at the operating frequency). The structure contains three $+90^\circ$ lines and one $+270^\circ$ line (equivalent to a $-90^\circ$ transmission line), as indicated in Figure 3. To obtain equal power splitting between the input (either the $D$ or the $R$ port) and the output ports, the characteristic impedance of the transmission lines must be set to $Z_0 = 70.71\ \Omega$.

Obviously, by changing the sign of the different line phases, the functionality is preserved. Thus, we can achieve dual-band operation in the rat race hybrid coupler by setting the phase of the three identical transmission lines to $+90^\circ$ and the phase of the additional transmission line to $-90^\circ$ at the lower operating frequency, $f_1$, and forcing the phases to exhibit the same magnitude and different sign at the upper frequency, $f_2$. The schematic of this dual-band rat race coupler is depicted in Figure 4.

The line located between ports 1 and 4 can be implemented by means of a conventional CRLH CSRR-based transmission line (dual-band impedance inverters with $-90^\circ$ and $+90^\circ$ phase shift at the lower and upper frequencies based on such lines have been already demonstrated [21, 22]). Figure 5 depicts the layout of a dual-band admittance inverter designed to provide $-90^\circ$ and $+90^\circ$ phase shift at $f_1 = 0.8$ and $f_2 = 1.6$ GHz, respectively, with a characteristic impedance of $70.71\ \Omega$ at both frequencies. The dependence of impedance and phase with frequency is depicted in Figure 6, where it can be appreciated that the required characteristics are satisfied. The other three dual-band impedance inverters are implemented by means of the structure shown in Figure 1 (designed to provide the required characteristics at identical frequencies).

The fabricated dual-band rat race hybrid coupler is depicted in Figure 7. Access lines have been added for the insertion of the different port connectors. The device has been fabricated on the Rogers RO3010 substrate with thickness $h = 0.635\ mm$, dielectric constant $\varepsilon_r = 12$, and loss tangent $\tan \delta = 0.0023$, by means of a photo-mask etching technique. The device has been simulated by means of the commercial software Agilent Momentum. The simulated power splitting, matching and isolation for $D$ and $R$ input ports are depicted in Figures 8 and 9, respectively, whereas the measured magnitudes (by using the Agilent

**Figure 9** Simulated power splitting, matching and isolation for the designed device taking the $\Delta$ port as the input port

**Figure 10** Measured power splitting, matching and isolation for the designed device taking the $\Sigma$ port as the input port. $S_{32} = -3.11\ \text{dB}$ and $S_{32} = -4.05\ \text{dB}$ at $f_1$ and $f_2$, respectively. $S_42 = -3.05\ \text{dB}$ and $S_42 = -4.04\ \text{dB}$ at $f_1$ and $f_2$, respectively.

**Figure 11** Measured power splitting, matching and isolation for the designed device taking the $\Delta$ port as the input port. $S_{31} = -3.6\ \text{dB}$ and $S_{31} = -4.01\ \text{dB}$ at $f_1$ and $f_2$, respectively. $S_{42} = -3.5\ \text{dB}$ and $S_{42} = -3.91\ \text{dB}$ at $f_1$ and $f_2$, respectively.

**Figure 12** Simulated and measured phase balance
E8364B vector network analyzer) are depicted in Figures 10 and 11. The simulated and the measured phase balance (a relevant parameter in rat-race hybrid couplers) are depicted in Figure 12.

By considering ±0.3 dB of amplitude mismatch, the bandwidth for power splitting (worst case) is 60 MHz for the first band and 84 MHz for the second band. Measured return losses and isolation are in the vicinity, or better, than 20 dB at the two operating frequencies for both Δ and Σ ports. Finally, the measured phase balance is 181.8° and 181.1° at \( f_1 \) and \( f_2 \), respectively, for Δ input port, and 0.8° at \( f_1 \) and 0.1° at \( f_2 \) for Σ input port. By considering a phase imbalance of ±10°, the bandwidth is 126 MHz for the lower band and 136 MHz for the upper band. These characteristics are comparable or superior than those reported in previous works related to the design of dual-band rat race hybrid couplers [23–27]. The device is slightly smaller than the conventional (mono-band) rat race hybrid coupler designed to operate at the first frequency onto the same substrate. We would also like to highlight that the device is fully planar, this reducing cost and fabrication complexity.

3.2. Dual-Band Power Splitter With Inverted Output Signals

The CRLH lines depicted in Figures 1 and 5 can also be applied to the design of a dual-band power splitter providing output signals with a relative phase shift of 180°. These power splitters can be implemented by using impedance inverters according to the schematic shown in Figure 13. The designed device is shown in Figure 14 (it has also been fabricated on the Rogers RO3010 substrate with thickness \( h = 0.635 \text{ mm} \) and measured dielectric constant \( \epsilon_r = 12 \)). Power splitting and matching is reported in Figure 15, whereas the phase response is depicted in Figure 16.

![Figure 13](image_url)  
Schematic of the proposed dual-band power splitter. The characteristic impedance of the access lines is 50 Ω.

![Figure 14](image_url)  
Photograph of the fabricated dual-band power splitter with inverted output signals. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

![Figure 15](image_url)  
Simulated (a) and measured (b) power splitting and matching for the designed device. The measured \( S_{21} \) is –3.31 dB and –4.43 dB at \( f_1 \) and \( f_2 \), respectively. The measured \( S_{31} \) is –2.91 dB and –4.84 dB at \( f_1 \) and \( f_2 \), respectively.

![Figure 16](image_url)  
Simulated (dashed line) and measured (solid line) phase balance.
By considering $\pm 0.3$ dB of amplitude mismatch, the bandwidth for power splitting (worst case) is 30 MHz for the first band and 35 MHz for the second band. Measured return losses are better than 15 dB at the two operating frequencies. The measured phase balance is $-177.0^\circ$ and $-188.6^\circ$ at $f_1 = 0.8$ and $f_2 = 1.7$ GHz, respectively. By considering a phase imbalance of $\pm 10^\circ$, the bandwidth is 271 MHz for the lower band and 97 MHz for the upper band.

4. CONCLUSIONS

In conclusion, we have reported novel artificial lines exhibiting a CRLH behavior with unconventional dispersion, that is, right-handed wave propagation at low frequencies and right-handed wave propagation at high frequencies. This has been achieved from the diplexer action of CSRR-based right-handed and left-handed unit cells arranged in a parallel connection. These lines have been combined with conventional CRLH lines based on CSRRs to design dual-band components that require the combination of both line types, as reported in the text. Specifically, a dual-band rat race hybrid coupler and a power splitter with inverted outputs have been designed, fabricated, and characterized. The experimental results are good, with dual-band operation demonstrated, and good performance in terms of insertion losses, power splitting, matching, isolation, and phase balance. Work is in progress by the authors to the synthesis of tri- and quad-band artificial lines, with an eye toward the design of multiband components.

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