Negative-order ridge substrate integrated waveguide coupled-resonator filter

Qingshan Yang and Yunhua Zhang

A negative-order resonator (NOR) based on a ridge substrate integrated waveguide (RSIW) structure and its application to a coupled-resonator filter (CRF) is investigated. The NOR is realised by etching an interdigital slot on the ridge surface of the original RSIW to achieve the composite right/left-handed (CRLH) characteristics, which makes the resonator exhibit the unique property of negative-order resonances. The −1st-order resonance can be generated with a much lower resonant frequency than that of the original RSIW resonator with the same size. Thus, miniaturisation can be achieved by using this NOR structure. Besides, the non-radiative property of the CRLH RSIW structure would help in avoiding radiation loss and electromagnetic interference to the other circuits, which is a better choice in guided-wave applications than other open radiative CRLH structures. Electric coupling is adopted between the neighbouring resonators in the filter design. This CRF shows the advantages of a low-profile, compact size, non-radiation as well as easy integration with other planar circuits.

Introduction: In the past decade, metamaterials have become a research hotspot in electromagnetics/microwave engineering communities owing to their unusual electromagnetic properties. In particular, composite right/left-handed (CRLH) transmission lines have attracted much attention because they have enabled numerous applications with new functionalities in microwave components and antennas [1]. Several miniaturised filters using different CRLH structures have been reported. Substrate integrated waveguide (SIW) negative-order cavity resonators were studied and applied to bandpass filters in [2]. Miniaturised partial *H*-plane filters based on the CRLH folded SIW were investigated in [3]. The present authors have proposed a non-radiative CRLH transmission line based on the ridge SIW (RSIW), which was expected to have better applications in filter design due to its non-radiative properties compared with the other open radiative CRLH structures [4]. In this Letter, a negative-order resonator (NOR) is first constructed using the CRLH RSIW unit cell with the dispersion simulated and the −1st-order resonance in the left-handed (LH) region obtained, and then a compact coupled-resonator filter (CRF) is designed and fabricated with satisfactory results measured.

NOR based on CRLH RSIW: The unit cell of the CRLH RSIW is shown in Fig. 1. The structure is based on a two-layer substrate of Rogers RT/Duroid 6002 with dielectric constant $\varepsilon_r = 2.94$ and loss tangent $\tan\delta = 0.0012$. The thicknesses of the two layers are $h_1 = 0.254$ mm and $h_2 = 0.508$ mm. A bonding film with a dielectric constant of 2.8 and a loss tangent of 0.01 is used in the fabrication to stick the two substrates together. The equivalent circuit model of this CRLH RSIW unit cell is also given in Fig. 1. Here, the interdigital slot serves as the LH series capacitance C_L, whereas the distributed inductance of the fingers provides the right-handed (RH) series inductance L_R. The LH shunt inductance L_L comes from the metallised vias, whereas the RH shunt capacitance C_R is from the capacitance between the top and the bottom metal planes as well as the ridge and the top metal planes. Apparently, this CRLH unit cell is closed, hence no radiation can occur in the air.

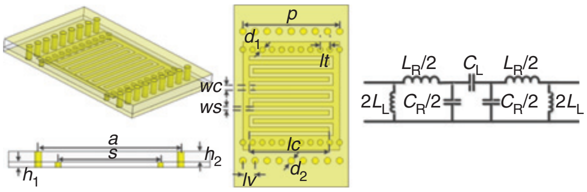

Fig. 1 *CRLH RSIW unit cell and its equivalent circuit*

Fig. 2 presents the dispersion curve of this CRLH unit cell obtained using the Ansoft high-frequency structure simulator. As a comparison, the dispersion curve extracted by the equivalent circuit is also given. The design parameters are all listed in the subcaption. A good agreement of the two dispersion curves is shown. This CRLH unit cell is unbalanced with a frequency band gap from f_{se} to f_{sh}, where f_{se} and f_{sh} are the series resonant frequency and shunt resonant frequency of the CRLH unit cell, respectively. This CRLH RSIW unit cell can be used as a resonator as shown in the following. It is clearly indicated that a −1st-order resonance is generated at 5.5 GHz in the LH region with the electrical length of $-\pi$. f_{se} and f_{sh} are the two zeroth-order resonance frequencies where the electrical length of the resonator is 0, but only f_{sh} is excited in this CRLH RSIW resonator since it is open-circuited in the two ends [1]. The +1st-order resonance happens at 9.6 GHz with the electrical length of π. Using the −1st-order resonance of this NOR, miniaturisation can be achieved since it has a much lower resonant frequency than that of the +1st-order resonance.

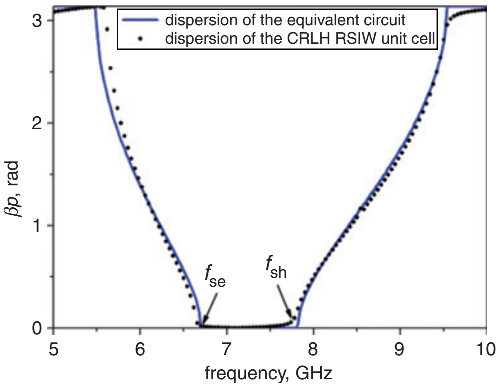

Fig. 2 *Dispersion curves of CRLH RSIW unit cell and equivalent circuit shown in Fig. 1*

The design parameters for the CRLH RSIW unit cell are: $a = 7.25$ mm, $s = 5.19$ mm, $p = 5.2$ mm, $d_1 = 0.3$ mm, $d_2 = 0.35$ mm, $lv = 0.65$ mm, $lt = 0.52$ mm, $lc = 4.15$ mm, $wc = 0.25$ mm, $ws = 0.2$ mm. The equivalent circuit parameters are: $L_L = 0.0179$ nH, $C_L = 1.9357$ pF, $L_R = 0.2915$ nH, $C_R = 23.0230$ pF, $f_{se} = 6.7$ GHz and $f_{sh} = 7.84$ GHz.

Three-order CRF design: The detailed configuration of a three-order CRF is given in Fig. 3. It consists of three RSIW NORs. All three NORs resonate at the −1st-order resonance frequency. The neighbouring NORs are coupled with each other through a transverse slot, i.e. it is electric coupling similar to [3]. The CRF design procedure follows the classic method in [5]. A lowpass prototype filter is first chosen according to the specified requirements. Then, the internal coupling coefficients and the external quality factors can be determined. After that, the relationships between the filter design parameters and the physical structures are established through a full-wave simulation. Finally, the filter is synthesised and optimised.

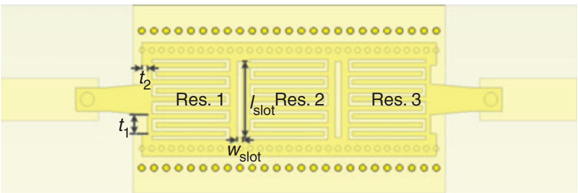

Fig. 3 *Configuration of three-order CRF*

The final optimised dimensions are: $a = 7.25$ mm, $s = 5.19$ mm, $p = 5.2$ mm, $t_1 = 1$ mm, $t_2 = 0.3$ mm, $l_{slot} = 4$ mm and $w_{slot} = 0.3$ mm. For Res. 1 and 3, $lc = 3.9$ mm, $wc = 0.25$ mm, $ws = 0.2$ mm. For Res. 2, $lc = 3.92$ mm, $wc = 0.25$ mm, $ws = 0.2$ mm.

In this Letter, a three-order Chebyshev lowpass prototype filter with a passband ripple of 0.043 dB is demonstrated. The centre frequency is designed at 5.5 GHz with a fractional bandwidth (FBW) of 7%. Thus, the internal coupling matrix and the external factor quality are given by

$$\boldsymbol{M} = \begin{bmatrix} 0 & 0.0722 & 0 \\ 0.0722 & 0 & 0.0722 \\ 0 & 0.0722 & 0 \end{bmatrix}, \quad Q_{e1} = Q_{e3} = 12.17 \qquad (1)$$

A doubly loaded NOR is simulated using the CST Microwave Studio to determine the relationship between the external factor quality and the physical structure, as shown in the inset of Fig. 4. The external factor quality can be adjusted by varying the insertion depths of the feedlines, denoted by t_2. Fig. 4 shows the simulated external quality factor against t_2 for the input/output coupling. The internal coupling between the neighbouring NORs can be controlled by the transverse slot width w_{slot}, as shown in Fig. 5. Both the low mode and the high mode of the two coupled NORs are excited. Their resonant frequencies as well as the calculated coupling coefficients are presented in Fig. 5.

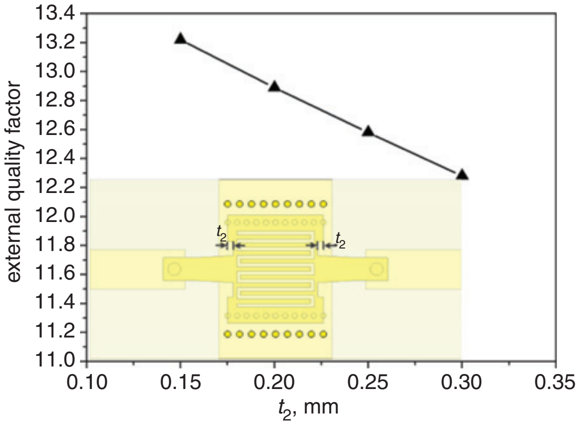

Fig. 4 *Simulated external quality factor against t_2 for input/output coupling*

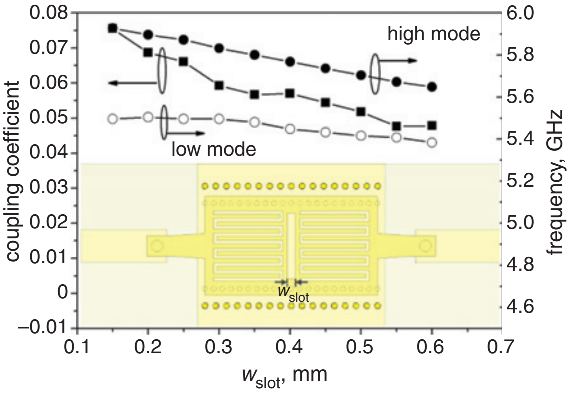

Fig. 5 *Simulated resonant frequencies and internal coupling coefficients against w_{slot}*

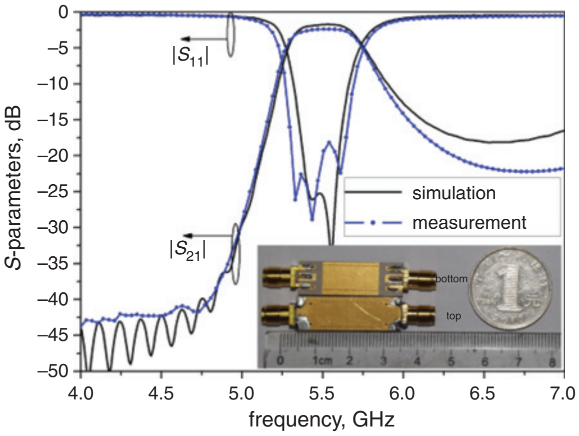

Fig. 6 *Simulated and measured S-parameters for three-order CRF*

According to the obtained relationships between the filter design parameters and the physical structures as provided in Figs. 4 and 5, respectively, the filter is initially synthesised. In the final optimisation, the interdigital finger length *lc* can be adjusted to make the resonance take place at 5.5 GHz. The optimised dimensions are listed in the caption of Fig. 3.

The CRF was fabricated and measured. The simulated and the measured *S*-parameters agree well with each other as shown in Fig. 6, from which one can see that the measured in-band insertion loss is about 2.4 dB, and the return loss is <-17.5 dB. The measured centre frequency is 5.505 GHz with a 3 dB bandwidth of 455 MHz (FBW: 8.27%). The occupied area of this CRF is only 16.55×8 mm ($0.52\lambda_g \times 0.25\lambda_g$) without including the input/output feedlines, hence it is quite compact.

Conclusion: A miniaturised CRF is realised by using the RSIW based NORs. The miniaturisation property of the NOR is exhibited. Both the simulated and measured results are provided, which agree with each other very well. The designed CRF has demonstrated the advantages of low-profile, compact size, non-radiation as well as easy integration with other planar circuits.

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One or more of the Figures in this Letter are available in colour online.

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