Quad-band power divider based on left-handed transmission lines

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A quad-band equal power divider has been designed by exploiting the multi-band operation of left-handed transmission lines. Unit cell design based on dispersion analysis is provided. A practical power divider that demonstrates equal power division at frequencies 0.47, 0.8, 1.85 and 3.35 GHz was designed and fabricated by implementing the left-handed cells in microstrip technology.

Introduction: With the trend of integrating several applications in communication devices becoming increasingly common, the need to design multi-band microwave components has become more important than ever. Metamaterial lines or left-handed transmission lines (LHTLs), on account of their unique dispersion properties, are suitable for multi-band applications [1, 2]. This Letter presents a quad-band power divider which is implemented by replacing the transmission line (TL) segments of a previously proposed dual-band power divider (shown in Fig. 1*a*) [3] with left-handed (LH) cells.

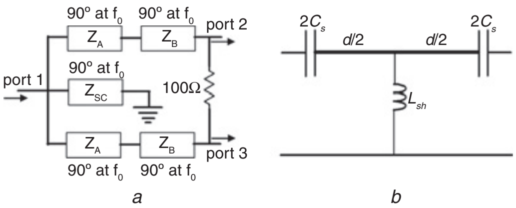

Fig. 1 *Dual-band power divider of [3], and typical metamaterial or left-handed unit cell*

a Dual-band power divider of [3]
b Typical metamaterial or left-handed unit cell

Design equations: The three-branch power divider of Fig. 1*a* demonstrates dual-band action around the centre frequency f_o when the following impedance conditions are satisfied [3]:

$$Z_A = \pm\frac{\sqrt{2}Z_S}{\tan\phi}, Z_B = \frac{\pm\sqrt{2}Z_S}{\cot\phi}, Z_{SC} = \frac{\pm Z_S\cos^2\phi}{\sqrt{2}\tan\phi\cos 2\phi} \quad (1)$$

where Z_S is the impedance of the external microstrip circuit and $\phi = \pi/2 \pm \Delta\theta$, $\Delta\theta$ being the phase deviation from f_o. To understand the multi-band operation of an LHTL, consider the following approximate dispersion equation obtained from the unit cell, given in Fig. 1*b* [1]:

$$-\nu_p/2\pi f + 2\pi f d/\nu_p = \theta \quad (2)$$

where θ is the unit cell phase shift, v_p is the speed of light in the substrate, $\nu = 1/\sqrt{L_{sh}C_s}$, and d is the unit cell length. By solving the above quadratic equation, a lower backward-wave frequency band and a higher forward-wave band are obtained. When the impedance sections of the three-branch power divider are replaced by LHTL cells, four unique non-harmonic frequencies of power division (f_1 and f_2 centred at f_{o1} while f_3 and f_4 centered at f_{o2}) are obtained. The centre frequencies are defined in terms of the unit cell shift θ_o as:

$$f_{o1} = (8\pi\alpha)^{-1}\left[-\theta_o + \sqrt{\theta_o + 16\nu\alpha}\right]$$
$$f_{o2} = (8\pi\alpha)^{-1}\left[\theta_o + \sqrt{\theta_0 + 16\nu\alpha}\right] \quad (3)$$

where $\alpha = d/v_p$. It may be noted that the Bloch impedance of the LHTL is dominated by the characteristic impedance of the transmission line section Z_o in the forward-wave band and by the ratio $\sqrt{L_{sh}/C_s}$ in the backward-wave band. The approximate frequency ratios in the two bands are given by:

$$N_1 = \frac{f_2}{f_1} = \frac{-(\theta_o + \Delta\theta) + \sqrt{(\theta_o + \Delta\theta) + 16\nu\alpha}}{-(\theta_o - \Delta\theta) + \sqrt{(\theta_o - \Delta\theta) + 16\nu\alpha}} \quad (4)$$

$$N_2 = \frac{f_4}{f_3} = \frac{(\theta_o - \Delta\theta) + \sqrt{(\theta_o - \Delta\theta) + 16\nu\alpha}}{(\theta_o + \Delta\theta) + \sqrt{(\theta_o + \Delta\theta) + 16\nu\alpha}} \quad (5)$$

Practical example: To obtain practical lumped component values and hence to demonstrate a representative case, the power divider is designed around centre frequencies $f_{o1} = 0.6$ GHz and $f_{o2} = 2.6$ GHz. With two-stage LHTL sections ($\theta_o = \pi/4$) and $Z_s = 50\ \Omega$, solving (3) gives $d = 0.02v_p$ and $\nu = 1/\sqrt{L_{sh}C_s} = 3.5\times 10^9$. The section impedances are obtained by solving (1), (4), and (5). Assuming $N_1 = N_2 \simeq 1.8$ simplifies the representative case as it gives equal section impedances in forward and backward-wave band, given by $Z_A = 61\ \Omega$ and $Z_B = Z_{SC} = 82\ \Omega$. The lumped elements are obtained by the relations $C_s = 1/\nu Z_x$, and $L_{sh} = 1/\nu^2 C_s$ ($Z_x = Z_A, Z_B$, or Z_{SC}). The values are adjusted according to the available components and are given by $L_{sh} = 15$nH and $C_s = 4$pF for the Z_A sections and $L_{sh} = 20$nH and $C_s = 3$pF for the Z_B and Z_{SC} sections. Each of the impedance sections of Fig. 1*a* is replaced by two corresponding periodically arranged LH unit cells of lengths (d) 1.38 cm. The power divider is implemented using microstrip technology on a Rogers 5880 substrate with a height of 31 mils and a dielectric constant of 2.2. The photograph of the fabricated power divider is provided in Fig. 2. As shown, the widths of the TL segments vary according to the section impedance.

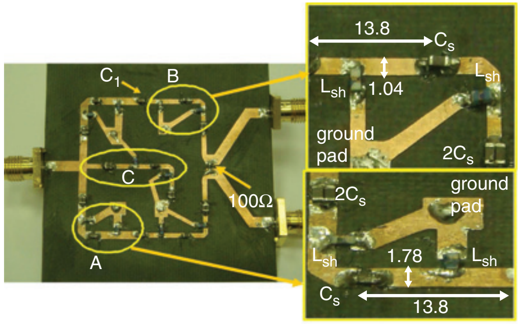

Fig. 2 *Photograph of proposed LHTL quad-band power divider*

C_1 denotes combination of series capacitances of adjacent Z_A and Z_B stages. All dimensions in mm

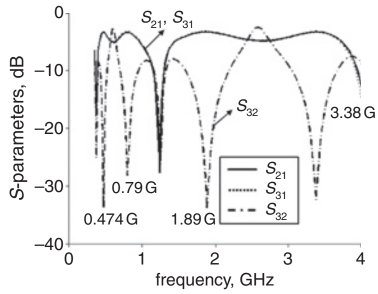

Fig. 3 *Simulated S-parameters of quad-band power divider*

Results: The power divider is analysed by the full-wave simulator IE3D software from Zeland Inc. The simulated *S*-parameters (Fig. 3) show good transmission and isolation characteristics (S_{21}, S_{31}, S_{32}). The isolation (S_{32}) plot clearly demonstrates four frequencies of power division given by 0.474, 0.79, 1.89, and 3.38 GHz. A small change in N_1 and N_2 is due to the approximations in the dispersion relation (2). Some loss in transmission is attributed to the conductor and dielectric losses that take place in the substrate and TL segments. The *S*-parameters of the fabricated device are provided in Fig. 4. The value of the transmission coefficients at the four power divider frequencies is approximately −3.5 dB. The additional losses are mainly due to the resistive losses in the lumped capacitors and inductors which are not taken into account in the simulations. The practical divider demonstrates better than −18 dB isolation at 0.47, 0.79, 1.81, and 3 GHz. Furthermore, S_{21} and S_{31} track each other, resulting in balanced power division. Small shifts in the first three simulated and experimental frequencies of operation come from the fabrication and component tolerances. The largest drift of 0.38 GHz is noted at the fourth band as it is located very close to the self-resonant frequency of the 15 and 20 nH inductors [4]. The plot of reflection coefficients (S_{11}), provided in Fig. 5, shows that the divider is well matched at all the four frequencies. Note that the LHTL-based quad-band power divider published earlier [2] employs conventional Wilkinson design with quad-band LH cells. The proposed configuration, however, represents a generalised method to utilise an N-band LH cell to construct power dividers that operate at $2N$ frequency bands.

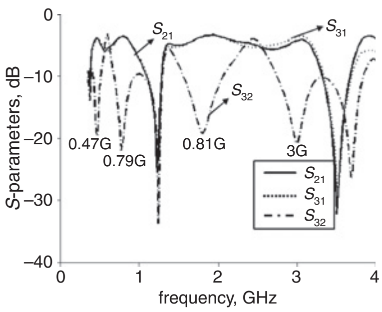

Fig. 4 *S-parameters of fabricated quad-band power divider*

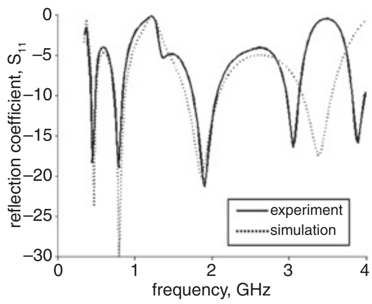

Fig. 5 *Simulated and experimental results of reflection coefficients (S_{11}) showing matched response at quad-band frequencies*

Conclusion: An LHTL-based quad-band power divider, which demonstrates the power divisions at 0.47, 0.8, 1.85, and 3.35 GHz, is designed and synthesised using microstrip technology. Practically, the operating frequencies are slightly shifted, mainly due to the component and fabrication tolerances.

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

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