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A reconfigurable Wilkinson power divider based on transmission-line phase shifter for 5G new radio

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To overcome the high path loss of millimeter-wave (mm-Wave) signals in the air, phased-array systems have excited growing interest in the academic and industrial fields since they can prominently improve the signal-to-noise ratio of the receiver and the equivalent isotropic radiated power of the transmitter. The power divider, as a key component in the phased-array transceiver front-ends to manipulate the RF signal, plays a significant role in the RF performance and chip area. To support international roaming and reduce system costs, broadband or multi-band Wilkinson power dividers (WPD) with a compact size are urgently needed for 5G NR applications. However, conventional WPDs suffer from large areas and limited operating bandwidth.

Several efforts have been made to expand the operating bandwidth of the WPD. In [1–3], multi-stage cascading, broadband filters, and cascading broadband impedance converters are proposed for broadening the frequency band. Nevertheless, these methods adopt distributed components; thus, the WPDs encounter large footprints and are difficult to integrate on a chip. Alternatively, reconfigurable WPDs based on lumped components are researched [4,5], which are able to achieve multi-band operation with compact chip areas. However, they still face some technical challenges, such as high loss and limited impedance-matching and isolation performances.

To cover all the issued 5G NR bands, a reconfigurable WPD is proposed in this letter. It adopts a two-bit transmission-line-based phase shifter (TL-PS) with a compact layout to extend the operating frequency bands. Due to the proposed reconfigurable scheme and TL-PS, the circuit also achieves excellent return loss at each port and isolation between the two output ports. In addition, the WPD possesses the compact area and low implementation complexity compared with other broadband or frequency-reconfiguration structures.

Principle of the proposed reconfigurable WPD. As shown in Figure 1(a), the overall bandwidth of the classic WPD is limited by the relatively poor isolation and input impedance matching. To tackle this issue, a frequency-reconfiguration structure is developed, as revealed in Figure 1(b). Its basic idea is to tune the WPD's center frequency (f_C) whose corresponding phase delay is 90° to different frequencies, then splice the operating bandwidths of different modes to broaden the supported bandwidth of the WPD. Distinct from canonical reconfigurable WPDs, it is composed of two identical TL-PSs, and each TL-PS possesses two phase-shifting cells (PS1 and PS2), hence having four working modes. By tuning the phase shifting cells' operating states, the insertion phase of the TL-PS is changed, as well as its equivalent electrical length (θ). It leads that the f_C of the WPD is adjusted accordingly (Figure 1(b)). In this design, the effective center frequencies of the four modes are set at 29, 31.9, 35.5, and 40 GHz, respectively. The detailed analysis is provided in Appendix A. As a result, the theoretical isolation is higher than 20 dB from 23.8 to 47.2 GHz. Similar to the isolation bandwidth, the bandwidths of the input and output impedance matching of the proposed WPD can also be extended by reconfiguring the working modes, which is introduced in Supporting information.

Circuit implementation. Figure 1(c) presents the layout view of a phase-shifting cell of the TL-PS. It can be seen that each cell is realized by a grounded coplanar waveguide which is composed of two sets of parallel ground wires, two capacitors ($C_{1,2}$), and 6 transistor-based switches (M_{1-6}) which are controlled by logical signals (PQ). As shown in Figure 1(c), the direction of the ground-loop current is opposite to the signal current. Therefore, the mutual inductance between them decreases the equivalent inductance of the coplanar waveguide. When PQ is high, switch transistors $M_{1/4}$ and $M_{3/6}$ are turned on and short a group of wires that are closer to the signal line to the ground. As a result, the mutual inductance between the signal and ground lines increases, while the equivalent inductance L_H of the coplanar waveguide is reduced. Meanwhile, $M_{2/5}$ is turned off, and the equivalent capacitance C_H is also decreased. This method maintains the characteristic impedance of the TL-

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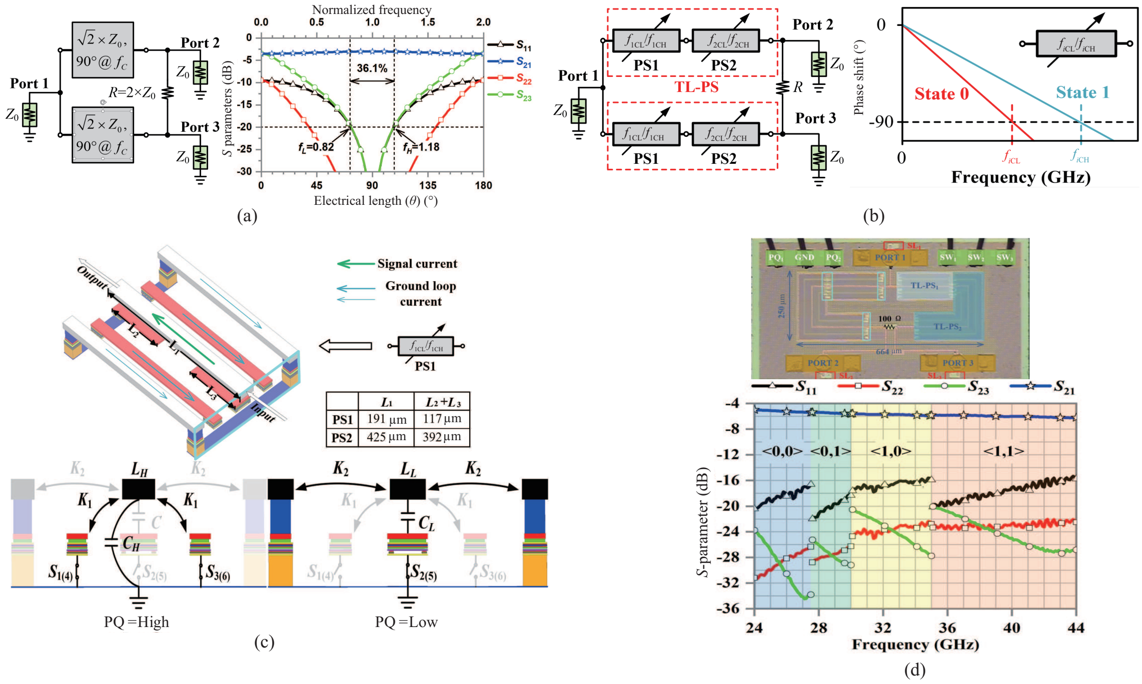

	L_1	L_2+L_3
PS1	191 µm	117 µm
PS2	425 µm	392 µm

Figure 1 (Color online) (a) Circuit model of a classical WPD and its theoretical the magnitudes of S parameters versus θ of TL and normalized frequency; (b) topology of the proposed reconfigurable WPD and phase response of a TL-based phase-shifting cell in States 0 and 1; (c) structure of the used TL-PS and its corresponding equivalent circuits when PQ are high and low; (d) die photo and tested S parameters (with 3-dB power-division loss) of the reconfigurable WPD in the four states.

PS but decreases the equivalent electrical length compared with that of State 0 (PQ = Low) whose equivalent structure is also shown in Figure 1(c). The switches in the TL-PSs are realized by n-type MOSFETs with bulk isolation resistors, and their sizes or values are optimized by SPECTRE simulation to balance the insertion loss in ON mode and isolation in OFF mode.

Measurement results. As a proof of concept, the proposed reconfigurable WPD is fabricated in a commercial 65-nm CMOS process. Figure 1(d) shows the micrograph of the chip, and its core area is 648 µm × 250 µm. The S-parameters measurement for the WPD in the four working states is done to check its performance. From 20 to 30 GHz, as presented in Figure 1(d), the reflection coefficients (S_{11} and S_{22}) in States $\langle 0,0\rangle$ and $\langle 0,1\rangle$ are less than -13.9 and -23.1 dB, respectively. By choosing the appropriate working state, the loss of the WPD is 2.0–3.3 dB in the entire frequency band. At 30–44 GHz, the S_{11} and S_{22} are less than -12.7 and -16.7 dB in States $\langle 1,0\rangle$ and $\langle 1,1\rangle$, and the loss is less than 3.3 dB (Figure 1(d)). The measured isolation ($|S_{23}|$) in the four states are 34.4, 29.2, 28.92, and 27.39 dB at 27.1, 30.1, 36.9, and 43.1 GHz, respectively. Owing to the proposed reconfigurable structure, the >20-dB-isolation bandwidth is up to 20 GHz which ranges from 24 to 44 GHz. The reconfigurable WPD also features good frequency-response consistency between the two output ports, and the amplitude and phase mismatches are less than 0.27 dB and 1.4° in the entire frequency band, respectively.

According to the measurement results, a reconfigurable scheme for this WPD is formulated, as shown in Figure 1(d). It can be seen that the proposed WPD successfully covers all the frequency bands of 5G NR frequency range 2 (n257, n258, n260, and n261), and the fractional bandwidth is up to 58.8% which is defined as the intersection of the >10-dB-return-loss and >20-dB-isolation bandwidths. Furthermore, the chip area is only 0.162 mm^2 ($1.3 \times 10^{-3}\lambda_0^2$ @ 27.1 GHz). The excellent overall performance of the proposed WPD indicates that it is suitable for broadband on-chip multi-channel wireless systems in the mm-Wave regime.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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