UWB Gilbert downconverter with lumped-distributed phase-inverter rat-race coupler based on Chebyshev band-broadening technique

H.-J. Wei, C. Meng, C.-H. Chang and G.-W. Huang

A broadband Gilbert downconverter with a miniature phase-inverter rat-race coupler is demonstrated using 0.35μm SiGe BiCMOS technology. By lumped-distributed and band-broadening techniques, a large shrinkage ratio with wide bandwidth of Chebyshev response can be simultaneously attained in the spiral-shape coplanar-stripline phase-inverter rat-race coupler. The area of the demonstrated lumped-distributed phase-inverter rat-race coupler is 0.65×0.65 mm^2 and the experimental bandwidth ranging from 2.5 to 12.5 GHz is large enough to cover the UWB bandwidth. As a result, a broadband Gilbert downconverter with the proposed coupler achieves a conversion gain of 11–12 dB, IP_{1dB} of −11 dBm, IIP_3 of −1 dBm and noise figure of 16 dB from 3 to 11 GHz.

Introduction: In the past decades, many quarter-wavelength-based passive components, such as phase-inverter rat-race couplers, have been fully-integrated into silicon-based ICs at microwave and millimetre frequency regimes. Recently, directly implementing quarter-wavelength-based passive components on silicon substrate is the most effective way to achieve size reduction because of the higher dielectric constant, despite higher loss. To shrink the size and minimise the loss, miniaturisation methods such as the spiral-winding structure [1], and the step-impedance structure [2], were proposed for the phase-inverter rat-race coupler. The spiral-shaped phase-inverter rat-race coupler (2.5 to 13 GHz) with a Butterworth response has an area of 1.4×1.4 mm^2 and is demonstrated with a mixer for UWB applications [1]. The step-impedance technique also effectively reduces the size because of the large high impedance ratio between the high-impedance and low-impedance inter-digital sections. On the other hand, the bandwidth reduction caused by the step-impedance structure can be alleviated by designing the equivalent characteristic impedance of each arm of a phase-inverter rat-race coupler for a Chebyshev response [2]. Thus, a step-impedance rat-race coupler (7 to 18 GHz) with a Chebyshev response with an area of 0.63×0.63 mm^2 has been realised with a mixer [2]. The inter-digital low-impedance section of a step-impedance section behaves as a capacitor and is hard to meander owing to its wide shape. Thus, for lower operating frequencies, incorporating spiral-winding [1] and lump-distributed [3] techniques with a Chebyshev response is the effective way to achieve size reduction and bandwidth extension. In this Letter, a spiral-shaped lumped-distributed phase-inverter rat-race coupler (2.5 to 12.5 GHz) with a Chebyshev response has been implemented with a mixer for UWB applications. The resulting coupler occupies an area of only 0.65×0.65 mm^2. As a result, the demonstrated rat-race coupler has about 80% area reduction when compared with our previous spiral-shaped Butterworth-response design [1] and maintains a broad bandwidth for UWB Gilbert mixer applications.

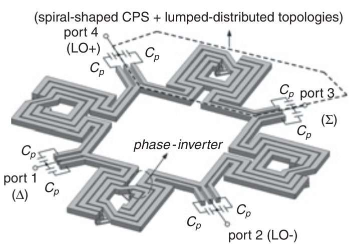

Fig. 1 *Schematic of lumped-distributed spiral-shape CPS phase-inverter rat-race coupler*

Circuit design: Fig. 1 shows the lumped-distributed phase-inverter rat-race coupler by shunting capacitors at the two terminations of each arm with the Gilbert micromixer. Each arm of the lumped-distributed coupler is equivalent to an imitated quarter-wavelength TL, as shown in Fig. 2. When loss is negligible, the equation to establish the equivalence at the centre frequency between the imitated quarter-wavelength TL and the lumped-distributed TL is expressed in (1):

$$\begin{bmatrix} 0 & jZ_{imitated} \\ jY_{imitated} & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ j\omega C & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & jZ\sin\theta \\ jY\sin\theta & \cos\theta \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ j\omega C & 1 \end{bmatrix} \quad (1a)$$

$$\rightarrow \begin{cases} \dfrac{Z_{imitated}}{Z} = \sin\theta \\ \omega CZ = \cot\theta \end{cases} \quad (1b)$$

The impedance ratio of $Z_{imitated}/Z$ is reduced as the length of Q is shrunk. Because of the physical layout, the characteristic impedance (Z) of the spiral-shaped coplanar-stripline (CPS) is limited at 80 Ω. Here, $Z_{imttated}$ is chosen as 50 Ω (below 70.7 Ω) for the Chebyshev response and the input return loss has two splitting matching dips [4, 5]. When the spacing of the two dips increases by reducing $Z_{imitated}$, the bandwidth can be extended. In this work, the length (θ) is shrunk below 40°, representing that small θ accompanies Chebyshev response instead of Butterworth response. Thus, the targets of small size and broad bandwidth are achieved in the lumped-distributed design. From (1b), the shunt capacitance can be obtained. The proposed rat-race coupler directly on the silicon substrate uses the top thick metal with 3μm thickness to reduce metal loss, and the spacing and width of the CPS are 4μm and 15μm in the spiral shape, respectively. Since the RF transconductance stage of the 0.35μm SiGe BiCMOS Gilbert micromixer has excellent frequency response, the operating bandwidth of the Gilbert micromixer is finally determined by the lumped-distributed phase-inverter rat-race coupler (used in LO port).

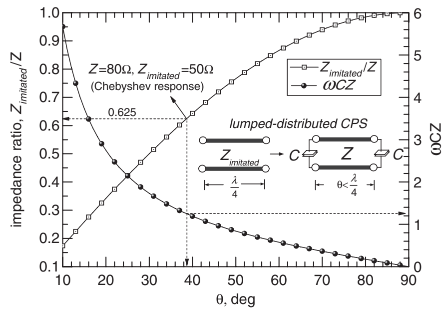

Fig. 2 *Impedance ratio of $Z_{imitated}/Z$ and required shunt capacitance against length (θ) for lumped-distributed technique*

Experimental results: The proposed rat-race coupler is employed at the LO port of the UWB Gilbert micromixer and the area excluding pads is 0.9×0.8 mm^2, as shown in Fig. 3. The current consumption of the mixer core is 4.1 mA at 5V supply voltage. Fig. 4 shows the measured conversion gain (CG), P_{1dB}, IIP_3 and noise figure with respect to the RF frequency. The CG keeps 11–12 dB within 1dB variation and the noise figure is 15–17 dB from 3 to 11 GHz. IP_{1dB} and IIP_3 keep around −12 to −10 dBm and −1 dBm for each UWB band group, and the measured IF 3dB bandwidth is up to 1.0 GHz. The measured LO-to-RF/ LO-to-IF/ RF-to-IF isolation is better than 40 dB/35 dB/20 dB.

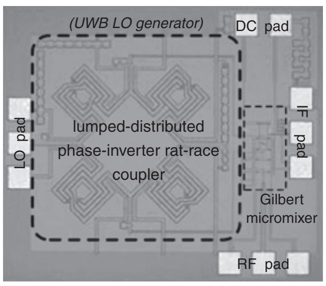

Fig. 3 *Die photo of demonstrated 0.35μm SiGe BiCMOS UWB Gilbert downconverter using proposed lumped-distributed phase-inverter rat-race coupler*

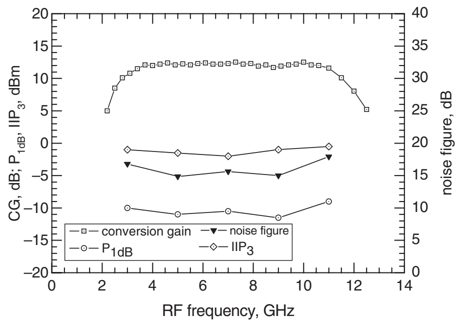

Fig. 4 *Measured conversion gain, P_{1dB}, IIP_3, noise figure of demonstrated 0.35µm SiGe BiCMOS UWB Gilbert downconverter*

Conclusion: An effective way to achieve size reduction and bandwidth extension is proposed to greatly shrink a phase-inverter rat-race coupler, and a 0.35µm SiGe BiCMOS Gilbert downconverter with the lump-distributed phase-inverter rat-race coupler is successfully demonstrated for UWB applications.

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