A Novel Reduced-Size Rat-Race Broadside Coupler and Its Application for CMOS Distributed Sub-Harmonic Mixer

Chun-Lin Kuo, Che-Chung Kuo, Chun-Hsien Lien, Jeng-Han Tsai, *Member, IEEE*, and Huei Wang, *Fellow, IEEE*

Abstract—A broadband distributed sub-harmonic resistive field effect transistor mixer with a novel modified rat-race broadside coupler using a $0.13\text{-}\mu\text{m}$ CMOS foundry process is presented in this letter. Using the broadside coupler, a reduced-size rat-race is fabricated with a compact size of $110 \times 80 \mu\text{m}^2$. From the measurement results, the mixer achieved a conversion loss of 12 dB from 32 to 70 GHz of RF frequency. The passive sub-harmonic mixer has zero power consumption. With the modified rat-race broadside coupler, the mixer achieves a good LO-IF isolation of better than 30 dB and a compact core chip size of $0.55 \times 0.4 \text{ mm}^2$.

Index Terms—CMOS, distributed circuit, monolithic microwave integrated circuit (MMIC), sub-harmonic mixer.

I. INTRODUCTION

A sub-harmonic mixer allows the use of a local oscillator at a frequency that is only half of a fundamental mixer. Since the local oscillation (LO) frequency is relatively lower, the output power and phase noise can be superior to the fundamental source. The anti-parallel diode topology is most commonly used in passive sub-harmonic mixer design [1], [2]. However, the matching stubs using in the mixer restrain the bandwidth and the chip area. Another passive sub-harmonic mixer is the field effect transistor (FET) resistive mixer [3]. Active sub-harmonic mixers were proposed using the Gilbert-cell topology [4], but the requirement of a precise quadrature LO signal restrains the monolithic microwave integrated circuit (MMIC) design.

Recently, the bandwidth requirement is increasing in broadband and wireless communication system. As a good choice for high frequency application, distributed circuits are commonly used in the fundamental mixer design [5]–[7]. For a distributed sub-harmonic pumped mixer, the topology was only realized on hybrid circuit [8]. Distributed sub-harmonic mixers can achieve a wide bandwidth, but the bandwidth is usually restricted by the on-chip balun.

In this letter, we propose a broadband distributed sub-harmonic mixer with a reduced-size rat-race broadside coupler. The sub-harmonic mixer was fabricated using $0.13\text{-}\mu\text{m}$ CMOS process. A novel reduced-size rat-race is implemented using

Fig. 1. Circuit schematic of the distributed sub-harmonic mixer with a rat-race type broadside coupler.

three metal layers forming a broadside coupler with a Marchand balun and two directional couplers. The measured results show that the conversion loss is 12 dB from 32 to 70 GHz of RF frequency. The local oscillation intermediate frequency (LO-IF) isolation is better than 30 dB within the operation band. The output $P_{1\text{ dB}}$ is -4 dBm at 55 GHz of RF frequency. The chip size is only 0.36 mm^2 including bonding pads and the core area is only 0.22 mm^2 .

II. CIRCUIT DESIGN AND FABRICATION

The schematic of the proposed distributed sub-harmonic mixer with a reduced-size, rat-race, broadside coupler is shown in Fig. 1. In the single mixer cell, a single-balanced topology is selected and the transistor pair, $M_1 - M_2$ ($48 \mu\text{m}/0.13 \mu\text{m}$) are biased at nearly turn-off region. The LO and RF signals are applied to the gates of the transistor pair with differential and equal phase respectively.

Since the LO and RF signals are applied to the gates of the transistor pair, a rat-race hybrid is required in the design. However, a typical rat-race is fabricated using three 0.25λ and one 0.75λ transmission lines. It will occupy a lot of chip area. Thus, some modified rat-races such as those reported in [9]–[11] were used on chip for MMIC design, but the 0.25λ transmission lines or lumped elements still occupy large chip areas. Conventional Marchand balun is a three-port element which can offer differential signals. In the letter, we proposed to add one more coupling element to extend the Marchand balun to a four-port modified rat-race with a miniature size. This concept can also be applied to a five-port dual balun for a different application (star mixer design) [12]. Here we design the broadside coupler with three metal layers. Top two layers (metal 8 and metal 7) is a three-port Marchand balun and we insert two lines (using metal

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The authors are with the Department of Electrical Engineering and Graduate, Institute of Communication Engineering, National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: hueiwang@ew.ee.ntu.edu.tw).

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Fig. 2. The rat-race broadside coupler (a) structure (b) physical layout.

6) under the balun, as shown in Fig. 2(a). In operation frequency band, the signal of the port 1 will couple to the line of the next lower layer, and the port 2 and port 3 will be 180° out of phase. In addition, the signal of the port 4 will couple to the line of next top layer, and the port 2 and port 3 will be in phase. Therefore, the LO signal from port 1 and RF signal from port 4 can be applied to the gates of the transistor pair with differential and equal phase, respectively. In order to design for low insertion loss, the low odd-mode impedance of the balun should be chosen [1], and the spacing and width of the couple-lines are determined accordingly. In addition, the length of the couple-lines is decided by the quarter wave length at the desired frequency, which is $800 \mu\text{m}$ in this work. As shown in Fig. 2(b), these couple-lines are wound into a compact size of $110 \mu\text{m} \times 80 \mu\text{m}$, which is the same size of a Marchand balun. Finally, the full-wave EM simulator SONNET is used to determine the final dimensions of the rat-race broadside coupler. The line width and gap are both $3 \mu\text{m}$ in this design.

The differential LO signals modulate the FET linear channel resistance and the mixing occurs due to the time-varying channel conductance. Three stages of mixer cell are selected with the trade-off between conversion gain and bandwidth. The transmission lines at gates are terminated to the characteristics impedance ($R_1 = R_2 = 70 \Omega$). At IF port, the desired IF signal frequency is usually lower than 1 GHz thus it can be summed up by using short transmission lines at the drains and the termination resistor is also omitted at drain. The RF and twice of LO frequency leakages to the output port are far away from the IF and can be easily filtered out.

The broadside coupler and transmission lines are all complemented using thin-film microstrip (TFMS) structures with the bottom metal 1 as ground and top thick metal 8 as signals. All the passive components including the reduced-size rat-race broadside coupler, the MIM capacitors, and the TFMS lines were simulated using a full-wave EM simulator (Sonnet Software). The complete circuit was simulated using Agilent Advanced Design System (ADS).

III. MEASURED RESULTS

The broadband distributed sub-harmonic mixer chip was measured using on-wafer probing. The output was connected to the spectrum analyzer through the bias-T network. The chip size is $0.6 \text{ mm} \times 0.6 \text{ mm}$, as show in Fig. 3. Fig. 4 shows the measured and simulated results of the reduced-size rat-race

Fig. 3. Chip photograph of the distributed sub-harmonic mixer.

Fig. 4. Measured and simulated (a) insertion loss and (b) phase difference frequency response of the reduced-size rat-race broadside coupler test chip.

broadside coupler test circuit. The simulations agreed with the measurements reasonably. The measured insertion loss of the coupler is about 7 dB; phase errors of in-phase and out-phase signals are within 8° and 10° , respectively, from 30 to 60 GHz. The insertion loss which is about 4 dB higher than ideal case is due to the lossy Si substrate and the high resistivity of the thin metals using in the 2nd and 3rd layers of the balun coil.

The measured conversion loss swept with LO power is saturated at 13 dBm at RF frequency of 55 GHz and a fixed IF frequency of 1 GHz. Fig. 5 shows the measured conversion gain from 25 to 75 GHz. With the distributed topology, the circuit achieved a conversion loss of better than 12 dB from 32 to 70 GHz with a fixed IF frequency of 1 GHz.

Fig. 6 plots the measured port-to-port isolation. The LO-IF isolation is better than 30 dB due to the single-balanced topology and the 2LO-IF and LO-RF isolation is also better

TABLE I
SUMMARY OF THE PRESENTLY PUBLISHED BROADBAND MIXER AND THIS WORK

Ref.	Process	Design Topology	Bandwidth (GHz)	Conversion Gain (dB)	Area (mm ²)
This Work	0.13- μ m CMOS	Subharmonic Distributed	32-70	-11~-13	0.36
[2]	0.15- μ m GaAs pHEMT	Subharmonic Anti-parallel Diode	38-48	-12~-15	0.72
[13]	0.15- μ m GaAs pHEMT	Subharmonic Ring-quad	25-40	-14	0.7
[14]	90-nm CMOS	Subharmonic Source-pumped	9-31	-8~-11	1
[5]	0.15- μ m GaAs pHEMT	Fundamental Distributed	3-33	-1~-4	1.7
[7]	0.15- μ m GaAs pHEMT	Fundamental Distributed	4-41	3.5-8	2

Fig. 5. Measured conversion gain versus RF frequency with a LO power of 13 dBm and a fixed IF frequency of 1 GHz.

Fig. 6. Measured port-to-port isolation.

than 20 dB. The output 1-dB compression point of the distributed sub-harmonic mixer is about -4 dBm at RF of 55 GHz. Table I summarizes the performance of previously published wide-band sub-harmonic mixer integrated-circuit [13], [14]. The MMIC in this letter is believed to be the widest bandwidth CMOS sub-harmonic mixer to date.

IV. CONCLUSION

A broadband 32 to 70 GHz distributed sub-harmonic mixer is designed and fabricated using TSMC 0.13- μ m CMOS

process. A novel reduced-size rat-race using broadside coupler is proposed to provide an out-phase LO signal and an in-phase RF signal simultaneously. With the broadside coupler, the distributed sub-harmonic mixer achieves a broad bandwidth with a compact size. The sub-harmonic mixer exhibits -12 ± 1 dB measured conversion gain from 32 to 70 GHz with a miniature chip size of 0.36 mm².

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