A 30–100 GHz Wideband Sub-Harmonic Active Mixer in 90 nm CMOS Technology

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Abstract—This letter presents a 30–100 GHz wideband and compact fully integrated sub-harmonic Gilbert-cell mixer using 90 nm standard CMOS technology. The sub-harmonic pumped scheme with advantages of high port isolation and low local oscillation frequency operation is selected in millimeter-wave mixer design. A distributed transconductance stage and a high impedance compensation line are introduced to achieve the flatness of conversion gain over broad bandwidth. The CMOS sub-harmonic Gilbert-cell mixer exhibits -1.5 ± 1.5 dB measured conversion gain from 30 to 100 GHz with a compact chip size of 0.35 mm². The OP_{1 dB} of the mixer is -10.4 dBm and -9.6 dBm at 77 and 94 GHz, respectively. To the best of our knowledge, the monolithic microwave integrated circuit is the first CMOS Gilbert-cell mixer operating up to 100 GHz.

Index Terms—CMOS, E-band, Gilbert-cell, millimeter-wave (MMW), monolithic microwave integrated circuit (MMIC), sub-harmonic.

I. INTRODUCTION

RECENTLY, the Federal Communications Commission (FCC) announced new frequency bands of 71–76 GHz, 81–86 GHz, and 92–95 GHz are available for fixed point-to-point high bandwidth wireless links [1]. The allocation provides for new products and services, such as wireless fiber for the “Entire Last Mile” [2]. There emerges a strong demand for a low-cost transceiver operating at millimeter-wave (MMW) frequencies. With the continued scaling of CMOS technology, there are new opportunities for CMOS circuits operating above 100 GHz. A 104 GHz Colpitts oscillator and a three-stage narrow-band amplifier using 90 nm CMOS were reported in [3]. For broadband application, an 86 to 108 GHz broadband amplifier is demonstrated by 90 nm CMOS [4]. However, CMOS fundamental mixers have only been demonstrated up to 75 GHz [5].

Among the building blocks in MMW front-end, the mixer, which translates the radio frequency (RF) signals to and from intermediate frequency (IF) band, plays an important role. In conventional CMOS mixer designs, fundamental Gilbert-cell mixer

Fig. 1. Summary of fully integrated wideband Gilbert-cell mixers in modern CMOS technologies.

with the advantages of good conversion gain, high spur suppression, and compact chip size, are widely used. Fig. 1 is the summary of the fully integrated wideband Gilbert-cell mixers in modern CMOS technologies. The operation frequency of the fundamental Gilbert-cell mixer has progressed along with the modern CMOS technologies from 180 nm to 90 nm. However the lack of high power and low phase noise local oscillation (LO) source in MMW, particularly above V-band, limit the performance and operation frequency of the fundamental mixer. Therefore the sub-harmonic Gilbert-cell mixer, which has a LO frequency of one half of the desired RF frequency, is an alternative to push MMW mixer to higher operation frequency [6].

In this letter, we continually promote the Gilbert-cell mixer up to 100 GHz by using sub-harmonically pumped technique in 90 nm standard CMOS technology. For wide bandwidth, the distributed transconductance stage and high impedance compensation line are incorporated into the sub-harmonic Gilbert-cell design [6]. The presented sub-harmonic Gilbert-cell mixer achieves a wide 3 dB bandwidth of 70 GHz while maintaining excellent conversion gain flatness of -1.5 ± 1.5 dB from 30 to 100 GHz. To the best of our knowledge, the monolithic microwave integrated circuit (MMIC) is the first MMW CMOS mixer for use over the 71–76 GHz, 81–86 GHz, and 92–95 GHz which is suitable for E-band wireless fiber applications.

II. CIRCUIT DESIGN

The MMIC is fabricated using TSMC standard 90 nm 1P9M CMOS process. The RF transistors provide a $f_{\max}$ of 142 GHz.

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Fig. 2. Schematic of the sub-harmonic Gilbert-cell mixer.

The schematic of the sub-harmonic Gilbert-cell mixer, illustrated in Fig. 2, is similar to [6] using 0.13- μm CMOS. With downscaling of the transistor gate length in 90 nm CMOS and proper selection of device size, the sub-harmonic Gilbert-cell mixer can operate up to 100 GHz in this work. The M_1 and M_2 (24 $\mu\text{m}/0.1 \mu\text{m}$, and 12-finger each with 2 μm unit finger length) act as transconductors. The LO switching quad are $M_3 - M_{10}$ (8 $\mu\text{m}/0.1 \mu\text{m}$). The current mirror source M_{13} (64 $\mu\text{m}/0.1 \mu\text{m}$), M_{14} (16 $\mu\text{m}/0.1 \mu\text{m}$), and R_1 (2400 k Ω) determines the tail current. A current bleeding circuit R_2 (400 Ω) and R_3 (400 Ω) introduces a bypass current path to reduce the bias current through R_6 (1200 Ω) and R_7 (1200 Ω) while maintaining a sufficient dc current for the transconductance stage. Finally a source-follower buffer is consisted of M_{11} (64 $\mu\text{m}/0.1 \mu\text{m}$), M_{12} (64 $\mu\text{m}/0.1 \mu\text{m}$), R_4 (300 Ω), and R_5 (300 Ω).

For wide operation bandwidth and flat conversion gain, a distributed transconductance stage design and high impedance compensation line are incorporated into the sub-harmonic Gilbert-cell design to compensate the parasitic capacitance of the CMOS transistor. The design strategies are referred in [6]. In addition, an embedded LO four-way quadrature divider using 90° coupler and 180° baluns was implemented in the CMOS technology [6] for MMW sub-harmonic Gilbert-cell mixer applications. A broad-side coupler is used as 90° coupler and a Marchand-type transformer is used as 180° baluns. The 90° coupler and 180° baluns are both calculated using the full-wave EM simulator (Sonnet software). The completed circuit of the Gilbert-cell mixer was simulated using Agilent ADS. Fig. 3 illustrates the chip photograph of the wideband CMOS sub-harmonic Gilbert-cell mixer. The chip size is $0.61 \times 0.58 \text{ mm}^2$.

III. MEASURED RESULTS

The performances of the mixer were measured via on-wafer probing. The output of the differential IF was connected to a spectrum analyzer (50- Ω load). At an RF frequency of 77 GHz and IF frequency of 100 MHz, the conversion gain is measured

 Fig. 3. Chip photo of the fully integrated sub-harmonic CMOS Gilbert-cell mixer with chip size of 0.61 mm $\times$ 0.58 mm.

Fig. 4. Simulated and measured conversion gain of the fully integrated sub-harmonic CMOS Gilbert-cell mixer from 10 to 110 GHz.

as a function of LO power. The conversion gain peaks at an LO power of 10 dBm. Fig. 4 plots the simulated and measured conversion gain versus RF frequency of the mixer from 10 to 110 GHz. The simulated performance of the mixer without the distributed design and high impedance compensation line is also included for comparison. The mixer has poor gain flatness (4.5 to -6 dB) from 30 to 100 GHz without distributed design and compensation line. With distributed design and high impedance compensation line, the flatness of conversion gain over broad bandwidth, from 30 to 100 GHz, can be achieved. The measured conversion gain is $-1.5 \pm 1.5 \text{ dB}$ from 30 to 100 GHz and the measured 3 dB bandwidth is 70 GHz. The simulated and measurement results have a good agreement. The measured IF output power versus swept RF input is shown in Fig. 5. The output 1 dB compression point of the mixer is -10.4 and -9.6 dBm at RF of 77 and 94 GHz, respectively. Provided an LO power of 10 dBm, the measured LO to RF and twice LO to RF isolation are better than 47 dB. The total dc power consumption of the mixer is 58 mW. Table I summarizes the performance of previously published CMOS wideband Gilbert-cell mixers for comparison [7]–[11]. The presented MMIC is believed to be the highest frequency CMOS Gilbert-cell mixer, up to 100 GHz, to date. The MMIC also

Fig. 5. Measured RF input power versus conversion gain and IF output power of the sub-harmonic CMOS Gilbert-cell mixer at 77 and 94 GHz.

TABLE I
REPORTED PERFORMANCES OF WIDE-BAND
GILBERT-CELL MIXERS IN CMOS PROCESS

Process	Circuit Topology	3-dB Bandwidth (GHz)	Conversion Gain (dB)	LO to RF Isolation (dB)	Chip Size (mm ²)	Power Consumption (mW)	Ref.
0.18- μ m CMOS	Fundamental Gilbert-cell	24.7 (0.3–25)	11 (dB)	>25 (LO to RF)	0.5	71	[7]
0.18- μ m CMOS	Fundamental Gilbert-cell	28 (2–30)	12.5 (± 1)	>37.5 (LO to RF)	0.71	40	[8]
0.13- μ m CMOS	Fundamental Gilbert-cell	1.4 (18.5–19.9)	1	>41 (LO to RF)	1.5	6.9	[9]
0.13- μ m CMOS	Fundamental Gilbert-cell	41 (9–50)	8.5 (± 3)	>20 (LO to RF)	0.25	97	[10]
0.13- μ m CMOS	Fundamental Gilbert-cell	8 (55–63)	1.5 (± 1.5)	>35 (LO to RF)	0.81	N/A	[11]
90-nm CMOS	Fundamental Gilbert-cell	50 (25–75)	3 (± 2)	>30 (LO to RF)	0.3	93	[5]
0.13- μ m CMOS	Sub-harmonic Gilbert-cell Demodulator	20 (35–65)	-7.5 (± 1.5)	>50 (2*LO to RF)	1.0 (Demodulator)	45.4 (Each Mixer)	[6]
90-nm CMOS	Sub-harmonic Gilbert-cell	70 (30–100)	-1.5 (± 1.5)	>47 (2*LO to RF)	0.35	58	This Work

achieves the widest 3 dB bandwidth and good conversion gain with a compact chip size.

IV. CONCLUSION

A 30–100 GHz wideband sub-harmonic Gilbert-cell mixer has been designed and fabricated using TSMC 90 nm CMOS

process. The sub-harmonically pumped scheme, distributed compensation line are introduced in this MMW mixer design. The MMIC exhibits -1.5 ± 1.5 dB measured conversion gain from 30 to 100 GHz with a miniature chip size of 0.35 mm^2 , transconductance stage design, and a high impedance. The measurement results demonstrate the potential of CMOS technology for sub-THz applications.

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