2.4/5.7 GHz Dual-Band High Linearity Gilbert Upconverter Utilizing Bias-Offset TCA and LC Current Combiner

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***Abstract*—A 2.4/5.7 GHz dual-band Gilbert upconversion mixer is demonstrated using 0.35 μm SiGe BiCMOS technology. A bias-offset cross-coupled transconductance amplifier (TCA) is employed in the intermediate frequency port for the linearity improvement. The dual-band LC current combiner and the output shunt-shunt feedback buffer amplifier are in the radio frequency (RF) port. The mechanisms of the high linearity upconverter and the design flow of the dual-band LC current combiner are established in this letter. The dual-band upconverter has conversion gain of 1.5/−0.2 dB, $\mathrm{OP}_{1\mathrm{dB}}$ of −10.5/−9 dBm, and OIP_3 of 12/13 dBm for IF=100 MHz, RF= 2.4/5.7 GHz, respectively.**

***Index Terms*—Dual-band, Gilbert mixer, LC current combiner, shunt–shunt feedback, SiGe heterojunction bipolar transistor (HBT), transconductance amplifier (TCA), WLAN.**

I. INTRODUCTION

FOR wireless communication systems, the current trend is toward multistandards/multiservices, and thus it brings multiband circuit design on a single chip, especially for dual-band WLAN applications. Traditionally, it can be procured by using a dual-band filter cascaded after radio frequency (RF) output stage at the cost of extra loss. In this letter, a dual-band upconversion mixer is demonstrated with a dual-band resonator load followed by the Gilbert mixer core to achieve both the operating frequencies of 2.4/5.7 GHz. Linearity is another important issue in communication systems, especially in transmitters. However, a conventional Gilbert mixer with emitter-coupled (source-coupled) pair input stage suffers from a poor linearity problem that OIP_3 is about 10 dB larger than $\mathrm{OP}_{1\ \mathrm{dB}}$ [1], [2] and therefore the signals of adjacent channels easily interfere with the desired channel. Many ideas are utilized to improve linearity. For example, multitanh approach [3] and class-AB transconductance [4] are designed to provide more linear transfer function of the transconductor by eliminating high order terms of the exponential function of bipolar transistors or the short channel effect of the metal oxide semiconductor (MOS) transistors. Feedback technique is also widely employed by severely suppressing high order distortion at the cost of gain [5], such as emitter degeneration.

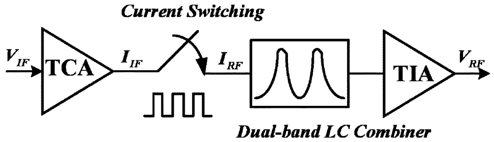

Fig. 1. Block diagram of the dual-band Gilbert upconverter.

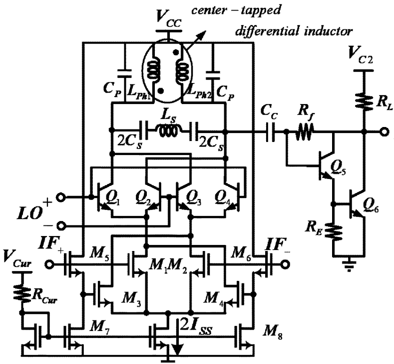

Fig. 2. Schematic of the SiGe BiCMOS dual-band Gilbert upconverter with the bias-offset cross-coupled TCA and dual-band LC current combiner.

The block diagram of the dual-band upconversion Gilbert mixer is illustrated in Fig. 1. A Gilbert mixer core is employed to commutate I_{IF} with local oscillation (LO) frequency to produce I_{RF} while I_{IF} is generated by a bias-offset TCA (transconductance amplifier) input stage. The differential I_{RF} current passes through the passive dual-band LC current combiner with extra gain improvement [6] and then a wideband transimpedance amplifier (TIA) translates the output current (I_{RF}) to the voltage signal (V_{RF}) and achieves output matching simultaneously.

The passive resonator and the Gilbert cell switching mechanism are both inherently linear. Thus, a bias-offset cross-coupled TCA with linear transfer characteristic [7] and a shunt-shunt feedback TIA with strong feedback factor are implemented in the intermediate frequency (IF) input port and RF output port for linearity improvement in this work. Consequently, the upconverter implemented in this letter has 22 dB difference between OIP_3 and $\mathrm{OP}_{1\ \mathrm{dB}}$. Furthermore, the dual-band LC current combiner is proposed and demonstrated for the first time to the best of our knowledge.

II. CIRCUIT DESIGN

The schematic of the 2.4/5.7 GHz dual-band SiGe BiCMOS Gilbert upconversion mixer is shown in Fig. 2. The upconverter in Fig. 2 consists of a SiGe HBT LO Gilbert mixer core

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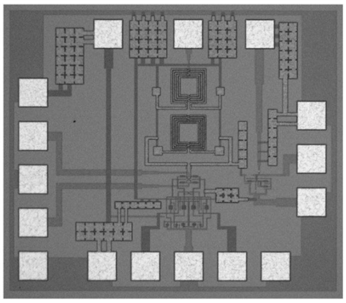

Fig. 3. Photograph of the SiGe BiCMOS dual-band Gilbert upconverter with the bias-offset cross-coupled TCA and dual-band LC current combiner.

$(Q_1, Q_2, Q_3$, and $Q_4)$, an IF bias-offset CMOS TCA $(M_1$-$M_4)$, and an RF output dual-band LC current combiner with a SiGe HBT TIA output buffer (Q_5 and Q_6).

The photograph of the dual-band upconverter is shown in Fig. 3. The die size is 1.13×0.97 mm^2. In the dual-band LC current combiner, a five-square-turn symmetric inductor (L_S) is 3 μm line width, 3 μm line spacing and outer diameter of 120 μm while a center-tapped symmetric differential inductor (consisting of L_{Ph1} and L_{Ph2}) is composed of a five-square-turn with line width, spacing and outer diameter of 4, 2.5, and 120 μm, respectively.

III. LINEARITY MECHANISMS OF THE GILBERT UPCONVERTER

An upconversion mixer is formed by a TCA, a current switching Gilbert core, a passive resonator and an output TIA. The current commutation is a highly linear process because it only translates the IF signal to the RF signal with every odd order LO frequencies while the passive resonator does not suffer from any nonlinear effect. Consequently, the input TCA and output TIA play important roles for the linearity issue. To achieve high linearity in this work, a bias-offset cross-coupled TCA is implemented in the IF port while the shunt-shunt feedback TIA is in the RF port.

The transconductance of the TCA equals to 2 kV_B [7] as long as the NMOS I-V characteristics is in the square-law long channel region, where k is the transconductance parameter of M_1-M_4 and V_B is the gate-source dc voltage drop of $M_5(M_6)$. The NMOS devices M_1-M_4 are biased at a small gate overdrive voltage and the gate lengths of the MOS transistors are 0.5 μm to mitigate the short channel effect. By ADS simulation, the output impedance of the dual-band resonator at resonant frequency of 2.4 and 5.7 GHz are both 120 Ω. A shunt-shunt feedback TIA is employed in the output stage to achieve output matching. A wideband TIA with the 3 dB bandwidth of 20 GHz is designed because strong feedback results in high linearity improvement. Passive matching output network is another choice for high linearity performance [8].

IV. ANALYSIS OF THE DUAL-BAND LC CURRENT COMBINER

The schematic of the Π-shaped dual-band LC current combiner is illustrated in Fig. 4. At low frequencies, the series branch is dominated by 1/jωC_S while the shunt branch is dominated by 1/jωL_P, here $L_P = L_{\mathrm{Ph1}} = L_{\mathrm{Ph2}}$. On the other hand, the series and shunt branches are dominated by $j\omega L_S$ and $j\omega C_P$ at high frequencies, respectively. Therefore, the Π-shaped dual-band LC current combiner can be treated implicitly as a combination of a low-frequency bandpass $(L_{\mathrm{Ph1}}, L_{\mathrm{Ph2}}$, and $C_S)$ resonator and a high-frequency bandpass (L_S, C_P) resonator as shown in Fig. 5.

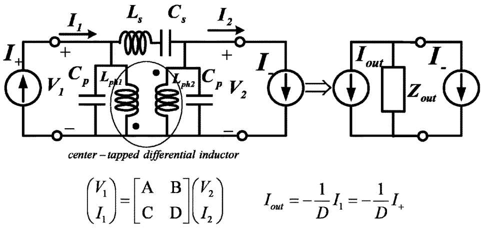

Fig. 4. Operational principle of the dual-band LC current combiner.

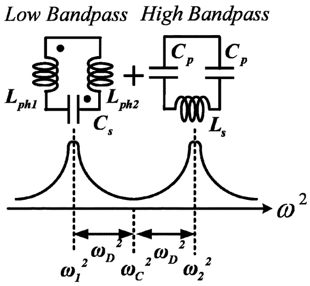

Fig. 5. Frequency response of a dual-band LC current combiner.

The combination of the LC current combiner and the current source I_+ can be represented by its Norton equivalence I_{out} and Z_{out} as shown in Fig. 4. The I_{out} can be related to the ABCD matrix elements of the dual-band LC current combiner.

When the element D of the ABCD matrix equals -1

$$\omega^4 L_P C_P L_S C_S - (L_P C_P + L_S C_S + 2L_P C_S)\omega^2 + 1 = 0. \quad (1)$$

$I_{\mathrm{out}} = I_+$ is achieved, and therefore the equivalent total output current doubles. The roots of (1) ω_1 and ω_2 are found as

$$\omega = \sqrt{\omega_C^2 \pm \omega_D^2} \quad (2)$$

where

$$\omega_C^2 \equiv \frac{\omega_1^2 + \omega_2^2}{2} = \frac{(L_P C_P + L_S C_S + 2L_P C_S)}{2L_P C_P L_S C_S} \quad (3)$$

$$\omega_D^2 \equiv \frac{\omega_2^2 - \omega_1^2}{2} = \frac{\sqrt{(L_P C_P + L_S C_S + 2L_P C_S)^2 - 4L_P C_P L_S C_S}}{2L_P C_P L_S C_S}. \quad (4)$$

The design procedure of the dual-band LC current combiner is as follows: a) Define the dual band frequencies ω_1 and ω_2, and thus the center frequency ω_C and difference frequency ω_D are specified by (3) and (4). b) Choose proper inductors (L_{S} and L_P) with high qualify factor at the desired frequencies. c) Calculate the value of C_S and C_P by known ω_C and ω_D.

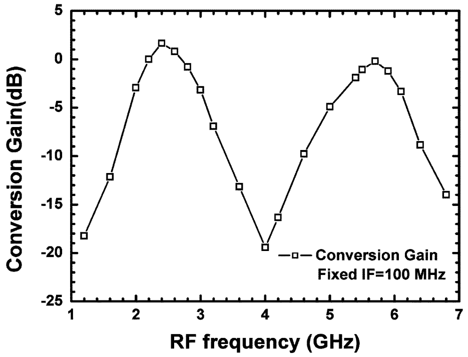

Fig. 6. RF frequency response of the SiGe BiCMOS dual-band Gilbert upconverter with the bias-offset cross-coupled TCA and dual-band LC current combiner.

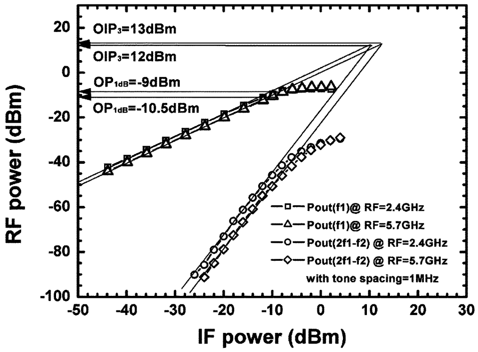

Fig. 7. Power performance of the SiGe BiCMOS dual-band Gilbert upconverter with the bias offset cross-coupled TCA and dual-band LC current combiner. The tone spacing is 1 MHz in two-tone power measurement.

In this work, the two desired frequencies are 2.4 and 5.7 GHz. As a result, the designed values of L_S, L_P, C_S, and C_{P} are 4.6 nH, 2.1 nH, 0.4 pF, and 0.88 pF, respectively. The relation of $L_P C_P = L_S C_S$ is chosen for a simple design condition.

V. MEASUREMENT RESULTS

The SiGe BiCMOS 2.4/5.7 GHz dual-band upconverter facilitates on-wafer rf measurements. The supply voltage is 3.5 V and the current consumption of the mixer core with the common-drain-configured M_5 and M_6 input buffers is 6.95 mA.

In Fig. 6, the measured peak conversion gain at 2.4 GHz and 5.7 GHz is 1.5 and -0.2 dB, respectively, with 3 dB bandwidth of 750 MHz when LO pumping power is -5 dBm. The measured conversion gain varies within 1 dB when LO power changes from -12 dBm to 4 dBm with RF$=$ 2.4 GHz, LO$=$ 2.3 GHz and IF $=$ 100 MHz while it changes from -6 dBm to 5 dBm with RF $=$ 5.7 GHz, LO $=$ 5.6 GHz and IF $=$ 100 MHz. The output RF return loss is better than 13 dB at both 2.4/5.7 GHz. The power performance of the dual-band upconverter is illustrated in Fig. 7. It has $\mathrm{OP}_{1\ \mathrm{dB}}$ of $-10.5/-9$ dBm, and OIP_3 of 12/13 dBm when input IF$=$ 100 MHz, RF $=$ 2.4 and 5.7 GHz, respectively. The measured LO–RF isolation is 38/43 dB when LO $=$ 2.3 and 5.6 GHz, respectively.

TABLE I
COMPARISON OF THE UP-CONVERSION GILBERT MIXERS

	This Work	Ref[1]	Ref[2]	Ref[6]	Ref[9]
RF (GHz)	2.4/5.7	5.8	19-31	5.2	5.2
Gain (dB)	1.5/-0.2	-2.9	-0.8	1	-1
LO-RF Isolation (dB)	38/43	NR	NR	38	39
$\mathrm{OP}_{1\mathrm{dB}}$ (dBm)	-10.5/-9	-3.4	-8.6	-10	-10
OIP_3 (dBm)	12/13	4.6	1.4	2	6
Supply Voltage (V)	3.5	V_{EE}= -2.7	3.3	5	3.3
Power Consumtion (mW)	45	40.5	38	32.5	37.95
Technology	0.35μm SiGe HBT	0.8μm SiGe HBT	0.18μm SiGe HBT (f_t=150GHz)	2μm GaInP/ GaAs HBT	0.35μm SiGe HBT

The difference between OIP_3 and $\mathrm{OP}_{1\ \mathrm{dB}}$ can be used to indicate the linearity and our work shows excellent linearity of 22 dB difference between OIP_3 and $\mathrm{OP}_{1\ \mathrm{dB}}$. The state-of-the-art Gilbert upconverters are summarized in Table I [1], [2], [6], [9] for performance comparison purpose.

VI. CONCLUSION

A 2.4/5.7 GHz dual-band high linearity Gilbert upconverter is demonstrated using 0.35 μm SiGe BiCMOS technology. The input TCA and output TIA dominate the linearity performance of the whole mixer. Hence, a bias-offset cross-coupled TCA and the shunt-shunt feedback buffer are utilized in IF and RF port, respectively. The dual-band upconvesion mixer has conversion gain of $1.5/-0.2$ dB, $\mathrm{OP}_{1\ \mathrm{dB}}$ of $-10.5/-9$ dBm, and OIP_3 of 12/13 dBm for IF$=$ 100 MHz, RF$=$ 2.4 and 5.7 GHz, respectively.

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