A *K*a-Band Sub-harmonically Pumped Mixer Using Diode-Connected MOSFET for 5G mm-Wave Transceivers

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***Abstract* — A *K*a-band (27~40-GHz) sub-harmonically pumped mixer (SPM) fabricated in 180-nm CMOS technology is demonstrated for 5G mm-wave transceivers in this paper. The proposed SPM is composed of anti-parallel gate-source connected FET diode pair (APDP). The SPM measuring 0.48 mm^2 demonstrates a conversion-gain response of -16.8 ~ -12.4 dB for both up- and down-conversion over 27~40 GHz, the required LO frequency from 13.5 to 20 GHz, and a high 2LO-to-RF isolation of 60 ~ 80 dB.**

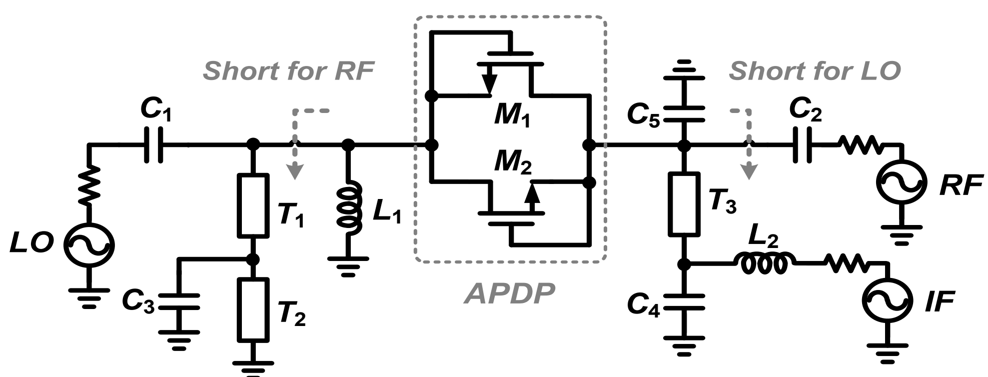
Index Terms — Ka-band, CMOS, APDP, diode-connected, SPM, subharmonic mixer, up/down-converter, 5G

I. Introduction

In light of the tremendous data demand in 5G wireless communications, millimeter-wave (mm-wave) technology has been spotlighted. The candidate frequency bands ranging from 24.25 GHz to 86 GHz attracts much attention [1]. In mm-wave communication systems, mixers play a vital role in frequency conversion by utilizing the nonlinear behavior of transistors. With the need for higher carrier frequency, the design of a local oscillator (LO) becomes a rigorous issue in terms of poor noise performance and low output power. Therefore, a sub-harmonically pumped mixer (SPM), where only half the required LO frequency of a common mixer is needed, manifests itself outstandingly in the mm-wave region. In reality, it combines both the function of a frequency multiplier and of a mixer.

For a direct-converted transceiver, LO-to-RF/IF isolation is highly significant. An SPM has no concern about the LO leakage since the LO leaking tone is far away from the user band. However, some SPM topologies fail to provide a good elimination of 2LO signal, still making the output band suffer from carrier interference. Therefore, The anti-parallel diode pair (APDP) is a prime candidate for SPMs, since it has a complete suppression of even harmonics (i.e., a perfect 2LO-to-RF/IF isolation). Moreover, APDP-SPM is inherently a bilateral frequency converter, which can act as both up- and down-converter. Such bilateral feature is enchanting, making the design of an mm-wave transceiver illustrated in Fig. 1 much easier to implement.

Most of the APDP-SPM designs take place in III-V technologies, e.g., GaAs MESFET, pHEMT, as a result of the existence of Schottky diodes [2]-[7]. With the trend towards 5G communication, Si-based CMOS process would be



	W(μm)	L(μm)
T_1	29	420
T_2	14	600
T_3	16	540

C_1	C_2	C_3	C_4	C_5	L_1	L_2	$M_{1,2}$
1pF	1pF	405fF	693fF	220fF	0.65nH	0.2nH	112/0.18

Fig. 2. *K*a-band subharmonically pumped mixer (SPM) using gate-source connected APDP.

favourable for low-cost SoC applications in contrast to III-V technologies. Whereas, for lack of diode models from the foundry, APDP-SPM is difficult to realize in CMOS process. Recently, much effort has been made to introduce diodes into CMOS process. A 10-40-GHz SPM is fabricated in CMOS process with Wilkinson power combiner and APDP [8]. Another APDP-SPM design is based on Schottky diodes made with cobalt-silicon Schottky contacts [9]. This design sheds light on diode implementation in CMOS process. However, this method requires additional testing and building of the diode models.

This paper presents a *K*a-band (27~40-GHz) APDP-SPM core using gate-source connected FETs. With the simple gate-source connection, we can transplant diode into CMOS process and make the APDP-SPM a reality. The proposed SPM is fabricated in 180-nm CMOS technology, exhibiting a low-cost solution for 5G applications. This paper is organized as follows. Section II describes the design of the proposed APDP-SPM. Section III presents the measured and simulated results for up-conversion. Section IV summarizes the results of this design.

II. Circuit Design

For an APDP core as illustrated in Fig. 2, its conductance is given by [2],

$$g_T = 2\alpha I_0 \cosh \alpha V = \frac{2qI_0}{nKT} \cosh \alpha V \tag{1}$$

where n denotes the ideality factor, α is the diode slope parameter, V is decided mainly by LO signal, since IF/RF signal is comparatively small-signal. The total conductance as expressed in (1) is proportional to conversion gain (CG) of a mixer, revealing that we can improve the conversion gain by selecting a low-n diode. With the foundry model, we observe that the gate-source connected FET with n of 1.3 outstrips the gate-drain connected one, which is on the other hand with n of 1.6. Thus, the gate-source connected FET as a diode is adopted for the further SHP design.

The conventional configuration of an APDP-SPM entails 2 transmission lines of both $\lambda_{LO}/4$ connected as short and open stub respectively, to provide an ideal ground for RF and for LO signal. However, such arrangement occupies a large area and the quarter-wave transmission line imposes a restriction on the bandwidth. To overcome these issues, quasi-lumped $\lambda_{LO}/4$ short stub and open stub have been proposed [4]. With the help of lump capacitors, quasi-lumped $\lambda_{LO}/4$ stubs save the area effectively, since the capacitor can be realized by on-chip MIM capacitors, which occupy less space than bulky lines do. In this design, the RF center frequency is set at around 28 GHz for *K*a-band applications, where Thus $\lambda_{LO}/4$ is about 1380 μm. Fig. 2 illustrates the circuit schematic and all the design parameters. The quasi-lumped $\lambda_{LO}/4$ short stub and the quasi-lumped $\lambda_{LO}/4$ open stub substitute for the original 1380-μm stub with a reduced length of 1020 μm (T_1+T_2) and 540 μm (T_3) respectively. Nevertheless, it is worth noting that the tradeoff exists since the small capacitance has PVT variation, which likely leads to inaccuracy in the measured frequency band.

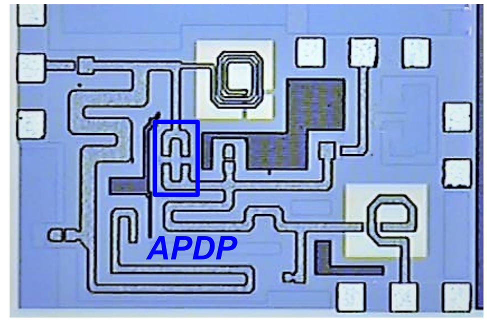


Fig. 3. Chip micrograph of the fabricated APDP-SPM.

III. Experimental Results

A *K*a-band APDP-SPM using diode-connected FET has been fabricated in 180-nm CMOS technology. Fig. 3 shows the die photo, which measures 0.80 × 0.60 mm^2 including pads. The chip is characterized using wafer probing.

As shown in Fig. 4, the measured 2LO-to-RF isolation is higher than 60 dB over the desired band of 27 ~ 40 GHz, proving the advantage of APDP-SPM. Fig. 5 illustrates the CG of this APDP-SPM at up-converted mode. According to Fig. 5(a), we are able to determine the LO power needed for the entire measurement, which is about 4 ~ 6 dBm for desired LO-frequency (e.g. 14 and 16 GHz). Fig. 5(b) shows the conversion gain versus RF frequency. The conversion gain varies from -16.8 to -12.4 dB, where the lowest position is at 27 GHz. Here the LO frequency (f_{LO}) is sweeping from 13.5 to 20 GHz. Therefore, the RF frequency ($2f_{LO}$+f_{IF}) due to second-harmonic pumping is from 27.1 GHz to 40.1 GHz with a fixed IF frequency (f_{IF}) of 0.1 GHz. Fig. 5(c) shows the CG over IF power. The measurement results demonstrate that the P_{1dB} is about -5 dBm and OP_{1dB} is about -20 dBm.

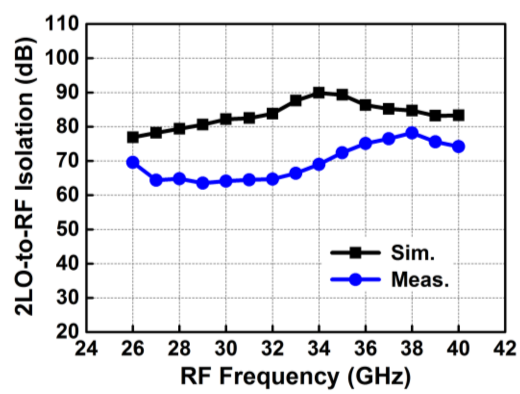


Fig. 4. Measured and simulated 2LO-to-RF isolation of the Ka-band APDP-SPM.

IV. Conclusion

A *K*a-band APDP-SPM has been implemented in 180-nm CMOS technology. It can be employed for both up- and down-conversion, which is suitable for 5G mm-wave transceivers. The performances of this work are summarized and compared with those of the previous works in TABLE I. This work achieves a premium 2LO-to-IF/RF isolation of up to 80 dB and a moderate LO driving power of 6 dBm, making the low-cost APDP-SPM realizable.

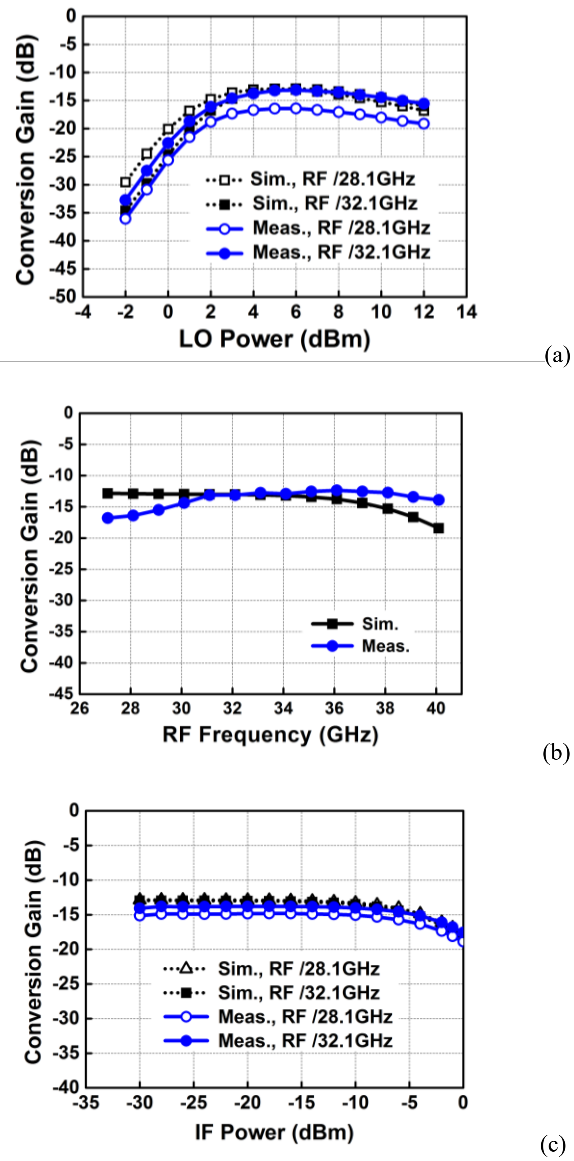


Fig. 5. (a) Measured and simulated CG of the Ka-band APDP-SPM versus LO power. (b) Measured and simulated CG versus RF frequency. (c) Measured and simulated CG versus IF power. (For up-conversion, IF frequency is fixed at 0.1 GHz, LO power is 6 dBm.)

TABLE I
Comparison of Reported APDP-SPMs

Ref.	Technology	RF frequency (GHz)	LO power (dBm)	CG (dB)	2LO-to-RF/IF Isolation (dB)	OP_{1dB} (dBm)
[3]	GaAs	36 ~ 40	6	-10.6~ -9.5	75	-15.7
[4]	0.3-μm GaAs MESFET	20 ~ 30.6	8	-13.1~ -11.7	N/A	-10.9
[5]	0.15-μm GaAs pHEMT	50 ~ 70	6	-18~ -11	34*	-15
[6]**	180-nm CMOS	10 ~ 40	8	-17.6~ -15.6	<40 (sim.)	-8.6
[7]	180-nm CMOS	50 ~ 70**	1	-15	60 ~ 65	-21
		57 ~ 65	1	-2***	65 ~ 70	-17
[8]	InGaAs pHEMT	23 ~ 37	13	-12 ~ -9.4	22	-6
[9]	0.15-μm GaAs pHEMT	24 ~ 44	11	6 ~ 10.5***	48.4 ~ 65	-11.5
This Work	180-nm CMOS	27 ~ 40 (up-conv.)	6	-16.8~ -12.4	60 ~ 80	-20
		27.1~40.1 (down-conv.)	6	-15.8~-14.6		-15.7 ~ -14.6

* Calculated from its spectrum.
** For down-conversion.
*** With IF or with RF buffer.

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