A Miniature 25-GHz 9-dB CMOS Cascaded Single-Stage Distributed Amplifier

Ming-Da Tsai, *Student Member, IEEE*, Kuo-Liang Deng, Huei Wang, *Senior Member, IEEE*, Chun-Hung Chen, Chih-Sheng Chang, and John G. J. Chern

Abstract—A 25-GHz complementary metal oxide semiconductor (CMOS) cascaded single-stage distributed amplifier (CSSDA) using standard 0.18- μm CMOS technology is presented in this letter. It demonstrates the highest gain-bandwidth product (GBP) with smallest chip area reported for a fully-integrated CMOS wideband amplifier using a standard Si-based integrated circuit process. The chip size including testing pads is only 0.36 mm², and the ratio of GBP to chip size achieves 552 GHz/mm². This circuit is the first CSSDA realized in CMOS technology, and represents state-of-the-art performances.

Index Terms—Complementary metal oxide semiconductor (CMOS), distributed amplifier, helical inductor, microwave monolithic integrated circuit (MMIC).

I. INTRODUCTION

DISTRIBUTED circuits can defy some of the performance trade-offs in conventional circuits by taking advantage of multiple parallel signal paths. A distributed amplifier has a more relaxed gain-bandwidth trade-off than a conventional amplifier since the parasitic capacitances of the transistor are absorbed into the transmission lines or the LC ladder filter to become part of the passive network. Table I summarizes the recently reported performances of complementary metal oxide semiconductor (CMOS) broadband amplifiers compared with this work [1]–[9]. Using the 0.6- μm CMOS process, a fully integrated DA using on-chip planar spiral inductors achieves a measured pass-band gain of 6.1 dB with 5.5-GHz unity-gain bandwidth [1]. On the other hand, a fully differential DA achieves 5.5-dB pass-band gain and 8.5-GHz unity gain bandwidth [2]. Using a silicon-on-sapphire (SOS) n-type metal oxide semiconductor field effect transistor (n-MOSFET) process to avoid the substrate loss, a DA with a bandwidth of 10 GHz and 5-dB gain was demonstrated in a 0.5- μm SOS n-MOSFET (NMOS) process [3]. For DAs using 0.18- μm CMOS process, a three stage DA designed with coplanar strip

lines demonstrated a low frequency gain of 5 dB, sloping down to 1 dB at 15 GHz [4], two DAs using high impedance coplanar waveguides as inductive elements demonstrated 8 and 10-dB gain up to 10 GHz, respectively [5], and DAs of 14-GHz and 22-GHz bandwidth were also demonstrated in [6], [7]. The highest operation frequency of DA using 100-GHz f_{MAX} 0.18- μm CMOS technology based on modified source degeneration (parallel RC network) achieved 4-dB gain and 39-GHz bandwidth [8], and a 27-GHz CPW 0.18- μm CMOS DA had a measured gain of 6 dB [9]. A fully integrated conventional DA, however, suffers the disadvantage of huge chip size. Another type of distributed circuit called cascaded single-stage distributed amplifier (CSSDA) in CMOS technology were also presented their simulation results but no measurement data were demonstrated [10], [11]. A CSSDA with huge chip size has also been proposed to achieve wide bandwidth and realized in GaAs HEMTs or hybrid circuits [12], [13].

In this letter, a miniature CSSDA based on cascade configuration and monolithic helical inductors using a commercial CMOS process is first demonstrated. The gain-bandwidth product of our miniature chip is believed to be the highest among the recently published results for CMOS distributed amplifiers. The chip size including testing pads is only 0.75×0.48 mm, and the ratio of GBP to chip size achieves 552 GHz/mm². This circuit is the first CSSDA realized in CMOS technology, and represents state-of-the-art performances.

II. CIRCUIT DESIGN AND FABRICATION

In the design of wideband distributed amplifiers, artificial transmission lines can be realized by multiover LC ladder network. In conjunction with active devices connected in parallel, the parasitic capacitance of active devices is absorbed into the LC ladder network. The inductor can be realized with transmission lines or spiral inductors [1]–[9]. However, the drawback is large die size. In order to reduce chip size, the inductance of the artificial transmission line is realized with helical inductors. Helical inductor occupies less chip area than that of planar spiral since the turn is expanded vertically as shown in Fig. 1(a). Usually, top metal is thicker than the lower metal layers, and thus Q -factor of helical inductor would be lower than that of planar spiral inductor. However, the area occupation of helical inductor is much smaller. Furthermore, smaller area gives smaller substrate loss, so only little performance degradation of the helical inductor over the planar spiral inductor in circuit is prospective [14]. For example, a 2-nH of helical inductor can achieve peak quality factor of eight at 5 GHz and self-resonance frequency of 16 GHz [15].

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M.-D. Tsai and H. Wang are with the Department of Electrical Engineering and Graduate Institute of Communication Engineering, National Taiwan University, Taipei 10617, Taiwan, R.O.C. (e-mail: r90042@ew.ee.ntu.edu.tw; huei-wang@ew.ee.ntu.edu.tw).

K.-L. Deng was with the Department of Electrical Engineering and Graduate Institute of Communication Engineering, National Taiwan University, Taipei 10617, Taiwan, R.O.C., and he is now with Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan, R.O.C.

C.-H. Chen, C.-S. Chang, and J. G. J. Chern are with the Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan, R.O.C.

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TABLE I
RECENTLY REPORTED PERFORMANCE OF CMOS DISTRIBUTED AMPLIFIER. SOS: SILICON-ON-SAPPHIRE. CPW: COPLANAR WAVEGUIDE.
CPS: COPLANAR STRIP LINES. CC: CASCODE CONFIGURATION. DC BIAS USING BIAS-T

Process	Bandwidth (GHz)	Gain (dB)	Chip Area (mm ²)	GBP (GHz)	GBP/ ChipArea (GHz/mm ²)	Unit Gain Freq. (GHz)	P _{DC} (mW)	Chip Features	Ref.
0.6 μ m CMOS	4	6.5	1.12	18	16	5.5	83.4	Spiral inductors	[1]
0.6 μ m CMOS	7.5	5.5	2.86	27	9	8.5	216	Fully differential, Spiral inductors	[2]
0.5 μ m SOS MOS	10	5	-	-	-	-	-	CPW	[3]
0.18 μ m CMOS	-	5	0.45	-	-	23	90*	CPS	[4]
0.18 μ m CMOS	10	8	2.34	63	27	-	-	Darlington CC., CPW	[5]
0.18 μ m CMOS	22	7.3	1.35	118	88	24	52*	CC., Spiral inductors	[6]
0.18 μ m CMOS	14	10.6	1.6	161	100	18.5	52*	CC., Spiral inductors	[7]
0.18 μ m CMOS	39	4	3.3	98	30	39	140	RC degeneration, Microstrip line	[8]
0.18 μ m CMOS	27	6	1.62	107	66	29	68	CC., CPW	[9]
0.18 μ m CMOS	25	9	0.36	199	552	28	60	CSSDA CC., Helical inductors	This work

Fig. 1. (a) Cross-sectional view of helical inductor. (b) Simplified circuit schematic of cascaded single-stage distributed amplifier (CSSDA).

The schematic of the CMOS CSSDA is shown in Fig. 1(b). It consists of an input, output, and interstage transmission lines formed by using lumped helical inductors, coupled through the transconductance of the MOSFETs. The intrinsic gate and drain resistance (R_{ds}) would increase the loss of the artificial transmission line and thus degrade the gain and bandwidth. In this study, the cascade configuration is used for the gain cells. The cascade gain cell can increase the drain resistance and reduce the loading in transmission line, also has higher maximum available gain compared to a common-source FET. The cascade devices of this design employ a 20- Ω damping resistor in the gate of common-gate transistor to improve the high frequency stability.

Since the characteristic impedance of the inter-stage artificial transmission line (Z_{0int}) can be different from the input and output impedance, it shows that the gain can be increased by the gate voltage of the inter-stage transmission line with increasing Z_{0int} [12]. With the target gain and bandwidth, the increasing

Fig. 2. Measured small signal gain and I/O return losses.

Z_{0int} also can reduce the required gain stages and reduce chip area.

In this circuit, only two stages are used. The helical inductors were simulated with a full-wave EM simulator to ensure the model accuracy. The MMIC micrograph is shown in Fig. 4 with a chip size of 0.36 mm² including testing pads. The chip is fabricated by TSMCs 0.18- μ m MS/RF technology [16], [17], with a 2- μ m AlCu top metal layer. The substrate conductivity is approximately 10 S/m. With optimized CMOS technology and deep n-well, this technology provides a f_T and f_{max} of better than 60 and 55 GHz, respectively.

III. EXPERIMENTAL RESULTS

The CMOS CSSDA chip was tested via on-wafer probing. Fig. 2 shows the measured gain ($|S_{21}|$), and return losses ($|S_{11}|$ and $|S_{22}|$). The power gain is about 9 dB with a 3-dB frequency

Fig. 3. Measured group delay.

Fig. 4. Microphotograph of the CMOS CSSDA with a chip size of 0.75×0.48 mm (including testing pads).

band up to 25 GHz, and return losses are better than 8 dB. The measured S -parameters results agree with the simulated results reasonably. The measured group delay, as shown in Fig. 3, is about 45 ps with variation of 30 ps from 1 to 20 GHz. The measured output P_1 dB is -0.5 dBm at 10 GHz. The two-tone test result shows that the output IP3 is about 8 dBm at 10 GHz. The supply voltage is 3.5 V and consumes 17 mA. Although the dc bias current goes through termination resistors, the total power consumption (60 mW) is still comparable with those of the reported DAs using bias-T to supply drain voltages [4], [6], [7]. The overall performance rivals the recently published results reported for CMOS distributed amplifiers.

IV. CONCLUSION

A fully integrated CSSDA has been designed, fabricated and tested. This CMOS CSSDA demonstrated 9-dB gain and

25-GHz bandwidth, which indicates the highest gain-bandwidth product of reported to date for broadband CMOS amplifiers. The highest gain-bandwidth product is also achieved in only 0.36 mm^2 chip area. This amplifier has potential for the signal amplification for the receiver in the optical communication application. Since this CSSDA was fabricated using a commercial $0.18\text{-}\mu\text{m}$ CMOS technology, it can be easily integrated with other front-end circuits to build CMOS transceivers without requiring any additional masks or post-processing steps.

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