Research Advances in Silicon Based Millimeter and Sub-millimeter Wave Integrated Circuits

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***Abstract*- As the rapid development of silicon based process, it could be predicted that the silicon based integrated circuits will be practicable over millimeter wave band and partially applicable in submillimeter or terahertz band in recent years. In this paper, we will summarily review the new progress in the State Key Laboratory of Millimeter Waves, including various kind of CMOS based millimeter wave band active circuits and submillimeter wave band passive components. These ICs have been achieved under the support from National Basic Research Program ("973" Program) of China.**

I. INTRODUCTION

With the rapid development of commercial wireless communication system, the "golden spectrum" below several GHz is now crowded with various applications, such as mobile communication application, wireless access and wireless internet application. In recent years, the research focus has paid more attention to higher frequency band especially millimeter wave frequency band, since it has much more spectrum resources, which can also support very high speed wireless communications. Although the millimeter frequency up to 300GHz has been planned over world, it is still under development for many applications. Silicon based design of millimeter wave devices could be the most powerful way to explore the millimeter wave spectrum.

The frequency of CMOS devices is increasing rapidly, and even entering sub-millimeter frequency band now [1-3]. Table I shows the predicted RF/analog CMOS evolution map provided by International Technology Roadmap for Semiconductors (ITRS) [4]. In the next 10 years, the gate length of CMOS will scale down to 10nm, the characteristic frequency will approach 1 THz.

TABLE I
ITRS ROADMAP OF RF/ANALOG CMOS

Year	*2011*	*2012*	*2013*	*2014*	2015	2016	2017	2018	2019	2020
Gate Length (nm)	28	25	22	20	18	16	14	13	12	11
F_t (GHz)	320	360	400	440	490	550	630	670	730	790
F_{max} (GHz)	390	440	510	560	630	710	820	880	960	1050

With the advances of silicon process, the continuous decrease of gate length has compensated the effect of slow electron mobility, making the working frequency of CMOS devices increase continuously. At the same time, the silicon based circuit has reasonable noise performance and power capacity, it is expected that silicon based RF circuit will be suitable for small power and non-critical commercial millimeter wave applications. For example, a 140GHz CMOS receiver is reported by Toronto University [5] in 2008. A fully integrated transceiver with base band circuits is reported by University California Beckley using 90nm CMOS process in 2008 [6], with data rate over 4Gbps. Another CMOS transceiver at 60GHz is reported by Taiwan University, with date rate of 2.5Gbps [7]. By using silicon, the RF and base band could be integrated and thus decrease the system cost dramatically.

In China mainland, the research works on silicon based millimeter wave circuits are also on rapid progress. In the last 2 years, the state key lab of millimeter waves have developed several kind of CMOS based millimeter wave circuits at Q/V/W band, such as amplifiers, mixers, doublers and voltage controlled oscillators, and also designed several silicon based sub-millimeter wave passive components over 300GHz such as filters and antennas. In this presentation, we will summarily review our recent research advances in silicon based millimeter and sub-millimeter wave integrated circuits.

II. CMOS BASED MILLIMETER WAVE CIRCUITS

A. Millimeter Wave CMOS Amplifiers

Based on IBM 90nm CMOS, several amplifiers are designed and fabricated. The circuit topologies used in these amplifiers are common source and cascade structure.

Figure 1 shows the photo of a three stage CMOS low noise amplifier using common source structure. The measured gain is more than 15dB at 48~60GHz. The simulated noise figure is 4dB.

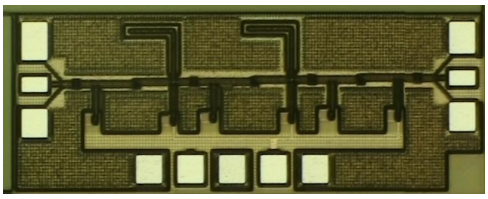


Figure 1. Photo of a CMOS three stage low noise amplifier.

Figure 2 shows a three stage CMOS small power amplifier using the same structure. The measured gain is more than 15dB at 45~54GHz, and output 1dB compression point of 8dBm.

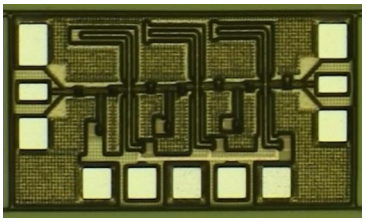


Figure 2. Photo of a CMOS three stage small power amplifier.

Figure 3 and Figure 4 show two CMOS small power amplifiers base on cascode structure. Figure 3 is a two stage amplifier with measured gain of more than 10dB at 40~60GHz, and output 1dB compression point of 7dBm. Figure 4 is a three stage amplifier with measured gain of more than 20dB at 45~56GHz, and output 1dB compression point of 9dBm.

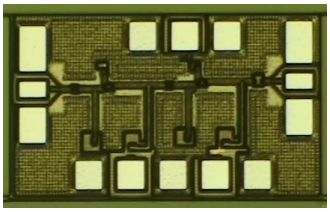


Figure 3. Photo of a CMOS two stage small power cascode amplifier.

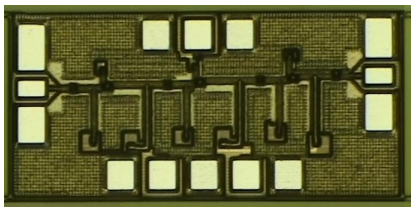


Figure 4. Photo of a CMOS three stage small power cascode amplifier.

Figure 5 and Figure 6 show two compact CMOS high gain amplifiers using cascode structure. The layout is optimized to get minimum chip size. Figure 5 is a two stage amplifier with measured gain of more than 15dB at 45~52GHz. Figure 6 is a three stage amplifier with measured gain of more than 20dB at 45~60GHz, and the peak gain is more than 25dB.

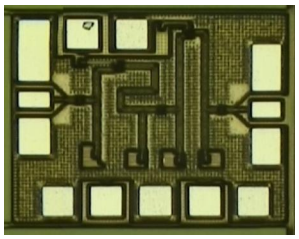


Figure 5. Photo of a CMOS two stage high gain cascode amplifier.

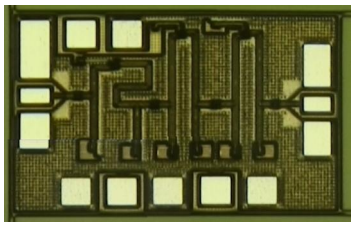


Figure 6. Photo of a CMOS three stage high gain cascode amplifier.

Figure 7 to Figure 9 are W band CMOS amplifiers, in which Figure 7 is a two stage cascode amplifier with measured gain of more than 5dB at 90~107GHz, Figure 8 and Figure 9 are two stage and three stage common source amplifier with measured gain of more than 5dB at 90~106GHz and 10dB at 95~102GHz respectively.

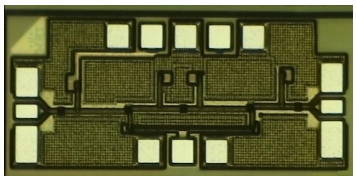


Figure 7. Photo of a W band CMOS cascode amplifier.

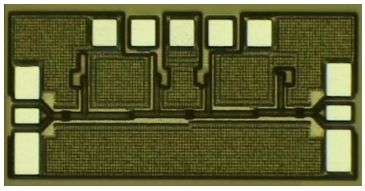


Figure 8. Photo of a W band CMOS two stage amplifier.

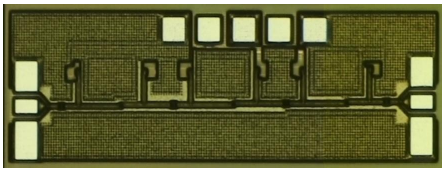


Figure 9. Photo of a W band CMOS three stage amplifier.

B. Millimeter Wave CMOS Mixers and Doublers

Based on IBM 90nm CMOS, several mixers are designed and fabricated, including fundamental and sub-harmonic mixers. And two doublers are also designed using IBM 90nm CMOS.

Figure 10 and Figure 11 are CMOS fundamental mixers with conversion loss less than 10dB at V band (50~75GHz),

and less than 14dB at W band (75~100GHz). These two mixers employ resistive mixing structure.

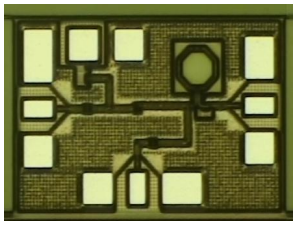


Figure 10. Photo of a V band CMOS mixer.

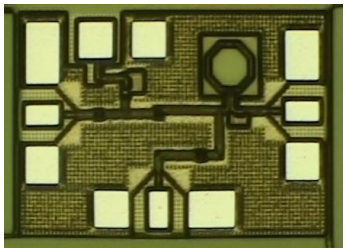


Figure 11. Photo of a W band CMOS mixer.

Figure 12 and Figure 13 are CMOS sub-harmonic mixer with conversion loss less than 15dB at V band (50~75GHz).

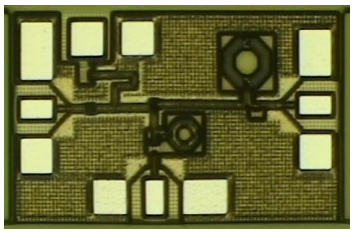


Figure 12. Photo of a V band sub-harmonic CMOS mixer Type A.

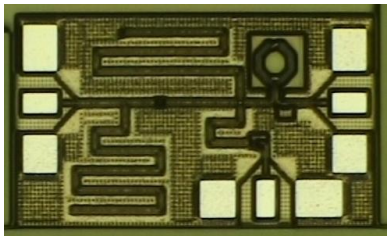


Figure 13. Photo of a V band sub-harmonic CMOS mixer Type B.

Figure 14 and Figure 15 are two doublers base on IBM 90nm CMOS, with measured conversion loss of less than 8.5dB and 11dB, respectively at 50~70GHz.

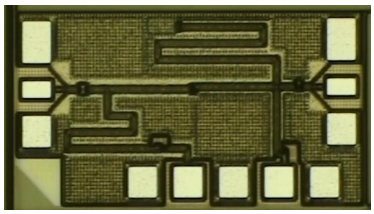


Figure 14. Photo of a V band CMOS doubler Type A.

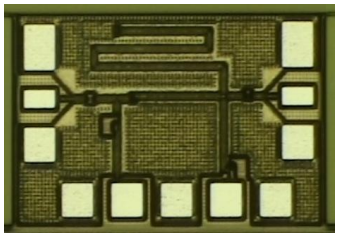


Figure 15. Photo of a V band CMOS doubler Tpye B.

C. *Millimeter Wave Oscillators*

Based on IBM 130nm CMOS, two voltage controlled oscillators are designed and fabricated. Cross-coupled transistor is used as oscillator core. Inductor and tunable capacitor is used as tuning circuit of VCO.

Figure 16 is a V band CMOS VCO designed using push-push structure. The tuning range is 59-69GHz, output power is -10dBm, and the phase noise is -103dBc@10MHz offset.

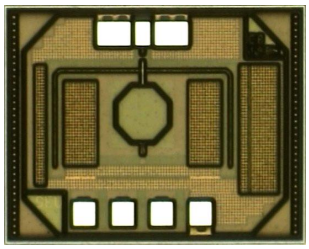


Figure 16. Photo of a V band CMOS VCO.

Figure 17 is a W band CMOS VCO using the same structure. The tuning range is 93-104GHz, output power is -20dBm, and the phase noise is -93dBc@10MHz offset.

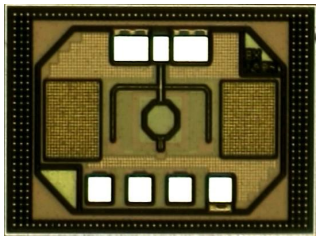
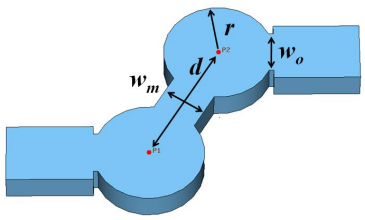


Figure 17. Photo of a W band CMOS VCO.

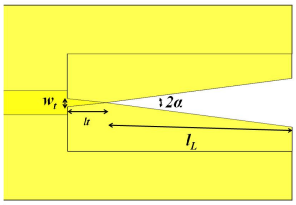
III. Silicon Based Sub-millimeter Wave Circuits

A. *Sub-millimeter Wave Antenna and Filter on MEMs*

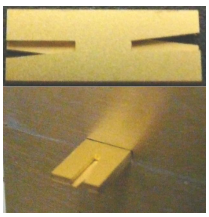
A silicon based bandpass filter over 300GHz is designed and fabricated on MEMs process. It is based on Substrate Integrated Waveguide (SIW) structure [8]. A pair of antipodal linearly tapered slot Antennas (ALTSA) is designed and fabricated with MEMS process, as shown in Figure18. A prototype with passband range 350GHz~370GHz is measured by using a quasi-optic measurement system. The measured data is in agreement with the simulated results, which show the good selection performance and verified the wideband characteristic of the ALTSAs.



(a)



(b)



(c)

Figure 18. Structure of Silicon Based THz Antenna and Filter on MEMS. a. Filter topology, b. ALTSA antenna port, c. Photo of fabricated chip.

B. Sub-millimeter Wave Filter on CMOS

A novel sub-millimeter wave filter is designed based on IBM 130nm CMOS process. It is also a SIW bandpass filter. For the convenience of measurement, two multisection impedance transformers have been designed to transform the SIW cavity to microstrip, as shown in Figure 19.

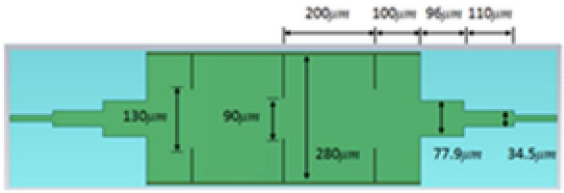


Figure 19. Photo of a CMOS SIW filter.

The cavity of SIW is designed using the thick dielectric layers on the of process structure, in which the top and bottom plane is utilized by cutting slots in the thick metal layer, in order to fulfill the requirements of design rule. The cavities and filter are optimized with the process parameters. The filter is designed at center frequency on 400GHz. This chip is in measurement now.

IV. Conclusions and Acknowledgment

In this presentation, we summarily review the recent advances in silicon based millimeter wave active ICs and sub-millimeter wave passive ICs developed in state key lab of millimeter waves, Southeast University, China. Details of individual designs will be published on research papers.

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