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A Highly-Efficient 120 GHz and 240 GHz Signal Source in A SiGe-Technology

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***Abstract*—This work presents a highly-efficient signal source for radar applications at 120 GHz and 240 GHz in a 130-nm SiGe-technology. A low DC-Power consumption of only 78 mW – respectively 264 mW is needed to provide as much as 7.1 dBm (7 dBm) output power at RF-frequencies. The resulting DC-to-RF efficiency is 6.58 (1.88) %. For the signal generation, a Colpitts VCO followed by a bootstrapped gilbert doubler and two power amplifier stages are used at a supply voltage of 3.3 V. The used technology offers new HBTs with an f_t of around 470 GHz and f_{max} of 700 GHz. For the use in radar applications, the VCO frequency can be swept with a bandwidth of 16.3 GHz, while the center frequency can be adjusted using laser-fuses.**

***Index Terms*—VCO, frequency doubler, power amplifier, signal source, SiGe BiCMOS, mm-Wave, efficiency**

I. Introduction

With the ongoing success of SiGe-Technologies in RF applications like radar, the operation frequency of these systems is departing from the 77 GHz automotive radar [1] to higher frequencies. There are several systems in the D-Band [2] [3] and even higher in frequency at 240 GHz [4].

With the introduction of new SiGe-Technologies that reach maximum oscillation frequencies of more than 700 GHz [5], radar systems at lower frequencies also profit from higher transistor gain, therefore higher efficiency. Simultaneously, the center frequencies of radar systems increase, having the advantage of better material characterization capabilities and potentially higher bandwidths. In this proposed work, the focus is on creating an efficient and tuneable radar signal source with high output power for improved system's dynamic range. In the current research, radar is moving towards mobile applications, in which saving energy is a crucial objective. The chosen architectures of the VCO, frequency doubler, and PA are well-known topologies [7] and therefore are suitable for a comparable low-power design in a new technology. The VCO has a center frequency of 120 GHz while being fully differential. The MMIC concept is shown in Fig. 1. The left part is the VCO at 120 GHz only, while the circuit on the right has a subsequent frequency doubler and power amplifier at 240 GHz.

II. Circuit Design

All circuits are implemented in the SiGe BiCMOS technology SG13G3 that is currently developed by IHP [6]. Main features of the HBT technology are outlined in [5]. The HBTs

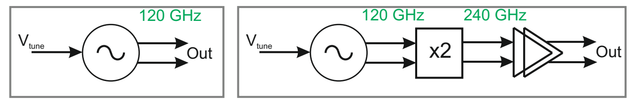


Fig. 1. Realized MMIC building blocks. Left part: VCO only. Right part: VCO, x2 and PA.

of the present fabrication feature peak f_t values of 470 GHz and f_{max} of about 700 GHz. The metal stack consists of 7 aluminium layers with 2 μm and 3 μm aluminium thickness, respectively.

A. 120 GHz signal source

The Voltage-Controlled-Oscillator is based on the well-known Colpitts architecture. The circuit has fully differential RF outputs and a DC input for frequency tuning and current density optimization. The schematic is given in Fig. 2.

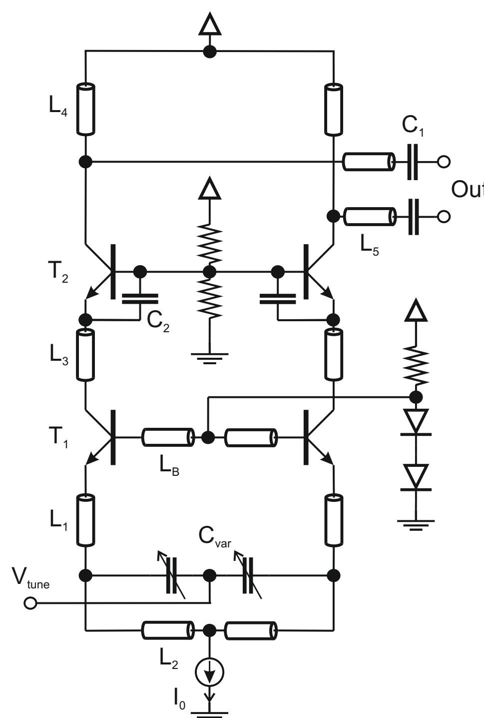


Fig. 2. Schematic of the presented Colpitts-VCO.

TABLE I
PARAMETER VALUES FOR THE VCO. TRANSISTOR DIMENSION IS EMITTER LENGTH.

Component	Value	Component	Value
L_1	50 μm	T_1	9 μm
L_2	200 μm	T_2	9 μm
L_3	30 μm	C_1	50 fF
L_4	235 μm	C_2	50 fF
L_5	280 μm	L_B	105 μm

In FMCW radar applications, an adjustable oscillator frequency is needed. The frequency tuning is realized by using a voltage-controlled MOSCAP at the emitter of the transistors T_1. The MOSCAP can be tuned from -1 to +5 V. Due to the very high frequency, oscillating inductors and loads are realized as controlled impedance transmission lines. Due to higher quality factor Q at high frequencies, the resulting phase noise at 120 GHz is better compared to a discrete on-chip inductor. The oscillator utilizes a current mirror as current source and has a DC current I_0 of only 17 mA. The total DC-Power consumption of the VCO is 78 mW only. In order to further decrease the phase noise, which is important for measurement accuracy, the bias voltage on the main oscillating transistor's T_1 bases is realized by using diodes for voltage drop, resulting in a better phase noise compared to using resistors only. The nominal parameter values of the core are given in Tabel I. To compensate for technology variance and parasitic effects, the base inductor L_B utilizes laser fuses, which allow post-manufacturing tuning of the transmission line length. With these, the center frequency of the oscillator can be tuned to lower frequencies. Laser fuses are also enabling tuning of the output impedance and therefore give the possibility to fit the following stages' input impedance if needed.

B. 240 GHz signal source

The 240 GHz signal source is realized by feeding the differential 120 GHz signal generated by the VCO into a frequency doubler. To maintain fully differential operation for following power amplifiers, the chosen topology is a bootstrapped gilbert-cell doubler [8] [9]. The advantage is that there is no extra phase shift needed in a matching network for the switching quad stage base input because it is provided within the cell itself and is realized by using a $\lambda/4$ transmission line. A disadvantage of the gilbert cell doubler is that its conversion gain is mediocre at least. To enable radar applications with high detection and dynamic range, a subsequent power amplifier is used at 240 GHz. It consists of two stages, where each stage has a different DC current selected to have the best possible efficiency. The first stage is designed to transform the impedance and has a rather low output-referred 1-dB compression point of around 3.59 dBm, while the second stage has 7.32 dBm. This also fits the scaling of main currents I_0, which is 15.9 mA and 18 mA respectively. The PA's output design is optimized for on-chip measurement using 50 Ω probes and pads. The schematic of the differential cascade amplifier with transmission line-based inductive load is given in Fig. 3. It is used in both PA stages with the given parameters in Table II that differ between the two stages. The transmission line between transistors T_1 and T_2 is used for interstage matching and has an influence on the stability of the PA, therefore has to be designed carefully. A photography of the fabricated MMIC is presented in Fig. 4.

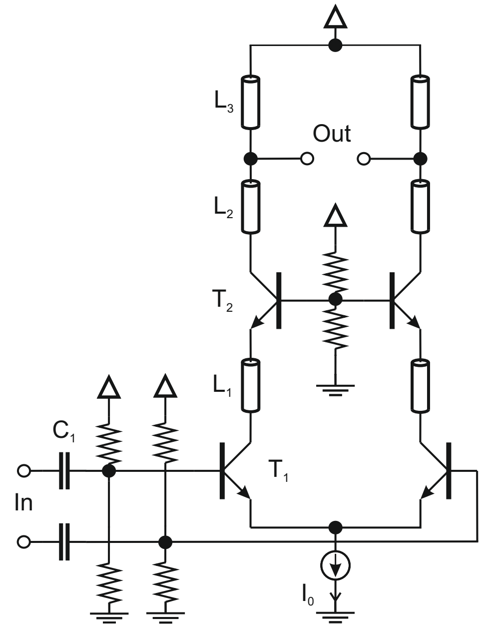


Fig. 3. Schematic of each power amplifier stage with the same topology. The parameter values differ from the first to the second stage.

TABLE II
PARAMETER VALUES FOR THE POWER AMPLIFIERS. TRANSISTOR DIMENSION IS EMITTER LENGTH.

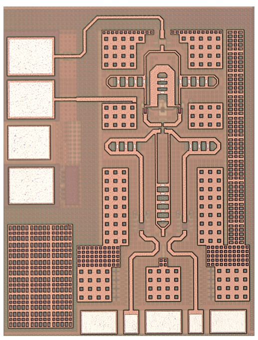
Stage 1		Stage 2	
Component	Value	Component	Value
L_1	65 μm	L_1	50 μm
L_2	70 μm	L_2	10 μm
L_3	70 μm	L_3	70 μm
C_1	250 fF	C_1	90 fF
T_1	2.7 μm	T_1	3.6 μm
T_2	2.7 μm	T_2	3.6 μm

III. EXPERIMENTAL RESULTS

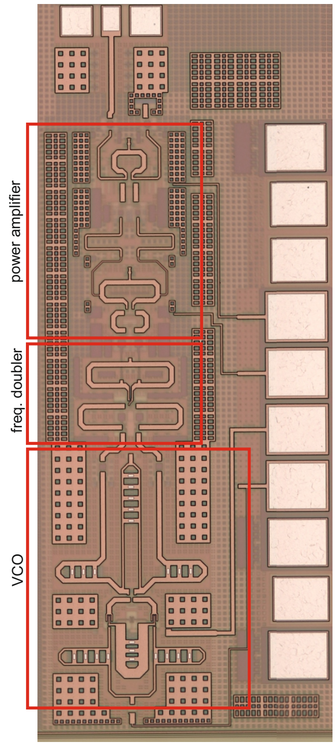
In this chapter, the measured results are given and discussed in detail. For the 120 GHz source, the tuning curve was measured with the Keysight UXA N5247B signal analyzer extended with VDI SA-X, output power with the Ericsson PM4 power meter, and phase noise with $R\&S$ FSWP phase noise analyzer. For the 240 GHz source, the same extended UXA and PM are used with respective SA-X and probes. All measurements were done at room temperature.

A. 120 GHz source

The tuning curve of the VCO is given in Fig. 5 (top). The achieved bandwidth is 16.3 GHz at a center frequency of 118.85 GHz. This results in a relative tuning range of 13.7 %. This value is sufficient for wideband radar applications. Three



(a) VCO with padframe, the size is 760x580 μm.



(b) 240 GHz source with padframe, the size is 1290x520 μm.

Fig. 4. Photograph of the manufactured MMIC test circuits.

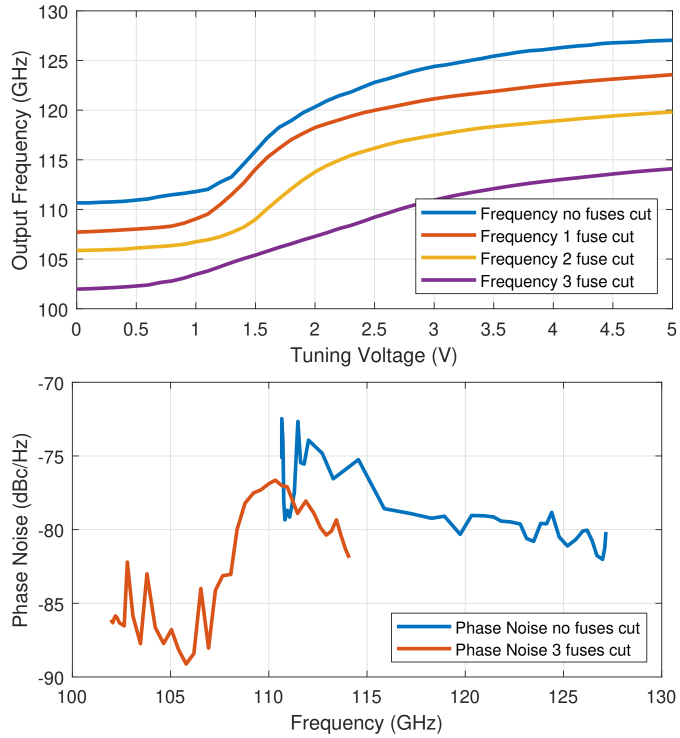


Fig. 5. Top: Measured tuning curve of the VCO with four laser-fuse configurations. The more fuses are cut, the bigger is the resonance inductance L_B and thus lower the center frequency of the VCO.
Bottom: Measured phase noise of the oscillator at 1 MHz offset, with all and none fuses cut.

different laser fuse configurations are shown in Fig. 5 (top). Therefore, the VCOs operating frequency can be decreased to lower values. The measured phase noise at 1 MHz offset frequency can be seen in Fig. 5 (bottom). Note that the two presented curves differ in frequency due to cutting fuses as well. The last measurement for the 120 GHz source is the output power illustrated in Fig. 6. The peak of 7.1 dBm output power is fairly high, given the fact that the overall DC-power consumption of the VCO is 78 mW only. Furthermore, the flatness or amplitude variation of just 1.2 dB over frequency is very good. The resulting DC-to-RF efficiency of the VCO is 6.57 % at 120 GHz. The key feature of the VCO is the ability to generate a high-power, tuneable signal with extremely high efficiency.

B. 240 GHz source

In this paragraph, the measurement of the 240 GHz signal source is presented. A frequency from 225.3 to 248.4 GHz is reached, leading to a bandwidth of 23.1 GHz. Compared to the VCO, this is not twice the bandwidth, most likely because of load-pulling effects. The differential output power of the source is given in Fig. 7 and is about 7 dBm until dipping down to 5.4 dBm at the highest VCO oscillation frequency with no fuses cut. This is due to the fact, that the design of the PA was done without the ability to do parasitic extraction of the layout because of missing software options of Assura at the time. Therefore, the resonance of the PA's load is shifted down in frequency, resulting in the shown dip. Worth noting is the flatness of the power before the dip, which only varies less than 0.2 dB, essentially being a flat line versus frequency. Most outstanding is the efficiency. The whole source, consisting of a VCO, a frequency doubler and a two-stage power amplifier only consumes as low as 264 mW of DC-power, which is an outstanding DC-to-RF efficiency of 1.88 % in SiGe-Technology. The estimated PAE of the power amplifier is 3 % at 236 GHz, though the input power could not be measures individually. This is a record for SiGe-amplifier [16].

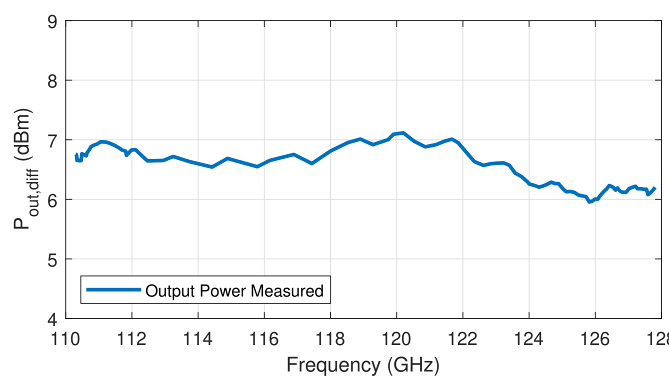


Fig. 6. Measured differential output power of the VCO with no fuses cut.

TABLE III

COMPARISON TO STATE-OF-THE-ART SIGNAL SOURCES AT 120 AND 240 GHZ.

Reference	Technology SiGe	Circuit	Freq (GHz)	3-dB BW (GHz)	P_{out} (dBm)	DC-Power (mW)	DC-to-RF Eff. %	Area (mm^2)
This work	130-nm	VCO	120	111-127	7.1	78	6.58	0.44
This work	130-nm	VCO+Doubler+PA	240	226-248	7	264	1.88	0.67
[10]	55-nm	VCO-PA+Doubler	245	234-261	7.2	566	0.93	0.825
[11]	130-nm	8^{th} Tupler	300	223-350	2.3	537	0.32	1
[12]	130-nm	x16+PA	255	235-265	2.5	700	0.254	0.98
[13]	130-nm	VCO	92	75-110	5.8	129	2.95	0.5
[14]	55-nm	x4+Amp.	140	130-154	10	610	1.64	2.3
[15]	130-nm	VCO	140	138.5-148	-1.5	47	1.51	0.275

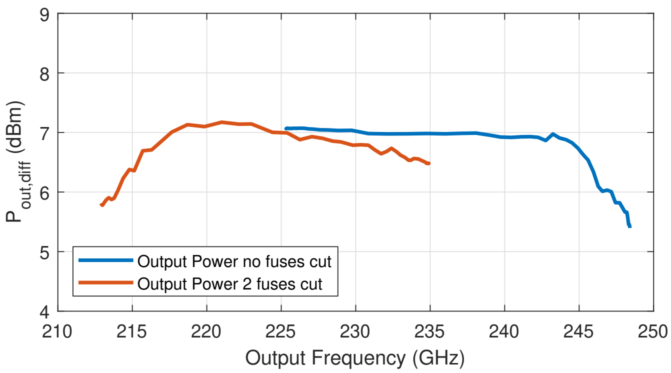


Fig. 7. Measured differential output power of the 240 GHz signal source with none and two fuses cut.

IV. CONCLUSION

In this work, highly efficient signal sources for radar applications at 120 GHz and 240 GHz are presented. Consuming 78 mW and 264 mW respectively, they are, to the authors' best knowledge, the most efficient signal sources in the respective frequency ranges in SiGe-technology, while achieving output powers of 7 dBm. The achievable bandwidths of 16.3 GHz at 120 GHz and 23 GHz at 240 GHz are feasible for FMCW radar applications.

By reaching and exceeding the state-of-the-art signal sources, the paper has shown, what is possible in future mobile radar systems in terms of center frequency, efficiency and output power.

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