Citation	Wouter Steyaert, Patrick Reynaert (2015) A THz Signal Source with Integrated Antenna for Non-Destructive Testing in 28nm bulk CMOS Proceedings of the A-SSCC 2015, 170-120.
Archived version	Author manuscript: the content is identical to the content of the published paper, but without the final typesetting by the publisher
Published version	http://dx.doi.org/10.1109/ASSCC.2015.7387436
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A THz Signal Source with Integrated Antenna for Non-Destructive Testing in 28nm bulk CMOS

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Abstract—This work presents two fully integrated above- f_{max} signal sources (570GHz and 600GHz) with on-chip antenna, implemented in a 28nm bulk CMOS technology. A VCO generates a signal at the fundamental frequency, which drives a non-linear amplifier to generate the wanted third harmonic above. The above- f_{max} third harmonic signal is coupled directly to a folded dipole antenna (570GHz, -34.3dBm EIRP) or to a collinear dipole antenna through a transformer (600GHz, -43dBm EIRP). Both sources provide a wide tuning range and 3dB output power bandwidth while maintaining a compact layout footprint. These are the highest reported fully integrated signal sources in bulk CMOS with on-chip antennas and used as transmitters in a THz imaging setup for non-destructive quality control.

Keywords—THz, CMOS, harmonics, signal generation, THz imaging, on-chip antenna

I. INTRODUCTION

The bridging of the THz gap with Silicon technologies has gained momentum over the years. Supported by CMOS technology scaling, the many possible applications (medical/security imaging, data communication, ...) and the drive towards integrated circuits for consumer products has sparked the research interest towards THz electronics [1]–[5]. The non-destructive testing of products, both in an industrial and consumer setting, could benefit from these advances as THz CMOS systems would allow cheap, mass-producible and high-density imaging solutions for quality control. While the output power and system complexity of CMOS chips is increasing for frequencies at the high end of the mm-wave spectrum [5], the number of radiating (CMOS) sources above 400GHz remains low due to technology limitations (f_{max}), the increasing dominance of parasitics and simulation model inaccuracy.

The frequency limitation imposed by the technology-dependent f_{max} can be circumvented by using the higher-order harmonics of a below- f_{max} signal. In this work, two fully integrated signal sources with on-chip antenna are implemented in 28nm bulk CMOS to generate above- f_{max} signals using harmonics. A VCO is driving a non-linear amplifier, which generates the wanted third harmonic. This signal is coupled to the on-chip antenna by two different approaches: directly to a folded dipole antenna or to a collinear dipole antenna through a transformer. The results are 570GHz and 600GHz signal sources, which are used as transmitters in a THz imaging setup for non-destructive testing. Thanks to their small silicon footprints, the sources would allow high-pixel density transmitter arrays for lens-free THz imaging.

Fig. 1: 3D representation of the layout of the VCO core transistors and the interconnection with the amplifier and the inductor leads.

II. SIGNAL GENERATION AND CIRCUIT/ANTENNA DESIGN

As the f_{max} limits the frequency at which a fundamental oscillator could work, signal generation above this limit can be achieved by utilising higher-order harmonics of a fundamental frequency situated below the f_{max} of the used semiconductor technology.

The VCO generating the fundamental frequency ω_1 around 200GHz is a cross-coupled LC VCO (Fig. 1). In order to achieve this high fundamental oscillation frequency, the tank consists of the parasitic capacitance from the cross-coupled and amplifier transistors and the tank inductor (L_{ind}). No varactors are used, as they would increase the total tank capacitance (reducing the oscillation frequency) and their low quality factor at high frequencies would degrade the oscillation capabilities. The tank inductance is kept small by using a single-turn inductor. On-chip inductors greatly benefit from the availability of an top ultra-thick metal (UTM) to reduce the trace resistance. As this UTM was not part of the metallization scheme, L_{ind} is implemented by combining the 3 highest metal layers together (metal layers 7 to 9), which improves the quality factor of the inductor and compensates for the lack of UTM. The resulting inductor has a simulated inductance of 18pH and quality factor of 33.2. All passive components and interconnecting metals are designed using 2.5D EM-simulations.

Both the VCO and amplifier were optimized for their required sub-THz functionality. By separating the fundamental generation to the VCO and third harmonic generation to the amplifier, both functions can be optimized separately. For the

Fig. 2: Schematic of the 600GHz source with third harmonic coupling to the on-chip antenna through a transformer. The transformer has a self-resonance frequency between the fundamental and third harmonic.

oscillator core, ultra-low V_T (ULVT) transistors with finger widths of 600nm and gate contacts on both sides were used to increase the maximum oscillation frequency of the cross-coupled pair. This provides the optimized trade-off between gate resistance and routing capacitance. To further reduce the parasitic capacitance, the transistor gate and drain metals are stacked up and the cross-coupling of the VCO transistors is made in metal layer 6, thus reducing the capacitance to the substrate [6]. The layout also reduces the gate-drain line overlap and thus C_{gd} , which together with gate resistance form the dominant limiters on high-frequency performance. By mirroring one of the core transistors, the cross-coupling becomes very compact, as shown in Figure 1.

The amplifier that generates the wanted above- f_{max} third harmonic acts as a buffer between the VCO core and the antenna. To improve the generation of this third harmonic, the transistors should be operating in the weak-inversion operation region where they show the highest nonlinear behavior. Since the supply voltage of the oscillator core determines the gate-source voltage biasing of the amplifier transistors, ultra-high ultra-low V_T (UHVT) transistors are used to enhance nonlinear behavior of the amplifier. The amplifier size is kept small to minimize the capacitive contribution to the oscillator tank, which would lower the oscillation frequency.

Varying the supply voltage VDD1 of the oscillator core, which changes the parasitic capacitances in the cross-coupled transistors, is used to tune the frequency. At design time of this work, no RF transistor-model was available, nor was there any simulation model validation for these operating frequencies. Therefore, extensive use was made of parasitic extraction and 3D-EM simulation tools.

To emit the generated sub-millimeter waves, the first signal source couples the third harmonic signal from the amplifier to the on-chip antenna through an integrated transformer (Fig. 2). Implementing a transformer with a self-resonant frequency (SRF) above 600GHz would require very small trace widths and winding diameter, resulting in low signal coupling towards the antenna. Therefore, a transformer is used where the SRF is positioned between the fundamental (ω_1) and third harmonic (ω_3). The resulting transformer behavior differs for these two frequencies of interest: at ω_1 , the transformer impedance is

Fig. 3: Schematic of the 570 GHz signal generator. The drains of the harmonic-generating transistors of the amplifier are connected to a folded dipole antenna.

inductive and works towards compensating the output capacitance of the amplifier. At ω_3 , the structure couples the wanted third harmonic capacitively to the antenna, as this frequency is above the SRF of the transformer's inductors. The transformer is implemented as three stacked, single-turn inductors in the top 3 metals with the middle inductor leading to the antenna load.

The antenna is an on-chip collinear broadside dipole, implemented in the top metal layer. Biasing of the amplifier's transistors is done through the center tap of the transformer winding. The antenna is driven differentially by the uneven harmonics, resulting in a suppression of the second and fourth harmonic.

A second signal source was implemented using an alternative approach for the connection between the output transistors and the antenna by removing the transformer and connect the amplifier directly to the antenna (Fig. 3). To be able to provide the DC bias to the transistors, the two ends of a dipole antenna are 'folded' together to realize a folded dipole. The antenna is dimensioned to radiate at the third harmonic, while acting as an inductor at the fundamental with a center DC feed tap, eliminating the need for RF chokes.

Fig. 4: Chip measurement setup and example of the received signal spectrum.

The circuits and antennas are fully compliant with all strict

layout rules of the 28nm bulk CMOS process, with manually placed dummy metals near the oscillator core and antennas to meet metal density requirements to minimize any negative impact on the circuit's behaviour.

III. MEASUREMENT RESULTS

Absolute power measurements are challenging, especially at THz frequencies where the output power declines with frequency. Detectors such as bolometers are able to detect low power levels, but their broadband nature means that great care must be taken to de-embed any unwanted signals picked up by the detector, such as the fundamental and other harmonics. In the measurement setup of this work, the radiated signal was measured with a WR1.5 horn antenna connected to a VDI WR1.5 MixAMC module at a distance of 20mm to satisfy far-field criteria. A baseband amplifier amplifies the down-converted signal before being analyzed by a R&S FSU spectrum analyzer (Fig. 4). To accurately verify the power levels from the spectrum analyzer, the receiver setup was calibrated using an Erickson PM4 power meter and a VDI WR1.5 source module. The resulting measured frequencies and equivalent isotropically radiated power (EIRP), calculated using Friis' equation [7], are shown in Fig. 5 for a varying supply voltage (used for frequency tuning).

Fig. 5: Measured EIRP and frequency for the 570GHz (a) and 600GHz (b) signal sources. The supply voltage of the VCO core is changed to vary the oscillation frequency.

Fig. 6: Non-destructive quality control of hypodermic 21G needle (0.8mm x 40mm) inside its plastic casing. A non-centered position of the needle inside the casing can be detected by repeating the line scan at different positions.

For the chip with transformer and collinear antenna the frequency tuning range is 24.7GHz (588.9-613.6GHz) and the 3dB output power bandwidth is 14.25GHz. The peak measured EIRP is -43dBm for a DC power consumption of 21.2mW. The core and total area (including bond pads and decoupling capacitors) are $50 \times 110 \mu\text{m}^2$ and $300 \times 500 \mu\text{m}^2$, respectively. The folded-dipole approach radiates signals from 559.1GHz to 577.6GHz (18.5GHz tuning range) and has a peak EIRP of -34.3dBm for 21.4mW of DC power. The 3dB output power bandwidth is 4.92GHz and the core and total area are $50 \times 45 \mu\text{m}^2$ and $325 \times 500 \mu\text{m}^2$, respectively. While the radiation efficiency and performance of both chips would benefit from the usage of high-resistivity Silicon lenses [8], the steep increase in packaging cost due to the addition of such a lens would conflict with CMOS' low-cost process advantage. Therefore, this work focuses on lens-free THz imaging.

IV. NON-DESTRUCTIVE QUALITY CONTROL USING THZ TRANSMITTERS

One of the possible applications to benefit from fully integrated CMOS imagers is the non-destructive testing of various industrial and consumer products. To illustrate the potential of lens-free THz CMOS imaging, the fabricated signal sources are used as transmitter in a setup for the contact-less, non-destructive quality control of a 21G hypodermic needle (0.8mm diameter, 40mm long) inside their protective plastic casing (5.5mm diameter). The sample-under-test is placed in a setup similar to Figure 4 to create a 1-pixel imaging system, which measures the power transmission at a specific point of the scanned object. A mechanical stepper moves the sample in the vertical direction in steps of 0.1mm, thus creating a cross-section image of the received power. The metallic needle will prevent the transmission of the THz waves, and thus will cause a lower received power when it is moved in front of the transmitter. By repeating this line scan at different positions, the position of the needle inside the protective casing can be monitored along the sample's length (Fig. 6).

TABLE I: Comparison with state-of-the-art signal generators in bulk CMOS

Ref.	Frequency (GHz)	Tuning Range (GHz)	Output Power (dBm)	EIRP (dBm)	DC power (mW)	Area (mm ²)	Process Technology
[1] JSSC 2010	410	3	-49	-	16.5	0.25	45nm CMOS
[2] ISSCC 2014	530	17	-11.3	25*	150	0.26	130nm SiGe
[3] JSSC 2014	543	11	-31 [†]	-31.8	19	0.15	40nm CMOS
[4] VLSI 2011	553	< 1	-36.6	-	64	0.29	45nm CMOS
Folded Dipole	559.1-577.6	18.5	-39.7	-34.3	21.4	0.16	28nm CMOS
Collinear Dipole	588.1-613.6	24.7	-48.1	-43	21.2	0.15	28nm CMOS

* Uses a hemispherical lens

[†] Measured on version with probe

Fig. 7: Die photographs of the fabricated sources with collinear dipole antenna (a) and with folded dipole antenna (b).

If both the top and bottom end cross-section show a centered needle, the needle is straight and is correctly positioned inside the package. A non-centered position of the needle at the top compared to the bottom indicates a sample that is curved and therefore does not correspond to quality specifications. Possible causes are needle production error or collision of the needle tip with the inner wall of the casing while being assembled, which might results in needle tip damage and a reduced sharpness.

V. CONCLUSION

Die photos of the two fully integrated radiating signal generators fabricated in a 28nm bulk CMOS process are shown in Fig. 7. A comparison with state-of-the-art THz radiation sources above 400GHz in Silicon is shown in Table I. Compared to the work shown in the table, the presented sources are the highest radiating THz sources in CMOS and the first to be implemented in a 28nm bluk CMOS process.

The signal sources exhibit a wide tuning range and 3dB output power bandwidth while maintaining a compact layout footprint with on-chip antenna. The circuits are used as THz transmitters in a measurement setup for the contactless, non-destructive testing of hypodermic needles inside their protective casing. A lens-less, fully integratable CMOS imaging system with high-pixel density could enable the widespread use of THz imaging as a cost-effective solution for non-destructive quality control, both for industrial and consumer applications.

ACKNOWLEDGMENT

The authors would like to thank Mike Keaveney, Matt Mitchell and Analog Devices, Limerick, Ireland for supporting this project.

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