

RESEARCH PAPER

245 GHz SiGe sensor system for gas spectroscopy

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A 245 GHz sensor system for gas spectroscopy is presented, which includes a SiGe receiver (RX), a SiGe transmitter (TX), and a 0.6 m long gas absorption cell between the TX and RX. The integrated local oscillators of the RX and the TX are controlled by two external phase locked loops (PLLs), whose reference frequencies are swept with constant frequency offset for a low IF of the RX. The RX consists of a differential low noise amplifier (LNA), an integrated 122 GHz local oscillator (LO) with 1/64 divider, a 90° differential hybrid, and active subharmonic mixer. The TX consists of an integrated 122 GHz LO with 1/64 divider, and a frequency doubler. The RX and TX are fabricated in 0.13 μm SiGe BiCMOS with f_t/f_{max} of 300/500 GHz. Using external dielectric lenses for the TX and RX, the absorption spectrum of gaseous methanol has been measured. The reference frequency of the TX-PLL is modulated for frequency-modulation spectroscopy. The performance of the sensor system is demonstrated by measuring the 2f absorption spectrum (second harmonic detection) of gaseous methanol.

Keywords: SiGe, mm-wave, Sensor, Gas spectroscopy

Received 28 October 2014; Revised 06 January 2015; Accepted 11 January 2015; first published online 5 February 2015

1. INTRODUCTION

In recent years significant progress has been made in mm-wave sources based on frequency synthesis techniques starting with a fundamental oscillator in the region around 10 GHz and subsequent frequency multiplication. This has led to the development of mm-wave/THz spectrometers for molecular absorption spectroscopy [1, 2]. Recently, sensor systems for gas spectroscopy in the mm-wave region, which are based on commercial available components, have been reported, which use frequency synthesis techniques in the region around 10 GHz, with frequency multiplication to 210–270 GHz [1]. In [1] the mm-wave power was propagated quasi optically with horn antennas and lenses through a 1.2 m long gas absorption cell. Using this technique a chemical analysis of exhaled human breath was performed, and this sensor system may become the technique of choice for a broad range of chemicals [3]. The capability of an mm-wave/THz spectrometer for breath analysis has been demonstrated [3]. It was shown that for selected species, unambiguous detection at a ppt level is possible [3]. The high specificity is due to the very high spectral resolution (0.1 MHz) in combination with large spectral coverage (30 GHz). This results in

300 000 spectral channels, allowing identification of many different molecules and their isotopologues. Another push for mm-wave/THz spectroscopy comes from the rapid developments regarding silicon semiconductor technology and circuits. Silicon technology has made progress toward ever higher device cut-off frequencies, enabling the development of circuits in SiGe for mm-wave applications beyond 200 GHz. Key circuits have been developed and demonstrated [4–8]. SiGe BiCMOS technologies have become very attractive, as they allow high integration, low-cost and combination with digital CMOS control circuits. The European project DOTFIVE has developed novel process modules to push SiGe BiCMOS toward 500 GHz f_{max} [9]. This has allowed the utilization of SiGe BiCMOS technology for circuits operating in the frequency range above 200 GHz. Implementing transmitters (TX) and receivers (RX) with integrated antenna in SiGe BiCMOS for applications in the range 200–300 GHz requires an innovative architecture to fulfill all requirements concerning performance, low power dissipation, and low cost. For the receiver architecture, an advantage can be obtained by applying subharmonic mixing, to improve the performance [5]. For the TX in the frequency range up to 300 GHz, an advantage is obtained by applying frequency multiplication using frequency triplers and frequency doublers, for improved performance and reduced power dissipation [4]. The implementation of integrated mm-wave radiation sources and detectors offer a path toward a compact and low cost system for gas spectroscopy. Mm-wave sources and detectors for this frequency range are now available as demonstrated by integrated TX and receivers RX [4, 5, 10, 11] in advanced SiGe technology. A TX for the range 240–251 GHz has been presented consisting of a push-push voltage controlled oscillator (VCO) tuned by an external

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PLL, a power amplifier (PA), a frequency doubler, and an integrated antenna [10]. A RX for 245 GHz has been reported consisting of a push–push VCO for the 122 GHz range, which can be tuned by an external PLL, a LNA, a Gilbert-cell subharmonic mixer (SHM), and an integrated antenna [11].

This paper is an extended and updated version of our paper [12], which presents now a considerably higher sensitivity for our gas spectroscopy system due to applying frequency modulation (FM). This paper presents a system for *in-situ* gas spectroscopy at about 245 GHz, which consists of 245 GHz TX- and RX-chips, whose local oscillator (LO) frequencies are swept by two external PLLs with constant frequency offset. This frequency region was chosen, because many volatile organic compounds and toxic industrial chemicals have characteristic fingerprint-like absorption spectra around 250 GHz [13]. Compared to similar systems based on GaAs or InP technology, SiGe offers the potential to be more cost-efficient. In comparison with laser-based systems, for example a Nd:YAG laser in combination with a master oscillator/power oscillator, a SiGe TX/RX *in-situ* absorption spectrometer can be more compact and less power-consuming [14]. The effective antenna gain of the TX and RX, respectively, is increased by a dielectric lens to allow the implementation of a 0.6 m long gas absorption cell. The performance of the system is demonstrated by measuring the absorption spectrum of gaseous methanol. Methanol was chosen, because it has a rich absorption spectrum. At this stage no systematic spectroscopic investigation of many different gases and gas mixtures has been performed, because this has been demonstrated already with the other more conventional GaAs-based TX/RX systems [13, 15]. In Section II of this paper, we describe the design of the circuits, which were used for the RX and TX. Section III is dedicated to the design of the integrated antenna, used for the RX and TX, and the design of the lens, which is used to increase the effective antenna gain for the gas spectroscopy system. The measurement results of the RX and TX are presented in Section IV, followed by the presentation of the gas spectroscopy system in Section V. Finally, this paper ends with conclusions.

II. CIRCUIT DESIGN OF RECEIVER AND TRANSMITTER

The RX and TX of the sensor system were fabricated in the new generation of IHP's 0.13 μm SiGe BiCMOS technology [16]. The RX and TX was designed with the design kit of IHP for

its 0.13 μm BiCMOS technology with seven metal layers, and with high-speed SiGe:C heterojunction bipolar transistors (HBTs) featuring a transit frequency (f_T) of 300 GHz and a maximum oscillation frequency (f_{max}) of 500 GHz [17]. We used subsequent fabrication runs of this technology for the fabrication of our RX- and TX-chips.

We used the GoldenGate[®] RF integrated circuit simulator to design and optimize the RX and TX. The subcircuits of the RX and TX, respectively, were designed using GoldenGate and ADS from Agilent. The transmission lines and transformers were simulated with a 2.5D planar EM-simulator (momentum). For the transformers we applied S-parameter-based models. The passive circuits for frequencies around 245 GHz were simulated using three-dimensional EM-simulator (EMPro from Agilent).

The building blocks for the gas spectroscopy system are a TX- and a RX-chip including on-chip-antenna with localized backside etching (LBE). An integrated LO is used for the TX as well as for the RX, whose frequency is tuned by an external PLL. The two PLLs of the system are controlled by the two external reference frequencies with frequency offset to realize a constant IF frequency in the range up to about 100 MHz during a frequency sweep. The very small change in the IF-signal amplitude due to gas absorption is used for gas spectroscopy. The LO of the TX and the RX, respectively, consists of a 120 GHz push–push VCO with an 1/64 frequency divider for the fundamental frequency, and a 120 GHz differential one-stage PA (see Fig. 1).

The PA uses one-stage with a differential cascode, transformer-coupled topology. The PA draws 33 mA at 4 V supply voltage. The TX consists of the 120 GHz LO, which is coupled to a frequency doubler, whose single-ended output feeds an on-chip antenna, as shown in Fig. 1. The TX output power is 1 dBm at 245 GHz [18]. The RX consists of the 120 GHz LO as described, a Gilbert-cell based SHM, a LNA, and the same on-chip antenna as used for the TX (see Fig. 2).

The quadrature LO outputs are generated by a differential $90^\circ - 3\text{-dB}$ transmission line coupler, similar as described in [5], which is connected to the LO-buffer by a 120 GHz Marchand balun. The LNA is a five-stage design with amplifier stages, which are coupled by identical transformers, and baluns at the input and output transformer, respectively, as reported in [19]. Each stage contains four HBTs with $A_E = 8 \times (0.12 \times 0.96) \mu\text{m}^2$. We used weak emitter degeneration in three stages to ensure stability of the 245 GHz LNA. A measured gain of 18 dB and a measured noise figure of 11 ± 1 dB

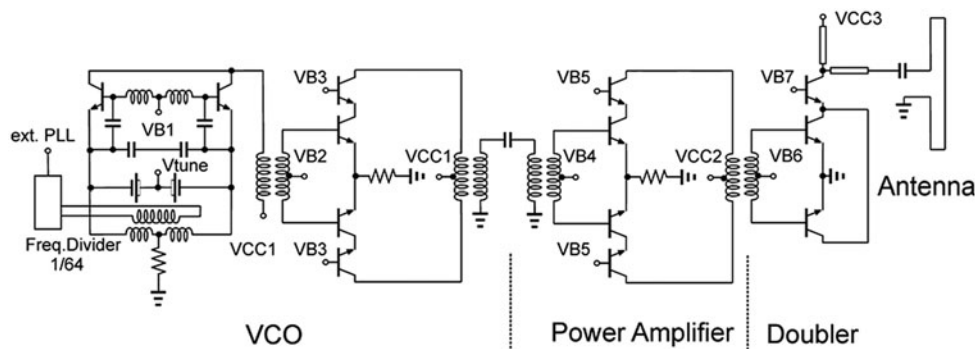


Fig. 1. Schematic of the 245 GHz transmitter: 120 GHz push–push VCO with 1/64 frequency divider, the one-stage 120 GHz PA, the frequency doubler, and the antenna.

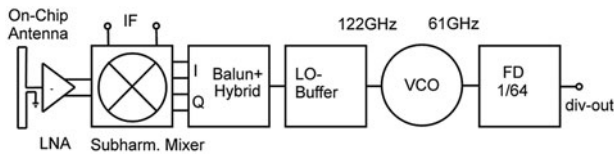


Fig. 2. Schematic of the 245 GHz subharmonic receiver.

have been achieved for the LNA at 245 GHz [19]. The LNA draws 82 mA at 3.7 V supply voltage. We used a SHM design based on two stacked switching quads [6, 8]. The mixer core contains ten HBTs with $A_E = 8 \times (0.12 \times 0.96) \mu\text{m}^2$. The differential IF output was obtained by emitter followers connected to 150 Ω load resistors. The SHM draws 23 mA at 3.6 V supply voltage. Figure 3 shows the micrograph of the fabricated RX-chip with integrated antenna. The die area is 2.7×1.3 mm. Breakup circuits of this RX are described in [11].

Figure 4 depicts the micrograph of the fabricated TX-chip with integrated antenna. The die area is 2.34×1.3 mm.

III. ANTENNA AND LENS DESIGN

In the following, we describe the on-chip antenna design and the design of the external lens, which increases the effective antenna gain.

The LBE available at IHP is an effective way to improve the efficiency of the on-chip antenna by removing the lossy silicon

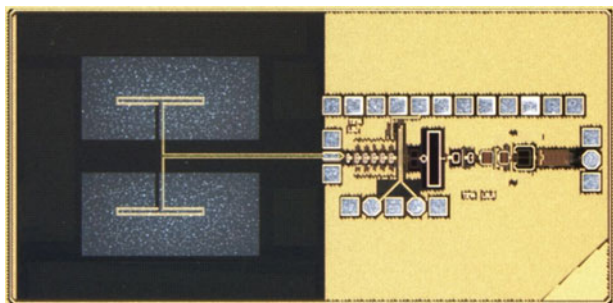


Fig. 3. Micrograph of the receiver chip with on-chip antenna.

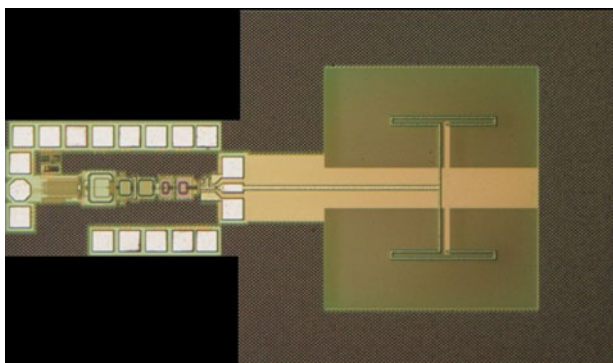


Fig. 4. Micrograph of the transmitter chip with on-chip antenna.

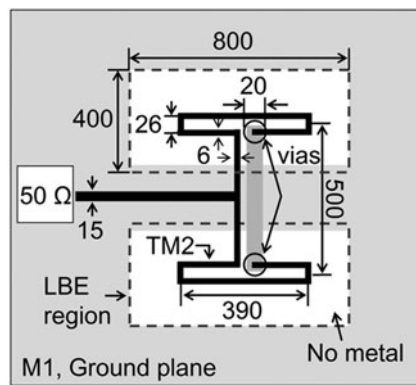


Fig. 5. Geometry of the on-chip antenna (units is μm).

under the radiator. This technique is part of a standard through silicon via (TSV) process. The antenna design is shown in Fig. 5.

The antenna design is shown as part of the RX-chip and TX-chip, in Figs 3 and 4, respectively. The top thick layer TM2 is used to realize the radiators and the feeding transmission lines, whereas M1 serves as ground layer for both the circuit and the feeding lines. The antenna is composed of two half-wavelength folded dipoles. The ground plane of the module acts as a reflector for the antenna. The thickness of the silicon substrate is 200 μm for optimal performance. To improve the gain a dielectric lens has been attached above the antenna. The lens is made of high density polyethylene with a permittivity of $\epsilon_r = 2.32$ and has a diameter of 40 mm and a focal length of 25 mm. It is of plano-convex type with two refracting surfaces. Thus energy reflected at the lens surface is not radiated back toward the antenna and hence it does not disturb its performance. Figure 6 shows the simulated radiation pattern of the on-chip antenna alone and of the antenna together with the lens. As it can be seen the gain increases from 7 to 33 dBi. The half power beamwidth (HPBW) decreases from 62 to 2.1° . The lens itself is shown as part of the gas spectroscopy system in Fig. 13.

An additional advantage of the dielectric lens is that its focal distance can be used to tune the gain of the antenna-lens combination. Thus for each application the best compromise between HPBW and gain can be chosen.

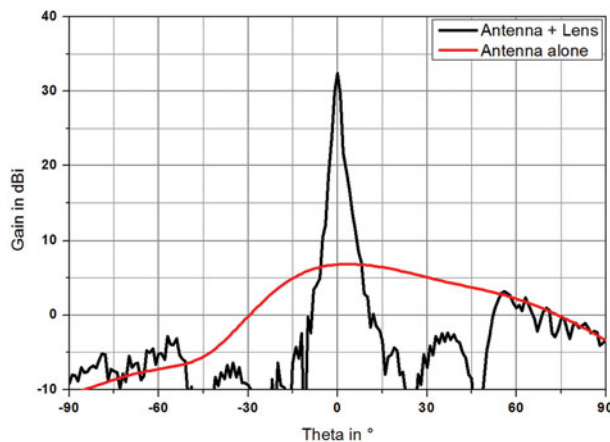


Fig. 6. Radiation pattern in e-plane of the antenna alone and together with the lens.

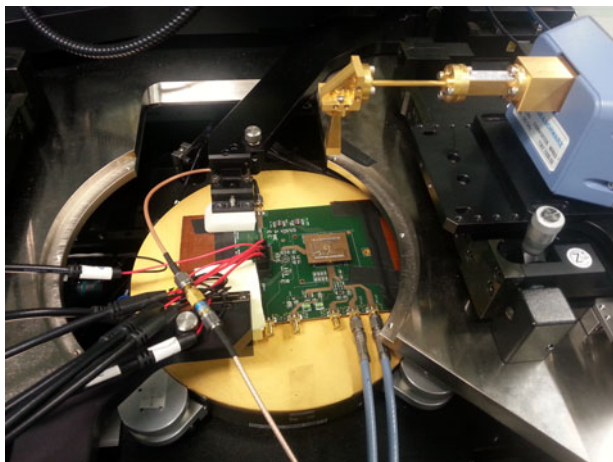


Fig. 7. Photograph of the quasi-optical set-up for on-wafer measurements: the carrier board with PLL and the small plug-in board with 245 GHz receiver chip.

IV. RECEIVER AND TRANSMITTER RESULTS

In the following, we describe the performance of the RX and TX used in our gas spectroscopy system, and we present the parameters of their subcircuits.

The measurements of 245 GHz receiver were carried out in the setup shown in Fig. 7. The 245 GHz receiver chip was bonded on a plug-in board. An efficient thermal backside contact of the RX-chip with the large Cu-layer of the board was realized using liquid metal. The plug-in board was then mounted on the carrier board with the PLL device (ADF4007 with divide ratio 8) (see Fig. 7).

The VCO of the RX was controlled by the PLL to obtain a stable IF signal at frequencies up to 130 MHz. The reference signal (about 120 MHz) for the PLL was delivered from a high-quality signal generator (SML01 from R&S) to enable reception of the RF signal in the 235–253 GHz range. The mm-wave signal was generated by a commercial transmitter (R&S® ZVA-Z325 Converter) attached to a standard WR-3.4 horn antenna with 25 dBi gain (specified at

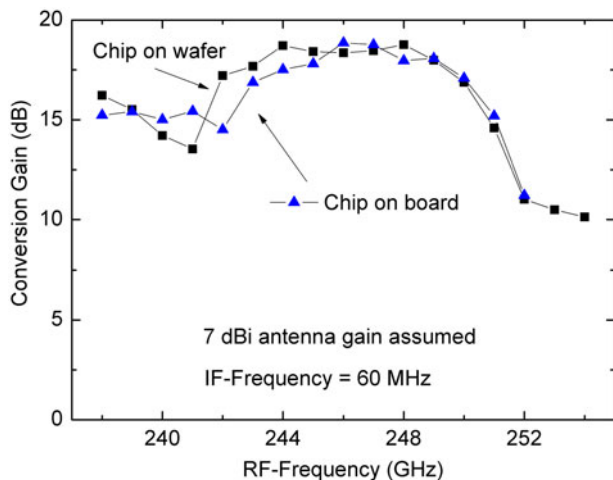


Fig. 8. Conversion gain versus RF-frequency with 60 MHz IF-frequency: (i) receiver-chip on wafer, (ii) receiver-chip mounted on board with external PLL.

Table 1. Performance of the RX-chip.

LNA: DC current	82 mA at 3.7 V
SHM: DC current	23 mA at 3.6 V
VCO: DC current	32 mA at 3.3 V
Divider: DC current	29.5 mA at 3 V
LO-Buffer: DC current	33 mA at 4 V
RF frequency range	239–250 GHz
Conversion gain	18 dB at 245 GHz
IP1 dB CP	−25 dBm at 245 GHz
NF	18 dB at 245 GHz
Antenna gain	7 dBi at 245 GHz

Table 2. Performance of the TX-chip.

VCO: DC current	32 mA at 3.3 V
Divider: DC current	29.5 mA at 3 V
PA1: DC current	33 mA at 4 V
Doubler: DC current	19 mA at 2.8 V
Frequency range	239.5–250.8 GHz
Output power	1 dBm at 245 GHz
EIRP	7 dBm at 245 GHz

270 GHz). The distance between the horn antenna and the on-chip antenna was set to 9.5 cm. Assuming far field conditions, we calculated the conversion gain from the received input power and the IF output power (see Fig. 8).

We assumed for this estimation a 7 dBi antenna gain as obtained for the on-chip antenna [14]. Applying the same setup, we performed also on-wafer measurements for the RX with LBE to obtain the RX conversion gain. We observed 18 dB conversion gains at 245 GHz (see Fig. 8), in agreement with the results for the RX-chip on the plug-in board. As the conversion gain of RX decreases considerably at higher temperature [11], this result indicates that the thermal contact of the RX-chip with the plug-in board is sufficient to avoid a decreased conversion gain of the RX-chip due to its relatively large power dissipation of 0.6 W. According to the −3 dB gain bandwidth the RX can be used in the frequency range from 238 to 250 GHz. Table 1 presents the technical data of the RX.

Table 2 summarizes the technical data of the TX.

V. SIGE GAS SPECTROSCOPY SYSTEM

In the following, we describe our gas spectroscopy system, and we present spectra of gaseous methanol observed with this system.

Prior to implementation into the gas spectroscopy system the TX and RX were characterized. To improve their effective antenna gain a lens as described in Section III was mounted at a distance of 22 mm in front of each module. We used an optical rail for movable mounting of the TX and RX boards with the lenses (see Fig. 9).

The effective antenna gain of the TX and RX, respectively, is increased by the lens. Figure 10 shows the received IF spectrum for 2 m distance between the apex of the lenses of the TX and RX (peak value: −21.9 dBm at 49.1 MHz).

Figure 11 presents the received IF power as function of the distance between TX and RX. The effective antenna gain,

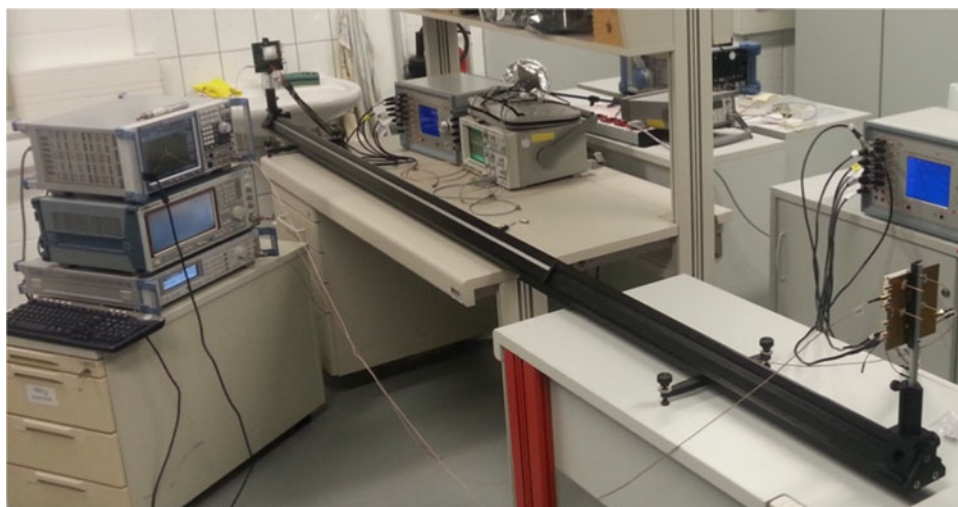


Fig. 9. Optical rail with TX-module (left) and RX-module (right).

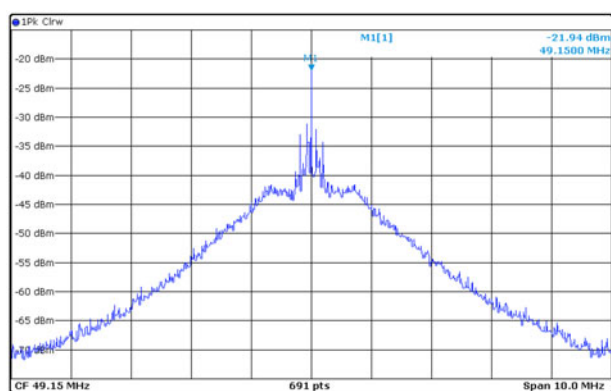


Fig. 10. The IF-spectrum of the received signal: IF-center frequency at 49.1 MHz; single-ended IF; TX and RX modules with lenses; 2 m distance between TX and RX.

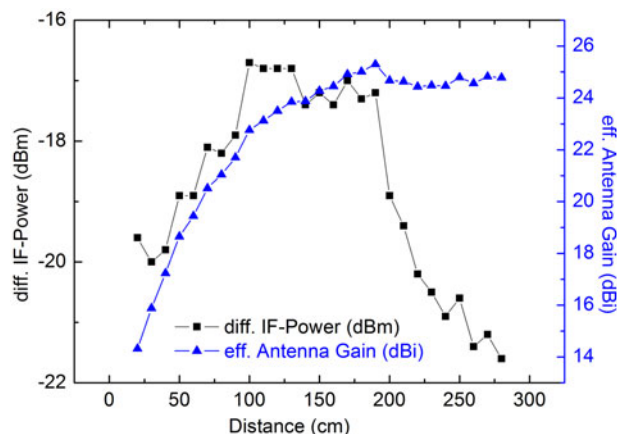


Fig. 11. Differential IF-power of the receiver and effective antenna gain of the on-chip antenna in combination with lens: the parameter is the distance between transmitter and receiver.

estimated by Friis radio link formula, reaches saturation for far-field conditions (distance >2.6 m) with a gain of 25 dBi. The measured effective antenna gain is somewhat lower than the simulated gain of 33 dBi probably due to a misalignment of the TX and RX modules. The IF power increases from -19 to -17 dBm when the distance between TX and RX increases from 0.5 to 1 m. This IF-signal strength is sufficient for performing gas spectroscopy with our 56-cm long absorption cell.

The block diagram of the sensor system is shown in Fig. 12. The reference signals for the PLLs were delivered from two signal generators with a frequency offset of 24 kHz (corresponding to 2048×24 kHz = 49.152 MHz for IF). The frequency step of the frequency sweep was set by the stepper for the reference frequency at the signal generator. A step size of 244 Hz corresponds to a frequency step of 2048×244 Hz = 0.5 MHz. FM with an amplitude (frequency deviation) of 1.38 MHz (2048×675 Hz) for the TX frequency and a FM of 100 kHz was applied to the reference frequency of the TX-PLL.

We have used a 0.6 m long gas absorption cell between the TX and RX for gas spectroscopy [6] (see Fig. 13). The effective

antenna gain of the TX and RX, respectively, is increased by the external dielectric lenses as described above. The second harmonic content ($2f$) of the absorption spectrum was obtained by detecting the IF power of the RX using a diode power sensor connected to a lock-in amplifier. The 100 kHz modulation frequency serves as the reference for the lock-in amplifier. A DAQPad multifunction data acquisition device provided the connectivity for acquiring the output data of the lock-in amplifier.

The applicability of our SiGe sensor system is demonstrated by measuring spectra of gaseous methanol. For this purpose methanol was evaporated from a small container with liquid methanol. The gaseous methanol was introduced into the absorption cell through a series of a two needle valve, which controlled the gas flow. A turbo molecular pump was used for obtaining the low pressure in the range from 0.1 to 30 hPa, which is needed for the gas spectroscopy. The pressure in the absorption cell is measured with a capacitive pressure gauge. The spectra were obtained by applying frequency ramps to the reference frequency of TX and RX, respectively, with a constant frequency offset to generate the 50 MHz IF signal of RX. The IF-power was recorded during

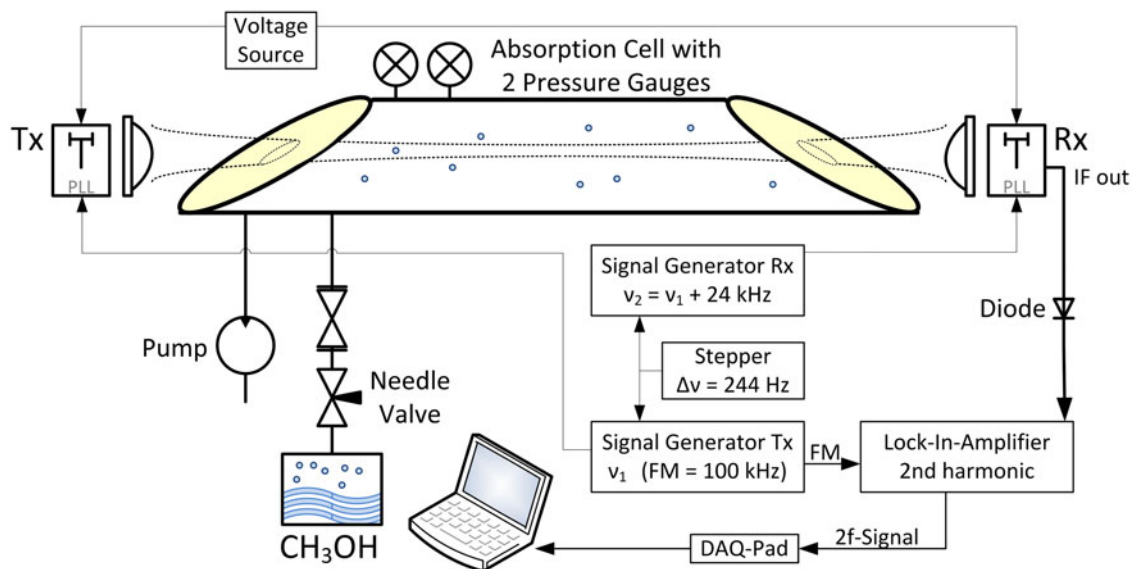


Fig. 12. Block diagram of the TX/RX sensor system with gas absorption cell, TX-module, and RX-module.

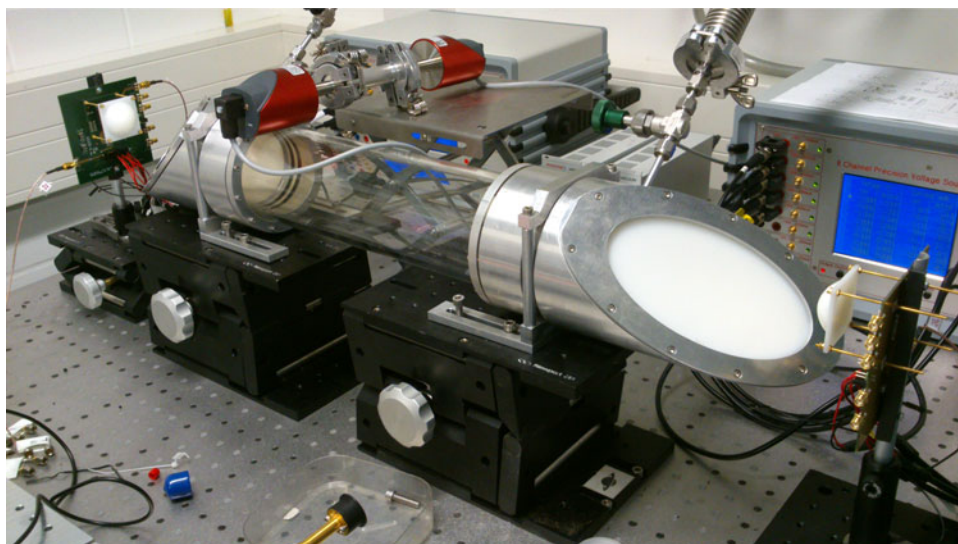


Fig. 13. Photograph of the TX/RX system demonstrator with lenses and the gas absorption cell: left – RX-module, right – TX-module..

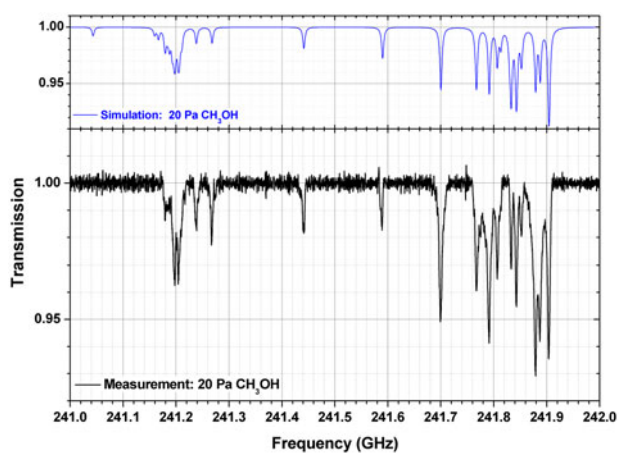


Fig. 14. Calculated (top) and measured (bottom) absorption spectrum of methanol at a pressure of 20 Pa.

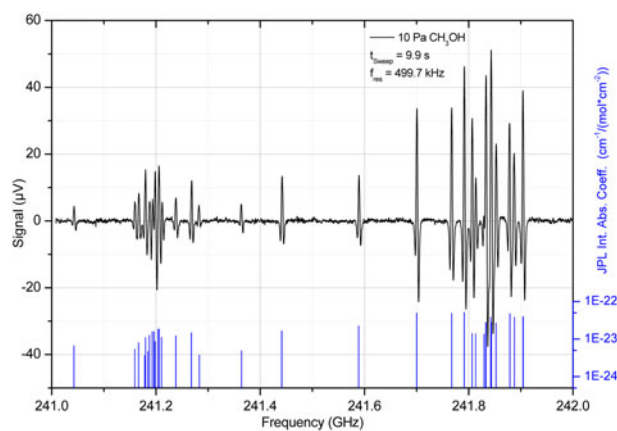


Fig. 15. Measured 2f absorption spectrum of methanol (top), and simulated spectrum of absorption coefficient (bottom).

ramping by a spectrum analyzer. The ramping time was 1616s to measure the spectrum shown in Fig. 14. The spectrum analyzer recorded 16 160 data points during this time. Along with the measured spectra, simulated spectra of methanol are also shown. These spectra were calculated using the HITRAN [20] spectral data base. Note the excellent agreement between the simulated and the measured spectrum. Figure 14 shows a spectrum taken without FM after data processing (baseline correction and averaging).

Figure 15 presents the 2f absorption spectrum at a gas pressure of 10 Pa for a sweep time of 10 s after baseline correction and the simulated spectrum of the absorption coefficient.

It is worth noting, that the frequency sweep time is considerably shorter in the case of 2f absorption spectroscopy with FM compared with the sweep time in the case of spectroscopy without FM.

VI. CONCLUSION

A system for gas spectroscopy in the frequency range 240–250 GHz is presented consisting of a SiGe TX and RX, whose internal local oscillators are tuned by external PLLs. The RX and the TX are fabricated in 0.13 μm SiGe:C BiCMOS technology with f_T/f_{max} of 300 GHz/500 GHz. The effective antenna gain of the RX and TX is increased using additional dielectric lenses. Using a 0.6 m long gas absorption cell between the TX and RX, the absorption spectrum of methanol has been measured. The performance of the sensor system is also demonstrated by measuring the 2f absorption spectrum (second harmonic detection) of gaseous methanol using FM. Our mm-wave SiGe spectroscopy system presents the highest integration level of such a system reported so far. An extension of the frequency range is feasible by modifying the internal local oscillator. The further development of the presented spectroscopic system will be aimed to meet a wider frequency range. The relevant frequency ranges are, e.g. from 230 to 260 GHz for breath analysis, and from 240 to 280 GHz for the detection of important toxic gases. The wide frequency span could be addressed by switchable local oscillators in the transmitter and receiver.

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