

A Fully Integrated 30-to-160GHz Coherent Detector with a Broadband Frequency Comb in 65nm CMOS

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Abstract— This paper presents a broadband millimeter-wave coherent detector that uses an on-chip frequency comb with a tunable repetition frequency as a high-precision frequency ruler. A heterodyne MOSFET detector mixes the received signal with the reference comb and downconverts it to an intermediate-frequency signal below 2 GHz. The receiver is able to detect signals from 30 to 160 GHz with a 2-Hz resolution. The detector chip is fabricated in TSMC 65-nm CMOS technology, occupies an area of 0.56 mm², and consumes 34 mW dc power.

Keywords— CMOS, detector, frequency comb, heterodyne, metasurfaces, millimeter-wave, non-linearity, on-chip antennas.

I. INTRODUCTION

Broadband integrated circuits in mm-wave and terahertz frequencies provide low-cost and compact solutions for novel applications, such as molecular spectroscopy [1] and hyperspectral imaging [2]. Systems based on picosecond pulses have been explored to facilitate such applications [3] and high-speed samplers were investigated to detect these pulses [4]. Direct CMOS THz detectors based on plasma-wave effect in field-effect transistors have been utilized in building imaging arrays in the mm-wave/THz regime [5]. Non-linearity of these detectors recovers the power of the mm-wave/THz signal, which can be used for imaging applications. However, in order to develop hyperspectral imaging systems or trace-gas spectrometers, coherent detectors are required to extract the frequency content. Sub-harmonic mixers were used in [6] to coherently receive sub-THz signals. High-power LO signals are needed in these mixers to downconvert the received signal to low frequencies and multiple VCOs need to be implemented to cover a wide LO frequency range. A spectrum estimation technique was introduced in [7] that used a number of detectors on various locations on an antenna in order to estimate the received power at each frequency over a large bandwidth. The frequency resolution of this receiver was limited to 1 MHz, which sets the minimum absorption line width in detecting trace gases. The receiver in [8] used two frequency combs, each consisting of 10 tones, to perform dual-comb spectroscopy over a 100-GHz bandwidth. Each of these tones is generated by a separate upconversion chain so the chip area increases substantially with the number of comb tones and the bandwidth.

In this paper, an mm-wave coherent detector is presented that uses a non-linear high-speed switch to generate a broadband mm-wave frequency comb with tunable spacing. A broadband heterodyne detector based on an NMOS transistor utilizes the reference comb as an LO signal to downconvert the received tones to distinguishable low-frequency components. The detector, which is integrated with a broadband on-chip antenna, is operated from 30 to 160 GHz,

where the maximum frequency is limited by measurement equipment.

II. COMB-BASED COHERENT DETECTION

The fundamental concept of this comb-based detector is illustrated in Fig. 1. A broadband frequency comb with equally spaced tones in the mm-wave regime is used as a reference to downconvert the received signal to intermediate frequencies. The time-domain waveform of such a comb is an ultra-short pulse train with repetition frequency of f_{rep} , equal to the frequency spacing of the comb. A slight difference between the repetition frequencies of the RF and LO signals creates a unique difference between every adjacent pair of RF and LO tones, as shown in Fig. 1. Therefore, by mixing the LO and RF signals, an IF comb with repetition frequency of Δf is generated. Each tone in this IF comb uniquely represents one of the tones in the RF comb. The circuit schematic of this chip is depicted in Fig. 2. An external clock is fed to the input of the frequency comb generator circuit to set the repetition frequency of the LO signal. The repetition frequency can be tuned from low frequencies (100 MHz) up to 6 GHz.

A. Frequency Comb Generator

The mm-wave frequency comb which is used as a reference in this system is generated by fast switching of a transistor. A series of inverter stages sharpen the clock signal at the input by reducing the rise and fall times of the signal which sets the repetition frequency of the comb. Two stages of switching transistors with transmission line loads follow the inverters chain. The first switch is turned on and off by the clock signal to generate voltage spikes for driving a fast switching transistor loaded with a 150- μm transmission line. A similar method has been used in [3] to radiate picosecond pulses. The fast switching that happens at the rising edge of

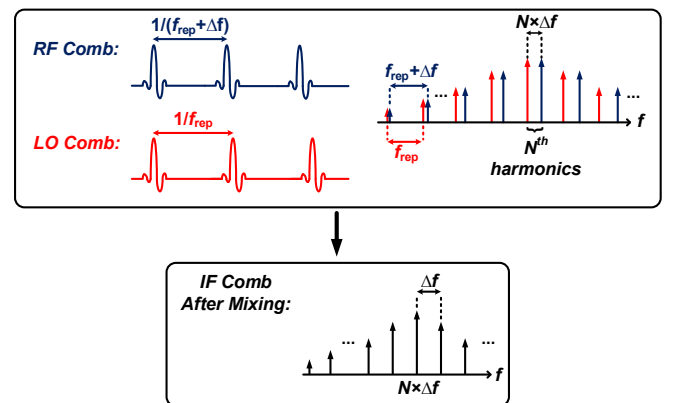


Fig. 1. Broadband mm-wave detection technique using frequency combs.

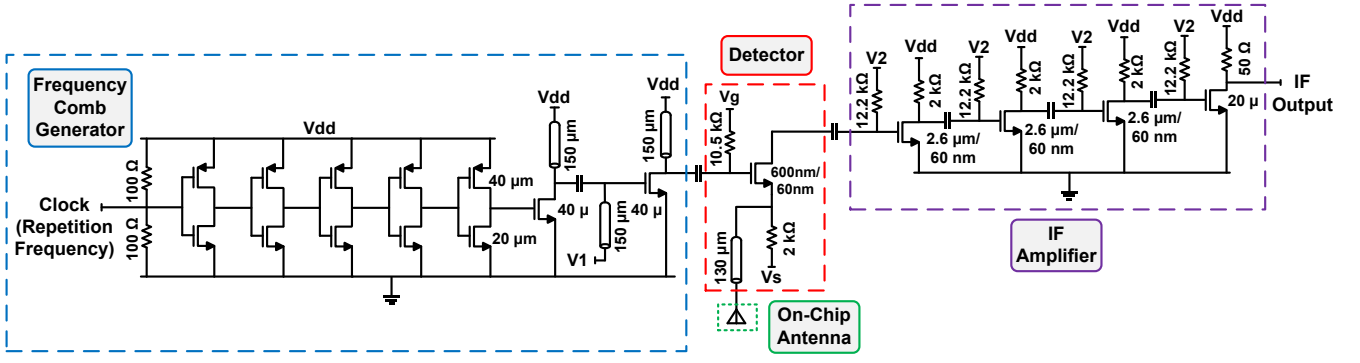


Fig. 2. Circuit schematic of the comb-based coherent detector.

the clock generates a short impulse with a broadband comb-shaped spectrum centered at 120 GHz. The spacing between the frequency comb tones is equal to the repetition frequency. This reference signal is used as a tunable frequency ruler to downconvert received frequency tones over a wide bandwidth.

B. Heterodyne Detector

An NMOS field-effect transistor with width-to-length ratio of 10 is directly connected to the feed of the on-chip antenna to be used as a heterodyne detector. The received signal from the antenna is fed to the source and the LO signal is fed to the gate of the transistor. These two mm-wave/THz signals modulate the gate-source voltage of the FET transistor, which produces a low-frequency IF signal between the drain and the source. This mixing operation is based on the non-linearity of the device and resistive mixing observed in FET channel in the mm-wave/THz regime. Incoming waves can be detected up to frequencies higher than $f_{\max}$ of the transistor by exciting carrier density waves in the FET channel. This detection mechanism can be exploited for heterodyne detection where there is a frequency difference between the gate and source signals [9]. In this detector, the RF signal received by the antenna, is downconverted using the LO frequency comb. The IF signal is then amplified using a baseband amplifier with a simulated gain of 15 dB and 3-dB bandwidth of 1.9 GHz. Δf should be selected in a way that the entire IF tones fall within this frequency range.

C. On-Chip Elliptical Antenna

An elliptical antenna, illustrated in Fig. 3, is implemented on the chip to receive frequency tones in a broad frequency range. Mm-wave on-chip antennas usually take advantage of a silicon lens on the backside of the chip to improve the efficiency. In this chip, a periodic metasurface structure is implemented on the first metal layer to enhance the directivity of the on-chip antenna by acting as a high-impedance surface. A metasurface is a periodic planar structure in which the pattern period is much smaller than the operating wavelength. Metasurfaces exhibit interesting electromagnetic behaviors, such as small refractive index and high impedance, in selective frequencies. Eleven stripes made of copper with widths and gaps of 25 μm are implemented on the bottom layer of the metal stack to improve antenna efficiency by hindering the propagation of surface waves in lossy silicon substrate. Due to process design rules, each stripe is divided into five smaller stripes in parallel. The simulation results using IE3D solver are plotted in Fig. 3 where the antenna gain improvement after using the metasurface is clear. The simulations are done with a ground

shield beneath the chip for the frequency range in Section III.A measurements.

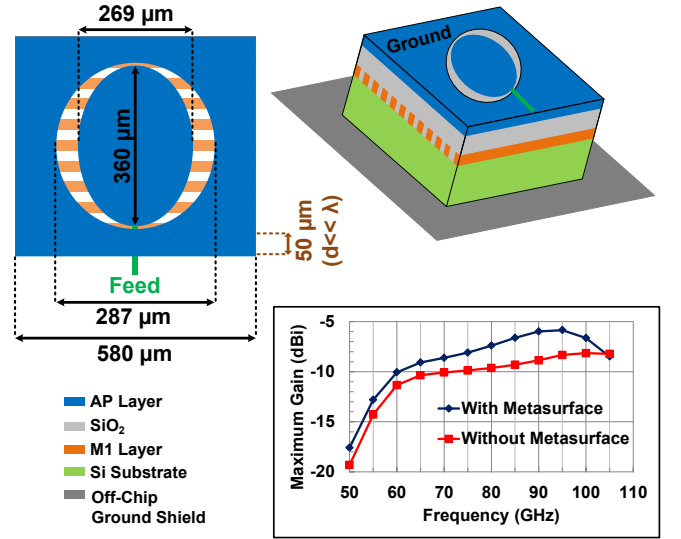


Fig. 3. Structure and simulated gain of the on-chip elliptical antenna including a metasurface for enhanced performance.

III. MEASUREMENTS

This comb-based detector is fabricated in TSMC 65-nm CMOS technology. The chip micrograph is shown in Fig. 4. To characterize the performance of the receiver over a wide frequency range, multiple signal sources are used. These experimental setups are shown in Fig. 5. In these tests, V_{GS} of the FET detector is set to 0.46 V for biasing the detector in non-resonant broadband detection mode with highest output voltage.

A. Detector Characterization

In the first setup, a Keysight signal generator is connected to standard horn antennas to radiate CW signals up to 70 GHz. For higher frequencies, a Millitech active multiplier chain is connected to a horn antenna to radiate CW signals from 75 to 110 GHz. The detector is operated with repetition frequency (f_{rep}) of 5 GHz to generate a reference frequency comb with spacing of 5 GHz. By sweeping the CW frequency, the IF output is observed when the CW tone is mixed with its adjacent tones and is downconverted to a low-frequency IF signal.

Measurement results of the CW tests are shown in Fig. 6. Fig. 6(a) and 6(b) show the conversion loss and sensitivity of the receiver when f_{IF} is fixed at 25 MHz but f_{RF} is changing. The conversion loss and sensitivity calculations are based on

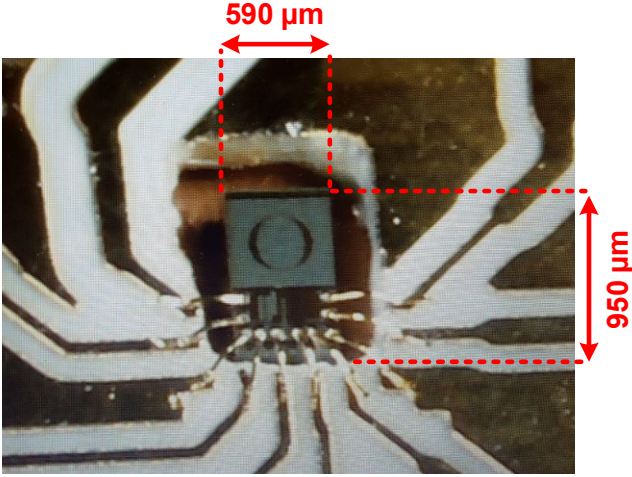


Fig. 4. Photo of the comb-based coherent detector assembled on a board.

Friis transmission equation, measured output power, source output power (+11 dBm), and horn antenna gain (+24 dBi). The conversion loss values include the on-chip antenna gain and the loss of the receiver circuit. Fluctuations in the conversion loss are caused by the antenna gain pattern but they will not degrade spectroscopy or sensing applications since the IF power will be measured before and after injecting a gas at a given frequency. The sensitivity of the detector is determined by the minimum detectable IF output. This minimum detectable IF output is equal to the output noise floor of the detector with resolution bandwidth of 1 Hz, which is -122 dBm. The repetition frequency (f_{rep}) of the detector is swept in the third plot, while f_{RF} and f_{IF} are set to 90.025 GHz and 25 MHz, to verify the tunability of the reference comb. As f_{rep} gets smaller, the power spreads into more tones so the power of each LO tone and the conversion gain get smaller. Fig. 6 (d) shows the conversion loss for different IF frequencies when $f_{RF} = 80 \text{ GHz} + f_{IF}$. As it has been discussed in [9], the output power of the heterodyne detector drops as f_{IF} gets larger because of the high resistance of the FET channel.

B. Dual-Comb Detection

A silicon chip based on direct digital-to-impulse generation technique, which was reported in [3], is used to radiate a frequency comb with equally spaced tones beyond 110 GHz. The comb spacing is set to 5 GHz and is locked to a Keysight signal generator. In this test setup, shown in Fig. 5, the detector is operated with a repetition frequency of 5.011 GHz ($\Delta f = 11 \text{ MHz}$). Two mm-wave Polyethylene lenses are placed at their focal lengths from the source and detector chips to collimate the radiated beam and then focus it on the detector

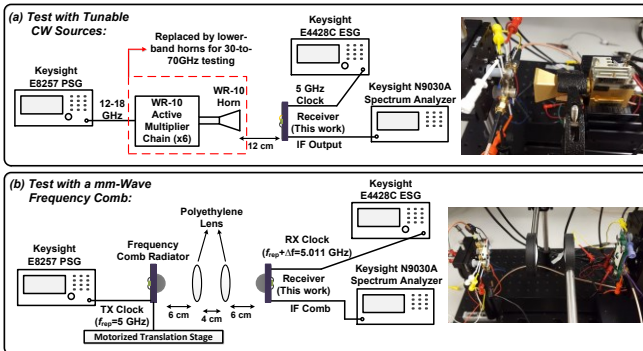


Fig. 5. Measurement setups for characterizing the coherent detector with tunable CW sources as well as an mm-wave frequency comb radiator.

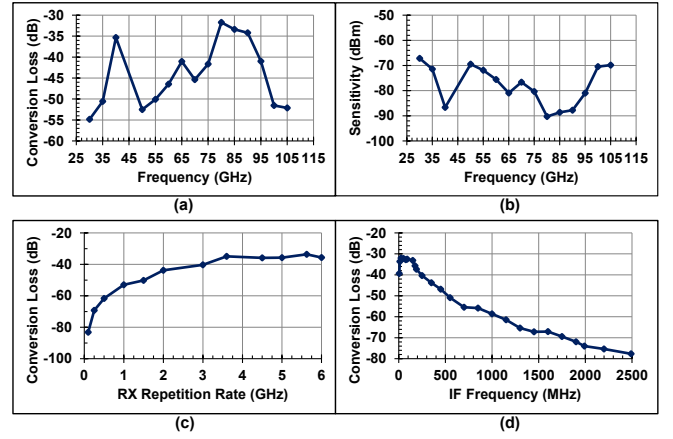


Fig. 6. Measurements results of detector characterization tests: (a) conversion loss and (b) sensitivity for various RF frequencies; (c) effect of the repetition frequency on the conversion loss; (d) conversion loss variation for various IF frequencies. Conversion loss is derived as ratio of the IF output power to the received power ($P_t \times G_t \times [(\lambda/4\pi R)^2]$) and it includes the on-chip antenna gain. Sensitivity is calculated as the minimum detectable received power ($P_t \times G_t \times [(\lambda/4\pi R)^2]$).

chip. In this test, a silicon lens is attached to the backside of the RX to increase the antenna efficiency, due to the small received power. Since repetition frequencies of the source and the detector have a slight difference (11 MHz), each transmitted tone will be downconverted to a unique tone in the IF output (see Fig. 1). Fig. 7 depicts one of the measured tones at the output of the detector. This 154-MHz IF tone corresponds to the $154/11 = 14^{\text{th}}$ tone of the frequency comb, which lies at 70 GHz. It has a line width of less than 2 Hz, which verifies the high precision in recovering frequency tones. The recovered frequency comb in this measurement is plotted in Fig. 8. The highest frequency that could be downconverted in this test is 160 GHz. By tuning the repetition frequency of the LO accordingly, the detector can successfully detect every frequency tone from 30 to 160 GHz with resolution of 2 Hz. Therefore, the receiver can be used as a broadband spectrometer to detect frequency tones with 2-Hz resolution, or as a dual-comb spectrometer to detect gases with absorption lines as small as 2 Hz.

IV. CONCLUSIONS

A novel 30-to-160GHz coherent detector is demonstrated in 65nm CMOS that uses an on-chip frequency comb as its reference. The frequency comb is locked to an external sub-

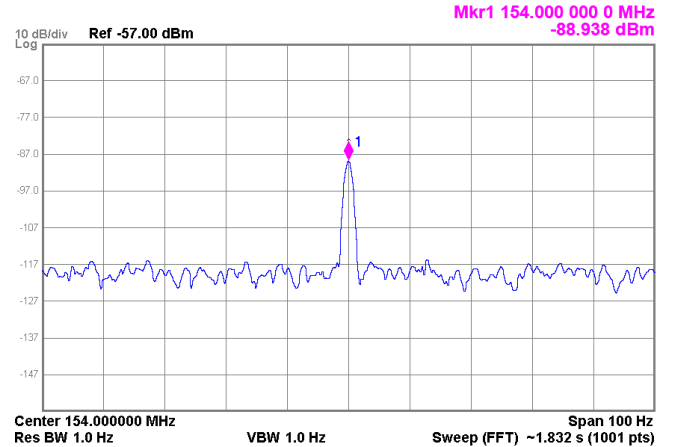


Fig. 7. An IF tone at the output of the detector which is produced by downconverting a received tone at 70 GHz.

Table 1. Performance comparison with state-of-the-art coherent mm-wave/terahertz detectors in silicon

	ISSCC '16 [6]	ISSCC '16 [7]	ISSCC '17 [8]	This Work
Process	130nm SiGe BiCMOS	130nm SiGe BiCMOS	65nm CMOS	65nm CMOS
Receiver Method	Coherent (Sub-harmonic)	Spectrum Estimation	Coherent (w/ Frequency Comb)	Coherent (w/ Frequency Comb)
Frequency (GHz)	320	40 to 330	220 to 320	30 to 160
Bandwidth (GHz)	3.9	290	100	130
Frequency Resolution (Hz)	N/A	10 M	380 k	2
Antenna	On-Chip Patch	On-Chip Log-Periodic	On-Chip Folded Slot	On-Chip Elliptical
Area (mm ²)	3.06 (Array of 8)	4.94	6.0 (TX+RX)	0.56
DC Power (mW)	117	212	1700 (TX+RX)	34

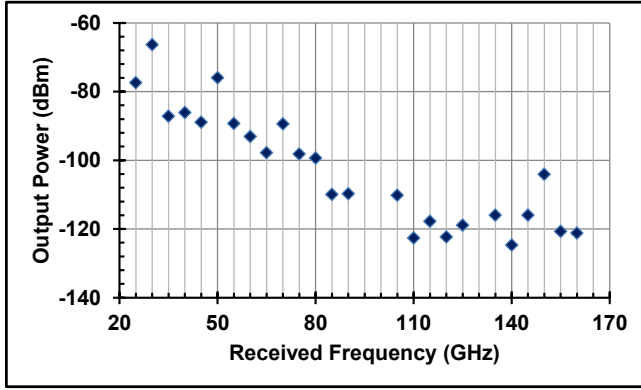


Fig. 8. Measured output tones of the receiver in a dual-comb test with a frequency comb radiator.

6GHz signal that sets its tunable repetition frequency. The tunable comb is used as a frequency ruler to downconvert mm-wave frequency tones to intermediate frequencies between 10 MHz and 1.9 GHz. A heterodyne FET detector mixes the received signal with the on-chip frequency comb. An on-chip elliptical antenna with a metasurface bottom layer receives the radiated signal and feeds it to the source of the heterodyne detector. This chip consumes 34 mW from a 1.2V power supply. Measurement results show a 2-Hz line width on the detected tones, which sets the minimum detection resolution. Table 1 compares the performance of the reported mm-wave detector with other coherent mm-wave/THz receivers in silicon [6]–[8]. This detector can coherently detect any frequency tone from 30 to 160 GHz with a resolution that is only limited to the line width while consuming a low power consumption. Therefore, this chip can be utilized in high-resolution mm-wave sensing and spectroscopy applications. Integrated systems based on the presented comb generation and heterodyne detection techniques demonstrate strong potential in developing broadband coherent detectors in the mm-wave/THz regime.

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