In the doubler mode, an NMOS pair is driven differentially at serves as a radiating frequency doubler and a subharmonic mixer simultaneously. In the AMP, the energy efficiency is further improved with multifunctional narrowband operation also eliminates the aforementioned bandwidth-scalability to higher bandwidth with extended cascading of narrowband channels. The proposed comb architecture enables seamlessly cover 220-to-320GHz band. The narrowband operation is achieved at the expense of degraded radiated power (0.1mW) and noise figure (NF=18.4 to ~23.5dB). In addition, a 14GHz bandwidth in [3] and [4], broader bandwidths are achieved with the same tunable tone. The drain voltage associated with the differential mode at /4 resonators, Slot1. In these AMPs, phase and amplitude imbalance of baluns (Fig. 17.6.1) deteriorate the efficiency and LO-leakage rejection. Figure 17.5.3 shows an on-chip balun using orthogonal-mode filtering similar to that in Slot2 (Fig. 17.6.2). Only the fully differential quasi-TEM wave is allowed to propagate from the input port to the perfectly symmetric output ports of the balun. This mechanism leads to near-zero imbalance between the two output ports, which is verified by the simulation results in Fig. 17.6.3. Figure 17.6.3 also shows the up/down mixer for comb-spectral generation. Up and down frequency conversions are achieved by selected combination of quadrature signals at fi and 5GHz. In simulation, the LO and image rejection is better than 30dB, and the conversion loss is 2.3dB. The 5GHz I/Q signals are generated by a digital frequency divider inside each mixer.

The chip is implemented using a bulk 65nm CMOS process. A hemispheric silicon lens, rather than a hyper-hemispheric one, is used for its small sensitivity to position offset. The chip DC power is 1.7W. Each AMP is characterized independently with the bias of other AMPs turned off to entirely eliminate irrelevant radiation. The antenna pattern is measured by a VDI WR-3 even-harmonic mixer (EHM) with a horn antenna at 10cm distance. Figure 17.6.4 shows the antenna pattern for the AMP at 265GHz. The average directivity of the 10 AMPs is 10.1dBi. The equivalent isotropically radiated power (EIRP) of each comb line is measured using a FM4 power meter. The total radiated power of the 10 comb lines is 5.2mW (24±75GHz, f0=10GHz). The average noise power of the 10 comb lines is ~12dBc/pW at 1MHz offset. By measuring the conversion gain using an OML WR-3 frequency extender and the noise floor in the receiver mode, 14.6 to ~19.5dB SSB NF is obtained under zero AMP bias current. The calculation of NF uses the power received by the AMP antenna aperture, hence includes the antenna loss but de-embeds the performance improvement due to the beam collimation. Lastly, Fig. 17.6.5 presents a spectroscopy setup for the sensing of acetonitrile (CH3CN) with pressure of 3Pa. One measured spectral section from 275.5 to 276GHz is shown, which agrees with the JPL molecular spectroscopy catalog [6]. An absorption line at 275.8671GHz is obtained using direct transmission as shown in Fig. 17.6.5. To further eliminate the standing wave formed inside the gas chamber, wavelength modulation with modulation frequency fi, of 50kHz, frequency deviation Δ of 240kHz is applied in one comb. The second-order derivative of the same spectrum line is then obtained by measuring the output signal at fi, from another comb, which shows a line width of 380kHz, demonstrating the absolute detection specificity. Figure 17.6.6 shows the comparison table with other state of the art systems implemented in silicon and operating above 200GHz. Through rapid combing of the spectrum, a high energy efficiency of 0.17mJ/point (1ms integration time) is achieved, demonstrating a new path for broadband sensing via parallelism.

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Millimeter-wave/terahertz rotational spectroscopy offers ultra-wide-detection range of gas molecules for chemical and biomedical sensing. Therefore, bandwidth, energy-efficient, and fast-scanning CMOS spectrometers are in demand. Spectrometers using narrowpulse sources and electromagnetic scattering [1] are broadband, but their resolutions do not meet the requirement (<10kHz) of the absolute specificity. Alternatively, a scheme using a single tunable tone exhibits significant trade-off between bandwidth and performance. The 245GHz spectrometer in [2] presents 4mW radiated power, but only has a 14GHz bandwidth. In [3] and [4], broader bandwidths are achieved at the expense of degraded radiated power (0.1mW) and noise figure (NF=18.4 to ~23.5dB). In addition, a typical 10kHz resolution and 1ms integration time, scanning a 1GHz bandwidth with a single tone takes as long as 3 hours. This paper reports a rapid, energy-efficient spectrometer architecture based on dual-frequency-comb scanning. A 220-to-320GHz CMOS spectrometer prototype based on this architecture is demonstrated with a total radiated power of 5.2mW and a NF of 14.6 to ~19.5dB.

The spectrometer shown in Fig. 17.6.1 consists of two identical comb chips with a fixed frequency offset fi. From each comb, 10 frequency lines are transmitted through the gas sample and are simultaneously used as a local-oscillator (LO) signal for the heterodyne mixing of the wave from another comb. The maximum scanning speed of a single-tone spectrometer with certain sensitivity is determined by the probing signal power, which is fundamentally limited by the population saturation of molecular states. In comparison, in a comb, each probing channel reaches such maximum speed, leading to a much shorter total scanning time through parallel operation. Each comb chip is driven by a tunable reference signal, fi, (45 to 46.67GHz). This signal is tripled to 3fi, (135 to 140GHz) and power-divided into up- and down-conversion chains. The chains produce tones evenly spaced every 5GHz using an external clock signal f0, which is frequency-divided by 2 inside every up/down mixer. Each tone is then doubled and radiated by an active-molecular-probe (AMP) block. The final 10 comb lines located at 6fi,±10GHz (i=-5…+4) are simultaneously radiated from the chip backside and seamlessly cover 220-to-320GHz band. The proposed comb architecture enables scalability to higher bandwidth with extended cascading of narrowband channels. The narrowband operation also eliminates the aforementioned bandwidth-performance trade-offs in circuits.

In the AMP, the energy efficiency is further improved with multifunctional structures and optimum device feedback. Shown in Fig. 17.6.2, the AMP core serves as a radiating frequency doubler and a subharmonic mixer simultaneously. In the doubler mode, an NMOS pair is driven differentially at fi. The drain voltage swing is boosted via two λ/4 resonators, Slot1. At Zref, in-phase standing waves are formed inside Slot1, which acts as a folded slot antenna with a simulated radiation efficiency of 45%. Next, Slot2, which supports the quasi-TEM wave associated with the differential mode at f0, partially reconfigures the amplified signal back to the input. When harmonic signal at 2f0, is generated at the NMOS drains, the TM wave associated with its common mode is rejected in Slot2. That prevents the leakage of f0 signal into the lossy gate through the feedback path. The amplitude and phase of the recycled signal at f0 is controlled by the characteristic impedance and phase of TL1 and Slot2. Shown in Fig. 17.6.2, their optimum values (ZTL1=50Ω, θTL1=55°, ZSlot2=80Ω, θSlot2=88°) enable in-phase addition between input and recycled waves without causing instability. Compared to conventional designs without feedback, the simulated doubler conversion efficiency at 275GHz increases from 18% to 43%. In the mixer mode, the input wave at 2f0 is coupled into the heavily driven transistors via the folded slot antenna (Slot1). Both the input signal and the LO signal at f0 are in common mode, which enable the extraction of the combined, down-converted signal f0 through an integrated RF chock. The simulated single-sideband (SSB) NF is 20.2dB at 275GHz and is improved to 16.3dB when the transistor drain-bias current is zero due to lower thermal and flicker noise.
Figure 17.6.1: Dual-frequency-comb spectrometer in CMOS.

Figure 17.6.2: Active-molecular-probe (AMP) block.

Figure 17.6.3: Slot balun and up/down-conversion mixer.

Figure 17.6.4: Measurement results of the chip.

Figure 17.6.5: Spectroscopy for molecular sensing.

Figure 17.6.6: Die micrograph and performance comparison table.