CMOS Receivers for Active and Passive mm-Wave Imaging

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ABSTRACT

This article discusses recent advances in CMOS-based mm-wave receivers for both passive and active mm-wave applications. System level configurations including scanning and array configurations are discussed as well as the advantages of pre-amplification vs. simple detection for active and passive imaging applications. Finally, several recent mm-wave receviers implemented in CMOS technology for both passive and active imaging applications are reviewed in detail.

AN OVERVIEW OF MM-WAVE IMAGING SYSTEMS

Imaging at millimeter-wave (mm-wave) frequencies has recently gained interest for applications ranging from security screening to bio-imaging and spectroscopy. Unlike other regions of the electromagnetic spectrum, mm-wave offers the unique ability to penetrate clothing and other textile materials, enabling new approaches for weapon and contraband detection. Additionally, the transmission and reflective responses of many materials have distinct features within the mm and sub-mm wave bands, allowing for the possibility of remote material identification [1]. Such systems could potentially detect explosives, poisonous materials, and other chemical threats from several meters away. While the basic building blocks of mm-wave imaging systems are similar to those used in wireless communications (transmitters, receivers, detectors and antennas, etc.), the configurations and requirements for mm-wave imaging are quite different. Unlike mm-wave communications that wirelessly transmit and receive modulated signal/data through an mm-wave carrier, mm-wave imagers detect features of an object based on its radiation, reflection or absorption properties in the mm-wave spectrum.

Traditionally mm-wave imagers were implemented in III-V compound semiconductor technologies for their superior noise and high-frequency performance when compared with silicon counterparts [2–4]. Although a III-V based imaging system does offer higher performance, it also has its own limitations including excessive pixel power consumption, limited integration in forming two-dimensional receiver arrays, pixel readout circuits, and digital signal processing (DSP) electronics. In response to many emerging applications of mm-wave imaging and the limitations of III-V technology, the silicon community has proposed several approaches to implement mm-wave imaging systems in complementary metal oxide semiconductor (CMOS) technology based on both simple detector [5] and pre-amplified detector approaches [6–8]. Each of these approaches provides solutions to address the fundamental challenges of mm-wave imaging systems in operation modes, detection time/range, power consumption, and portability.

There are several challenges that must be overcome to realize mm-wave imaging systems in CMOS. First, illumination source (i.e., transmitter) power in active imaging remains quite limited in silicon, so high receiver sensitivity is extremely crucial to balance the link budget for longer-range or stand-off imaging applications. Second, detection or receiving at higher frequencies (> 100 GHz) can lead to higher image resolution based on wavelength diffraction considerations of available optics. Limited by intrinsic device gain near cutoff frequencies (f_{max} and f_t), the CMOS low noise amplifier's (LNA's) gain is relatively low above 50 GHz, which becomes a major drawback to high resolution imaging system design. Third, wide front-end bandwidth and high detector responsivity are essential to achieve high quality passive mm-wave imaging due to the extremely weak received signals. Such performance is again more difficult to be obtained in CMOS due to its limited gain-bandwidth product versus that of III-V devices. The noise performance of CMOS detector is further exacerbated by it's stronger presence of flicker (or 1/f) noise, which requires additional circuitry to calibrate and compensate.

Despite all of its challenges, CMOS mm-wave imaging is still highly desirable due to its compatibility with mainstream integrated circuit (IC) technology and its great promise to offer a low-power, fully integrated, and compact system-on-a-chip (SoC) solution for mm-wave imaging systems.

IMAGING SYSTEM CONFIGURATIONS

The detection of objects based on mm-wave radiation or reflection/absorption can be divided into three separate approaches [1] as shown in

Fig. 1, each with a unique set of requirements placed on the mm-wave detector circuitry and its supporting optics.

The first approach, commonly named *transmissive imaging* and depicted in Fig. 1a, is relatively straightforward when compared to other approaches. A target is placed between a transmitter and receiver. The attenuation or blocking of the target at mm-wave frequencies is then measured at multiple points in space to construct an image. While this is the simplest type of imaging, it inherits a major disadvantage of requiring the system to surround the target for remote security screening and contraband detection.

The second approach, shown in Fig. 1b, is to focus the source of mm-wave illumination (transmitter) into a narrow beam, then reflect the signal off the surface of a remote target and return it back to a receiver. This approach is commonly called *backscatter* or *reflective* imaging. The reflection coefficient information at different points in space is utilized to create an image. While this is conceptually simple, the signal must travel the path twice (forward and backward) in free-space and makes the link budget more difficult.

The third approach, commonly called "passive imaging," is shown in Fig. 1c. It constructs imaging by detecting subject's own blackbody radiation, without the need of mm-wave radiation sources or any compliance to FCC regulations. That can simplify the system and facilitate its wide applications. However, passive imaging is considered to be the most difficult approach in mm-wave imaging systems because it must detect the emitted thermal noise kT from the target, where k represents the Boltzmann constant and T represents the absolute temperature measured by Kelvin (or K). While the concept seems relatively simple as compared with communication links, it is actually quite challenging as the temperature variation across a typical scene (contrast ratio) may vary only by a few K. Since scene content varies by such small temperatures a passive mm-wave imager requires <1K in temperature resolution to capture usable images for object detection. One major challenge is that this level of thermal resolution often corresponds to several orders of magnitude lower than the receiver's input referred noise. For this reason, techniques such as double-sampling and long windows of integration must be implemented to process the receiver noise to levels where the target small temperature difference becomes detectable. One extremely important application of passive mm-wave imaging is the radio-telescope used for astronomical study, where the noise integration window typically lasts several weeks per frame [1].

The scanning or capturing configuration of an imager is another important issue. Regardless of imager type (transmissive, reflective or passive), measurements must be performed at multiple points in space for image construction. To obtain sufficiently high image quality for typical security or weapon detection applications, the required measurement points may approach a very large number ($> 10^5$ pixels), which would seriously challenge the system's power consumption and form factor as indicated in the later sections.

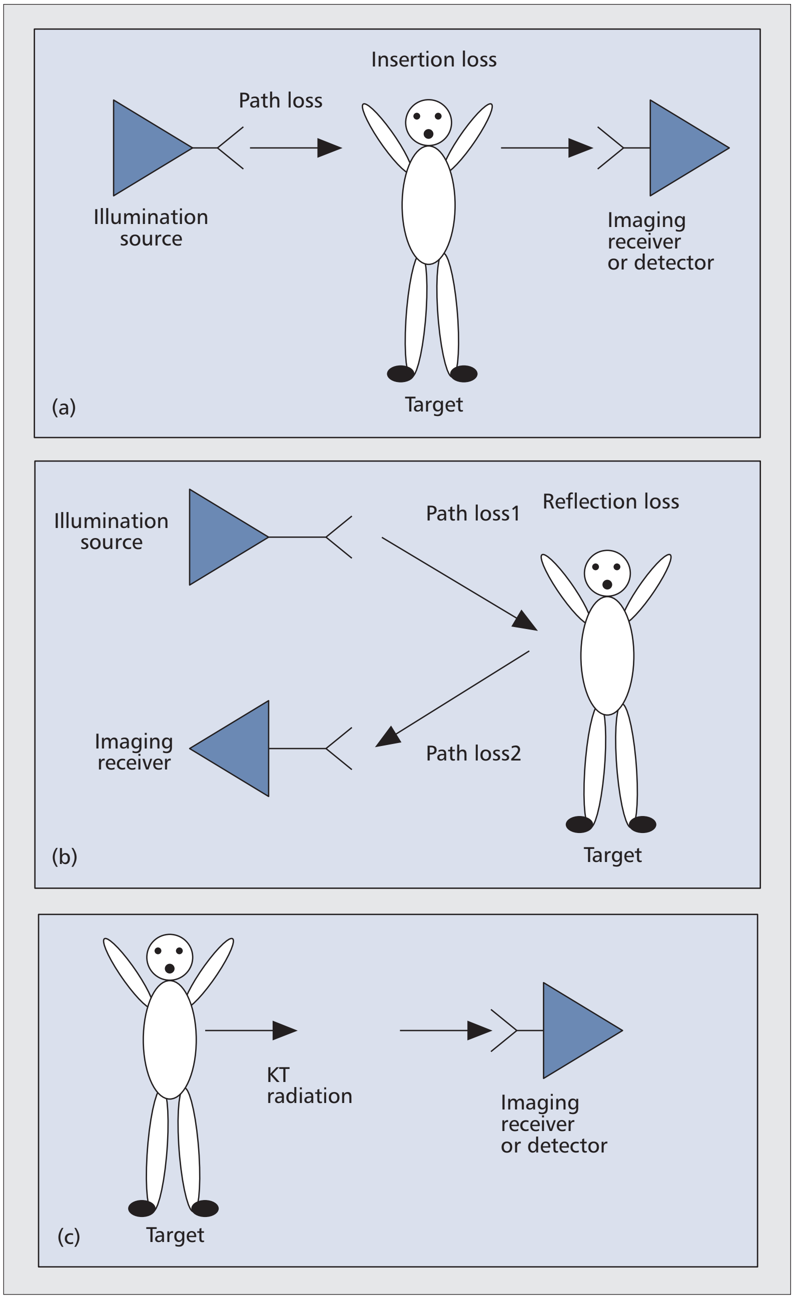

Figure 1. *a) Transmissive mm-wave imaging system; b) reflective (backscattering) mm-wave imaging system; c) passive mm-wave imaging system.*

For active imaging, it is possible to create geometries where a single transmitter provides mm-wave radiation that can illuminate all points required to form the image simultaneously. The receiver used to construct the image, however, will still need to be positioned throughout each point in space. The obvious solution to ease the need of high pixel count is time-sharing the same pixel to perform measurements over multiple-points. Based on this time-sharing concept, there are three possible configurations that an mm-wave imaging system may choose.

The first and most obvious configuration is shown in Fig. 2a using a single receiver for either passive or active imaging and letting the target be scanned through optical or beam-forming means. While this is the simplest receiver configuration, it presents several major challenges. The first is to attain a sufficiently small beam-width to facilitate the scanning mechanism so that the imager's resolution can be maintained. The second is to meet the finite frame time requirement for video applications. Since the frame time must be divided among all constituent pixels as shown in Fig. 2 right, it consequently imposes strict limits on the permissible sampling time of the receiver. This requirement on sampling time becomes exceptionally difficult in passive imaging where long integration times, on the order of 1ms, are required for each pixel. An additional consideration is that the optical or beam-forming system becomes very complicated because it must move in two dimensions as opposed to one. For an optical system, this also hinders reliability as it leads to large numbers of moving parts and relatively high power consumption as the optics are in continual motion.

The second option shown in Fig. 2b is to exploit a line or linear scanner, where many receivers are constructed on one chip in a one-dimensional array and scanned in the perpendicular direction. While a line scanner is considered a balance between the other two configurations, it still incurs the problems of both. Pixel sample time is still relatively short for passive imaging, and the system must still incorporate moving optics or beam-forming with extremely fine angular resolution. Using multiple receivers also introduces new problems. The power and area of the receiver is inflated by "n," proportional to the number of pixels in the linear array. The length of the array must fit within the diameter of the wafer to facilitate fabrication on a single substrate and hence further limits the pixel area. While in some systems multiple sections are mechanically combined into one array, this increases cost and complexity and defeats the major advantages of using CMOS. Other issues must be considered, similar to those found in multi-channel communication transceivers, including the antenna coupling, power distribution, and the local oscillator (LO) distribution.

The third and final option is to implement pixels into a two-dimensional array of receivers on one chip (often called a focal plane array), which greatly relaxes pixel's sampling time requirement and with the extra advantage of using non-moving optics. Despite those benefits, it creates difficulty in power and area budgets as

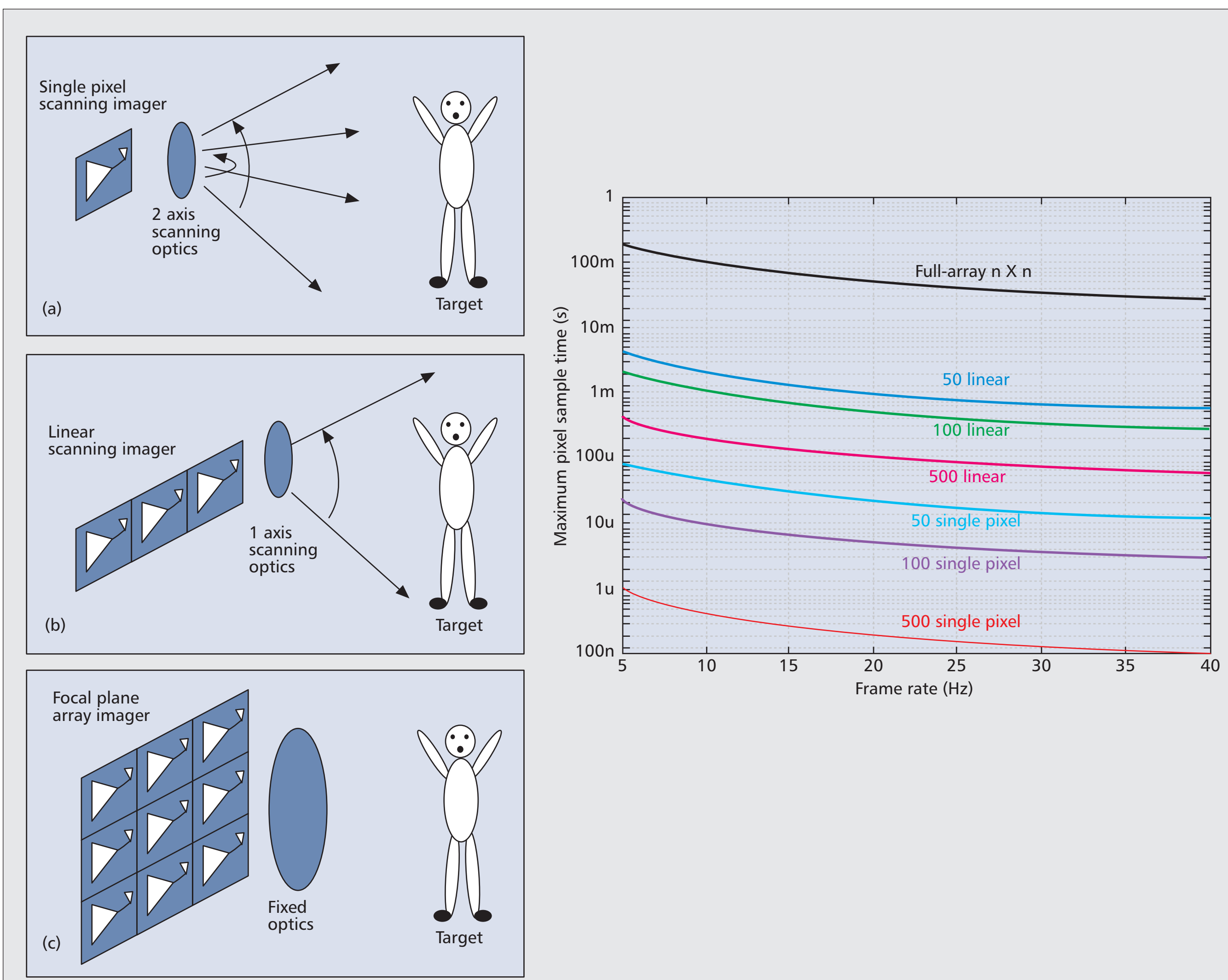

Figure 2. *Scan configurations for mm-wave imaging systems and their timing requirements: a) single pixel scanning imager; b) linear scanning imager; c) full focal-plane array imager.*

the pixel size and power consumption are inflated by n^2. This makes the receiver design particularly difficult. For example, if an array was constructed with receiver that consumes 100mW of power, a 100 × 100 full array would require a kilowatt of power. A $1mm^2$ receiver implemented in a 100 × 100 array would require 10cm × 10cm of chip area. Similar to the linear array, the typical issues of multiple receivers will still need to be considered.

Simple and Pre-Amplified Detection

In communication systems, detection and reception are terms often used to differentiate the received signal-to-noise ratio (SNR), where reception tends to have a higher SNR. Imaging also makes a similar distinction and can be partitioned into simple detection and pre-amplified detection. Figure 3 contains the block diagrams of both a simple detector (left) and a pre-amplified detector (right). While they are similar in construction, the order of the blocks is different.

For mm-wave imaging, the distinction between simple detection and pre-amplified detection is at which the first gain stage occurs. This is critical as it determines not only the noise performance, but the bandwidth and range of frequencies the imager is sensitive to. Amplifiers at mm-wave frequencies are typically narrowband while nonlinear mixing elements can be quite broadband in nature.

In the simple detector (Fig. 3, left), a nonlinear element first translates an incoming signal to a very low frequency (near DC) voltage and subsequently amplifies it by a chain of low frequency amplifiers. As the detector has no pre-amplification, the noise equivalent power (NEP) of the detector is typically up to several . Consequently, the detector's input referred noise is substantially higher than the target thermal noise, limiting its usage for passive imaging applications because of the excessive integration time required to overcome the detector noise. Given the high level of noise, simple detection sensitivity is typically ranged between –30 to –40 dBm, which seriously restrains its use in reflective or backscatter systems. Its front-end element is however non-linear at any frequency and can therefore be operated at frequencies above the device fmax, defined as the frequency at which a device delivers unity power gain. Nonetheless, as the frequency increases beyond fmax, the NEP increases drastically and the responsivity (volts out per watt in) falls off correspondingly. At frequencies beyond 300 GHz, diode based non-linear detectors and self-mixing based linear detectors [5] are employed to maintain useful responsivity and NEP up to 1–2 THz range.

Pre-amplified detectors (Fig. 3, right) behave quite differently from simple detectors as their first stage is made of a low noise amplifier (LNA) allowing suppression of noise from following cascaded stages. For this reason, pre-amplified detectors can achieve much better NEP, as low as 10s of $fW/\sqrt{Hz}$ range. As a result, the pre-amplified detector must operate at frequencies well below f_{max} to ensure sufficient LNA gain. While a wider bandwidth B is desired for the passive imaging to obtain higher received thermal power (KTB), a narrower bandwidth is favored by the active-imaging to increase the receiver sensitivity and decrease the source power requirements. Typical mm-wave pre-amplified detectors' sensitivity ranges are from –50 to –60 dBm. Since all passive imaging and most active mm-wave imaging systems are non-coherent in signal receiving (no phase information required), they can be constructed by using an LNA followed by a detector. The detector simply detects received radiation power from the LNA output so that the attenuation, reflection, or noise measurements can be carried out at very low frequency by a high-resolution and low-speed ADC.

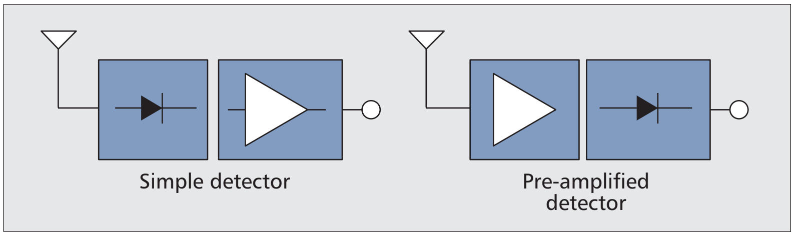

Figure 3. *Simple detector and pre-amplified detector block diagrams.*

CMOS Approaches for Active MM-Wave Imaging

Active mm-wave imaging usually works in either transmissive or reflective mode. In transmissive mode operation, as an example shown in Fig. 4, a target is placed between a source and a simple detector or pre-amplified detector. The attenuation of the source illumination is then measured at each point of the perpendicular plane to produce an image. This is by far the easiest in terms of meeting the system link budget as the free-space travel is only in one direction, keeping the path loss lower than that of the reflective one. This type of system is typically implemented by using a CW source, a lens in the "optical" path for beam focusing and a detector/pre-amplified detector array. Typical power needed for the CW source is between 5–10 dBm and the detector/ pre-amplified detector sensitivity is projected to be –30 to –40 dBm. With a path-loss of 10 dB typically for a 10 cm target distance, this provides an SNR of 30 to 40 dB which is more than sufficient for capturing details of small objects. For example, [5] presents a transmissive mode detector array, operating at 650 GHz in a 0.25 μm CMOS process to capture object image inside an envelope, by using a 0 dBm source over a gap distance of 10 cm. The detector itself is made of a single MOS device to sense the signal by a resistive self-mixing technique.

Reflective or backscatter mode imaging is much more difficult than its transmissive counterpart as the path loss is doubled (the signal must first travel from the imager to the target, then reflect back from the target to the imager) and the reflection coefficient of most materials is on the order of –20 dB, which further exacerbates the link budget. Considering the same illumination power of 10 dBm as in the previous

Speckle results from constructive and destructive interference of reflective waves from different surface depths. Several approaches are being proposed to reduce speckle with imaging at multiple frequencies and averaging received results to alleviate surface interference.

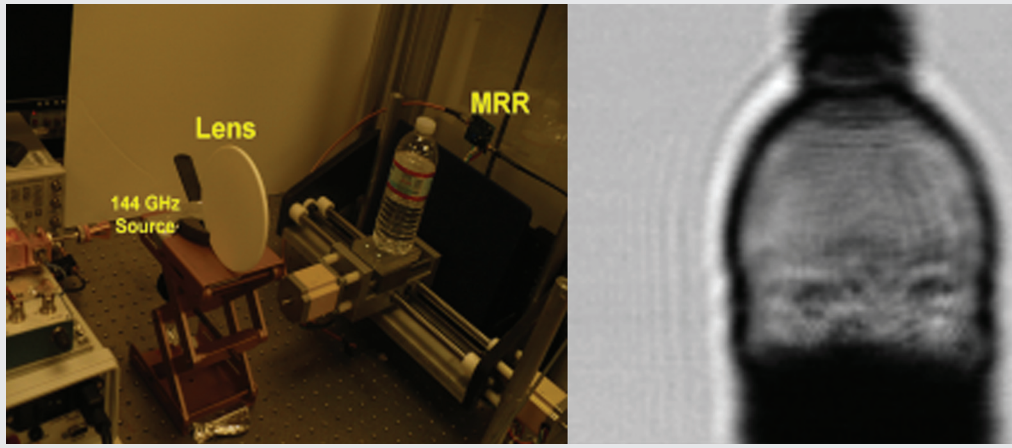

Figure 4. *Transmissive mode imaging and capture from a multi-regenerative receiver (MRR) imager at 144 GHz [10].*

transmissive case, a path loss of –20 dB for a similar target distance and a reflection coefficient of –20 dB (typical clothing), the received power at the imager would be only –50 dBm, which is far too low for detection based schemes. Modulation of the source can be used to improve detector sensitivity by moving the operating point away from the device flicker noise but the source bandwidth quickly becomes the limiting factor. Even with modulation, the best detectors are still limited to around –45dBm sensitivity [6]. A typical reflective imaging setup and its testing results are shown in Fig. 5a. With a –50 dBm received power, an imager sensitivity of –60 to –70 dBm is needed for a large enough SNR (about 10 to 20 dB) for image construction.

Although a conventional receiver with an LNA can be used for enhancing backscattering performance [8], it becomes very difficult for constructing an imaging array. Conventional receivers consume high-power and area due to their high stage-counts, large bias currents and inductive loads all necessary to achieve useful gain above 100 GHz.

In contrast, [9, 10] presented an alternative approach by using super-regenerative CMOS receivers to act as an imaging pixel. Unlike other receiver topologies, the super-regenerative receiver uses a single-stage topology and senses changes in the startup time of an oscillator to provide gain at mm-wave frequencies. One major advantage of this approach is that it can operate at frequencies much closer to device's maximum oscillation frequency of fmax, as it does not directly rely on device gain for amplification.

Figure 5b illustrates the operation of a digital regenerative receiver (DRR) with a super-regenerative front-end but a novel time-encoded digital output scheme. The receiver invented by the authors functions as the latch is first set by the system digital clock edge for engaging the oscillator. Once the oscillation envelope rises beyond a prescribed threshold, the envelope detector will be agitated to reset the latch and thus quench the rise of oscillation. The DRR principle suggests that the time between the latch set and reset is inversely proportional to the logarithmic input power. This DRR imager, under an illumination source of 183GHz, was tested with –72 dBm sensitivity and 1.4 GHz signal bandwidth. It consumes only 13.5 mW and occupies an area of only 1.31 × 10^4 um^2/pixel. Compared with other approaches, it demonstrates orders of magnitude improvement in NEP, responsivity and power/area consumption. Table 1 compares the performance of the DRR to that of other imaging receivers.

It suggests the DRR can support higher imaging resolution with better sensitivity than that of conventional receivers while also relaxing power and area budget for full array system applications.

Unlike transmission mode imaging, reflective imaging also has additional challenges related to the nature of reflection at mm-wave frequencies. As shown in Fig 5, many artifacts exist producing a low image quality even though the receiver's SNR is as high as 20dB. The first artifact is "image speckle" caused by the narrowband nature of the imager and the comparable source wavelength versus the object's surface feature dimensions. Speckle causes smooth and uniform surfaces to appear rough and spotted in captured images like the bottle in Fig. 5. Speckle results from constructive and destructive interference of reflective waves from different surface depths. Several approaches are being proposed to reduce speckle with imaging at multiple frequencies and averaging received results to alleviate surface interference.

The second and more difficult artifact to remove is "clutter," which is caused by stray reflections from surrounding objects as seen in Fig. 5a. The captured image of the tape roll contains several artifacts which are not in the original scene. Since the antenna itself may have side-lobes, and the optics may also exhibit some reflectivity, it is possible to get radiation returned that is unrelated to the target reflection. The clutter can be addressed by taking images at multiple angles or through double sampling techniques to first capture the known systematic clutter and then subtract it from the captured image.

The third and most difficult artifact in reflective imaging is the issue of "incidence." Placing a

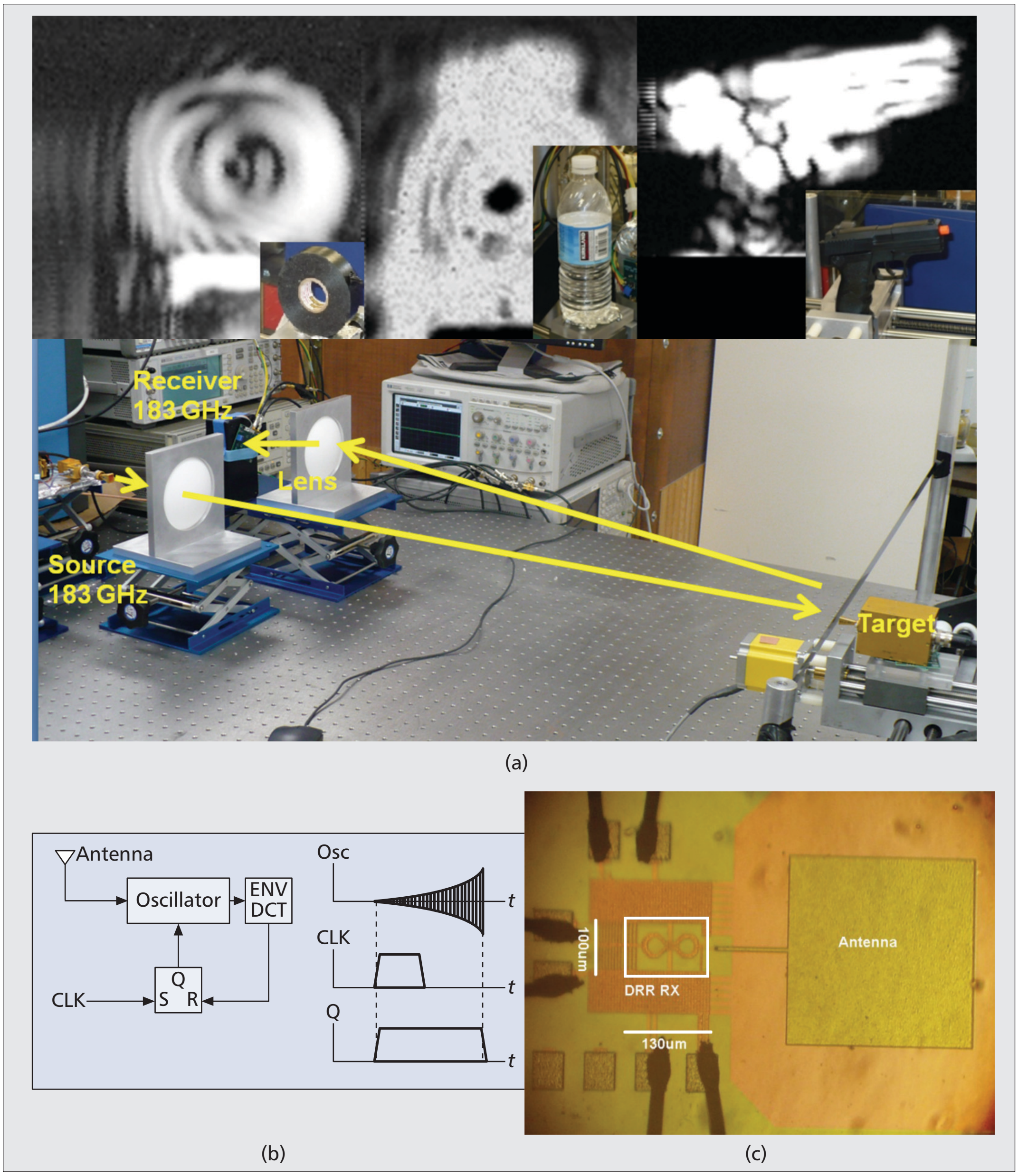

Figure 5. *a) backscatter imaging setup and images of common objects captured at 183 GHz; b) circuit schematic of 183 GHz DRR receiver [8]; and c) die photo of the 183 GHz DRR receiver in 65 nm CMOS*

One simple technique to overcome incidence is to plot the received pixel data on a logarithmic scale instead of a linear scale. While this is easy to implement, it requires much higher SNRs, which again places more challenging requirements on receiver sensitivity and illumination source power.

relatively smooth surface at an off-axis angle to the plane of observation may reflect all the power away from the receiver or detector and create an artificial dark spot. This causes key features such as the handle of the gun in the top-right image of Fig. 5 to evade the image capture and create problems for object recognition in security screening applications. On the other hand, large bright spots can also be created in the image, if the incident energy is concentrated by a curved or concave surface on the target to saturate the receiver. A few solutions have been proposed to address the incidence problem based on known radar techniques, such as range-gating and multiple angle imaging. One simple technique to overcome incidence is to plot the received pixel data on a logarithmic scale instead of a linear scale. While this is easy to implement, it requires much higher SNRs (> 50 dB), which again places more challenging requirements on receiver sensitivity and illumination source power. Other techniques including multi-band imaging and dual-polarized imaging (in which two antenna polarizations are imaged separately) also show some ability to reduce the high incidence contrast of reflective imaging systems.

CMOS Approaches for Passive MM-Wave Imaging

Today's mm-wave passive imaging systems are mainly based on III-V technologies, such as GaAs or InP HBTs/HEMTs [3, 4], which are generally less integrated, thus more sizable and expensive for array applications. To realize a single-chip imager with small form factor and low power consumption, advanced CMOS technology would be a better choice. However, the technology comes with higher substrate, metal and

Feature	[5]	[7]	[8]	[9] (this work)
NEP (pW/ √Hz)	400	0.013	0.2	0.0013
Area (mm^2)	0.03	1.2	0.21	0.0131
Power (mW)	5.5	200	93	13.5
Freq. (GHz)	600	94	94	183
Technology	0.25um CMOS	0.13um SiGe	65nm CMOS	65nm CMOS

Table 1. *Performance comparison of silicon mm-wave imaging receivers.*

contact losses that significantly degrade the Q-factor of on-chip passives (such as inductors, capacitors and transformers) and poorer device gain and noise performance. Flicker noise is another critical issue that can easily overwhelm the low frequency detector and render the selective noise filtering ineffective. CMOS detectors also demonstrated insufficient responsivity for very fine temperature resolution (or noise equivalent temperature difference i.e. NETD). In [11] by using Schottky diodes in CMOS technology, a NEP of 40 pW/√Hz was demonstrated, which would take unreasonably long integration time to resolve the high quality required by passive imaging. In [12], a 90 GHz passive imager is implemented in 65nm CMOS process, with a NEP of 0.11 pW/√Hz and a responsivity of 63 kV/W.

Despite relatively poor silicon-based detector performance, simulation also indicates that as long as the pre-amplifier has enough gain (>40dB), the detector noise becomes unimportant and the system sensitivity (reflected by NETD) is only determined by the pre-amplifier's noise contribution, as represented by the following equation [13]:

$$NETD = T_{SN}\sqrt{\left(\frac{1}{B_T}\right)+\left(\frac{\Delta G}{G}\right)^2}$$

which specifies NETD being inversely proportional to front-end (LNA) bandwidth B, gain G, integration time T, and proportional to gain variation ΔG and the system noise equivalent temperature T_{SN}. The gain variation ΔG is also significant in CMOS technology due to supply, temperature variations and device flicker noise. To minimize ΔG and high flicker noise effect in CMOS, a Dicke switch was used to sample and cancel the gain variation. A Dicke switch is an SPDT switch placed in front of the imaging receiver and alternates between sampling a reference resistor and the incoming signal allowing low frequency noises to be suppressed by cancellation. The detected power is also averaged over a certain integration time to further suppress receiver noise. Dicke switches are typically operated at a higher clock frequency than that of the NMOS flicker noise corner to further eliminate its effect on NEDT.

Figure 6a depicts the CMOS passive mm-wave imager in [14]. It includes both RF/analog front-end and digital back-end. The RF/analog front-end contains an input balun, a differential LNA and detector, filter, PGA, AD converter together with an on-chip Dicke switch. The digital back-end contains a digital multiplier, an integrator and the required digital signal processing. This architecture places a multiplier and an integrator in the digital domain to suppress their flicker noise effect. All circuit related flicker noise, including ADC's, can be sampled and cancelled through the digital multiplier and integrator.

Several challenges reside in passive imager design. First is the design of a high gain, low noise and wide bandwidth LNA, which sets the stage for the overall image system sensitivity and response time. Reference [14] presented a design approach to optimize the LNA performance with a demonstrated noise figure of less than 8 dB. The Dicke switch is another crucial component with its noise and loss directly affecting the receiver noise dB by dB. In [14], we demonstrated a Dicke switch structure based on a fully differential architecture (Fig. 6a) to minimize the insertion loss and facilitate 100GHz imager operation by placing the switch in the return path of the balun, instead of placing the switch directly in series with the signal path. Figure 6c shows the die photo of the integrated W-band passive mm-wave imager with an LNA, Dicke Switch, detector and filter in 65 nm CMOS with a measured NEP of 23fW/√Hz and 26fW/√Hz without or with Dicke switch, respectively. The measured responsivity is larger than100 MV/W. When integrating over 30 ms time, the derived NETD is about 2 K by multiplying with an additional factor of 2 to account for the Dicke switch effect of only half of the clock cycle for signal detection.

While CMOS mm-wave passive imagers have demonstrated promising performance of RF front-end [12–14], no CMOS passive imager system with fully integrated front and back end capable of image capture been demonstrated to date. Assembly and packaging of mm-wave receivers also requires further work. The current on-chip or in-package antenna operates inefficiently at mm-wave frequencies, which directly impacts the passive imager SNR margin. A phased array can improve receiving signal SNR through beam forming techniques and has the potential to relax the tight link budget. An additional issue is how to suppress the on-chip coupling noise and interference from other parts of the system, due to supply and ground coupling, common mode noise and clock leakage, etc. In this regard, fully differential circuit implementation and other isolation techniques become necessary. Many additional noise and interference sources in the environment may also overwhelm the small blackbody radiation from a distant target and hinder the imaging resolution. Phased arrays with sharp receiving beams can relax the issue with tightened power and area budget over each imaging element.

SUMMARY

While CMOS mm-wave receivers have become mature for communication purposes, much work is still needed to meet the stringent

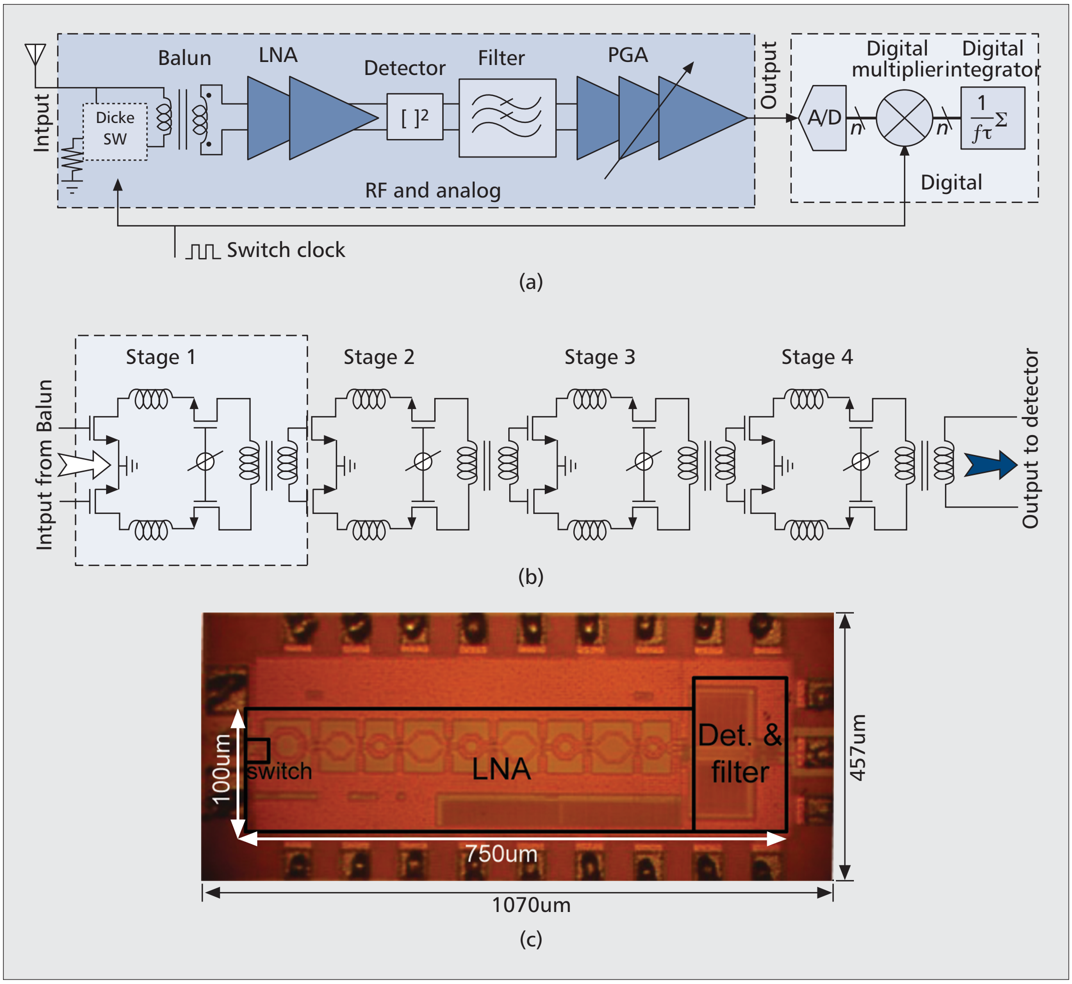

Figure 6. *a) One CMOS passive mm-wave imager structure; b) schematic of full differential cascaded LNA; c) die photo of fabricated W-band CMOS passive imager.*

Even with these challenges, the low power and high level of integration offered by CMOS is anticipated to enable interesting new applications including covert surveillance, low cost, and even portable mm-wave imaging systems which are not achievable with III-V imaging technology.

demands of forming high resolution and low power mm-wave imaging arrays. While detector based imaging has matured to the point where full array active imagers are possible for short-range transmission modes, there is still no clear solution for long-range reflective or backscatter imaging in CMOS technology. Receiver sensitivity, noise performance and carrier frequency must further improve while maintaining a strict power and area budget to make full array reflective systems feasible in CMOS. For passive imaging, no fully integrated CMOS systems capable of image capture have been demonstrated yet, which is mainly due to the stringent SNR margins and high susceptibility to interferece associated with capturing and imaging thermal radiation. Even with these challenges, the low power and high level of integration offered by CMOS is anticipated to enable interesting new applications including covert surveillance, low cost, and even portable mm-wave imaging systems which are not achievable with III-V imaging technology.

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FRANK CHANG is the Wintek Endowed Chair and Distinguished Professor of Electrical Engineering and Chairman of the Electrical Engineering Department, UCLA. Before joining UCLA, he was the assistant director and department manager of the High Speed Electronics Laboratory at Rockwell Science Center (1983–1997), Thousand Oaks, California. In this tenure, he developed and transferred the AlGaAs/GaAs heterojunction bipolar transistor (HBT) and BiFET (planar HBT/MESFET) IC technologies from the research laboratory to the production line (now Conexant Systems and Skyworks). HBT/BiFET productions have grown into multi-billion-dollar businesses and dominated the cell phone power amplifiers and front-end module markets (currently exceeding one billion units/year). Throughout his career, his research has primarily focused on the development of high-speed semiconductor devices and integrated circuits for RF and mixed-signal communication and imaging system applications. He was the principal investigator at Rockwell in leading DARPA's ultra-high speed ADC/DAC development for direct conversion transceiver (DCT) and digital radar receivers (DRR) systems. He was the inventor of the multiband, reconfigurable RF-interconnects, based on FDMA and CDMA multiple access algorithms, for Chip-Multi-Processor (CMP) inter-core communications and inter-chip CPU-to-Memory communications. He also pioneered the development of world's first multi-gigabit/sec ADC, DAC and DDS in both GaAs HBT and Si CMOS technologies; the first 60GHz radio transceiver front-end based on transformer-folded-cascode (Origami) high-linearity circuit topology; and the low phase noise CMOS VCO (F.O.M.<-200dBc/Hz) with Digitally Controlled on-chip Artificial Dielectric (DiCAD). He was also the first to demonstrate CMOS oscillators in the terahertz frequency spectrum (1.3 THz) and the first to demonstrate a CMOS active imager at the sub-mm-Wave spectra (180GHz) based on a Time-Encoded Digital Regenerative Receiver. He was also the founder of an RF design company G-Plus (now SST and Microchip) to commercialize WiFi 11b/g/a/n power amplifiers, front-end modules and CMOS transceivers. He was elected to the US National Academy of Engineering in 2008 for the development and commercialization of GaAs power amplifiers and integrated circuits. He was also elected as a Fellow of IEEE in 1996 and received IEEE David Sarnoff Award in 2006 for developing and commercializing HBT power amplifiers for modern wireless communication systems. He was the recipient of 2008 Pan Wen Yuan Foundation Award and 2009 CESASC Career Achievement Award for his fundamental contributions in developing AlGaAs/GaAs hetero-junction bipolar transistors. His recent paper "CMP Network-on-Chip Overlaid with Multiband RF-Interconnect" was selected for the Best Paper Award in 2008 IEEE International Symposium on High-Performance Computer Architecture (HPCA). He received Rockwell's Leonardo Da Vinci Award (Engineer of the Year) in 1992; National Chiao Tung University's Distinguished Alumnus Award in 1997; and National Tsing Hua University's Distinguished Engineering Alumnus Award in 2002. He earned his B.S. in physics from National Taiwan University in 1972, his M.S. in materials science from National Tsing Hua University in 1974, and his Ph.D. in electronics engineering from National Chiao Tung University in 1979.