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# Low-Cost Millimeter-Wave Radio-Frequency Sensors

## New Applications Enabled by Developments in Low Cost Chipsets

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### Abstract

This paper presents a range of novel low-cost millimeter-wave radio-frequency sensors that have been developed using the latest advances in commercially available electronic chip-sets. The recent emergence of low-cost, single chip silicon-germanium transceiver modules combined with license exempt usage bands is creating a new area in which sensors can be developed. Three example systems using this technology are discussed, including: gas spectroscopy at stand-off distances, non-invasive dielectric material characterization and high performance micro radar.

*Keywords—sensors; mm-wave; Si-Ge; radar*

### Introduction

Advances in sensor technology over the last twenty years have been well reported [1, 2], with new miniaturised sensors like MEMS accelerometers and high sensitivity gas sensors becoming available in low-cost, low power and small footprint packages. This trend has largely been driven by high volume consumer products, in particular smart phones and automotive applications. Here the need for accurate sensing and the economies of scale in the market place have created high performance components at price points which have facilitated totally new sensor applications, often in fields far removed from the component's original use case.

This trend is now progressing in new areas, with previously exotic technologies such millimeter-wave (mm-wave) radio-frequency (RF) electronics now becoming cheaper and more suitable for new sensing applications. Until recently, electronics working in this area have used monolithic microwave integrated circuit (MMIC) technology and the costs have been prohibitive for many sensor applications. The drivers for commercialisation of mm-wave RF is again cellular communications (5G standards and other communications tasks are exploring the high frequency spectrum as an area where increased bandwidths can be achieved) [3] and the transport sector (where sense and avoid systems are helping unmanned vehicles navigate) [4]. Chipset vendors are competing to supply these emerging high volume markets with low-cost components, primarily built using silicon-germanium (SiGe) technology.

Concurrently, international regulatory bodies have designated industrial scientific and medical (ISM) usage bands in which devices can operate without the need for expensive licenses. The upshot of these developments is a reduced barrier to entry for a wide range of sensor applications that can now affordably utilise mm-wave RF technology to solve sensing problems.

Using mm-wave technology allows sensor topologies operating at other frequencies to be extended with additional unique properties, and in some cases to create completely new sensors. In this paper, we present three sensors that can take advantage of these new platforms, we discuss the challenges of working in this area and we outline a direction for future developments.

## Properties Of Mm-Wave Sensors

Millimeter-wave electromagnetic energy is defined as frequencies in the range of 30 GHz to 300 GHz. Useful Si-Ge chip-sets are currently available primarily in sub 100 GHz models. The key parameter of mm-wave RF for sensing applications is the shorter wavelengths and thus the ability to detect interactions with different (usually smaller) objects and to do so with equipment that is itself physically small compared to other technologies. What is interesting about the mm-wave space, is that some techniques common to optics can be applied, as well as those common to RF sensing.

## Example Sensor Applications

### *A. Gas Identification*

A spectroscopy sensor is possible using the wide bandwidths available at mm-wave frequencies that allow detection and characterisation of gasses that would not be possible at other frequency ranges. This sensor makes use of the molecular rotational resonance (MRR) phenomenon, and measures frequency dependent features in the absorption spectra of chemicals (for example, see Fig. 1.).

The spectral features are caused by transitions between quantized rotational states, which can be used to perform chemical identification of gases. The technique is commonly used at low pressure in the laboratory, as collisions between molecules perturbs the rotational energy levels and causes the width of the absorption features to increase making them less characteristic. However, in ambient pressure conditions with a sufficiently large measurement bandwidth, it is still theoretically possible to use MRR to create stand-off gas sensors able to detect useful concentrations of a given substance in view.

Hardware implementations of such a wide bandwidth frequency sensor have so far been limited to sensors designed to pick-out a specific compound. However, using techniques common to multispectral electro-optic sensors, absorption levels at different discrete points across a wider frequency range can be measured to provide a multi-compound detector.

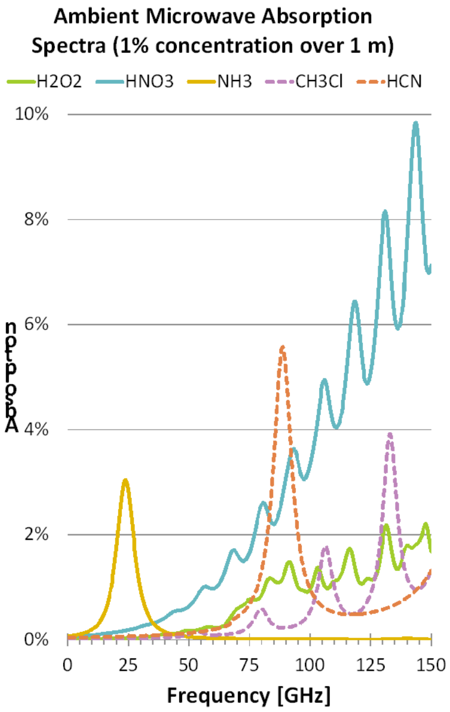

*Fig. 1. Absorbtion spectra across mm-wave bands for compounds of interest in security scanning applications [5].*

### *B. Solid Material Characterisation*

Just like optical spectroscopy, it is also possible to perform solid material identification and characterisation at mm-wave frequencies. This is currently an under-utilised technique because the spectral features can be very broad, which requires ultra-wideband transmitters / receivers. However, unlike at optical frequencies the measured spectral features at mm-wave frequencies are mainly produced by geometric effects. Let us assume a simple 2D model for a solid comprising a stack of layers where each layer is defined by three frequency independent parameters: complex permittivity (the real and imaginary components) and layer thickness. The constructive and destructive interference caused by reflections at each interface between the layers produces a specific spectral shape. By measuring the reflection coefficient over frequency (both amplitude and phase), it is possible to solve the inverse problem to retrieve the thickness and complex permittivity parameters for each layer.

The frequency independent complex permittivity calculated thus can be used to identify the composition of each layer and perform material characterisation. This technique is particularly valuable as a verification step in controlled manufacture of various substrate materials. An example result showing electromagnetic simulation and measured results for one sample substrate shows the power of the technique for identifying features over achievable bandwidths, and how close to a the simulated ideal result a real-world measurement device can achieve. This technique has potential for use in other applications where a known parameter feature in a solid material's reflection coefficient can be used to assess process quality.

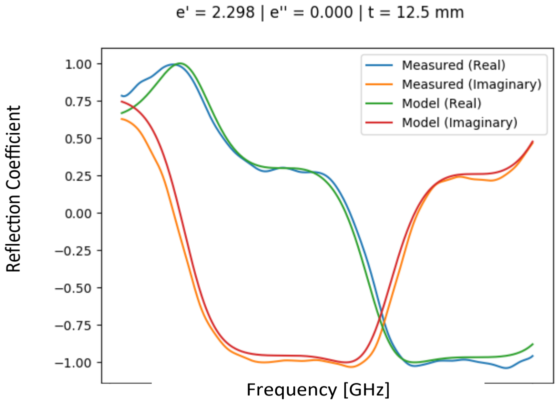

*Fig. 2. Simulated and measured reflection coefficient over frequency for a substrate showing a clear characteristic shape.*

### *C. Micro Radar*

A further application of mm-wave technology is in radar systems, where the short wavelength allows identification of very small objects and features that are not detectable at lower frequencies. The short wavelength also facilitates the potential for high gain antennas with a relatively small aperture and overall size. This offers improved angular resolution over an equivalently sized lower frequency radar sensor, while the large bandwidth available at mm-wave frequencies also provides a high range resolution.

Although radar sensors in these frequency ranges have been developed in the past, either for very low performance applications equally well served by products at other frequencies or for expensive, high performance applications such as foreign object and debris (FOD) detection on airfields, there has yet to be much work in the intermediate area of low-cost high performance systems. This area of sensing has been held back primarily by component availability.

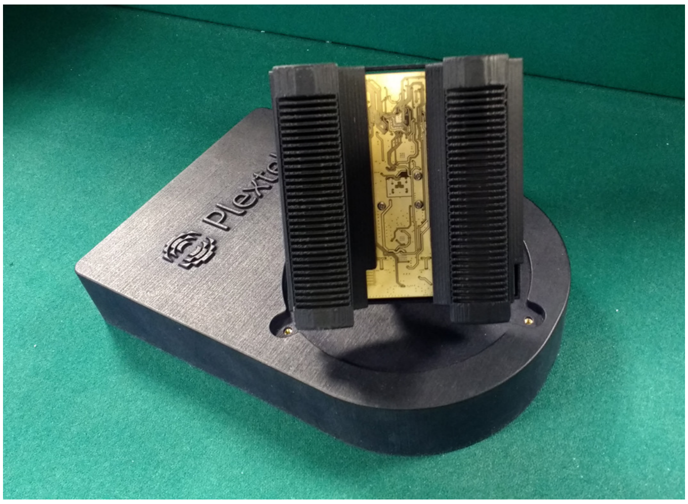

*Fig. 3. Micro-radar with mechanical azimuthal scan and electronic elevation scan, including a single circuit board measuring 10cm by 10cm which includes all antennas, RF and baseband processing circuitry.*

Here, a new high performance radar system has been developed that is a fraction of the cost of typical mm-wave radars with comparable capability using a new chip-set from a leading vendor. The system is built on a single circuit board that measures 10 cm by 10 cm and contains all circuitry from the baseband processing to electronically scanned antennas. The electronically scanning antennas allow a static sensor to monitor its environment with up to 90° degrees of either azimuth or elevation scan. A mechanical scanning variant providing 360° azimuth and 90° of elevation coverage has also been developed and is shown in Fig. 3. A result of a fixed beam radar scan using this platform is shown in Fig. 4, where the radar response for a small pole at a range of 17 m is 70 dB above the receiver noise floor, thereby allowing robust detection. Other scene features are also recognisable in the radar returns, such as the river which is characterised by lack of ground clutter and vegetation on the banks either side of the river. A photograph of the radar measurement scenario is shown in Fig. 5.

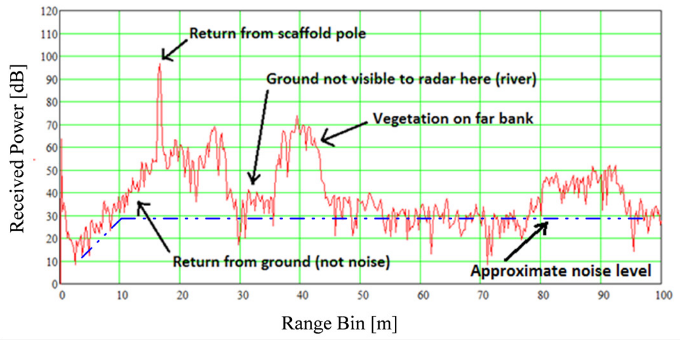

*Fig. 4. Micro-radar return for a fixed azimuth angle.*

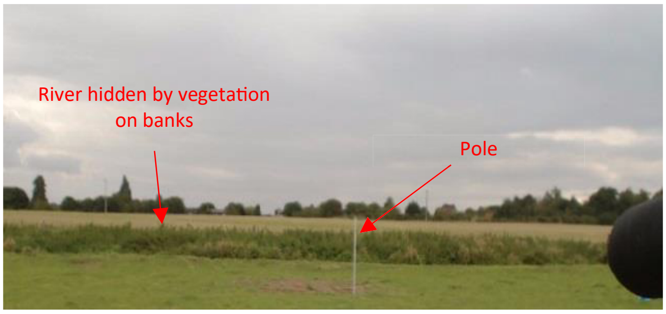

*Fig. 5. Photograph of the radar measurement scenario depicted in Fig. 4.*

Beyond sense and avoid applications, such a small and affordable radar can be used in a variety of sensing problems where poor light conditions, rain and other issues make technologies such as light detection and ranging (LiDAR) less attractive.

## Next Steps

Building functional electronic systems at mm-wave frequencies remains a highly challenging area, with great attention to circuit layout, system mechanics and component assembly required to achieve reliably functioning systems. Beyond the availability of mm-wave chip-sets themselves, working at these high frequencies still requires skilled design and manufacturing expertise. To see increased use of this technology in future sensors, particular developments are required in the wider availability PCB fabrication techniques such as impedance controlled micro vias and factory assembly processes (such as better controlled ball grid array solder reflow profiles). However, given the range of sensor applications that can benefit from systems operating at mm-wave frequencies such development effort seems likely in the coming years.

## Conclusions

Availability of low-cost integrated circuits and license exempt radio spectrum has opened up new opportunities for developing sensor systems that were impractical only a few years previously. Three examples of sensors have been presented: gas spectroscopy at stand-off distances, non-invasive dielectric material characterization and a novel micro-radar that has high resolution for a small sensor size and cost. Next steps for the field of mm-wave RF sensors have been discussed, suggesting a path for maturing printed circuit board techniques and component assembly methods are necessary to further develop this emerging field of sensing.

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