# Millimetre-Wave FMCW MIMO Radar System Development using Broadband SIW Antennas

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***Abstract*—In this paper, a novel millimetre-wave radar for collision avoidance and automotive applications is presented. The system uses frequency modulated continuous-wave (FMCW) transmission based on multiple input multiple output (MIMO) substrate-integrate waveguide (SIW) antennas operating in the K-band regime. The continuous sawtooth time-domain wave transmitted from two SIW antennas, by time-domain multiple access (TDMA), is detected with a half-lambda spaced four-element SIW receiver array at a distance of 4 meters in a calibrated anechoic chamber and verified with simulations. The high bandwidth and omnidirectionality of the SIW antennas in the horizontal plane, together with digital-beamforming for the achieved MIMO virtual array, offers an overall field-of-view of 130 degrees for the radar system. Also, the MIMO radar achieves an angular resolution of 14 degrees and offers a range resolution of 10 cm at a cost of only 6 transmitter and receiver elements in total.**

***Index Terms*—MIMO, SIW antenna, FMCW radar, SRR, TDMA, Digital Beamforming**

## I. Introduction

In the field of automotive radar, there has been an inevitable growing interest for multiple input multiple output (MIMO) systems due to the high resolution capabilities for target localisation. These systems are known to have less number of elements than conventional arrays while achieving the same or even better performance in terms of angular resolution. Even if theoretical calculations demonstrated the performance of MIMO systems in terms of spatial diversity [1] and speckle resolution for large arrays [2], limited works have been reported in the open literature showing the radar development and RF system integration while using broadband antennas to obtain a finer radar resolution.

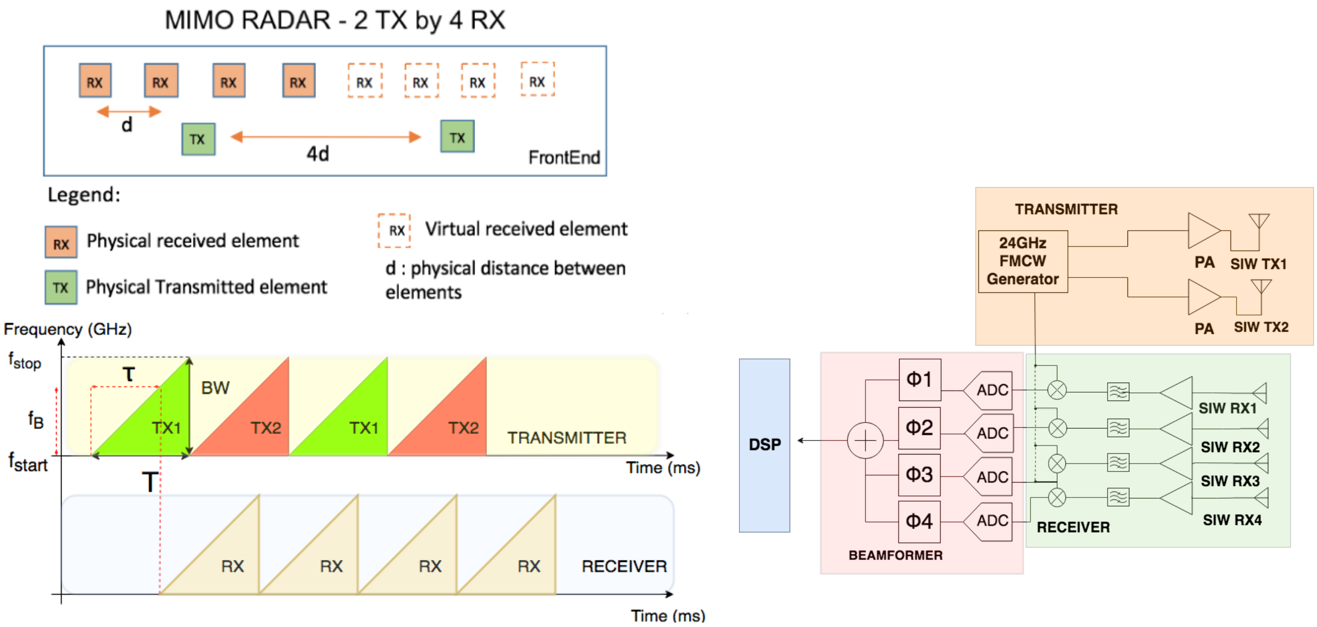
This work was initiated due to the growing need for the automotive industry to obtain accurate localisation at radar proximity (up to 50m) [3] while simultaneously achieving a wide field-of-view (FOV). Conventional patch array antennas provide a robust architecture and are easily fabricated at relatively low-cost, but often do not achieve high bandwidth performances when compared to substrate-integrated waveguide (SIW) technology at millimetre frequencies [4], [5]. For example, SIW antennas can exhibit the same ratio of bandwidth and operational frequency but with fewer losses (1.6 dB at 77GHz recorded in literature [6]).

The novelty of this work represents the integration of such SIW antennas within a MIMO radar system. This work also claims to be the first to provide a possible solution for enhanced range resolution when considering short-range-radar (SRR) systems. The expected high bandwidth and omnidirectional beampattern of the employed SIW antennas offers the radar augmented performance in comparison with a MIMO system which only uses patch array antennas. In this paper, the material is divided into four sections. The system design architecture and radar hardware is described in Fig. 1 and Section II, with an emphasis on the characteristics and performance of the SIW antennas and the radar (see Figs. 2 and 3 as well as Tables I and II). The radar signal processing methodology is further outlined for detecting target range and angle in Section III and the MIMO radar system measurement procedure is outlined in Section IV. An analysis of the measured ranges and angles is also provided followed by a short conclusion in Section V.

## II. Radar System Design

MIMO radar is capable of achieving higher resolution due to the fact that the target is illuminated from different angles. The positions of antennas at transmit $N_{TX}$ together with the positions at the receiver $M_{RX}$ form an equivalent array also called a virtual array, of $N_{TX} \times M_{RX}$ elements. In this paper, the $2 \times 4$ system is equivalent to an 8-element virtual array as depicted in Fig. 1a. Spacing between MIMO transmitters and receivers determines the field-of-view of the virtual array.

The architecture of the proposed radar consists of transmit chains, receiver chains, beamforming networks and a digital signal processing unit. The MIMO radar architecture can be observed in Fig. 1b. The transmitter block is formed by a K-band FMCW generator, power amplifiers (PAs) and substrate integrated waveguide (SIW) antennas. The frequency modulated continuous wave (FMCW) system generates a frequency modulated sinusoid with 100% duty cycle [7].




(a) 8-element MIMO virtual array receiver (upper fig.) and illustration of the transmitted and received signal (lower fig.).

(b) RF system architecture for the FMCW radar using mixers, amplifiers, SIW antennas and LNAs.

Fig. 1. System Design

The FMCW sawtooth wave generator connects with the mixer at the receiver frontend to downconvert the 24 GHz signal at an intermediate frequency (IF). The 4 receiver antennas have separate data streams, with different phases. Each of the signals is bandpass filtered before mixing. After this step, each receiver channel is sampled and processed.

The FMCW radar transmitters allow for time domain multiple access (TDMA)(see Fig.1a). Each transmitter sends a chirp during one period, while the other transmitter remains idle. The transmitting antennas are also aligned so that the distance between them matches the length of the receiver array. This is the case only if the transmitters are placed in the middle of the physical and virtual arrays. An equivalent configuration would have been to position each of the receivers at a distance $2 \cdot d$ from each other while placing the transmitters at a distance $d$. In that case, the virtual elements and physical elements alternate. More information about virtual array positioning can be found in [8].

The sum-and-delay algorithm adds the individual responses of each receiver channel to later obtain the beamscan spectrum. This permits one to identify targets with a radar angular resolution given by the half-power beamwidth ($\Theta_{3\text{dB}}$) of the resulting virtual array elements. For MIMO radar, the half power beam width can be determined by the number of equivalent virtual array elements [8]:

$$\Theta_{3\text{dB}} = \sin^{-1}\left(\frac{2}{N_{Total}}\right)^{\circ} \quad (1)$$

where $N_{Total}$ is the total number of elements for the equivalent virtual array (i.e. $N_{TX} \times M_{RX}$).

## A. Transmit and Receive Substrate Integrated Waveguide (SIW) Antennas and Arrays

SIW antennas for automotive radar have been investigated for other radar works [9]–[14], however, the authors believe their work to be the first FMCW MIMO radar for automotive applications to use broadband SIW antennas in a compact design. Also, the proposed SIW system has multiple advantages over conventional series-fed patch arrays. For example, SIW series fed-slot antennas are in some aspects better than resonant structures at millimeter-wave frequencies. However, most commercial radars for millimetre-wave applications use series-fed patch arrays because of their more classic design approach, yet these patch structures can present several problems:

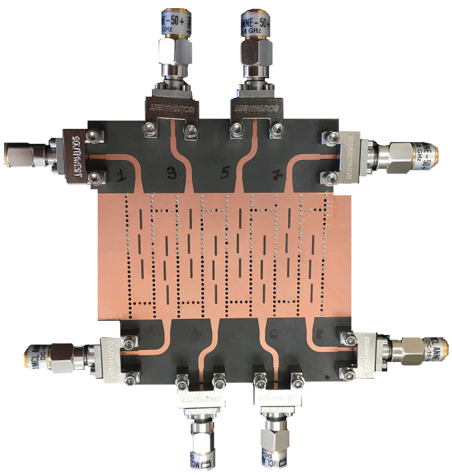
- The beam can scan as a function of frequency.
- Higher bandwidth antennas and arrays can be harder to design at millimetre-wave frequencies.
- Possible beam squint over frequency can add complexity in the radar calibration and signal processing.

SIW antennas, on the other hand, are capable of broader bandwidth which can increase range resolution. Other advantages include:

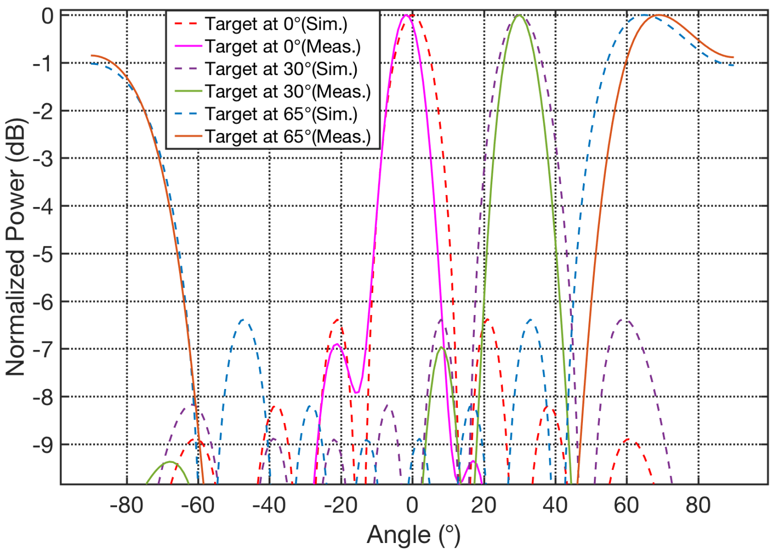
- Beam squint can be negligible due to the larger possible bandwidth, which is related to the low dispersion of the $\text{TE}_{01}$ like mode of SIW.
- Low leakage and surface-wave loss between elements which can improve antenna efficiency.

## B. Radar Antenna Design Approach

The designed SIW antennas used an array of longitudinal slots with short circuit terminations and operate as a resonant, standing-wave structure. This ensures that the beam is fixed at broadside over frequency. Generally, the impedance bandwidth of this type of antenna decreases



(a) Designed and fabricated 8-port SIW receiver.* *Note: in the measurements and simulations reported here, only 4-ports were used in the FMCW radar.




(b) Measurements and simulations of the 2 TX by 4 RX MIMO radar where a single target has been positioned at 0°, +30° and +65° in separate measurement trials.

Fig. 2. Receiver Performance

rapidly for an increased number of slots. However, the presented design features broadband behaviour and wide half-power beamwidth in the horizontal plane. This is because the required gain and beamwidth can be achieved by using only three slot elements.

After selecting a proper substrate (Rogers RT/-duroid®5880), the transmit antenna design was initiated by dimensioning the SIW for the desired frequency range. To this end, the via diameter, pitch and waveguide width were chosen according to the design guidelines in [15]. The dimensions and positioning of the slots is then optimised with the aid of design equations [16] and a commercial full-wave simulation software. For feeding the antenna, a microstrip-to-SIW transition was employed and completed by a tapered section for improved matching. This finally leads to a compact transmitter antenna design, with an individual antenna element size of 42 mm x 13 mm x 0.51 mm.

The fabricated 8-element SIW antenna receiver can be observed in Fig. 2a. Only 4 ports were used in this work since additional results will be discussed at the time of the conference. The implementation of the structure has $\lambda/2$ spacing since this is critical to obtaining a field-of-view which is close to the theoretical bound of $-90°$ to $+90°$ and minimises the appearance of grating lobes. The definition of the unambiguous field-of-view is [8]:

$$\Theta_{FOV} = \pm \sin^{-1}\left(\frac{\lambda}{2d}\right) \tag{2}$$

where $\lambda$ is the wavelength and $d$ is inter-element spacing of the equivalent virtual array. The S-Parameters and antenna gain patterns will be included in future work and are between 8 and 10 dBi over the working bandwidth and reflection coefficients do not exceed -10 dB.

The receiver array elements were arranged in an alternate fashion, so that enough space is provided between adjacent waveguides to place end-launch coaxial connectors for the measurements. The required adjustment of the via diameter and pitch minimises leakage loss through the via walls of the SIW array [15].

## III. Signal Processing

With the integration of analogue-to-digital converters for each of the receiving blocks, it is possible to perform digital beamforming with the MIMO radar. This method is advantageous to previous analogue beamforming techniques because of the improved signal-to-noise ratio (SNR) given by each of the ADC blocks along with other low-noise amplifiers. The beam is now digitally shaped for better signal processing, filtering and target information extraction.

By analysing the IF spectrum of the received FMCW MIMO radar system, it is possible to determine the range of the target by converting the received beat frequency. A peak in the received signal corresponds to a target for which the range can be calculated with the formula [17]:

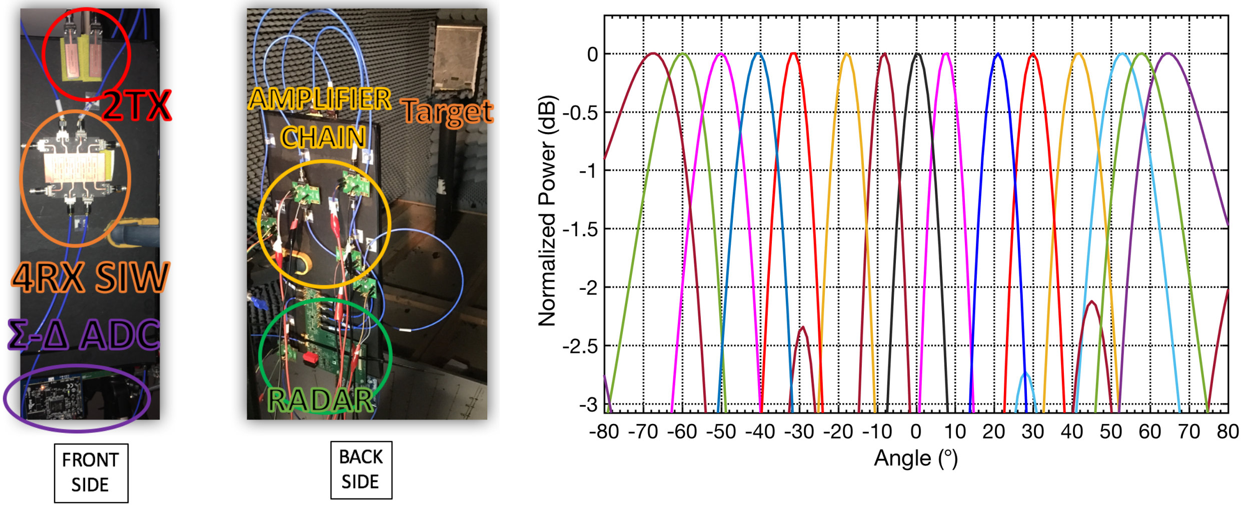
$$R = \frac{f_B \cdot c \cdot T_{sweep}}{2BW} \tag{3}$$

where $f_B$ is the beat frequency, c is the speed of light, $T_{sweep}$ is the FMCW chirp period, and BW is the bandwidth of the antennas and the radar system.

It was possible to calculate the direction-of-arrival for the targets by analysing the relative phases between the receivers and once the wave front reached all the receiver sensors [7]. Simulations in MATLAB were completed as well.

## IV. Experiments

The radar system has been tested and calibrated in an anechoic chamber to determine performance in close-




(a) Developed FMCW 2 TX by 4 RX MIMO radar system.

(b) Measured degree of arrival for a single target positioned between $-60°$ and $60°$ in $10°$ increments and $\pm 65°$(with maximum deviation error $\Delta_{error} = \pm 3°$).

Fig. 3. MIMO radar hardware and measurement setup.

to-ideal conditions. Millimetre-wave technology has the advantage of higher bandwidths, however the propagation loss at these frequencies is very high. For example, the free-space-path-loss (FSPL) is approximately -60 dB for detecting objects at a few meters for a 24 GHz radar. Also, amplification in the transmitter and receiver chains is important to improve signal detection. Although the receiver has 8 SIW antennas, only 4 antennas have been used for the study reported here. Agreement between MATLAB benchmark simulations and lab measurements can be observed in Fig. 2b. Additional results will be explained comprehensively in future work. A summary with the radar's characteristics is presented in Table I.

### A. Description of the Measurement Procedure

A target defined by an aluminium square plate (size is $\approx$ 40 by 30 $cm^2$) was used to ensure a suitable radar return. The target was positioned at different angles. For measuring direction-of-arrival (DoA), the target has been incrementally re-positioned for each test from -65° to +65° under the alignment of the virtual array location. The results for direction of arrival have been accepted as valid since errors up to $\pm 3°$ have been observed. The radar setup is depicted in Fig. 3a.

### B. Range Resolution

The target range was determined by measuring the IF or beat frequency ($f_B$) of the FMCW radar. Following Eq. (3), the range resolution (RR) can be obtained:

$$f_B = BW \times \frac{2R}{c \cdot T} \tag{4}$$

$$RR = \frac{c}{2 \cdot BW} \tag{5}$$

For this section of the experiment, just one transmit and one SIW receive antenna have been used to compute the range based on the IF frequency up to 4 meters due to size constraints of the anechoic chamber. The bandwidth for this experiment has been set to 1.5GHz, with a period of 5ms. The results for the displacement of a target between 0.5m-4m are available in Table II.

Excellent agreement between theoretical values and the measurements have been observed and all the sampled data passed the range resolution criteria. This result is very important since it proves the usefulness of SIW antennas for short-range-radars (SRRs) to offer improved range resolution when compared to band-limited series-fed patch antenna arrays. Experiments for longer ranges will be the subject of further work.

Also, it should be mentioned that poor resolution occurs when radars need to identify objects at close distances. If the bandwidth is small, according to Eq. (4), the beat frequency is also very small and it is not easily distinguished [18]. Even if the radar is able to detect an object in the far-field, the same radar can have trouble identifying a target very close to the radar because the beat frequency is very close to DC. In this case, the target shows more ambiguity and is more susceptible to different

TABLE I
FMCW RADAR SPECIFICATIONS

| | |
|---|---|
| TX / RX elements | 4 x 8 |
| $f_c$ | 24 GHz |
| $BW$ | 1.5 GHz |
| $T_{sweep}$ | 5ms |
| $ADC$ | 12-bit |
| $\Theta_{3dB}$ | 3.58° |
| FOV | $\pm 65°$ |
| RR | 10cm |

$f_c$ is the carrier frequency, $BW$ is the bandwidth, $T_{sweep}$ is the period, $ADC$ is the analogue-to-digital converter resolution, $\Theta_{3dB}$ is the half-power beamwidth, FOV is the field-of-view of the 8-element SIW receiver, RR is the range resolution of the radar

TABLE II
BEAT FREQUENCY ($f_B$) AND RANGE RESOLUTION (RR) VERIFICATION

| Bandwidth (GHz) | RR(cm) | Δ space (m) | Sim. $f_B$(kHz) | Meas. $f_B$(kHz) | Meas. distance (m) | Offset (cm) | within RR? |
|---|---|---|---|---|---|---|---|
| 1.5 | 10 | 0.5 | 5.53 | 5.42 | 0.47 | 2.84 | Yes |
| | | 1.00 | 7.53 | 7.39 | 0.96 | 3.59 | Yes |
| | | 1.50 | 9.53 | 9.59 | 1.51 | 1.41 | Yes |
| | | 2.00 | 11.53 | 11.79 | 2.06 | 6.41 | Yes |
| | | 2.50 | 13.53 | 13.85 | 2.58 | 7.91 | Yes |
| | | 3.00 | 15.53 | 15.6 | 3.02 | 1.66 | Yes |
| | | 3.50 | 17.53 | 17.7 | 3.54 | 4.16 | Yes |
| | | 4.00 | 19.53 | 19.19 | 3.91 | 8.59 | Yes |

noise sources. However, if the bandwidth is increased, the beat frequency of the target is further away from DC and filtering of the lower frequencies can remove any uncertainties [19].

### C. Direction-of-Arrival (DoA)

The target has been positioned at different angles corresponding to a referenced mechanical positioning system. The sum and delay algorithm has been used to identify the location based on the phase shifts. The target has been placed at 0°, 30° and 65°. Another exercise was carried out to obtain the real field-of-view and Fig. 3b shows that it exceeds ±65°.

## V. CONCLUSION

This work presented a novel multiple input multiple output (MIMO) frequency modulated continuous wave (FMCW) radar system which uses substrate integrated waveguide (SIW) antennas to provide high resolution target localisation for collision avoidance and automotive radar applications. The advantages of the employed SIW antennas with low leakage loss and negligible beam squint make them ideal candidates for future automotive radar designs which require high bandwidth and can be manufactured easily at a low cost. In addition to covering a field-of-view of ±65° with a half power beamwidth of 14°, this radar has reduced sensor cost from 9 elements of an uniform linear array to 6 elements by employing MIMO virtual arrays for direction-of-arrival detection. This enabled a radar with a high degree of both angular and range resolution for operation at millimetre-wave frequencies.

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