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## Capteurs radars haute précision en ondes millimétriques

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# DÉDICACE

*To my spouse Steven and our son Darian.*

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# Résumé

Les mesures qu'utilisent les radars sont une technologie essentielle, avec beaucoup d'applications. Les applications militaires, les observations météorologiques, le contrôle du trafic aérien, les radars anticollision, les applications de navigation, d'entretien des routes, les applications industrielles et biomédicales ne sont que quelques domaines. Cette thèse se propose d'introduire une technique de mesure innovatrice basée sur la technologie six-port pour diverses opérations de mesure, telles que la distance, la vitesse relative et la fréquence de vibration mécanique d'une cible.

Il y a 4 bandes de fréquence principales allouées pour les applications radar, une à environ 24,125 GHz avec une largeur de bande d'environ 200 MHz et, une autre à environ 24 GHz, avec une largeur de bande de 5 GHz, 76-77 GHz pour les radars bande-étroite, à longue portée et 77-81 GHz pour les radars large-bande, à courte portée. Cette contribution décrit un système radar à onde continue modulée en fréquence 77 GHz (FMCW) qui est entièrement basé sur une technologie intégrée MHMIC. A cette haute fréquence, la longueur d'onde et la taille du système diminuent; par conséquent, on obtient une sensibilité de détection et une résolution meilleures. L'excellente résolution de phase obtenue par le circuit six-port offre des capacités de mesure angulaire et de distance de haute précision. En outre, la faible consommation d'énergie, le bruit de phase extrêmement bas, la taille réduite, la conception simple et le faible coût de fabrication permettent son application dans différents types de systèmes de communication.

Deux corrélateurs six-port différents, en utilisant des coupleurs hybride 90°, avec ou sans un diviseur de Wilkinson, ont été conçus, fabriqués et mesurés à la fréquence centrale de 77 GHz sur une largeur de bande de 12 GHz, pour couvrir les deux standards à environ 77 GHz. Les deux circuits pris en compte ont des signaux de sortie relativement bons et peuvent être utilisés comme modulateur et démodulateur dans le circuit du récepteur et de l'émetteur. Le corrélateur de phase six-port, avec quatre coupleurs hybride 90°, est choisi pour le prototype final, grâce à sa largeur de bande plus grande, à son erreur de phase plus petite et aux pertes d'insertion plus réduites, en comparaison avec le corrélateur de phase six-port avec un diviseur de Wilkinson. Un modulateur QPSK (modulation par déplacement de phase en quadrature) et un modulateur 16-QAM (modulation d'amplitude en quadrature 16) ont été conçus sur la base des mesures des paramètres S du six-port. Ils se composent d'un réseau en micro-ondes six-port passif pour mettre en application le schéma de modulation avec la charge variable appropriée, comme impédance finale.

Le circuit modulateur est utilisé pour avoir une phase différente dans la section émettrice, afin d'établir la communication entre voitures. Il peut être aussi utilisé comme une alternative pour VCO, pour changer la fréquence, en utilisant les changements rapides dans la phase. Un démodulateur QPSK à base du circuit six-port, en combinaison avec les diodes Schottky sans polarisation a été conçu en logiciel ADS Momentum et fabriqué en substrat céramique. On obtient des positions des symboles très précises. Le circuit démodulateur est utilisé comme récepteur, pour convertir à la

baisse le signal RF du prototype final. Dans chaque port de sortie du circuit six-port, deux diodes Schottky (HSC9161) et un coupleur hybride sont utilisés dans notre capteur afin d'extraire les informations sur la magnitude et sur la phase du signal réfléchi sur la cible.

Le prototype complet du capteur est conçu, fabriqué et mesuré à  $77\text{ GHz}$ , pour des applications professionnelles et industrielles à courte portée. Ce capteur est utilisé pour mesurer la distance et la fréquence Doppler à un coût raisonnable et à des performances exceptionnelles. L'entier prototype du circuit, y compris l'antenne de l'émetteur et du récepteur, l'interféromètre six-port et les quatre détecteurs de puissance ont été intégrés sur une monture. Des diapasons sont utilisés pour démontrer la performance du capteur six-port, qui offre des mesures de la fréquence précises, à différentes fréquences. Le prototype du capteur peut être aussi utilisé en FMCW ou dans les configurations multi-tonales, pour mesurer de manière précise la distance et la vitesse de la cible. A cause de la puissance très faible des ondes millimétriques, utilisée dans l'essai, les résultats concernent la courte portée. L'utilisation d'un amplificateur à faible bruit dans le front-end du récepteur augmentera considérablement la plage de fonctionnement. Grâce à ce processus de fabrication robuste et à faible coût, ces capteurs peuvent être utilisés dans diverses applications.

Cette thèse comprend aussi les conclusions et les suggestions pour des travaux futurs, dans le but d'améliorer les capteurs radar à ondes millimétriques.

# Abstract

Direction finding and ranging techniques are a key technology with a large number of applications. Military, weather observation, air traffic control, collision avoidance radar, navigation, road maintenance, industrial and biomedical applications are just some fields of its application. The purpose of this dissertation is to introduce an innovative measurement technique based on the six-port technology for various measurement tasks, such as distance, relative speed, and mechanical vibration frequency of a target.

There are 4 major frequency bands allocated for radar applications, one around 24.125 GHz with a bandwidth of around 200 MHz, and the other around 24 GHz with a bandwidth of 5 GHz, 76-77 GHz for narrow-band long-range radars and 77-81° for short-range wideband radars. This contribution describes a 77 GHz frequency modulated continuous wave (FMCW) radar system that is completely based on a MHMIC integrated technology. At this high frequency, the wavelength and size of the system decrease, therefore a better detection sensitivity and resolution are obtained. The excellent phase resolution offered by the six-port circuit leads to high accuracy distance and angular measurement capabilities. Furthermore, low-power consumption, extremely low phase noise, small size, simple design, and low manufacturing price allow its application in many kinds of communication systems.

Two different six-port correlators by using 90° hybrid couplers, with or without a Wilkinson power divider, were designed, fabricated, and measured at the center frequency of 77 GHz for a 12 GHz bandwidth, to cover both standards around 77 GHz. Both circuits taken into consideration have relatively good output voltage signals and can be used as a modulator and demodulator in receiver and transmitter circuit. The six-port phase correlator with four 90° hybrid couplers is chosen for the final prototype due to its wider bandwidth, smaller phase error, and lower insertion losses in comparison to the six-port phase correlator with a Wilkinson power divider. A quadrature phase shift keying (QPSK) modulator and 16 Quadrature amplitude modulation (16-QAM) modulator are designed based on the S-parameter measurements of the six-port. It is composed of a six-port passive microwave network to implement the modulation scheme with suitable variable load as impedance terminations.

The modulator circuit is used to have a different phase at the transmitter section to enable car-to-car communication. It can also be used as an alternative for VCO, to change the frequency by using the rapid changes in the phase. A QPSK demodulator based on the designed six-port circuit in combination with zero bias Schottky diodes was designed in ADS Momentum software and fabricated in a ceramic substrate. It leads to very accurate symbol positions. The demodulator circuit is used as a receiver to down-convert the RF signal at the final prototype. In each output port of the six-port circuit, two Schottky diodes (HSC9161) and a hybrid coupler are used in our sensor to extract both magnitude and phase information of the reflected signal to the target.

The complete sensor prototype is designed, fabricated, and measured at  $77\text{ GHz}$  for short-range professional industrial applications. This sensor is deployed to measure distance and Doppler frequency for reasonable cost combined with exquisite performance. The whole circuit prototype, including the transmitter and the receiver antenna, the six-port interferometer, and four power detectors have been integrated on a die. Tuning forks are used to demonstrate the performance of the six-port sensor, which offers an accurate frequency measurement for different frequencies. The sensor prototype can also be used in FMCW or multi-tone configurations to precisely measure range and speed of a target. Because of the very low millimeter-wave power used in the experiment, the results are obtained in short range. The use of a low-noise amplifier in the receiver front-end will considerably increase the operating range. Due to this robust and low-cost schematic and manufacturing process, such sensors can be used in various applications.

This thesis also contains conclusions and suggestions for future work in order to improve the future millimeter-wave radar sensors.

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# Liste Des Abréviations

ADS	Advanced Design System
BER	Bit Error Rate
CW	Continuous Wave
DSP	Digital Signal Processor
FCC	Federal Communication Commission
FMCW	Frequency Modulated Continuous Wave
HFSS	High Frequency Structure Simulator
IEEE	the Institute of Electrical and Electronics Engineers
INRS	Institut National de la Recherche Scientifique
IF	Intermediate Frequency
LO	Local Oscillator
LRR	Long Range Radar
MDS	Minimum Discernible Signal
MHMIC	Miniature Hybrid Microwave Integrated Circuits
MMIC	Microwave Monolithic Integrated Circuit
MIMO	Multiple-Input Multiple-Output
MRR	Medium Range Radar
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RADAR	RAdio Detection And Ranging
RCS	Radar Cross Section
RF	Radio Frequency
RX	Receiver
RWG	Rectangular Waveguide

SNR	Signal to Noise Ratio
SOLT	Short-Open-Load-Thru
SRR	Short Range Radar
TRL	Thru, Reflect, Line
TX	Transmitter
VCO	Voltage Control Oscillator
VNA	Vector Network Analyser

# Chapitre 0

## Introduction

### 0.1 Contexte

Dans ce cadre, l'entier front-end RF à ondes millimétriques et les modules T/R du capteur à courte portée sont conçus, fabriqués et mesurés sur une largeur de bande de 70-82 *GHz*. La haute précision, la faible consommation d'énergie, le bas coût et la taille compacte sont les principaux paramètres que l'on prend en compte lors de la conception d'une nouvelle architecture radar appropriée pour un grand nombre d'applications, dans différents domaines. Le domaine de la sécurité, le domaine militaire, automobile, biomédical, l'automatisation industrielle ne sont que quelques exemples de la grande variété de ses applications.

### 0.2 Le principe radar et la revue de la littérature

#### 0.2.1 La technologie à ondes millimétriques

Selon le comité fédéral des communications des États-Unis (FCC), les ondes millimétriques font partie du spectre électromagnétique (généralement entre 30 *GHz* et 300 *GHz*, longueurs d'ondes correspondantes entre 10 *mm* et 1 *mm*), dédié aux applications spécifiques [1]. Comme illustré à la Fig. 1, les communications sans-fils multi-Gb/s dans les milieux de propagation intérieure en bande V (57 - 64 *GHz*) ou dans les milieux de propagation extérieure en bande E (71 - 76 *GHz*, 81 - 86 *GHz*,

92- 95 GHz), les capteurs radar pour les automobiles (76 - 77 GHz) et les systèmes de capteurs pour imagerie (85 -94 GHz) ne sont que quelques applications des ondes millimétriques [2, 3, 4].

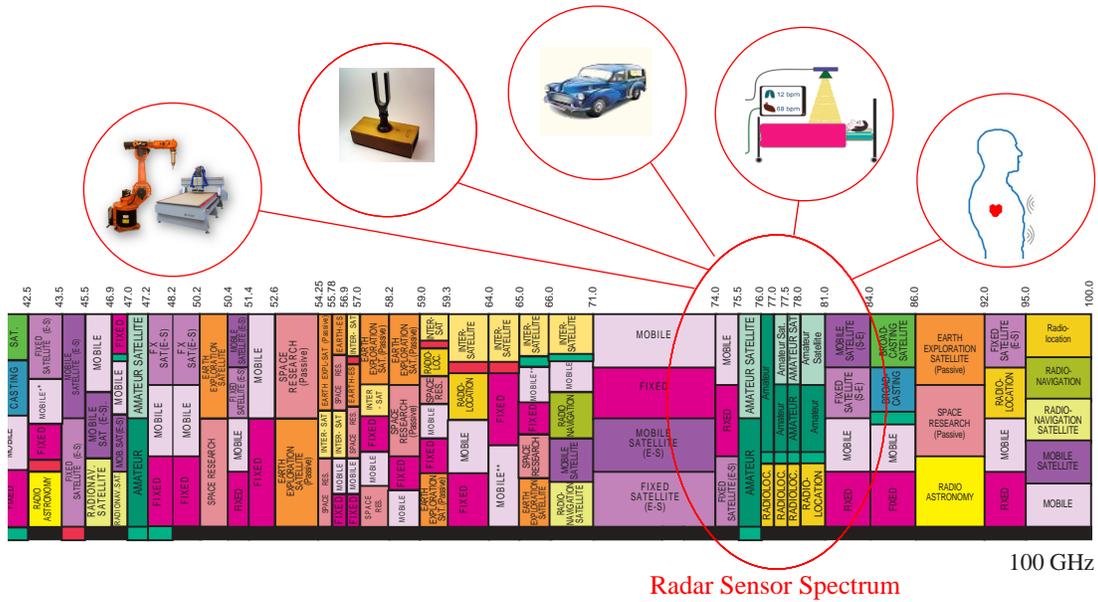


FIGURE 1 – Spectre FCC et quelques applications des capteurs radar à ondes millimétriques.

Un autre aspect important du spectre à ondes millimétriques est le niveau maximal de la densité de puissance auquel l'utilisateur peut s'exposer sans danger. Selon « National Radiation Protection Council » (NRPC) des Etats-Unis, le niveau maximal de la densité de puissance est  $1\text{ mW}/\text{cm}^2$  sur toute la bande de fréquence de 1,5 à 100 GHz [5].

Les études ont montré que les deux fréquences, 24 GHz et 77 GHz, sont capables de mesurer avec succès la distance jusqu'à la cible et la vitesse pour différentes applications [6]-[11]. Pour optimiser les mesures dans les applications radar à courte portée, les chercheurs ont proposé une fréquence supérieure (77 GHz) dans les ondes millimétriques. Même si les fréquences supérieures sont soumises à une atténuation du trajet supérieure, elles sont plus recommandées pour les applications à courte portée, avec une grande sensibilité. Dans le Tableau 3, on compare ces deux fréquences différentes.

Tableau 1 – Comparaison entre un radar de 24 GHz et un radar de 77 GHz

Avantages - 24 GHz	Avantages -77 GHz
Composants électroniques bon-marché	Bande de fréquence largement disponible aux Etats-Unis, au Japon, en Europe,...
Consommation d'énergie	Grande largeur de bande
Facteur de bruit	Meilleure résolution en distance
	Pourcentage plus petit de la bande de fréquence
	Ouverture plus petite de l'antenne
	Capacité multi-mode, multi-application

## 0.2.2 Applications des radars

La détermination très précise des distances et de la vitesse est omniprésente dans l'industrie actuelle. Les technologies radar à ondes millimétriques sont utilisées pour une gamme large d'applications, telles que:

- Le secteur automobile et la sécurité routière: surveillance et contrôle du trafic, avertisseur de collision, surveillance zone aveugle pour les automobiles et les autobus scolaires, régulateur de vitesse automatique, etc.
- Le domaine militaire: surveillance, défense, missile, localisation, etc.
- Le domaine des radars météorologiques: évitement de terrain et suivi du terrain, altimètre radar, navigateur Doppler, observation météorologique, etc.
- Le domaine de la navigation maritime: détection d'autres navires, des bouées, du terrain, radars côtiers pour la surveillance des ports et le contrôle du trafic.
- Le domaine industriel: mesures dans les environnements hostiles, la robotique, l'automatisation, la météorologie, etc.
- Le domaine spatial: le rendez-vous et l'amarrage, l'atterrissage sur la lune, la télédétection (RADARSAT), etc.
- L'imagerie: surveillance agricole, surveillance de l'environnement, tomographie micro-onde, imagerie radar à travers les murs, les mesures 3D, etc.

Comme on l'a déjà indiqué, l'une des principales applications du capteur radar est dans le secteur automobile et la sécurité routière. Chaque année, les accidents de la route constituent une des principales causes des décès. Selon la Banque mondiale et l'Organisation mondiale de la santé (OMS), presque 1,3 millions de personnes meurent en accidents de la route chaque année, et 20-50 millions sont blessées ou deviennent handicapées [12]. Les véhicules visibles, intelligents et résis-

tants aux accidents peuvent considérablement minimiser ces pourcentages. Grâce aux technologies actuelles du marché, telles que les capteurs à ultrasons et les réseaux de capteurs, les lasers, les caméras attachées aux miroirs et les unités radar électromagnétiques, on peut réduire ces pourcentages. Cependant, elles ne sont disponibles que pour les voitures de luxe et certaines technologies ne peuvent pas assurer la sécurité totale dans des conditions météo mauvaises telles que la pluie, la neige ou le brouillard.

En 1904, Christian Hulsmeyera German a été le premier qui a utilisé les ondes radar pour démontrer son système anticollision [13]. Les radars automobiles sont utilisés pour calculer la distance jusqu'à la cible, la vitesse de la cible et l'angle d'azimut dans un délai court, pour différentes situations cibles [radars à courte portée (SRR=0.2m à 30m), radars à moyenne portée (MRR)=30m à 80m et radars à longue portée (LRR=80m à 200m)]. LRR et MRR sont utilisés dans les systèmes de régulation de vitesse et anticollision, tandis que SRR est utilisé dans les systèmes anticollision, dans les systèmes de prévention des accidents et d'assistance au parking. Chaque type de radar a ses propres exigences en termes de précision et de largeur de bande, comme indiqué au Tableau 2.

Tableau 2 – Différents types d'exigences applicables aux radars.

<b>Bande de fréquence</b>	76-77 GHz	77-81 GHz	77-81 GHz
<b>Largeur de bande</b>	500 MHz	500 MHz	4 GHz
<b>Distance</b>	100-250 m	30-100 m	0.15-30 m
<b>Précision sur la distance</b>	0.1 m	0.1 m	0.02 m

Cette thèse analyse un radar de  $77\text{ GHz}$  avec une grande largeur de bande, qui peut couvrir toutes ces situations cibles. Les examens et les essais sont réalisés pour les radars à courte portée à cause de la puissance réduite de transmetteur. Pour avoir suffisamment de signal à la sortie en bande de base, un amplificateur à faible bruit en réception est bénéfique pour les applications radar à moyenne et à longue portée.

### 0.2.3 Types de modulations radar

Comme indiqué au Tableau 3, les types de modulation radar sont généralement classés en deux grandes catégories ; les radars à impulsions et les radars à ondes continues. Pour le bon choix de notre architecture radar, il est essentiel de faire une comparaison entre ces deux techniques.

Tableau 3 – Classifications des modulations radar.

Forme d'onde du radar					
Radar CW			Radar à impulsions		
Non-modulé	Modulé en fréquence	Modulé en phase	Fréquence fixe	Modulation intra-impulsion	Modulation à impulsions
FMCW linéaire, dents de scie, triangulaire	FMCW non-linéaire, sinusoïdal, fréquence multiple, bruit, pseudo-aléatoire		Modulé en fréquence, FM linéaire, FM non-linéaire		Modulé en phase, biphasé, polyphasé

Les radars à impulsions ont été conçus, fabriqués et mis à l'essai par William Webster Hansen (1900-1949). Ils ont été utilisés pour la défense de l'Angleterre au début de la Seconde Guerre Mondiale [15, 16]. Les radars à impulsions transmettent de brèves impulsions d'énergie électromagnétique et le récepteur du système analyse le signal réfléchi sur la cible. En fonction du signal réfléchi et de la présence de la cible, on peut calculer le délai entre le signal transmis et le signal reçu. Il est facile d'obtenir des informations sur la distance selon la différence de temps entre les signaux. Ils sont principalement utilisés comme une plateforme aéroportée, pour suivre le mouvement des personnes [17]. Les radars à impulsions sont généralement monostatiques (ils n'utilisent qu'une seule antenne pour la transmission et la réception) et utilisent une source stable de fréquence pour générer le signal de référence. L'architecture du radar à impulsions exige l'utilisation d'un commutateur, pour basculer entre la transmission et la réception. Dans la fréquence à ondes millimétriques, il faut transmettre une impulsion très courte, entre microsecondes et quelques nanosecondes. Les radars à impulsions utilisent un magnétron puissant pour générer des signaux à micro-ondes avec des impulsions très courtes de tension appliquée, ce qui augmente le coût et rend parfois le système encombrant.

Les radars CW transmettent un signal continu qui peut être non-modulé, modulé en phase, ou modulé en fréquence (FMCW). Le radar CW a été utilisé au début dans les projectiles d'artillerie pendant la Seconde Guerre mondiale et le premier modèle pratique d'altimètre FMCW a été développé par Western Electronic Company en 1938 [18, 19]. Le radar CW transfère une énergie radio connue, à fréquence stable et à ondes continues, qui est ensuite reçue par une cible réfléchissante. Les signaux transmis et reçus sont mélangés pour générer le signal en bande de base qui sera traité

par une unité de traitement des signaux. Il peut fournir des informations sur l'effet Doppler et sur la distance jusqu'à la cible, pour une portée limitée, inférieure à la moitié de la longueur d'onde.

L'avantage principal des radars CW réside dans le fait que le signal généré est un signal non-modulé à bande étroite, donc il est beaucoup plus facile de l'analyser et de le gérer, par rapport aux radars à impulsions [20]. Les radars CW peuvent aussi mesurer sans ambiguïté la vitesse et la distance des cibles (portée très courte, inférieure à la moitié de la longueur d'onde), avec une technique simple de traitement du signal, tandis que les systèmes à impulsions présentent des ambiguïtés tant pour la mesure de la distance que pour la mesure de la vitesse. Les radars CW sont généralement utilisés dans la navigation aérienne, pour estimer l'altitude et la vitesse de l'avion, pour détecter le mouvement et dans beaucoup d'autres applications [21, 22, 23].

Les radars CW utilisent une topologie simple comprenant une source de signal pour la transmission, ainsi qu'un récepteur hétérodyne ou homodyne. Ils ont l'avantage d'une haute résolution, parce que les données peuvent être analysées dans des segments arbitraires de temps. L'architecture du radar à onde continue n'exige pas l'utilisation d'un commutateur, pour basculer entre la transmission et la réception, par rapport aux systèmes radar à impulsions. La complexité du radar à impulsions par rapport au radar à ondes continues ne se traduit pas dans une augmentation proportionnelle de ses avantages.

Comme mentionné auparavant, le radar à onde continue sans modulation de fréquence ne détecte que les cibles mobiles et la portée très courte, donc pour mesurer la distance, des techniques de modulation spécifiques sont nécessaires. On utilise plusieurs types de modulation, telles que la modulation en dents de scie et la modulation de fréquence sinusoïdale. Si la modulation est une modulation de fréquence, le radar FMCW (à onde continue modulée en fréquence) mesure la vitesse Doppler de la cible et la distance entre l'antenne et la cible. Une discussion détaillée sur le signal post-mixage pour différentes formes de modulation FMCW est disponible dans Tozzi [24]. La plupart des travaux théoriques sur les radars FMCW ont été publiés entre les années 1940s et 1960s [18, 19, 20]. Pour les radars FMCW, la linéarité et la largeur de bande du balayage de fréquence sont essentielles pour la précision et la sensibilité du radar.

Les deux techniques radar, à ondes continues et à impulsions, ont été étudiées dans beaucoup d'applications. Le tableau 4 présente quelques performances comparatives des deux groupes de radars [24].

Tableau 4 – Comparaison entre le radar CW radar et le radar à impulsions [24].

Spécifications	Radar CW	Radar à impulsions
Structure du circuit	Simple	Complexe
Mesure à courte portée	Supérieure	Inférieure
Mesure à longue portée	Inférieure	Supérieure
Précision	Supérieure	Inférieure
Détection de l'effet Doppler	Affecte	N'affecte pas
Puissance d'émission	Elevée	Faible
Antenne	Duplexeur ou commutateur	Antenne distincte

Dans cette thèse, on se propose de mesurer la distance et la vitesse de la cible, donc un système radar modulé, à ondes continues, s'avère le choix idéal. Tant le radar modulé que le radar non-modulé CW ont une large gamme de domaines d'application. Cependant, le radar FMCW est un type de radar qui offre plus d'avantages, par rapport aux autres. Il assure l'obtention des informations sur la distance et sur la vitesse des objets environnants à détecter, d'une manière simultanée et précise. On peut conclure que les caractéristiques principales du radar FMCW sont les suivantes :

- Capacité de mesurer différentes distances avec une haute précision ; la distance maximale mesurée est définie par l'atténuation du trajet et la distance minimale mesurée est comparable avec la longueur d'onde transmise.
- Capacité de mesurer de manière simultanée la distance de la cible et sa vitesse relative à tout moment.
- Le traitement du signal est réalisé dans des gammes de fréquence relativement basses, commensurables avec la fréquence de modulation, ce qui simplifie considérablement la réalisation des circuits de traitement
- Poids faible et faible consommation d'énergie dus à l'absence de circuits hautes tensions
- Compacité, la taille du radar utilisant la technologie moderne étant déterminée par la taille du bloc micro-ondes

#### 0.2.4 Théorie du radar et équations de base

Essentiellement, le radar est un système électromagnétique utilisé pour détecter la taille, les caractéristiques, l'angle, la distance et la vitesse d'un objet, d'un système ou d'un milieu. Le schéma d'un radar conventionnel est indiqué à la figure 2.

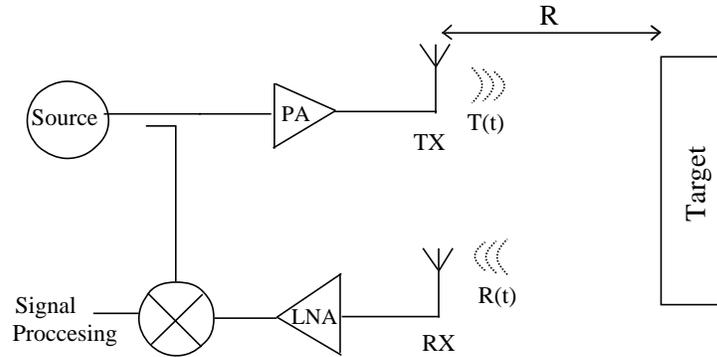


FIGURE 2 – Schéma fonctionnel d'un émetteur-récepteur simple de radar.

Un système radar comprend un émetteur qui émet un signal électromagnétique modulé, avec un certain type de forme d'onde, en fonction des exigences de l'application. Le signal est renvoyé par la cible et le signal réfléchi est détecté par le récepteur du radar et analysé pour extraire les informations nécessaires. Généralement, l'objectif du récepteur est de convertir à la baisse un signal reçu de la porteuse haute fréquence utilisée pour la transmission vers la bande de base, afin d'extraire les informations inhérentes au signal lui-même. Généralement, cette conversion de fréquence est obtenue en utilisant un mélangeur. Il y a une large variété de mélangeurs pour plusieurs types d'applications, tous ayant des avantages et des désavantages. Dans cette thèse, on présentera une technique innovante de mesure, basée sur le principe du récepteur six-port. Le circuit six-port est utilisé seulement comme alternative qui remplace un mélangeur conventionnel et peut avoir des avantages pour certaines applications. L'excellente résolution de phase offerte par ce récepteur six-port permet des capacités de mesure de haute précision.

La différence entre le signal reçu et la forme d'onde transmise réside principalement en trois éléments : amplitude, fréquence et délai. La distance de la cible ( $R$ ) peut être établie en mesurant le délai ( $T_d$ ) entre la transmission et la réception ( $R = cT_d/2$ ). Les dimensions de la cible peuvent être aussi établis en mesurant l'angle d'arrivée (AOA) du signal, qui nécessite une antenne à forte directivité. Les modèles d'antenne dont la largeur de faisceau est plus étroite permettent une détermination de l'angle plus précise. On peut estimer la vitesse relative entre le radar et la cible, en fonction du décalage Doppler de la fréquence porteuse. L'effet Doppler est causé par le mouvement relative de la cible. La fréquence du signal reçu est supérieure si les objets s'approchent et inférieure, si la cible s'éloigne. La figure 1.3 présente la modification de la fréquence pour les deux situations.

Un radar CW à différentes modulations ou un radar non-modulé est nécessaire pour mesurer la vitesse.

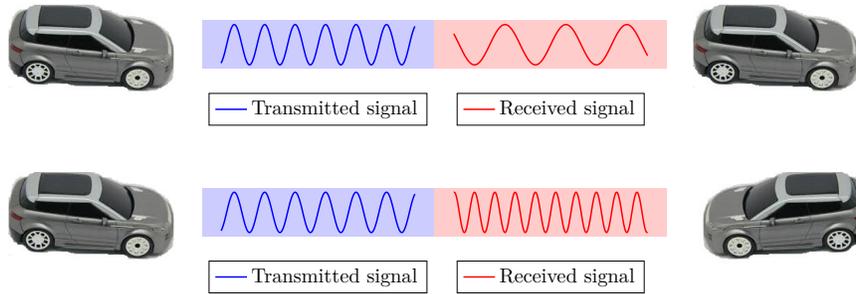


FIGURE 3 – Effet de la fréquence Doppler lorsque la voiture s'éloigne/s'approche

L'atténuation du signal, causée par l'affaiblissement du signal en espace libre, est proportionnelle au carré de la distance entre l'émetteur et le récepteur et, aussi, au carré de la fréquence du signal radio. A partir de l'équation radar [14], on peut voir que la puissance renvoyée vers l'antenne du récepteur sera comme suit:

$$P_r = P_t G_t G_r \left( \frac{1}{4\pi R^2} \right) \sigma \frac{\lambda^2}{4\pi} \left( \frac{1}{4\pi R^2} \right), \quad (1)$$

où  $P_r$  = la puissance reçue,  $P_t$  = la puissance transmise,  $G_r$  = le gain du récepteur,  $G_t$  = le gain de l'émetteur,  $\sigma$  la section effective, et  $A_e = \lambda^2/4\pi$ , le secteur d'ouverture effectif. Afin de séparer visuellement les différents termes, les termes relatifs à l'atténuation du trajet pour les deux parties sont mis entre crochets.

De cette équation, on peut voir que la puissance reçue est inversement proportionnelle avec la puissance quatre de la distance, ce qui signifie que la puissance réfléchiée des cibles éloignées sera très proche de la puissance de bruit. Le plus petit signal que le radar peut détecter est appelé « signal mesurable minimal, Minimum Discernible Signal » ( $P_{MDS}$ ). Les valeurs typiques du radar de l'écho MDS se situent entre -104 dBm et -113dBm [4]:

$$MDS = -174 + NF_{tot} + 10 \log BW_{FFT} + SNR_{min} \quad (dBm) \quad (2)$$

Par conséquent, une puissance d'entrée élevée, une antenne à gain élevé (le gain de l'antenne est proportionnel à sa taille) ou un amplificateur à faible bruit (LNA) sont nécessaires pour récupérer la puissance perdue. Toutes ces solutions ont leurs propres défis et limites ; ainsi, les radars à ondes millimétriques sont plus adéquats pour les mesures à courte portée.

$$R_{max} = \sqrt[4]{\frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 P_{MDS} L_s}}. \quad (3)$$

En outre, la résolution en distance des formes d'onde du radar est caractérisée par la capacité de détecter séparément deux ou plusieurs sources de réflexion. Dans le cas de cibles multiples, la RCS pour une seule cible sera remplacée par une RCS distribuée, multipliée par un domaine d'intérêt.

Il est aussi important de mentionner que l'équation radar suppose une cible ponctuelle (une cible très petite en ce qui concerne la taille de la cellule de résolution). Pour certaines applications, l'hypothèse de la cible ponctuelle n'est pas valable, parce que la taille de la cellule de résolution est similaire à la taille des cibles typiques. Par conséquent, l'équation radar et les paramètres RCS sont différents pour les applications radar en champ proche.

## 0.3 Composants du radar

### 0.3.1 Réflectomètre six-port

Le système radar proposé est basé sur un interféromètre six-port et une technique de démodulation I/Q est utilisée pour récupérer les informations nécessaires. Le circuit six-port est connu depuis le XXème siècle, étant découvert par F. Engen [26]. Depuis 28 ans dès son début, il a été utilisé comme un analyseur de réseau vectoriel deux ports (VNA) [27]. Récemment, la théorie six-port a fait son chemin dans d'autres domaines tels que la caractérisation des matériaux, les récepteurs et les radars [28]-[33]. L'utilisation d'un réflectomètre six-port pour la modulation et la démodulation a été bien étudiée [34, 35]. Toutefois, pour les applications radar à haute vitesse et à bande ultralarge, il reste encore de nombreux problèmes à résoudre. Dans ce travail, on a conçu et simulé tant le modulateur que le démodulateur à base du circuit six-port, à une fréquence de 77 GHz. Cette étude vise le démodulateur six-port, comme un convertisseur abaisseur de fréquence en quadrature dans un prototype radar.

L'interféromètre six-port peut être mis en œuvre en utilisant différentes architectures comprenant des coupleurs hybrides, des diviseurs de puissance et des déphaseurs [36]-[42]. Dans cette recherche, un six-port composé de quatre coupleurs hybride  $90^\circ$  et d'un déphaseur, ainsi qu'un six-port composé de trois coupleurs hybride  $90^\circ$  et d'un diviseur de Wilkinson sont caractérisés à titre expérimental et validés pour la conversion de fréquence en quadrature du signal en ondes millimétriques. Le circuit de fabrication hybride MHMIC est utilisé pour fabriquer le capteur proposé.

Pour les mesures deux ports, qui ont constitué l'une des parties les plus difficiles de notre recherche, on a fabriqué plusieurs configurations de circuit sur un substrat céramique. Chaque circuit est prévu avec des transitions coplanaires au ports de mesure et des charges intégrés aux autres ports. Le nombre de circuits dans le substrat est en relation avec la symétrie du circuit, pour permettre la mesure de tous les paramètres de dispersion nécessaires. Le dispositif de mesure comprend un analyseur de réseau de haute précision (E 8362 PNA), un contrôleur de têtes millimétriques (N 5260A), deux équipements d'extension en fréquence en ondes millimétriques pour couvrir 60-90 GHz (OML S12MS-A), et deux guides d'ondes courbés WR-12 utilisés pour connecter les sondes coplanaires avec une distance entre pointes de 150 micromètres. Pour des mesures plus précises et plus rapides, des kits de calibration TRL sont fabriqués dans le même substrat. Puisque les pointes de la sonde sont des guides d'onde coplanaires, les transitions des micro-rubans vers les guides d'onde coplanaires sont nécessaires. En outre, pour éviter les trous traversants et pour assurer la répétabilité des mesures, des lignes ou papillons terminés en circuit ouvert d'une longueur d'un quart de longueur d'onde sont utilisés comme des courts-circuits en ondes millimétriques [43]. Tous les détails sur la conception, la fabrication et les mesures des circuits six-port sont présentés dans cette thèse.

### 0.3.2 Le détecteur de puissance à diodes

Un détecteur de puissance est un dispositif deux ports qui convertit le signal RF d'entrée en un signal de bande de base de sortie. Généralement, les détecteurs de puissance utilisent la fonction de transfert d'un dispositif non-linéaire [44]-[47]. Pour un bon fonctionnement du six-port, il est nécessaire de pouvoir mesurer les rapports de puissance haute fréquence avec exactitude. D'habitude, les quatre sorties de chaque circuit six-port sont connectées aux détecteurs de puissance qui fournissent une tension liée de façon linéaire avec la puissance du signal RF aux quatre ports

de sortie. Les dispositifs non-linéaires communs utilisés dans les détecteurs sont des diodes, telles que les diodes Schottky ou les diodes tunnel [47, 48, 49]. La fonction de transfert courant-tension non-linéaire permet de faire une conversion de la puissance en courant, qui est nécessaire pour le processus de la détection de la puissance. Un signal RF avec une certaine puissance ou amplitude de la tension est redressé par la diode comme un courant unipolaire à travers le dispositif. Idéalement, la proportionnalité est définie selon la loi du carré de la fonction de transfert non-linéaire. Les détails du détecteur de puissance fabriqué en utilisant deux diodes Schottky (HSC9161) et un coupleur hybride  $90^\circ$  comme solution pour améliorer la correspondance d'entrée sont présentés dans les derniers trois travaux. Quatre détecteurs de puissance de ce type sont utilisés dans notre capteur, pour extraire les informations sur la magnitude et sur la phase du signal réfléchi sur la cible. Outre la modulation d'amplitude convertie à la baisse, le signal de sortie contient un décalage en tension continu (DC offset) à cause du processus de rectification.

### 0.3.3 Le réseaux d'antennes

La définition classique de l'antenne est donnée par « IEEE Standard Definitions of Terms for Antennas (IEEE Std 145-1983) » ; l'antenne est définie comme « la partie d'un système de transmission ou de réception qui est conçu pour émettre ou pour recevoir des ondes électromagnétiques » [50]. L'un des composants principaux du prototype radar est l'antenne. Les aspects pris en compte dans cette thèse sont la modélisation et la simulation du gain élevé, la taille réduite et le faible coût. Comme mentionné auparavant, pour récupérer la puissance perdue à cause de la distance de la cible, le gain d'antenne doit augmenter. Pour créer une antenne à gain élevé, qui émet des ondes radio en un faisceau étroit, on peut utiliser deux techniques générales [51, 52, 53]:

1. Utilisation de grandes surfaces métalliques, telles que les réflecteurs paraboliques, les cornets ou les lentilles diélectriques, qui changent la direction des ondes radio par réflexion ou réfraction, afin de focaliser les ondes radio d'une seule antenne à faible gain en un faisceau. Ce type d'antenne est appelé une antenne à ouverture.
2. Une deuxième technique est d'utiliser plusieurs antennes qui sont alimentées par le même émetteur ou récepteur ; ce type d'antenne est appelé une antenne réseau.

Pour ce projet, on a choisi un réseau d'antennes patch pour deux raisons. Premièrement, il est simple de le concevoir et de le fabriquer. Deuxièmement, il est petit et il peut être fabriqué sur

le même substrat céramique du circuit six-port. Les réseaux d'antennes sont la combinaison de plusieurs éléments d'antenne qui fonctionnent comme une grande antenne. En ajoutant plusieurs éléments, la directivité du réseau est améliorée.

Les performances du réseau d'antennes sont examinées en fonction de la largeur de bande, du gain et de l'efficacité de rayonnement. L'antenne et le réseau proposés sont prometteurs pour les applications des ondes millimétriques grâce à leurs avantages liés à une grande largeur de bande, au faible coût, à la haute efficacité et au profil bas. Cette antenne est fabriquée comme une antenne émettrice et réceptrice, dans le même substrat du circuit six-port. Elle est complètement intégrée dans un substrat céramique de 16.83 mm  $\times$  13.94 mm. Ce concept de conditionnement réduit la taille et le prix du circuit et présente d'excellentes performances.

## 0.4 Objectifs de la recherche

Les objectifs de la recherche de cette thèse peuvent être classés en un objectif principal et des objectifs spécifiques.

### 0.4.1 L'objectif principal

L'objectif principal de ce travail est de trouver des techniques de mesure basées sur le réflectomètre six-port pour la mesure simultanée de la distance et de la fréquence Doppler répondant aux exigences imposées par les applications industrielles et biomédicales de haute précision. La précision croissante, le faible coût et la taille compacte du radar à base de six-port sont les principaux objectifs des capteurs radar proposés. La grande largeur de bande, la diminution de la puissance requise par l'oscillateur local et une très bonne isolation entre les entrées sont les propriétés intrinsèques de l'utilisation de la technique six-port dans les capteurs à ondes millimétriques. En outre, la méthode proposée ne se confronte pas aux difficultés des capteurs conventionnels, telles que l'amplitude et le déséquilibre de phase, le décalage en tension continu (DC offset), le bruit de conversion FM-AM.

### 0.4.2 Objectifs spécifiques

Les objectifs de la recherche de ce projet sont:

- Etudier et faire une introduction aux capteurs conventionnels, pour formuler des commentaires sur la capacité du nouveau radar d'améliorer la structure et l'analyse de données par rapport au radar classique.
- Etudier et concevoir des structures six-port différentes, à 77 GHz, pour des mesures précises de la phase.
- Simplifier le modulateur/démodulateur comme émetteur et récepteur, afin de réduire le coût et/ou la consommation d'énergie, avec un maximum de précision.
- Identifier et trouver des solutions pour surmonter les limitations et les désavantages de l'architecture du radar six-port, pour des mesures plus précises.
- Etudier et concevoir un détecteur de puissance à diode avec une conversion précise puissance d'entrée-tension de sortie.

- Etudier et concevoir un réseau d'antennes pour le module émetteur et récepteur, avec suffisamment de gain, un faible coût et une taille compacte.
- Concevoir un prototype complet d'émetteur et de récepteur, dans la plus petite taille possible et au plus bas prix.
- Améliorer la performance, pour permettre des mesures de distance précises dans le système à ondes millimétriques modulées en fréquence.

## 0.5 Méthodologie

On a conçu et simulé deux circuits six-port passifs et linéaires différents, avec ou sans un diviseur de Wilkinson, en utilisant le simulateur électromagnétique de Keysight Technologies, « Momentum of Advanced Design System » (ADS). Les circuits six-port ont été fabriqués en technologie de fabrication hybride MHMIC. Le substrat est en alumine, parce que ce matériel a une haute permittivité ( $\varepsilon_r = 9.8$ ) et une très faible perte. Les circuits six-port sont remplacés par un modèle basé sur des mesures des paramètres S, sur toute la bande et utilisés comme modulateur et démodulateur.

On a simulé un modulateur QPSK (modulation par déplacement de phase en quadrature) et un modulateur 16-QAM (modulation d'amplitude en quadrature 16), basés sur le six-port. Il se compose d'un circuit six-port avec la charge variable appropriée, comme impédance finale. Le modulateur six-port à ondes millimétriques peut être utilisé pour générer des signaux avec une phase et une fréquence différentes (au lieu de VCO).

Pour le démodulateur, quatre diodes sans polarisation (HSC9161) sont utilisées aux quatre ports de sortie, comme détecteurs. Les ports d'entrée sont connectés au signal RF d'entrée et à l'oscillateur local. Le circuit est fabriqué et utilisé comme récepteur dans le prototype final, pour convertir à la baisse le signal RF.

Un réseau d'antennes est conçu et optimisé en utilisant le logiciel ADS. Pour avoir suffisamment de gain, 16 éléments patch sont connectés l'un à l'autre, pour réaliser un compromis entre la largeur du faisceau principal et le taux des lobes latéraux pour les applications radar. Sa performance est examinée selon la largeur de bande, le gain et l'efficacité de rayonnement. Il est utilisé dans le module émetteur et récepteur.

La structure complète du radar FMCW est conçue dans le logiciel ADS et fabriquée pour les essais de mesure. Des mesures en intérieur sont réalisées pour différents signaux d'onde d'entrée pour évaluer la performance du radar prototype proposé. On présente deux types de radars différents, en trouvant des solutions pour certains problèmes liés aux mesures. Premièrement, le radar CW est utilisé sans aucune modulation à l'entrée du circuit. Des diapasons sont utilisés comme cible pour démontrer la performance du capteur six-port, qui offre des mesures de la fréquence précises, à différentes fréquences. Deuxièmement, des schémas de modulation FMCW ou multi-tonales sont réalisées pour mesurer de manière précise la distance et la vitesse de la cible. La distance de la

cible est mesurée en envoyant des signaux à différentes fréquences et en mesurant les différences de phase correspondantes. Pour la mesure de la vitesse, une plaque en aluminium est déplacée devant le capteur avec plusieurs vitesses différentes et les fréquences Doppler sont mesurées.

A cause de la puissance très faible des ondes millimétriques, utilisée dans l'essai, les résultats concernent la courte portée. L'utilisation d'un amplificateur à faible bruit dans le front-end du récepteur augmentera considérablement la plage de fonctionnement. Grâce à ce processus de fabrication robuste et à faible coût, ces capteurs peuvent être utilisés dans diverses applications industrielles et biomédicales

## 0.6 Contribution de la recherche

La contribution de cette thèse comprend une contribution scientifique et l'impact socio-économique du projet, comme indiqué ci-dessous:

### 0.6.1 Contribution scientifique de la recherche

Les principales contributions sont dans la conception matérielle et les implémentations pour obtenir des données brutes sans besoin d'un étalonnage à six ports, notre philosophie d'équipe:

- Premier interféromètre à six ports conçu à 77 GHz sur substrat céramique de 5 mil
- Très premier capteur radar 77 GHz conçu sur un substrat de très petite taille, et à faible coût
- Consommation électrique très faible (fonctionnant à 0 dBm en émission et nécessitant une puissance LO très faible pour un signal de référence à six ports, inférieure à -20 dBm)
- Nouvelles plates-formes de simulation pour diverses cibles, y compris le modèle de circuit à six-ports basé sur les mesures des paramètres S. Preuve de concept de mesures précises avec le capteur intégré:
- Première mesure sur une vibration sub millimétrique d'un diapason, précision égale à la précision de l'oscilloscope (environ 1 Hz)
- Résultats précis dans la plage de 10 microns pour un circuit à six ports (lié aux erreurs de phase du circuit) et de l'ordre de 20 microns pour le prototype entier (basé sur la mesure)
- Publications de conférence (huit documents de conférence)
- Publications dans des revues (trois articles de revue)
- Thèse de doctorat

### 0.6.2 Impact socio-économique du projet

La province de Québec est bien placée dans le domaine des micro-ondes/ondes millimétriques, beaucoup d'entreprises et de laboratoires étant impliqués dans la recherche et le développement d'une gamme large de produits, du niveau des composants au niveau des systèmes. Aujourd'hui, les technologies à haute fréquences sont considérées un facteur déterminant dans le développement social et économique. Dans un contexte plus ample, ce projet contribuera au développement de l'industrie des ondes millimétriques par la conception de nouveaux modèles pratiques de radars.

Cette recherche vise la réduction des coûts, la réduction de la taille et une meilleure précision des radars FMCW, qui ont un rôle de plus en plus important dans la sécurité routière. Le radar proposé fonctionne très bien dans différentes conditions climatiques, ce qui est un facteur important dans la province de Québec. Il sera aussi moins coûteux, plus petit et plus facile à monter dans la production de masse de l'application automobile ou dans d'autres applications industrielles. C'est une technologie accessible pour les voitures de la classe moyenne inférieure, dans le but de réduire le nombre d'accidents de la route et de victimes.

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Première partie

Articles

## Article 1

# Performance Analysis for Two Different Structures of 77 GHz Six-port Correlator

H. Arab, C. Akyel, S. O. Tatu

International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM),  
Montreal, QC, Canada, pp. 1-2, 10-13 July 2016.

### Abstract

Dans cet article, on a conçu et simulé deux corrélateurs six-port différents, en utilisant des coupleurs hybride  $90^\circ$ , avec ou sans un diviseur Wilkinson, à une fréquence centrale de 77 GHz. La performance des corrélateurs conçus est évaluée via un simulateur électromagnétique commercial, Advanced Design System (ADS) de Keysight Technologies. Les résultats de la simulation indiquent que grâce à la structure du corrélateur six-port, avec quatre coupleurs hybride  $90^\circ$  et sans le diviseur de Wilkinson, on obtient une largeur de bande plus ample et une erreur de phase plus petite, par rapport à l'autre corrélateur six-port. En outre, la structure avec le diviseur de Wilkinson présente un faible taux d'erreur aux signaux de sortie, avec une différence de phase de  $0^\circ$ ,  $180^\circ$ ,  $90^\circ$ , et  $270^\circ$ .

Toutes les deux structures ont individuellement une importance relative dans la conception des terminaux sans-fils, comme modulateur et démodulateur dans le récepteur et le transmetteur, au lieu d'utiliser le mélangeur.

## Abstract

In this paper, two different six-port correlators by using  $90^\circ$  hybrid couplers, with or without a Wilkinson power divider, were designed and simulated at the center frequency of  $77\text{ GHz}$ . The performance of the designed correlators are assessed via full-wave commercial electromagnetic package, Advanced Design System (ADS) of Keysight Technologies. The simulation results show that the six-port correlator structure with four  $90^\circ$  hybrid couplers and without Wilkinson power divider gets wider bandwidth and smaller phase error in comparison to the another six-port correlator. Besides the structure with Wilkinson has low error at the output voltage signals with phase difference of  $0^\circ$ ,  $180^\circ$ ,  $90^\circ$  and  $270^\circ$ . Both structure individually have relative importance in the design of the wireless terminals as a modulator and demodulator in receiver and transmitter instead of using mixer.

## 1.1 Introduction

Recently, there has been much request in using small-sized and low-cost six-port structure in communication devices [1, 2, 3].

Many studies have been done on modulator and demodulator in receiver and transmitter where a six-port correlator is used instead of using mixer [2, 4, 5]. The configuration six-port correlator is usually composed of  $90^\circ$  hybrid couplers with or without Wilkinson power divider. Based on this configuration, an integer multiple of phase differences of  $90^\circ$  is presented between the output voltage signals.

In this paper, two different structures of six-port phase correlator with  $90^\circ$  hybrid coupler and/or Wilkinson power divider were designed and simulated. The performances for two six-port phase correlators were analyzed in frequency range of  $77\text{ GHz}$ . The four ports of each six-port junction are

terminated by four power detectors, while the remaining two ports provide a connection to the RF signal source and a local oscillator (LO).

The combination of six-port correlator with power detectors allows separation of the base-band in-phase (I) and quadrature-phase (Q) data in a six-port demodulator (receiver). Also, the combination of six-port correlator with variable impedance loads can instead be used to generation of a modulated radio frequency (RF) in a six-port modulator (transmitter).

## 1.2 Six-port Phase Correlator Structure

The six-port correlator layout with four  $90^\circ$  hybrid coupler is shown in Fig.1.1. Another six-port correlator is composed of a  $3\text{ dB}$  Wilkinson power divider and three  $90^\circ$  hybrid couplers which is shown in Fig.1.2.

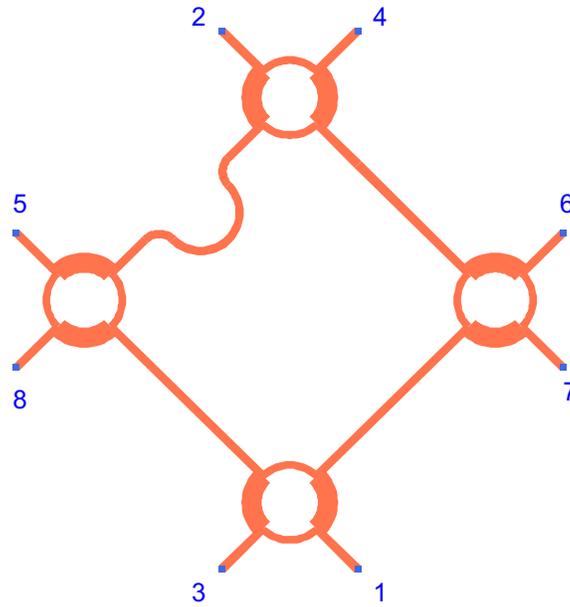


FIGURE 1.1 – Layout of six-port phase correlator with four  $90^\circ$  couplers.

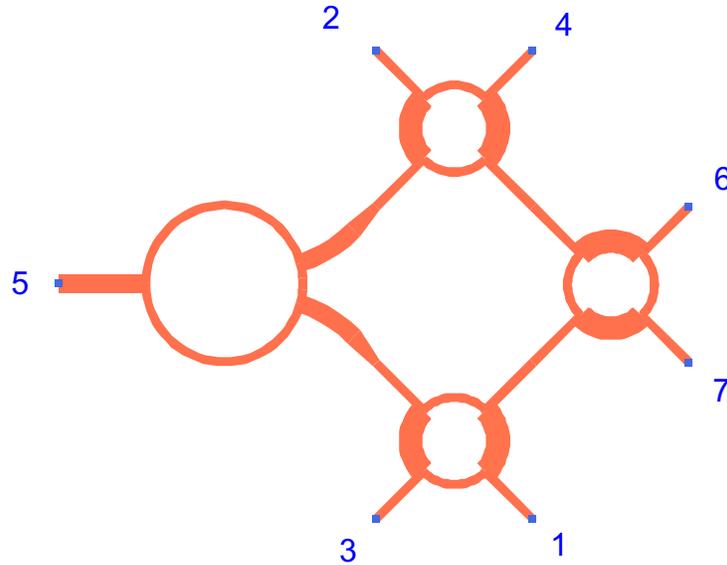


FIGURE 1.2 – Layout of six-port phase correlator with three  $90^\circ$  couplers and one Wilkinson power divider.

The port 5 is the LO port and the port 6 is the input RF signal source port. The circuit outputs are the ports 1 to 4 which will be terminated by four power detectors. Output ports of six-port phase correlator get different phase and amplitude signals according to two input signals. The six-port circuit substrate is alumina due to its high permittivity ( $\epsilon_r = 9.8$ ) and very low loss. The thickness of the substrate is  $127\mu m$ . The circuit cost is moderate and the circuit size in this technology is small.

### 1.3 Results and Discussion

The simulation results clearly show excellent amplitude and phase balance over the frequency range of 70 to 82 GHz, while preserving good isolation and return losses at all ports. The reflection coefficients at input and output ports ( $S_{55}$  and  $S_{66}$ ) are shown in Fig.1.3. For a reference reflection coefficient of less than  $-15$  dB, the six-port correlator without Wilkinson gets the frequency bandwidth of 70 to 82 GHz (12 GHz). Also, it can be noted that the reflection coefficient for layout in Fig.1.2 is lower than  $-15$  dB in the bandwidth of 72 to 77 GHz (5 GHz).

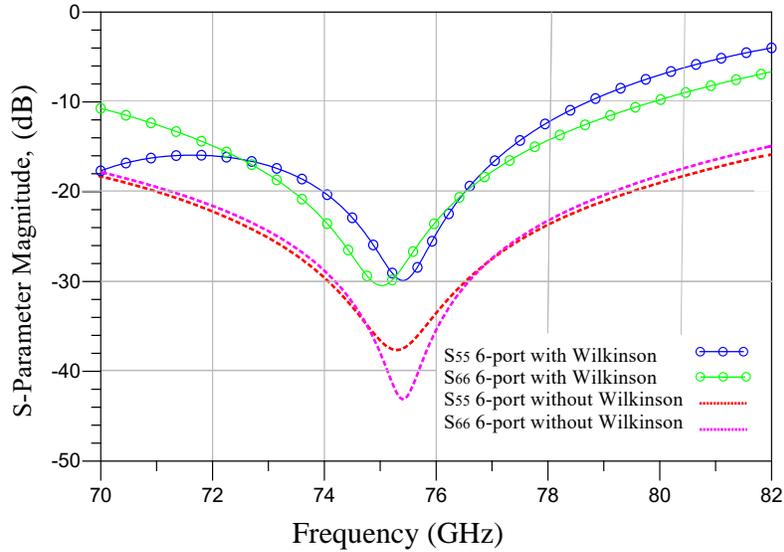


FIGURE 1.3 – Reflection coefficients at input and output ports ( $S_{55}$ ,  $S_{66}$ ) in the two different six-port correlator.

Transmission coefficient are in the range of  $-5.9 \text{ dB}$  to  $6.3 \text{ dB}$ , which gets loss difference of about  $4 \text{ dB}$  for six-port correlator in Fig.1.1. But it is in the range of  $-5.7 \text{ dB}$  to  $6.6 \text{ dB}$ , which gets loss difference of about  $9 \text{ dB}$  for six-port correlator in Fig.1.2. From the Fig.1.4, it shows the six-port phase correlator gets output signals with phase difference of  $90^\circ$ , the results are close together for the two six-port schematics. The maximum phase discrepancy and transmission coefficient are  $5^\circ$  and  $6.3 \text{ dB}$  over a bandwidth, respectively.

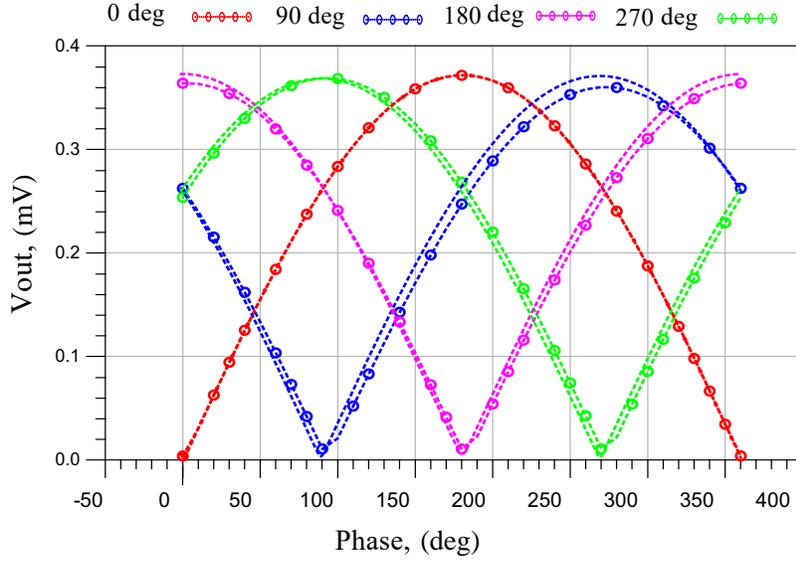


FIGURE 1.4 – Output voltage waveforms phase shift of the power detectors.

The  $q_i$  points for two six-port correlators are depicted in Fig.1.5 which are defined as the normalized complex value of the input RF signal at the port 6 ( $q_{1i}$  are related to six-port circuit in Fig.1.1 and  $q_{2i}$  are related to six-port circuit in Fig.1.2). The expected values are four  $q_i$  points spaced unite circle by  $90^\circ$  for millimeter wave processing without any calibration [4, 5].

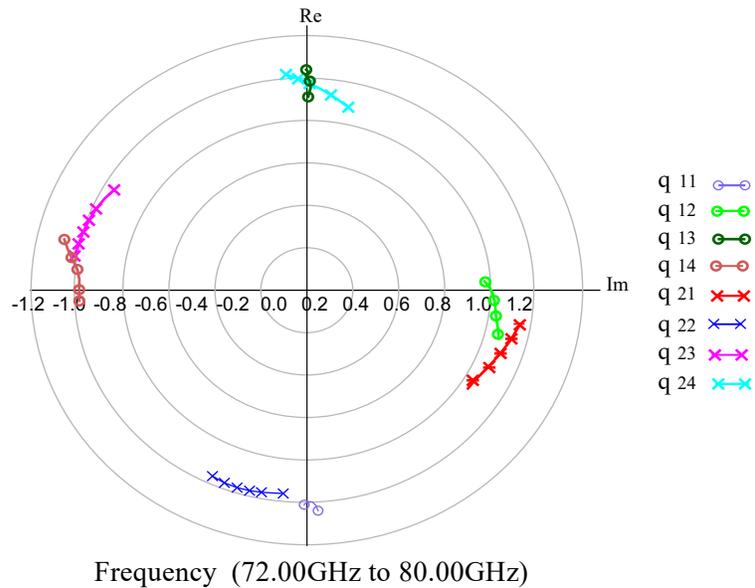


FIGURE 1.5 – Six-port correlator  $q_i$  points in the frequency of 77 GHz for BW=8 GHz.

It was found that the six-port phase correlator with four  $90^\circ$  hybrid coupler has wider bandwidth ( $12\text{ GHz}$ ). In comparison to the six-port phase correlator with three  $90^\circ$  hybrid coupler and Wilkinson power divider in the frequency range of  $77\text{ GHz}$ . Moreover, It has smaller phase error and lower insertion losses. Besides the results show that both circuit get output voltage signals with phase difference of  $90^\circ$ .

## 1.4 Conclusion

Two different structure of six-port phase correlator with  $90^\circ$  hybrid couplers and/or Wilkinson power divider were designed and simulated in the frequency range of  $77\text{ GHz}$ . The six-port phase correlator with four  $90^\circ$  hybrid coupler has wider bandwidth, smaller phase error, and lower insertion losses in comparison to the six-port phase correlator with Wilkinson power divider. Both considered circuit have relatively good output voltage signals and can be used as a modulator and demodulator in receiver and transmitter circuit.

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## Article 2

# Design and Characterization of a 77 GHz Six-port Modulator for an Automobile Radar

H. Arab, C. Akyel, S. O. Tatu

Vehicular Technology Conference (VTC-Fall), Montreal, QC, Canada, pp. 1-5, 18-21 Sept. 2016.

### Abstract

Un modulateur direct QPSK et un autre 16-QAM, basés sur la technique six-port ont été conçus et simulés à une fréquence centrale de 77 GHz sur d'une largeur de bande de 10 GHz. Le schéma de modulation utilise le circuit six-port avec des charges variables appropriées connectées aux ports. La plus importante application de ce modulateur est dans l'industrie automobile. Il effectue des mesures précises de la distance et de la fréquence Doppler, par la différence de phase entre les signaux transmis et les signaux reçus. Il a l'avantage potentiel d'une faible consommation d'énergie, d'un rapport signal sur bruit élevé et d'une réalisation compacte et simple. L'équilibre harmonique, l'analyse des points  $q_i$  et la modulation homodyne quadratique ont été réalisés pour analyser la performance du corrélateur six-port. Il est montré que le modulateur six-port proposé offre des

modulations précises des symboles QPSK et 16-QAM à un taux de symbole élevé, sur une largeur de bande de 72 à 82 *GHz*.

## Abstract

A quadrature phase shift keying (QPSK) and 16 Quadrature amplitude modulation (16-QAM) modulator based on the six-port technique were designed and simulated at the center frequency of 77 *GHz* over 10 *GHz* bandwidth. It is composed of a six-port passive microwave network to implement the modulation scheme with suitable variable load as impedance terminations. Its most important application of this modulator is for the automotive industry. It perform accurate distance and Doppler frequency measurements by means of the phase difference between transmitted and received signals. It has potentially the advantage of low power consumption, high signal to noise ratio, compactness and simplicity in realization. Harmonic balance,  $q_i$  points analysis, and homodyne quadratic modulation were performed to analysis the performance of the six-port correlator. It is shown that the proposed six-port modulator offers accurate QPSK and 16-QAM symbol modulations at high symbol rate across a bandwidth from 72 to 82 *GHz*.

## 2.1 Introduction

There has been much interest recently in using radar technology in the whole area of transportation [1]—[4]. Intelligent transportation system significantly raising road safety by the aid of speed, distance and distance resolution measurements.

In the near future, the full range of newly introduced vehicle models will be equipped with radar to improve safety in blurry conditions (dust, fog, and darkness) with low cost potential. For this aim, a 77 *GHz* transmitter radiates signals reflected from objects ahead, at the side and to the rear of the vehicle and are received by multiple receivers integrated throughout the vehicle.

In order to contribute to the advancement of applied mm-wave research, innovative MIMO (Multiple Input Multiple Output) six-port based architecture for radar application will be considered in this paper. This technology has the ability to transmit different waveforms on all antennas and improves the number of identifiable targets. The use of a six-port correlator for modulation

and demodulation has been well studied [5][1] [12]. However, for high-speed and ultra-wideband applications, there are still many problems to be solved.

For modulations, the six-port correlator can be used together with variable loads to generate the modulated RF signal [5], [9]—[11]. Switches are used as variable loads to generate different reflection coefficients on the respective ports on the six-port correlator. The excellent phase resolution of the Six-Port receiver leads to high accuracy distance and frequency measurement capabilities by means of phase difference between transmitted and received signals.

Furthermore, two methods are proposed for high frequency and high symbol rate Quadrature Phase Shift Keying (QPSK) and 16 Quadrature amplitude modulation (QAM) modulator. Both modulators show good performance on bandwidth efficiency and bit error rate. The proposed technique has potentially the advantage of low-complexity in design, low power consumption, high signal to noise ratio, compactness and simplicity in realization.

## 2.2 Principle of Six-port Interferometer

The studied six-port interferometer is a linear passive microwave network which has four hybrid  $90^\circ$  hybrid coupler. The layout of six-port is shown in Fig. 2.1.

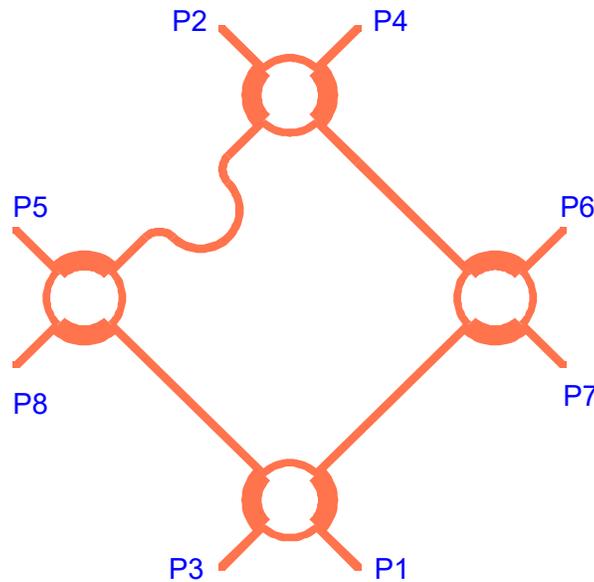


FIGURE 2.1 – Layout of six-port phase correlator with four  $90^\circ$  couplers.

The port 6 is the LO input port and the port 5 is the output RF signal source port. The circuit outputs are the ports 1 to 4 which will be terminated by suitable variable load. Output ports of six-port phase correlator get different phase and amplitude signals according to two input signals and reflection coefficients at four load ports. For an ideal six-port phase correlator get different phase and amplitude signals according to two input signals and reflection coefficients at four load ports. For an ideal six-port reflectometer, it can be shown that:

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & -j & +j \\ 0 & 0 & 0 & 0 & +1 & +j \\ 0 & 0 & 0 & 0 & +1 & +1 \\ 0 & 0 & 0 & 0 & -j & -1 \\ -j & +1 & +1 & -j & 0 & 0 \\ +j & +j & +1 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix}, \quad (2.1)$$

where  $b_1, b_2, b_3$  and  $b_4$  represent reflected wave at ports 1 to port 4 and  $a_5$  and  $a_6$  are the income signal and the reference local signal, respectively. Microstrip six-port interferometer were designed at  $77 \text{ GHz}$  by using ADS software. With adjustable reflection coefficient at output ports ( $\Gamma_1$  at ports 1 and port 3 and  $\Gamma_2$  at ports 2 and port 4), the output signal of six port at port 5 is:

$$b_5 = 0.5(\Gamma_1 + j\Gamma_2) \cdot a_6. \quad (2.2)$$

The six-port circuit was fabricated in Miniaturized Hybrid Microwave Integrated Circuit (MHMIC). Its substrate is alumina due to its high permittivity ( $\epsilon_r = 9.8$ ) and very low loss. The thickness of the substrate is  $127 \mu\text{m}$ . The circuit cost is moderate and the circuit size in this technology is small.

Several of the most important simulated S parameter of the MHMIC circuit are presented in Figs. 2.2 to 2.6. The reflection coefficients at the variable load port ( $S_{11}$  to  $S_{44}$ ) are shown in Fig.2.2. For a reference reflection coefficient of less than  $-15 \text{ dB}$ , the six-port correlator without Wilkinson gets the frequency bandwidth of  $70$  to  $82 \text{ GHz}$  ( $12 \text{ GHz}$ ).

Transmission coefficient at input and output ports are shown in Figs 2.3 and 2.4 which are in the range of  $-5.9 \text{ dB}$  to  $6.3 \text{ dB}$  for output port and in the range of  $-5.9 \text{ dB}$  to  $6.7 \text{ dB}$  for input port. As it is depicted in previous figures all the ports are well matched with good isolation and return losses at all ports.

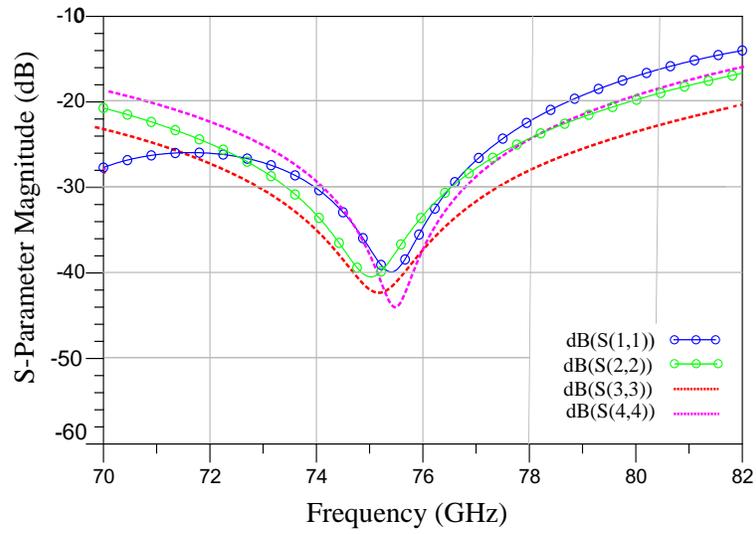


FIGURE 2.2 – Reflection coefficients at output ports of six-port interferometer.

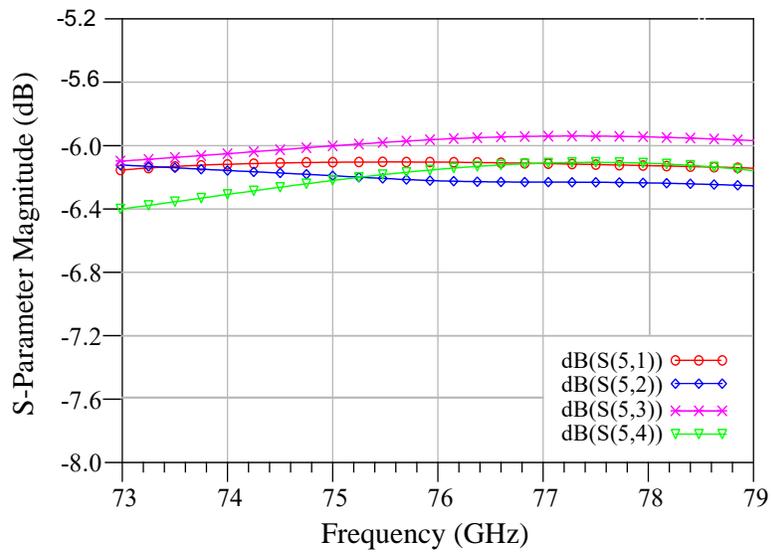


FIGURE 2.3 – Transmission coefficient magnitudes between RF port 6 and outputs load.

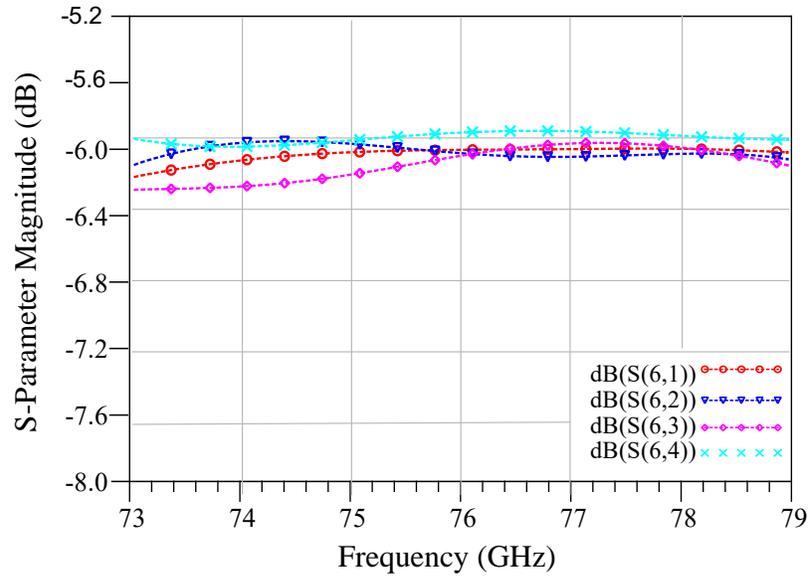


FIGURE 2.4 – Transmission coefficient magnitudes between output port 5 and outputs load.

Transmission phase between input RF and four outputs are shown in Fig. 2.5 and between output port and four outputs adjustable loadsfix picture position are shown in Fig. 2.6. They are important parameters for analog signal processing of six-port interferometer which keep to be almost  $90^\circ$  with less than even 5% error.

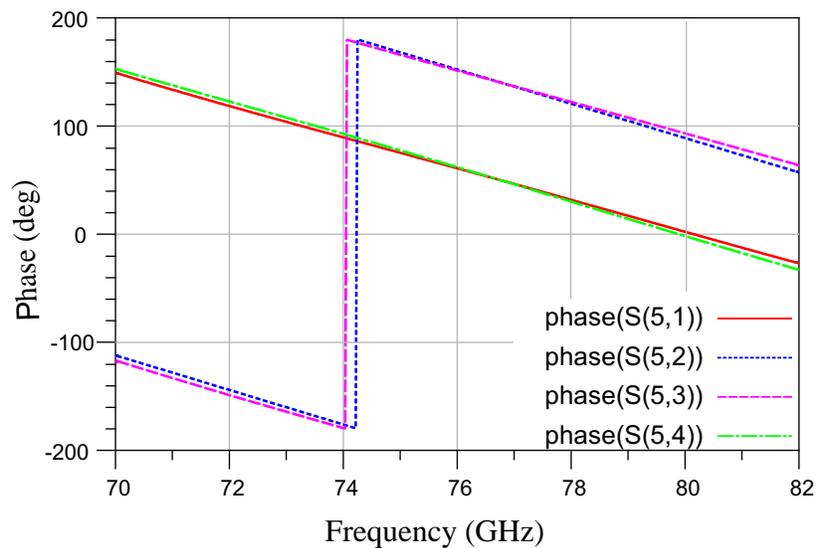


FIGURE 2.5 – Transmission phase between input Rf port with four outputs load.

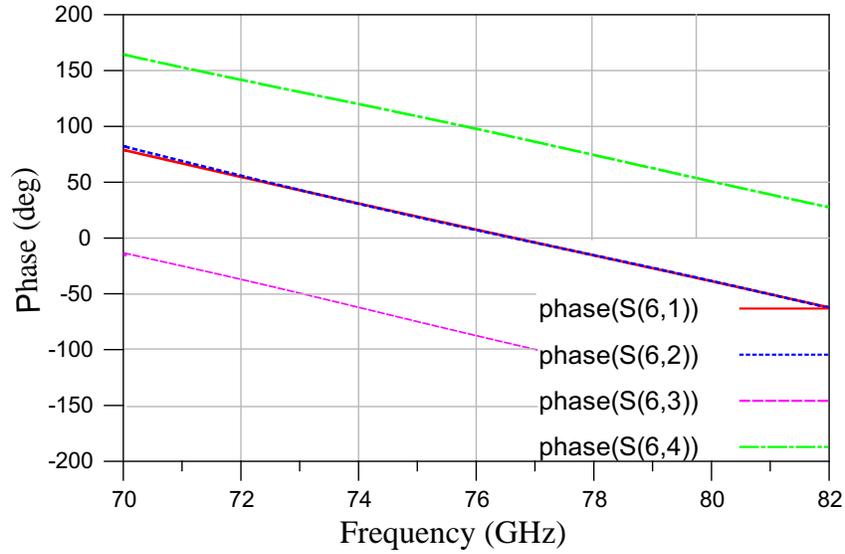


FIGURE 2.6 – Transmission phase between output RF and four outputs load.

The  $q_i$  points for six-port correlators is illustrated in Fig. 2.7. These points are defined as the ratio between transmission S parameter RF input to corresponding  $i$  port and RF output to the same  $i$  port.

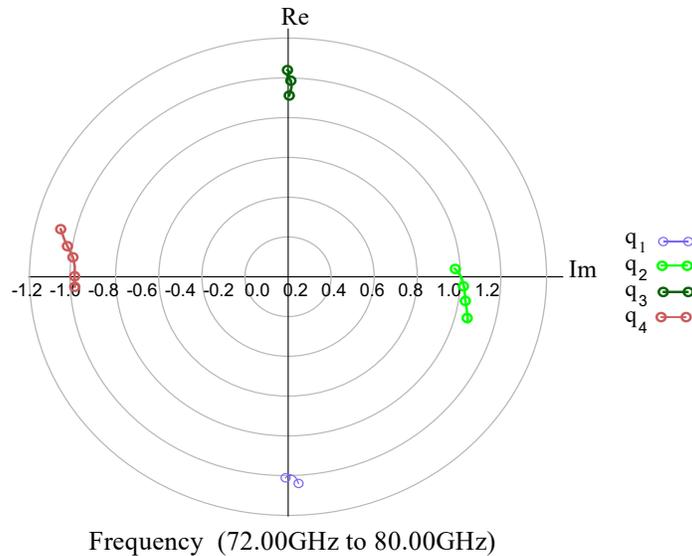


FIGURE 2.7 – Six-port correlator  $q_i$  points in the frequency of 77 GHz for BW=8 GHz.

The expected values are four  $q_i$  points spaced unite circle by  $90^\circ$  for millimeter wave processing without any calibration [4, 5].

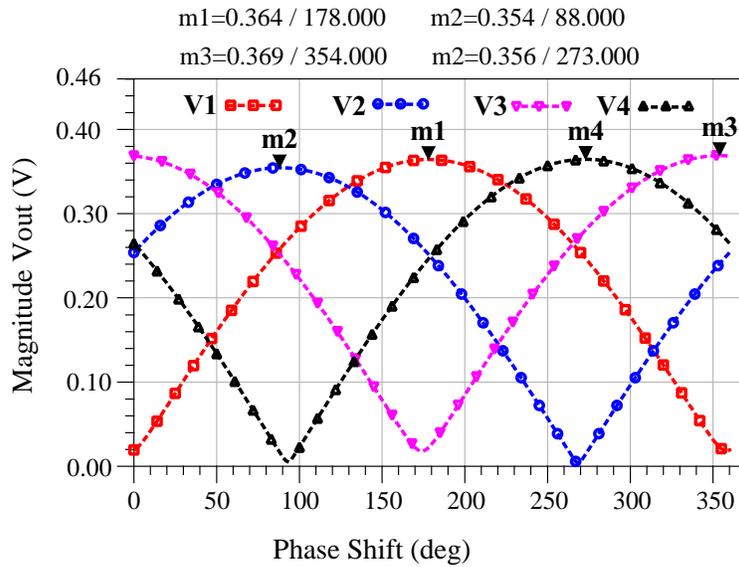


FIGURE 2.8 – Output voltage waveforms phase shift of the power detectors.

From the Fig.2.8, it shows the six-port phase correlator gets sinusoidal output voltage signals with phase difference of  $90^\circ$  and same amplitude.

## 2.3 QPSK and 16-QAM Modulation

A six-port modulator was implemented by using switches to vary the impedance in discrete steps into ADS software using the six-port model based on momentum simulations. The variable impedance loads are generated different reflection coefficient on the respective ports on the six-port interferometer. These variable reflection coefficient modulated an applied LO carrier signal to generate the modulated RF signal. For QPSK modulator, open-circuit and short-circuit, and for 16-QAM, open-circuit, short-circuit,  $3Z_0$  and  $1/3Z_0$  are used as variable load [18]. Simulated output signal constellation for QPSK and 16-QAM are presented in Figs 2.9 and 2.10.

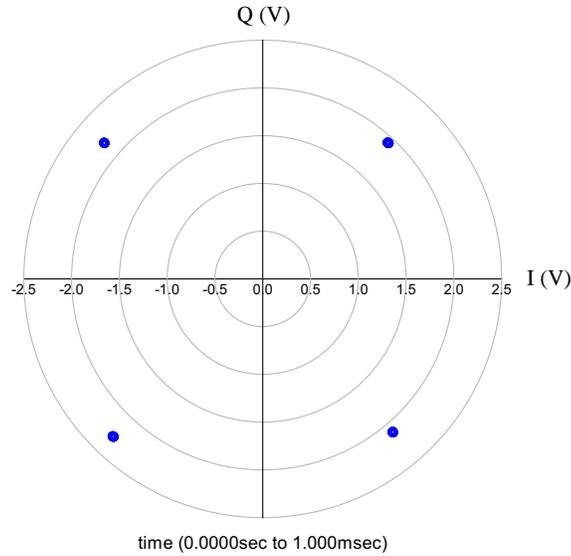


FIGURE 2.9 – Simulation output signal for QPSK modulation.

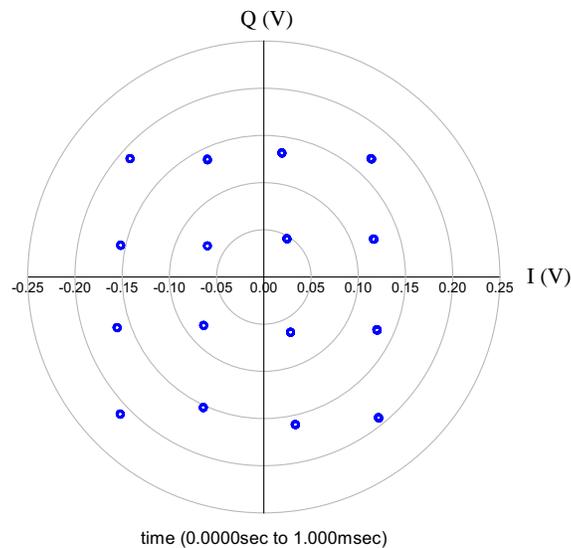


FIGURE 2.10 – Simulation output signal for 16-QAM modulation

The number of symbols and the modulation scheme can be adjusted with changing the reflection coefficient at output ports. As seen, the position of each symbol in the output complex plan are very closed to expected values. The variable reflection coefficient can also be implemented by using transistor or diodes [13]-[17]. A photo of the complete MHMIC circuit for full two port measurements is depicted in Fig. 2.11.

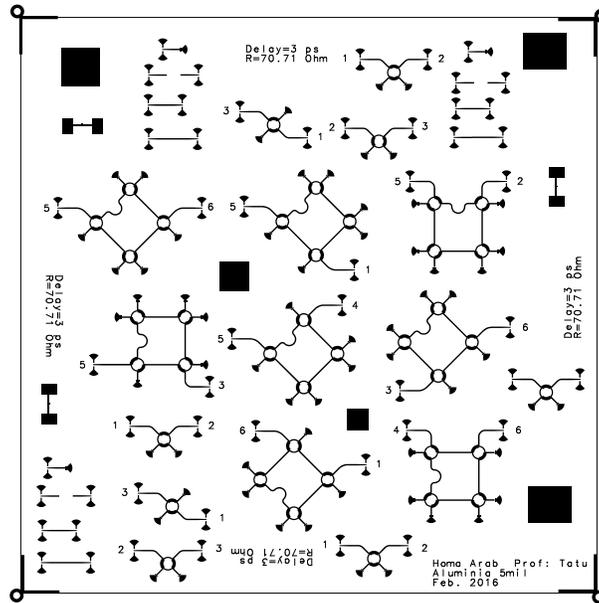


FIGURE 2.11 – MHPIC circuit on the ceramic substrate.

The output voltage spectrum was measured for QPSK and QAM modulation which are shown in Figs 2.12 and 2.13.

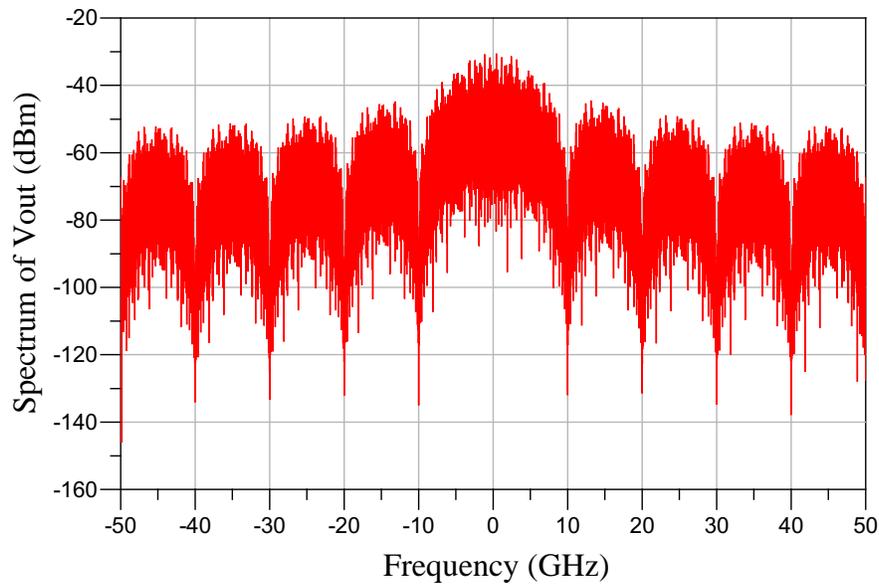


FIGURE 2.12 – Input and output voltage spectrum for QPSK modulation.

The constellation offset gives a carrier leakage is efficiently low in depicted figures. Anyway, carrier leakage will be presented when using six-port and variable impedance load. Some researches proposed to limit this effect by using balanced modulator.

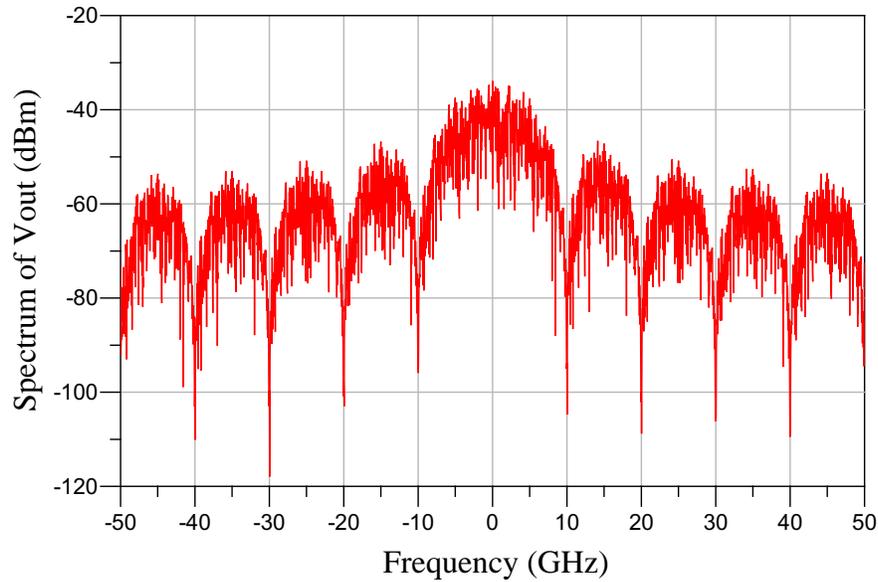


FIGURE 2.13 – Input and output voltage spectrum for 16-QAM modulation.

## 2.4 Conclusion

The passive and linear six-port circuit is designed and simulated for modulation in automotive radar systems. The excellent phase resolution of the Six-Port receiver leads to very accurate symbol positions in comparison to idea values. Therefore Error Vector modulation of designed modulator is very low. A six-port interferometer and QPSK and 16-QAM modulator with the center frequency of 77 GHz was designed in ADS Momentum software. Acceptable simulation results have shown and we have an acceptable measurement error for this low-cost radar sensor.

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## Article 3

# Accurate FMCW Frequency Synthesis Using Six-port Interferometry

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IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet),  
Anaheim, CA, USA, ISSN: 2473-4624, pp. 88-91, 14-17 Jan. 2018.

## Abstract

Cet article analyse un modulateur PSK large-bande à base de circuit six-port, utilisé pour générer un signal FMCW large-bande, au lieu d'un oscillateur conventionnel commandé en tension, qui est moins précis. La génération de la fréquence variable est basée sur une variation rapide de la phase du signal d'entrée CW dans un temps donné, tel que décrit dans cet article. A cette fin, il faut prendre en compte la rotation sens horaire ou anti horaire des symboles PSK et le débit de données variable correspondant, pour obtenir les rampes positives et négatives de la pente FMCW. Le même circuit large-bande peut avoir d'autres applications différentes, d'un modulateur simple à haut débit de données, à un module précieux dans les systèmes avancés émergents d'aide à la conduite automobile (76-81 GHz).

## Abstract

This paper analyses a wideband six-port based direct millimeter-wave PSK modulator, used to generate an accurate wideband FMCW signal, instead of a less precise conventional voltage controlled oscillator. Variable frequency generation is based on rapid variation of input CW mm-wave signal phase in a specific time, as described in the paper. In this purpose, the clockwise or anti-clockwise rotation of the PSK symbols and the corresponding variable data-rate must be considered to obtain the positive and negative ramps of the FMCW slope. The same wideband circuit can have other differed applications, from a simple high data-rate modulator to a valuable module in emerging advanced driver assistance systems (76-81 GHz).

### 3.1 Introduction

Direction finding and ranging techniques are a key technology with a large number of applications in military, weather observation, air traffic control, collision avoidance radar, navigation and road maintenance [1]-[4]. The purpose of this research is to introduce an innovative technique based on the six-port technology to replace the VCO, one of the most expensive module of radars and sensors.

Usually, in FMCW technique, a Voltage Controlled Oscillator (VCO) is employed to generate the triangular frequency modulated signal. The input tuning voltage ( $V_{tune}(t)$ ) of the varactor diode it leads to the variation of the net capacitance to generate an output triangular frequency [6, 10].

The six-port interferometer was introduced in the 1970's as a low-cost network analyzer [7]. Recently, the six-port interferometer has drawn a lot of attention for transceiver design [11]-[15]. Its small size, simple design and low-manufacturing price made it suitable in many kinds of radar and communication systems. The excellent phase resolution offered by six-port circuit leads to high accuracy distance, relative speed and angular measurement in radar sensing and direction of arrival systems. Considering today automotive radar applications (76-77 GHz) and emerging advanced driver assistance systems (76-81 GHz) [13], a wideband six-port circuit is designed, fabricated and measured. It operates with very good S-parameters, both in phase and amplitude, over 8 GHz band (73-81 GHz).

A computer model of the circuit, based on S-parameter measurements on millimeter-wave probe station, is built to further perform advanced system simulations on signal generation. A 16-PSK direct millimeter-wave modulator generates the output FMCW signal, modifying the frequency of the CW input signal by a rapid step by step phase variation, clockwise or anti-clockwise. The symbols, placed on a circle, are generated one after the other by incrementing or respectively decrementing the input signal phase with an equal value ( $22.5^\circ$  for 16-PSK). Because the rapid phase variation can be more accurately controlled, the FMCW performances will depend basically on the input CW signal ones.

### 3.2 Six-port Circuit

The studied six-port interferometers are a linear passive microwave network with three  $90^\circ$  hybrid coupler and one Wilkinson power divider. The six-port circuit is fabricated in a  $127\ \mu\text{m}$  ceramic substrate with relative permittivity ( $\epsilon_r$ ) of 9.8 ( size:  $3.81\text{mm} \times 4.50\text{mm}$ ). The six-port millimeter-wave direct modulator schematic with physical details of circuit lay-out is shown in Fig. 3.1.

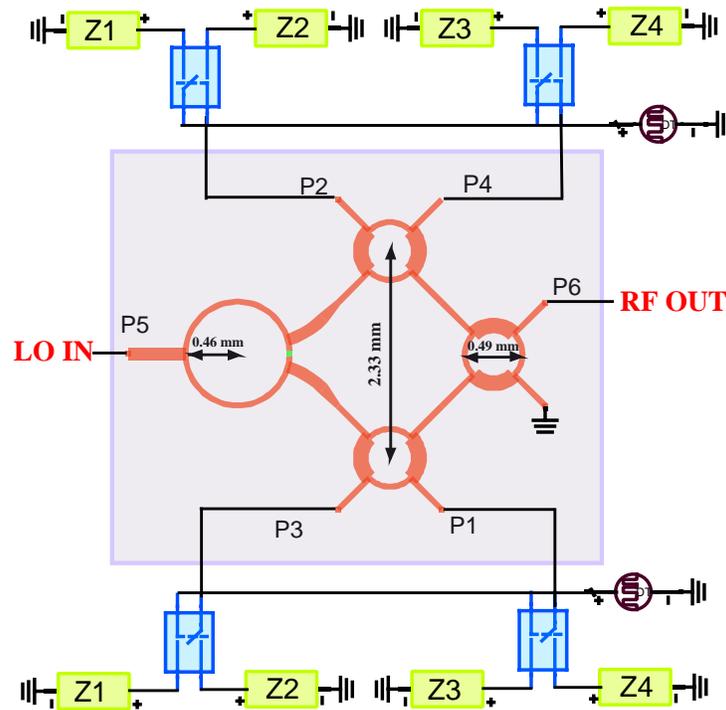


FIGURE 3.1 – Six-port modulator schematic with circuit lay-out.

The six-port circuit is designed and simulated with electromagnetic simulation tool software of Keysight Technologies: Momentum of Advanced Design System (ADS). It is fabricated in Miniaturized Hybrid Microwave Integrated Circuit (MHMIC) technology in thin alumina substrate.

For an ideal six-port interferometer get different phase and amplitude signals according to two input signals and reflection coefficients at four load ports. It can be shown that: the output signal of six port at port 6 is [11, 13]:

$$b_6 = 0.5(\Gamma_I + j\Gamma_Q) \cdot a_5, \quad (3.1)$$

where  $b_6$  represent output signal and  $a_5$  is the input CW signal. The reflection coefficient at output ports ( $\Gamma_I$  at ports 1 and port 3 and  $\Gamma_Q$  at ports 2 and port 4) are adjusted. Then choosing a suitable termination with proper reflection coefficient is important for having 16-PSK modulator. Four different impedances are defined at output ports of the circuit ( $Z_1 = 0$ ,  $Z_2 = \infty$ ,  $Z_3 = 12.14 \Omega$ ,  $Z_4 = 411.9 \Omega$ ). Four SPDT Dynamic switches are used to connect the impedances to six-port circuit and a discrete time steps voltage source defines the position and speed of the switches. ADS simulator is used to validate the 16-PSK modulation up to 500 Mbps data rate at 77 GHz carrier frequency. The results are presented in next section.

### 3.3 Results and Discussion

Measurement set-up includes network analyzer (E 8362 PNA), millimeter wave head controller (N 5260A), and two bended WR12 wave-guides (connected to millimeter wave extenders with a pitch of  $150 \mu m$ ). Two of the most typical simulation and measurement results are presented in Figs. 3.2 and 3.3. The reflection coefficients at the variable load port ( $S_{11}$  to  $S_{44}$ ) are shown in Fig.3.2.

For a reference reflection coefficient of less than  $-15 dB$ , the six-port interferometer gets the frequency bandwidth of 73 to 81 GHz (8 GHz). Transmission coefficient at output ports is shown in Fig. 3.3, which is in the range of 5.8 dB to 7.2 dB.

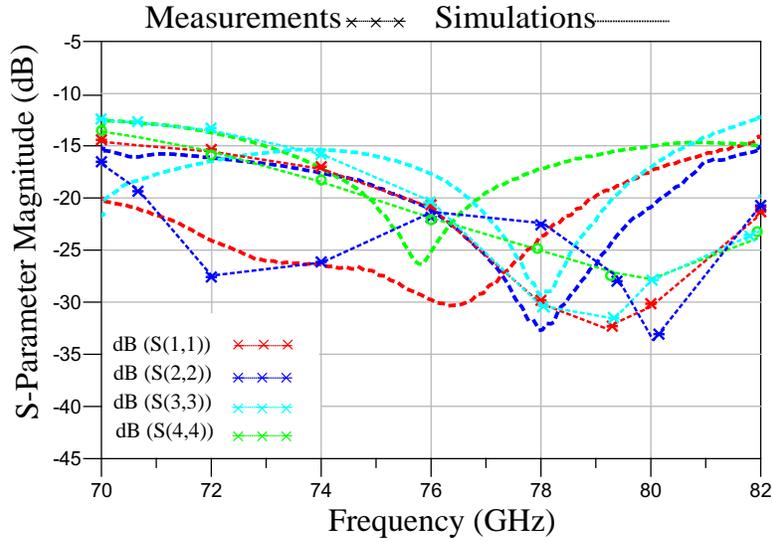


FIGURE 3.2 – Reflection coefficients at output ports of six-port interferometer.

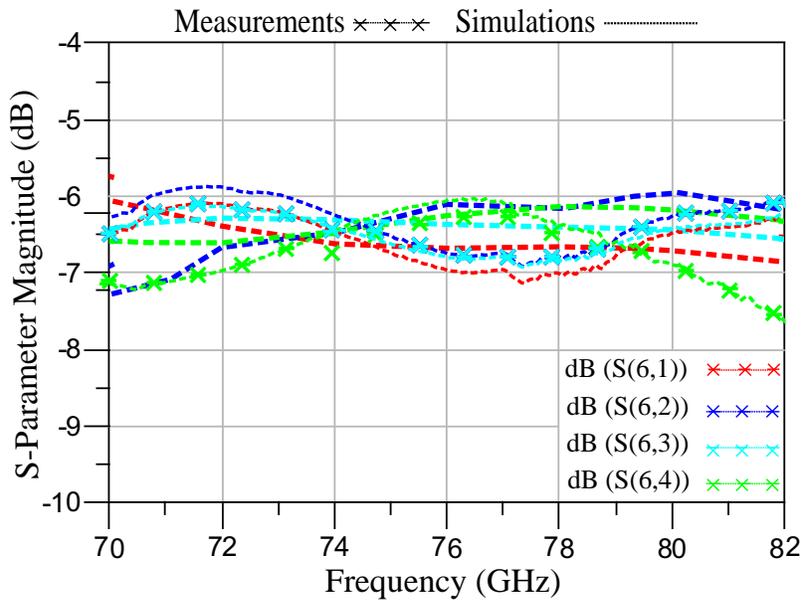


FIGURE 3.3 – Transmission coefficient magnitudes between output port and four load ports.

Due to the circuit symmetry, the results are similar all the ports. They are well matched with good isolation and return losses. The measurement results of six-port circuit are used to design 16-PSK modulator which shift the phase of carrier consecutively in 16 positions that are  $22.5^\circ$  apart. The six-port modulator constellation is shown in Fig. 3.4.

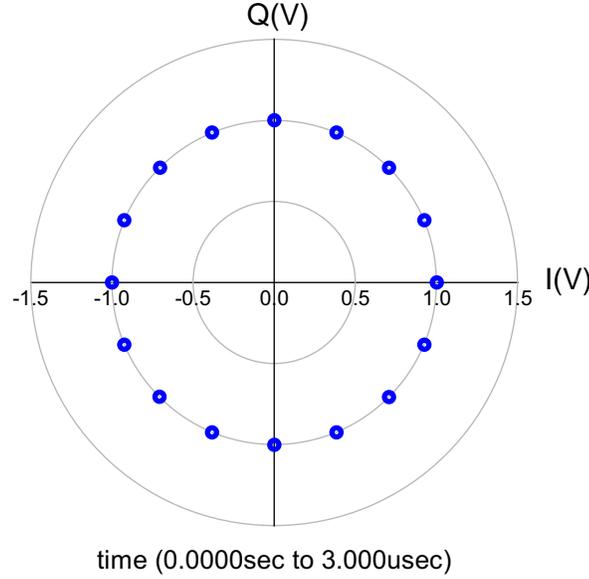


FIGURE 3.4 – 16-PSK modulator symbols (simulation).

It can be observed that symbols are placed equidistant on a circle, in good agreement with expected values for a 16-PSK modulator. The small DC offset of the constellation is compensated using a series capacitor (DC block). By changing the phase ( $\phi$ ) rapidly in a specific time, in the same sense, on 16-PSK modulator, we can generate a frequency modulated signal ( $f$ ) from the CW carrier with  $f_0 = 77 \text{ GHz}$  as:

$$\begin{aligned}
 f &= f_0 + \frac{d\phi}{dt} = f_0 + \frac{d(\phi_0 \pm f_s t \pm \frac{K}{2} t^2)}{dt} \\
 &= f_0 \pm f_s \pm Kt.
 \end{aligned}
 \tag{3.2}$$

where  $f_s$  is a frequency shift versus  $f_0$  (if needed) and  $K$  is related to the required FMCW signal slope. The phase rotation speed ( $\frac{d\phi}{dt}$ ) is increasing linearly. The clock wise or anti-clockwise rotation of the consecutive PSK symbols are considered in equation (3.2) by plus and minus signs. A typical FMCW signal is depicted in Fig. 3.5.

The range resolution is dependent on the chirp linearity and bandwidth. The bandwidth of 500 MHz is sufficient to have less than 0.3 [m] resolution. The circuit, as simple high data-rate 16 PSK modulator, can be used for vehicle to vehicle wireless communication and transmits and receives

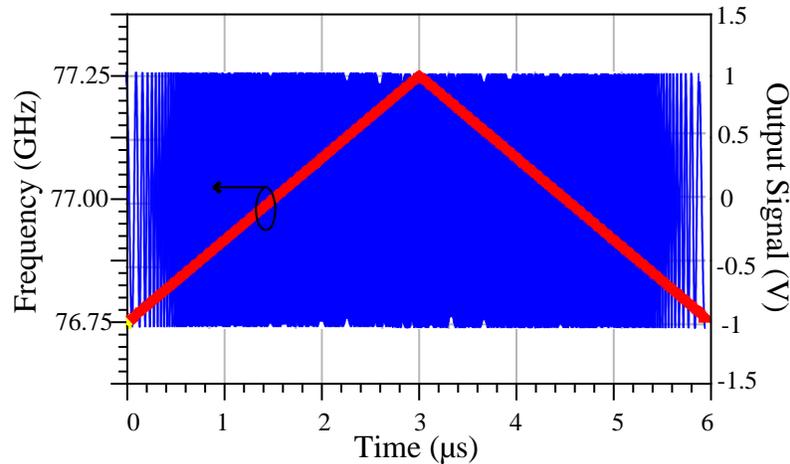


FIGURE 3.5 – FMCW ramp generated using the proposed technique.

important data and current safety functions. The 16-PSK spectrum for symbols rate of 500 MHz is presented in Fig. 3.6.

According to the U.S. Department of Transportation (USDOT), vehicle to vehicle communications can assist drivers in preventing 76% of the crashes on the roadway and consequently reducing fatalities and injuries that occur each year [16, 17]. It lets cars broadcast not just position and speed, but also brake status, wheel position and enables a car to send warnings to the car behind about traffics and weather changes within a few hundred meters. It can also be used for the realization of an offset phase between the radar's transmit and receive signal which improves FMCW radar range measurement of multiple targets and targets close to the radar.

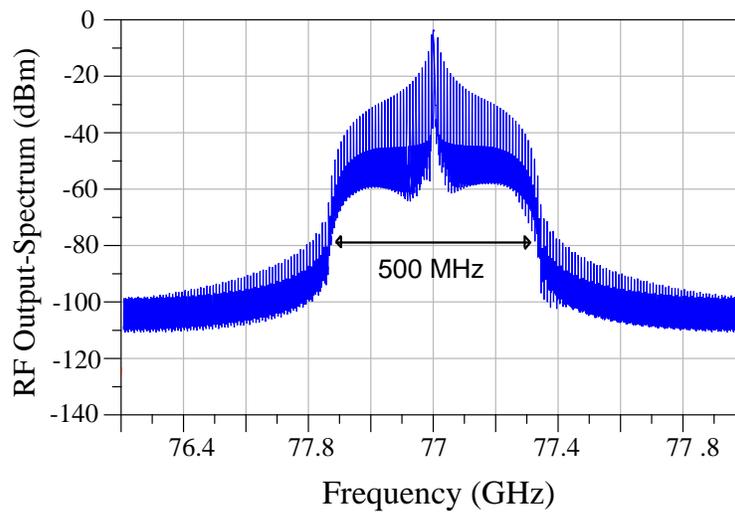


FIGURE 3.6 – 16-PSK spectrum at 500 Mbps data-rate.

### 3.4 Conclusion

A wideband and low-loss passive six-port circuit is designed, fabricated and measured for automotive radar applications at 77 GHz. The designed six-port circuit reaches a bandwidth of more than 8 GHz, very low insertion losses and excellent phase resolution. The paper shows that a FMCW signal can be generated using a less conventional technique than the VCO. The six-port is connected to variable impedance loads by switches to generate a frequency ramp by rapid phase variation in time. This is obtained by changing load impedance of the six-port rapidly, moving from a symbol to another on a 16-PSK symbol circle. The proposed modulator circuit can also be used as a simple PSK modulator for car to car communication or for emerging advanced driver assistance systems.

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## Article 4

# Wide-band Millimeter Wave Downconverter Based on Six-port Circuit for Radar and Sensing Applications

H. Arab, C. Akyel, S. O. Tatu

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### Abstract

Cet article présente un convertisseur abaisseur de fréquence pour ondes millimétriques basé sur un corrélateur six-port et des diodes Schottky zero-bias, sur une largeur de bande de 10 *GHz*, de 72 à 82 *GHz*. Le six-port est conçu de telle façon qu'il ait une résolution de phase excellente à quatre ports de sortie, ce qui entraîne une position des symboles très précise pour le démodulateur QPSK. Un circuit prototype a été fabriqué en utilisant la technologie de fabrication hybride MHMIC sur un substrat céramique de 127 $\mu$ m. Les résultats du démodulateur QPSK, opérant à fréquence centrale

de 77 GHz sont validés à l'aide d'un modèle informatique du circuit six-port basé sur des mesures des paramètres de dispersion S.

## Abstract

In this article a millimeter-wave (mm-wave) down-converter based on a six-port correlator and zero bias Schottky diode is presented over 10 GHz bandwidth, from 72 to 82 GHz. The six-port is designed in such a way to have excellent phase resolution at four output ports which leads to very accurate symbol position for QPSK demodulator. A prototype circuit has been manufactured with miniaturized hybrid microwave integrated-circuit (MHMIC) technology on a 127  $\mu\text{m}$  ceramic substrate. The results are validated using a computer model of the circuit based on S-parameter measurements for QPSK demodulator for center frequency of 77 GHz.

## 4.1 Introduction

Receivers in the mm-wave is under great development during the last decade due to the great amount of applications. The use of a six-port correlator for modulation and demodulation has been well studied [1]—[5]. Zero bias Schottky diode based on homodyne detectors have been widely used in the mm-wave frequency regime because its sensitivity, compact dimensions, good noise performance and fast response time [6, 10, 11]. The use of six-port technology in combination with Schottky diode at 77 GHz frequency is innovative, original, and very promising for not only automotive radars but also for multi-Gb/s wireless communications and imaging systems.

The focus of this study is on demodulator based on six-port circuit for 77 GHz radar application. The six-port is designed in such a way that its input impedance is matched to the conjugate of the input impedance of the diode ( $50\ \Omega$ ) which result in maximum power transfer between them.

Furthermore, the performance of proposed technique is evaluated for Quadrature Phase Shift Keying (QPSK) demodulator. It shows good performance on bandwidth efficiency and bit error rate. The proposed technique has potentially the advantage of low-complexity in design, low power consumption, high signal to noise ratio, compactness and simplicity in realization.

## 4.2 Principle of Six-port Based Down-converter

The studied six-port interferometer is a linear passive microwave network with four hybrid  $90^\circ$  hybrid coupler and a  $90^\circ$  phase shifter. The anti-parallel Schottky diode pairs are used to realize the single balanced harmonic diode at RF and LO ports. The layout of six-port with diode detectors is shown in Fig. 4.1.

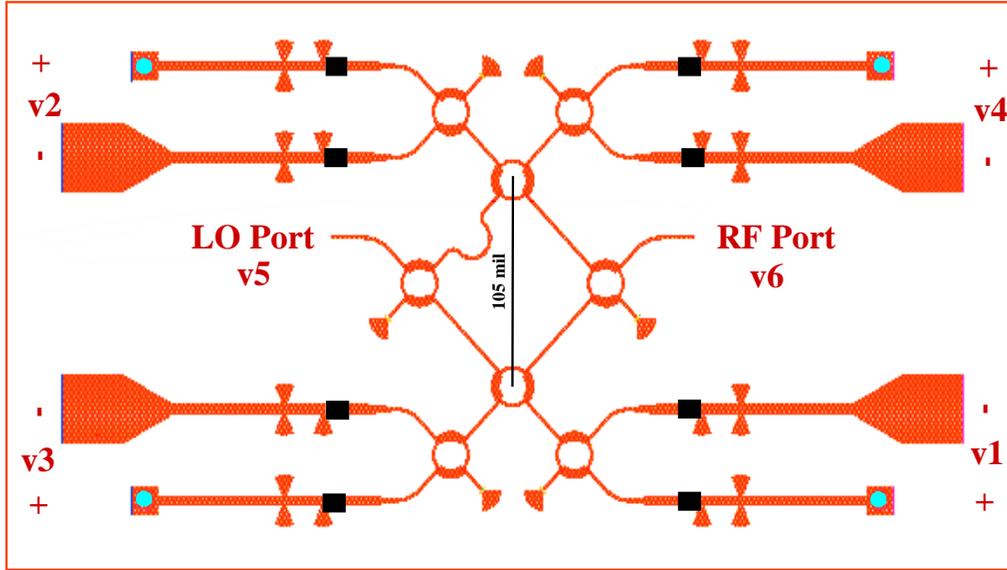


FIGURE 4.1 – Layout of six-port phase correlator with diode detectors.

By injecting the signal from the local oscillator to port 5 and the RF signal to port 6 and neglecting the reflections at ports 5 and 6, we obtain:

$$v_5 = V_{LO} \cos(\omega_{LO}t) \quad , \quad v_6 = V_{RF} \cos(\omega_{RF}t), \quad (4.1)$$

and then we have:

$$v_1 = -v_3 = V_{LO} \cos(\omega_{LO}t) + V_{RF} \sin(\omega_{RF}t), \quad (4.2)$$

$$v_2 = -v_4 = V_{LO} \sin(\omega_{LO}t) + V_{RF} \cos(\omega_{RF}t). \quad (4.3)$$

Considering the non-linear characteristic of the diodes:

$$I(v) = a_0 + a_1v + a_2v^2 + a_3v^3 + a_4v^4 \dots, \quad (4.4)$$

and all outputs are connected together on a high impedance resistor to have:

$$I_{IF} = I_1 - I_2 - I_3 + I_4 \quad (4.5)$$

$$I_{IF} = 2a_2(v_1^2 - v_2^2) + 2a_4(v_1^4 - v_2^4) + \dots \quad (4.6)$$

$$I_{IF} = 2a_2V_{LO}^2 \cos(2\omega_{LO}t) - 2a_2V_{RF}^2 \sin(2\omega_{RF}t) - \dots \quad (4.7)$$

$$\dots 4a_2V_{LO}V_{RF} \sin(\omega_{LO}t - \omega_{RF}t) + \dots \quad (4.8)$$



FIGURE 4.2 – MHMIC circuit for two port measurements and laboratory measurement set-up (millimeter wave probe station and network analyser).

As the results show, the DC current and all odd harmonics products are suppressed. This means that the six-port can only be used as a down-converter. A detailed discussion of the six-port correlator for mm-wave down-converter can be found in [5, 10, 11].

### 4.3 Simulation and Measurement Results

The six-port circuit was designed and simulated with electromagnetic simulation tool software of Keysight Technologies: Momentum of Advanced Design System (ADS). It was fabricated in Miniaturized Hybrid Microwave Integrated Circuit (MHMIC) and the die size is  $2.54 \times 2.54 \text{ cm}$ . A photo of the complete MHMIC circuit for full two port measurements and measurement set-up are depicted in Fig.4.2. Several of the most important measured and simulated S parameter of the MHMIC circuit are shown in Figs. 4.3 to 4.4.

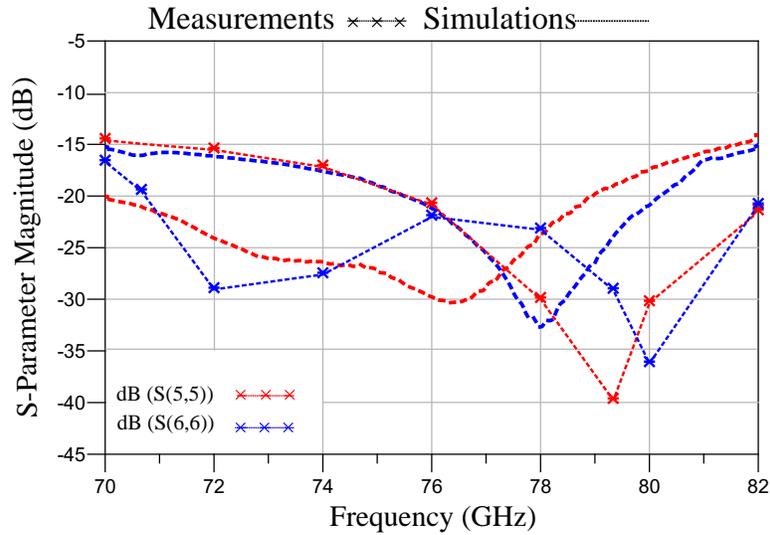


FIGURE 4.3 – Reflection coefficients at LO and RF ports of six-port interferometer (Measurements and simulations).

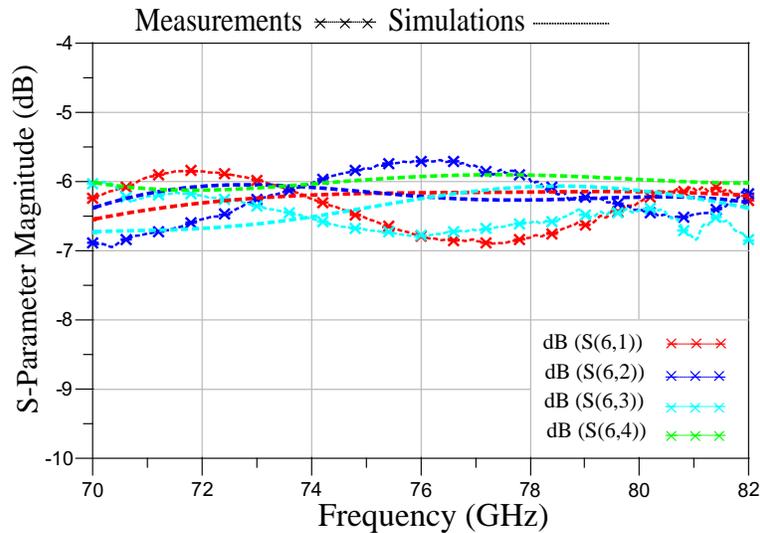


FIGURE 4.4 – Transmission coefficient magnitudes between RF port 6 with diode loads (Measurements and simulations).

The reflection coefficients at RF port and LO port ( $S_{55}$  to  $S_{66}$ ) are shown in Fig.4.3. For a reference reflection coefficient of less than  $-15$  dB, the six-port correlator with four  $90^\circ$  coupler gets the frequency bandwidth of 70 to 82 GHz (12 GHz).

Measurement and simulation results for transmission coefficient at LO and RF ports are shown in 4.4 which are in the range of  $-5.7$  dB to  $7.2$  dB (theoretical value =  $-6$  dB). As it is shown, all the

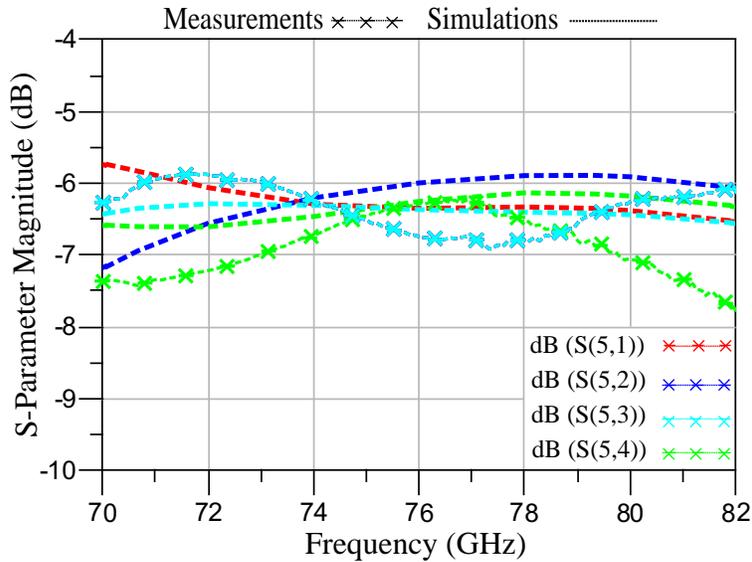


FIGURE 4.5 – Transmission coefficient magnitudes between LO port 5 with diode loads (Measurements and simulations).

ports are well matched with good isolation and return losses.

The six-port down-converter can be use also as a homodyne receiver, if the input frequencies are the same (see equations 1 to 8). Simulated output signal constellation for QPSK and input-output voltage signals are presented in Fig. 4.6.

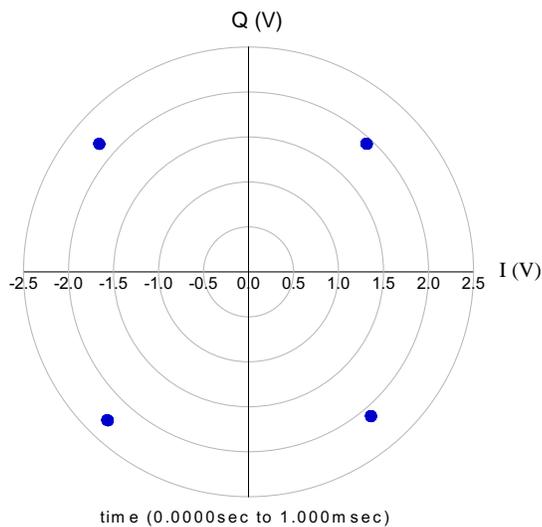


FIGURE 4.6 – Simulated output signal constellation for QPSK demodulation.

As seen, the position of each symbol in the output complex plane are very close to expected values. When the highly sensitive GaAsSb-based diodes are integrated with six-port correlator, high-performance mm-wave receivers can be realized.

## 4.4 Conclusion

The passive and linear six-port correlator is designed, manufactured and measured for 77 GHz demodulator circuit. The excellent phase resolution of the six-port correlator in combination with zero bias Schottky diodes leads to very accurate symbol positions. The error vector demodulation of designed demodulator is very low because of very accurate symbol position of presented circuit. A six-port interferometer and QPSK demodulator was designed in ADS Momentum software and fabricated in ceramic substrate. Acceptable simulation and measurement results have shown and we have an acceptable error for this low-cost, small down-converter circuit.

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## Article 5

# A 77 GHz Six-Port Sensor for Precise Near Field Displacement and Doppler Measurements

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### Abstract

Cet article présente un radar à onde continue (CW) basé sur un interféromètre six-port. Le prototype du capteur est conçu, fabriqué et mesuré à 77 GHz, pour les applications industrielles et professionnelles à courte portée. Ce capteur est utilisé pour mesurer la distance et la fréquence Doppler à un coût raisonnable et à des performances exceptionnelles. Grâce à la mesure précise de la phase en utilisant la technologie six-port, il est un candidat prometteur pour les applications CW. Les progrès des performances et de la fonctionnalité des capteurs six-port sont analysés pour souligner les développements récents dans ce domaine. Ces progrès incluent une meilleure conception, une faible consommation d'énergie, un rapport signal sur bruit élevé, la compacité, la robustesse et la simplicité de la réalisation. Globalement, en tenant compte des avantages de l'ultra-sensibilité

et de la facilité de fabrication (grâce au manque de circuits actifs), on s'attend à ce que le capteur six-port contribuera de manière significative au développement des capteurs pour le pistage humain et les capteurs industriels dans l'avenir immédiat. Des mesures des paramètres S entre deux ports sont réalisées sur plusieurs circuits intégrés, sur le même substrat céramique, choisi pour recueillir suffisamment de données pour une caractérisation complète du circuit multi-port. La simulation d'équilibre harmonique a été réalisée pour analyser la performance du corrélateur six-port. L'entier prototype du circuit, y compris l'antenne du transmetteur et du récepteur, l'interféromètre six-port et les quatre détecteurs de puissance ont été intégrés sur une monture. Le circuit est fabriqué en utilisant la technologie intégrée hybride sur un substrat céramique de  $127 \mu m$ , avec une permittivité  $\epsilon_r$  de 9,8. Des diapasons sont utilisés pour démontrer la performance du six-port, qui offre des mesures de la fréquence précises, à différentes fréquences.

## Abstract

This paper presents a continuous wave (CW) radar based on a six-port interferometer. The complete sensor prototype is designed, fabricated, and measured at  $77 \text{ GHz}$  for short-range professional industrial applications. This sensor is deployed to measure distance and Doppler frequency for reasonable cost combined with exquisite performance. The accurate phase measurement using the six-port technology makes it a promising candidate for CW sensor applications. Advances in the performance and functionality of six-port sensors are surveyed to highlight recent progress in this area. These advances include improvements in design, low power consumption, high signal to noise ratio, compactness, robustness and simplicity in realization. Overall, with the advantages of ultra-sensitivity and the ease of fabrication (due to the lack of active circuits), it is expected that six-port sensor will contribute significantly to the development of human tracking and industrial sensors in the immediate future. Two-port S-parameter measurements are performed on a number of circuits integrated on the same ceramic substrate, chosen to collect enough data for its full-port characterization. Harmonic balance was performed to analyze the performance of the six-port correlator. The whole circuit prototype including the transmitter and receiver antenna, the six-port interferometer, and four power detectors have been integrated on a die. The circuit is fabricated using hybrid integrated technology on a  $127 \text{ micrometer}$  ceramic substrate with relative permittivity

( $\varepsilon_r$ ) of 9.8. Tuning forks are used to demonstrate the performance of the six-port sensor which offers accurate frequency measurement for different frequencies.

## 5.1 Introduction

Recent advances in microwave and millimeter-wave (mm-wave) sensor technology have stimulated wide interest in its application to various industrial applications. Most of the designed and manufactured sensors are based on laser interferometry or camera which has high costs and difficulties to penetrate through dirt, steam and fog. They can cover a certain part of the required applications. However, in harsh industrial environments or for high precision measurements combined with update rates in the kilohertz domain, new concepts must be found.

With growing interest of employing radar for short range applications, many mm-wave sensors have been researched and tested in the recent years [1]-[5]. Operating in mm-wave band (77 GHz homodyne prototype) made up of a set of low-cost, small-size components which allows large operational bandwidth, and therefore, high range resolution and accuracy. Different radar architectures, including continuous wave (CW), frequency modulated continuous wave (FMCW), and pulsed Doppler radar are used for different applications [6, 10, 11]. The proposed sensor is able to send and process all these different signals. However, the CW radar is chosen due to its simplicity and range accuracy in this experiment [12].

The design of radar sensor system consists of two main aspects: radar hardware, and radar digital signal processing (DSP). The radar hardware is including transmit (TX) and receive (RX) radio frequency (RF) components, antennas, power detectors, amplifiers and so forth. The first Doppler sensor has been designed with heavy and expensive wave-guide components in the early 1990s [10].

Mm-wave technology have made it feasible to integrate various radar hardware architectures on a small chip. Single-chip Doppler radars based on bipolar transistor direct-conversion quadrature radar receiver, digital IF receiver (DRX), CW-FMCW hybrid radar, six-port radar are some of the proposed hardware architectures [11]-[15].

On the signal processing side, the small angle approximation, complex demodulation, arctangent demodulation, adaptive dc calibration, noise cancellation, distortion cancellation, and I/Q mismatch

mitigation are some of the demodulation technique have been developed by researcher [11, 13, 19, 20, 22]. Each of the architectures and demodulation techniques have designed for a specific application and have their own benefits and drawbacks.

In this framework, the entire mm-wave RF front-end and T/R-modules of the short-range radar are designed, fabricated and measured over a bandwidth of 70-82 GHz. The proposed system is based on a six-port interferometer and I/Q demodulation technique is used to recover the desired information. The six-port circuit has been known since the 20th century by F. Engen [23]. For 28 years from its first beginnings, it has been used as a two-port vector network analyzer (VNA) [24]. Recently, the six-port theory has made its way into other topics like material characterization, receiver, and radar [25]-[30].

The six-port interferometer can be implemented using various architectures consisting of hybrid couplers, power dividers and phase shifters [13, 14]. In the present paper, a six-port composed of four 90° hybrid couplers and a phase shifter is experimentally characterized and validated for mm-wave signal quadrature down-conversion. Miniaturized Hybrid Microwave Integrated Circuit (MHMIC) is used to fabricate the proposed sensor.

To validate the measurement accuracy of the proposed sensor, it uses the reflected wave phase shift to measure a mechanical oscillation frequency of the target. In fact, a single-tone unmodulated CW signals transmits to the target, and a non-linear phase modulated phase reflects to radar receiver. In the following, an overview and limits of this CW sensor will be explained by system simulations and an appropriate measurement set-up using a 77 GHz wideband six-port receiver system and a two-patch T/R antenna array.

## 5.2 Measurement Principle

Doppler CW sensor transmits an unmodulated RF signal to the target, which reflects part of the signal back to the receiver part of sensor. The moving target phase modulate the carrier RF signal non-linearly. The fundamental structure of CW sensor is shown in Fig. 5.1.

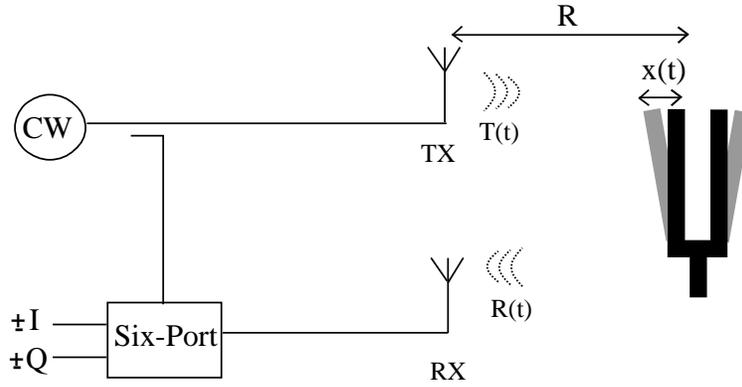


FIGURE 5.1 – Simplified block diagram of CW Doppler sensor.

The transmitted signal is generated by the waveform generator is:

$$T(t) = A_t \cos(2\pi ft + \theta(t)), \quad (5.1)$$

where  $f$  is the carrier frequency,  $\theta(t)$  is the phase noise from RF generator, and  $A_t$  is the amplitude of the transmitted signal. Therefore, the received signal can be approximated as:

$$R(t) = A_r \cos\left(2\pi ft - \frac{4\pi(R + x(t))}{\lambda} + \theta\left(t - \frac{2R}{c}\right)\right), \quad (5.2)$$

where  $A_r$  is the amplitude of receiver signal,  $R$  is the range of the target,  $x(t)$  is the target movement,  $\lambda$  is the carrier wavelength, and  $c$  is the speed of light. As shown in Fig. 5.1, the transmitter signal (TX) is used as local oscillator (LO) signal to down convert received signal as:

$$B(t) = \cos\left(\frac{4\pi(R + x(t))}{\lambda} + \theta(t) - \theta\left(t - \frac{2R}{c}\right)\right). \quad (5.3)$$

The residual phase noise  $(\theta(t) - \theta(t - \frac{2R}{c}))$  is negligible due to the coherent nature of sensor. In fact, both TX and LO signals have same source and phase noise which can compensate each other specially for short range sensor application [11]. As shown in (3), the movement of target  $x(t)$  is modulated the TX signal inside the cosine function. Then special technique is required to withdraw accurate information about the target movement. In this project tuning forks are used as a target which has an exponentially damped sinusoid movement. Therefore, for the ease of analysis and without loss of generality, sinusoidal movement in the steady state response of the fork movement is considered. As discussed in [20, 21], the baseband signal at output of sensor can be expanded

as Bessel function  $J_n(x)$  of order  $n$ ; for a single tone target movement ( $x(t) = m \sin(2\pi ft)$ ) the baseband output signal can be expanded as:

$$B(t) = \sum_{n=-\infty}^{\infty} J_n\left(\frac{4\pi m}{\lambda}\right) \cdot \cos(2\pi n f) \cdot \cos\left(\frac{4\pi R}{\lambda}\right). \quad (5.4)$$

We can see from (4), harmonics will be created at the baseband output signal due to the non-linear property of the cosine transfer function. The movement frequency is obtained from the fundamental frequency of  $B(t)$ , and the amplitude of vibration of the fork and the residual phase can be accurately determined from the rate of harmonics. Many researcher have been using the harmonics generated by non-linear phase modulation to recover the desired information about target movement [11, 22].

The proposed six-port interferometer is a linear passive mm-wave circuit which is the combination of four hybrid  $90^\circ$  hybrid couplers and a  $90^\circ$  phase shifter implemented as a meander line. The six-port layout and block diagram are shown in Figs. 5.2 and 5.3. The physical dimensions and characteristic impedances are plotted on the figure.

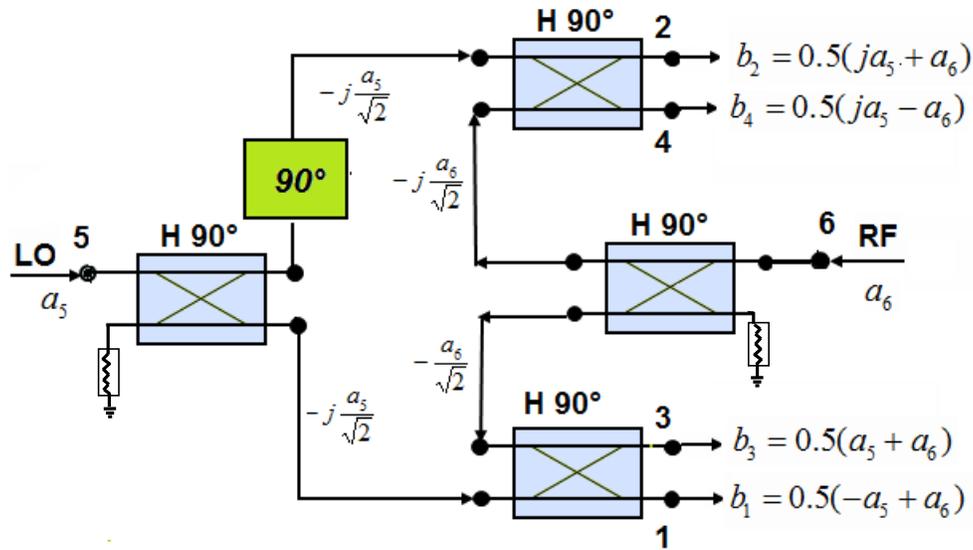


FIGURE 5.2 – Layout of six-port interferometer.

The studied six-port circuit has two input signals at RF and LO ports (received and reference signals). Ports 1 to 4 are connected to four power detectors to measure the phase and amplitude differences between two input signals. Ports 7 and 8 are connected to matched loads. The four

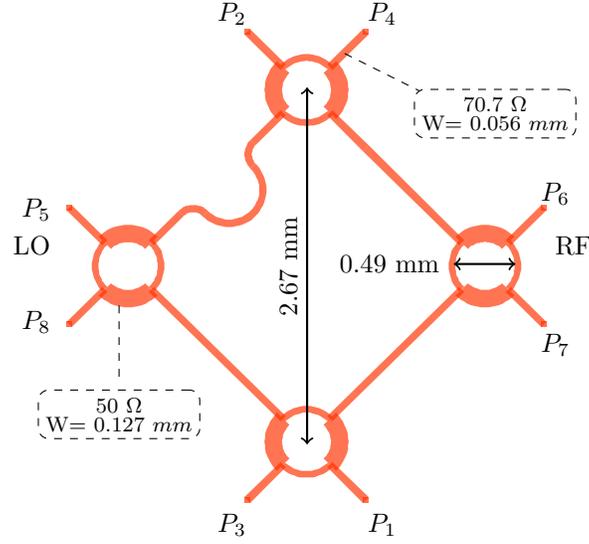


FIGURE 5.3 – Block diagram of six-port interferometer.

output signals at ports 1 to 4 can be expressed as:

$$b_1 = 0.5(a_5 + a_6), \quad (5.5)$$

$$b_2 = 0.5(ja_5 + a_6), \quad (5.6)$$

$$b_3 = 0.5(-a_5 + a_6), \quad (5.7)$$

$$b_4 = 0.5(ja_5 - a_6), \quad (5.8)$$

where  $b_1, b_2, b_3$  and  $b_4$  represent output waves at ports 1 to port 4,  $a_5$  is the input CW signal, and  $a_6$  is the received signal reflected from the target.

The six-port interferometer input signals have an amplitude ratio  $\alpha$  and different frequencies and phases as expressed by:

$$a_5 = a \cdot \exp[j(\omega_5 t + \phi_5)], \quad (5.9)$$

$$a_6 = \alpha \cdot a \cdot \exp[j(\omega_6 t + \phi_6(t))]. \quad (5.10)$$

Four diode-based power detectors are connected to the output ports of circuit and two differential amplifiers can be used in order to obtain the output in-phase and quadrature signals ( $I$  and  $Q$ ).

These  $I$  and  $Q$  signals and the related complex demodulated  $\Gamma$  are expressed as [33]:

$$I(t) = V_3(t) - V_1(t) = \alpha \cdot a^2 \cdot k \cos[\Delta\omega(t) + \Delta\phi(t)], \quad (5.11)$$

$$Q(t) = V_4(t) - V_2(t) = \alpha \cdot a^2 \cdot k \sin[\Delta\omega(t) + \Delta\phi(t)], \quad (5.12)$$

$$\Gamma(t) = I(t) + jQ(t), \quad (5.13)$$

where the constant value  $k$  is related to the gain of differential amplifiers and efficiency of power detectors. Using these baseband voltage values, it is possible to evaluate the instantaneous frequency, phase and amplitude difference between the received signal and the reference.

## 5.3 Circuit Design

### 5.3.1 Six-port Reflectometer

As shown in Fig. 5.4, various circuit configurations are fabricated on a ceramic substrate for two-port measurements. The measurement set-up includes a precision network analyzer( E 8362 PNA), a mm-wave head controller (N 5260A), two mm-wave extenders to cover 60-90 GHz (OML S12MS-A), and two bended WR-12 waveguides used to connect the co-planar probes with a pitch of 150 micrometer.

To obtain more accurate and fast measurements, through-reflect-line (TRL) calibration kits are fabricated in the same substrate. As the probe tips are coplanar waveguides, transitions from microstrip to coplanar waveguides are required.

Also, to avoid via holes, and ensure measurement repeatability, quarter wavelength open lines and butterfly wings open-circuited sectors are used as mm-wave short-circuits [34]. The reflection coefficients at the detector ports ( $S_{11}$  to  $S_{44}$ ) and transmission between input RF port ( $S_6$ ) and output ports are shown in Fig. 5.5 (more details can be find in reference [35, 36, 37]).

These results prove that the output ports are well matched over a wide frequency band. In addition transmission between input RF port and the four outputs is close to the theoretical value of -6 dB over the same 12 GHz band. The phase shift of 90° between output ports are also presented in Fig. 5.6.



FIGURE 5.4 – Two-port mm-wave measurement set-up and fabricated circuit for full-port characterization.

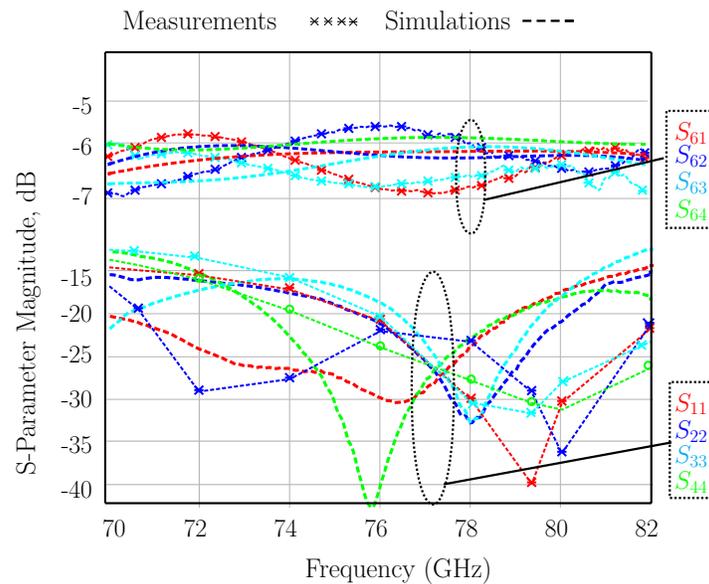


FIGURE 5.5 – Reflection coefficient at four output ports and transmission coefficient between RF port ( $S_6$ ) and four outputs.

Measurement results show a maximum error of  $\pm 2.5\%$  at  $77\text{ GHz}$  and less than  $\pm 5\%$  all over  $12\text{ GHz}$  bandwidth. To validate the operation of the six-port interferometer model, obtained with VNA measurement, harmonic balance analysis is implemented. This measurement based model will be used in ADS system simulations. The phase difference between LO and RF inputs is swept over

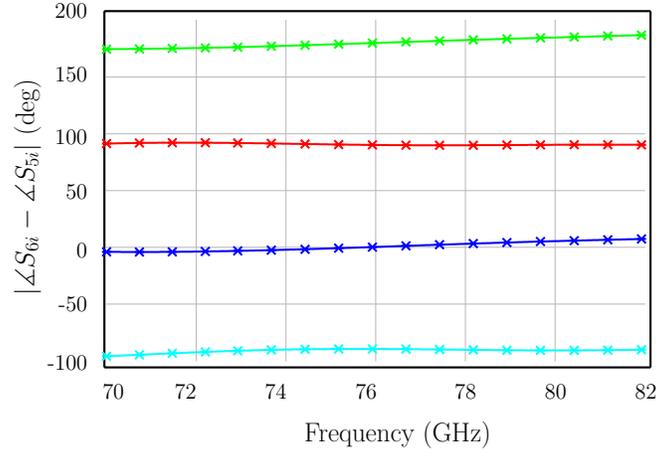


FIGURE 5.6 – Measured transmission phase between output ports.

360°. The expected voltage values are:

$$V_{3,1} = \frac{k}{2}a^2(1 \pm \cos(\Delta\phi)) \quad (5.14)$$

$$V_{4,2} = \frac{k}{2}a^2(1 \pm \sin(\Delta\phi)) \quad (5.15)$$

The simulated results obtained are presented in Fig.5.7. It shows the six-port phase correlator gets quasi sinusoidal output voltage signals with a phase difference of 90° and almost the same amplitude.

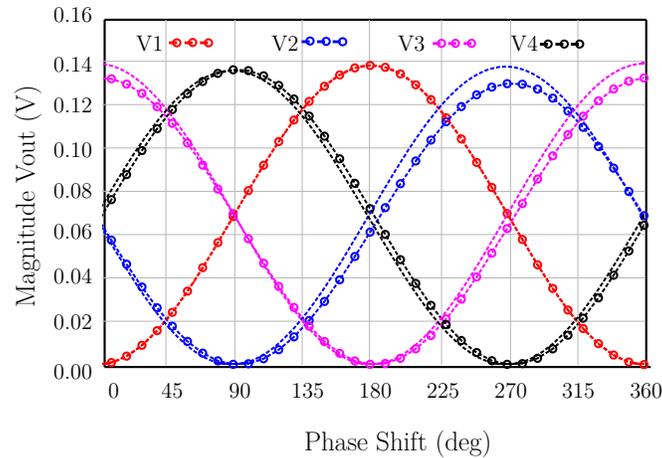


FIGURE 5.7 – Magnitude of the power detected voltages at 77 GHz.

### 5.3.2 Power Detector

A successful six-port operation needs the ability to measure high-frequency power ratios accurately. Usually, the four outputs of each six-port circuit are connected to power detectors that deliver a voltage linearly related to the power of the RF signal at the four output ports. Fig. 5.8 shows a detail of the fabricated power detector using two Schottky diodes (HSCCH 9161) and a hybrid coupler as a solution to improve the input matching. Four power detectors of this type are used in our sensor to extract both magnitude and phase information of the reflected signal to the target.

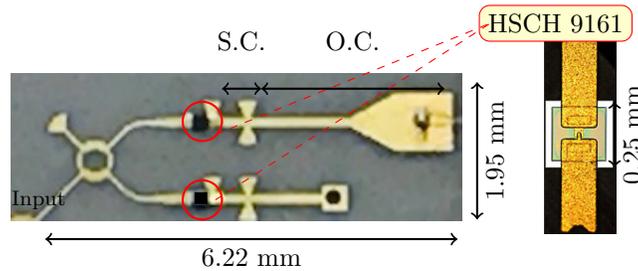


FIGURE 5.8 – Fabricated MHMIC diode-based power detector prototype.

The simulated return loss of the diode-based power detector is shown in Table. 5.1

Tableau 5.1 – Simulated reflected coefficient of the V-band power detector.

	72 GHz	74 GHz	76 GHz	78 GHz	80 GHz	82 GHz
$S_{11}$	-30.03	-33.69	-35.21	35.62	32.85	-30.19

The mm-wave energy can be rectified directly, producing a DC voltage proportional to the received power. However, these four outputs are usually transformed into two in-phase (I) and quadrature (Q) components of a down-converted signal using differential amplifiers.

### 5.3.3 WR-12 Rectangular Waveguide to Microstrip Line Transition

Waveguide to microstrip transition requires low transmission loss, low Voltage Standing Wave Ratio (VSWR), low insertion loss, enough bandwidth, and the structure as simple as possible and easy to install [18]. Considering this, an E-plane coupling probe and a substrate integrated

waveguide tapered transition structure are used for the rectangular waveguide to microstrip line (MSL) transition. The layout is presented in Fig.5.9.

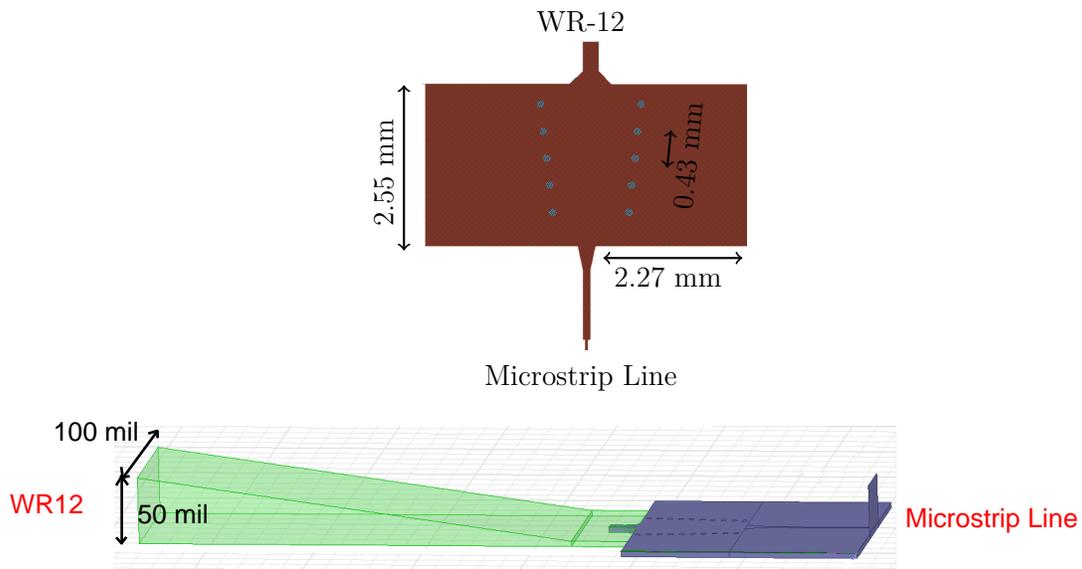


FIGURE 5.9 – WR-12 rectangular waveguide to microstrip line transition.

The measured and simulated transmission coefficient, and reflected coefficient of the fabricated transition prototype are shown in Fig. 5.10.

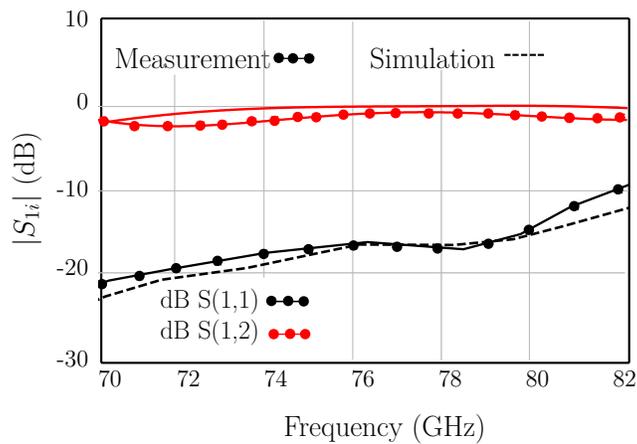


FIGURE 5.10 – WR-12 waveguide to microstrip line transition.

The reflection coefficient is less than -10 dB, in the entire bandwidth of 70-82 GHz, providing good matching between the MSL and the WR-12 waveguide. The insertion loss of each MSL to WR-12 transition is less than 2.5 dB over the same bandwidth. The obtained measurement and

simulation results show that the proposed WR-12 waveguide to microstrip line transition meets the RF front-end sensor requirements.

### 5.3.4 Antenna

A 16 *dBi* gain 77 *GHz* mm-wave  $16 \times 1$  microstrip patch antenna array is designed and fabricated. In order to reduce the size of the whole prototype and facilitate the integration with other integrated passive devices, the proposed antenna array has been designed on a same ceramic die.

The performances of the antenna array are investigated based on bandwidth, gain, and radiation efficiency. It is connected directly to the six-port circuit in the transmitter and receiver part. The photograph of the fabricated MHMIC antenna array and the dimensions of the antenna element and array are illustrated in Fig. 5.11.

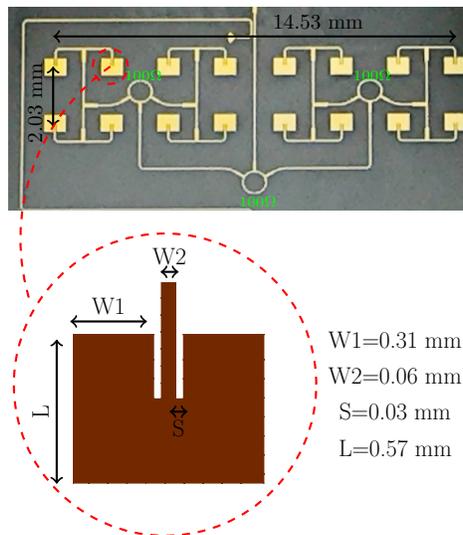


FIGURE 5.11 – Photograph of fabricated transmitter antenna array with dimensions of the antenna element and array.

The antenna operating at 77 *GHz* is designed and optimized using the software of ADS. The simulated scattering parameter of the antenna array and element array are depicted in Fig. 5.12.

As seen, less than -10 *dB* input reflection is achieved for both antenna element and array over a wide range of bandwidth (70-82 *GHz*). The simulated 3D radiation pattern of the antenna array at 77 *GHz* is presented in Fig. 5.13. The use of two lines of 8 patches produces a directional beam that

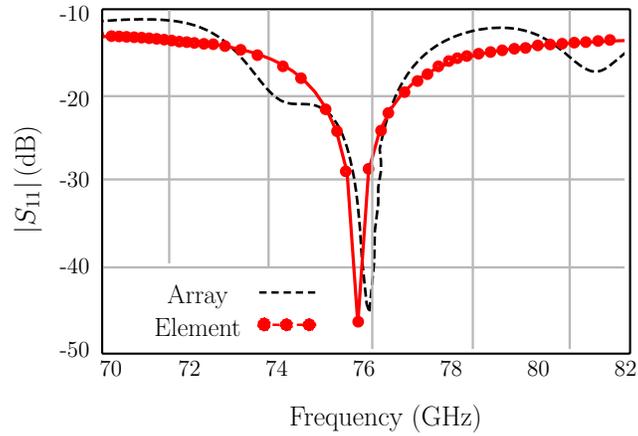


FIGURE 5.12 – Simulated reflection coefficient of 77 GHz antenna element and array.

is optimal for measurements in a perpendicular direction to the line of patches (that are aligned in 0-180° in the figure).

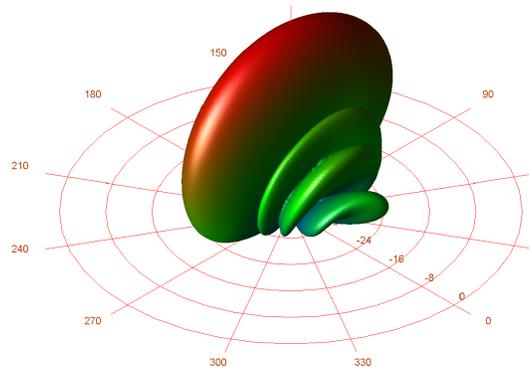


FIGURE 5.13 – Simulated 3D radiation pattern of antenna array at 77 GHz.

The simulated peak gains are  $6.3 \text{ dBi}$  for the element and  $16.2 \text{ dBi}$  for the array at  $77 \text{ GHz}$ . The proposed antenna and array are promising for mm-wave applications due to their merits of wide bandwidth, low cost, high efficiency, and low profile. This designed antenna is fabricated as a transmitter and receiver antenna in the same substrate of the six-port circuit. They are completely integrated into a  $16.83 \text{ mm} \times 13.94 \text{ mm}$  ceramic substrate. This packaging concept reduces the size and price of the circuit and has an exquisite performance.

## 5.4 Prototype and Test Results

For performance measurements, a sensor prototype was realized and several simulations and measurements have been undertaken. A  $77 \text{ GHz}$  CW signal having  $0 \text{ dBm}$  output power is transferred to the transmitter antenna and the reference signal derived through a  $-10 \text{ dB}$  parallel line coupler from CW source. The passive six-port circuit and diode detectors will interferometrically generate I and Q signals. The frequency and phase of the derived I and Q signals represent the phase difference between transmitter and receiver signal. From the I and Q signals, the movement of the target and its range from sensor can be accurately calculated [41, 42]. The block diagram of the  $77 \text{ GHz}$  sensor is shown in Fig.5.14.

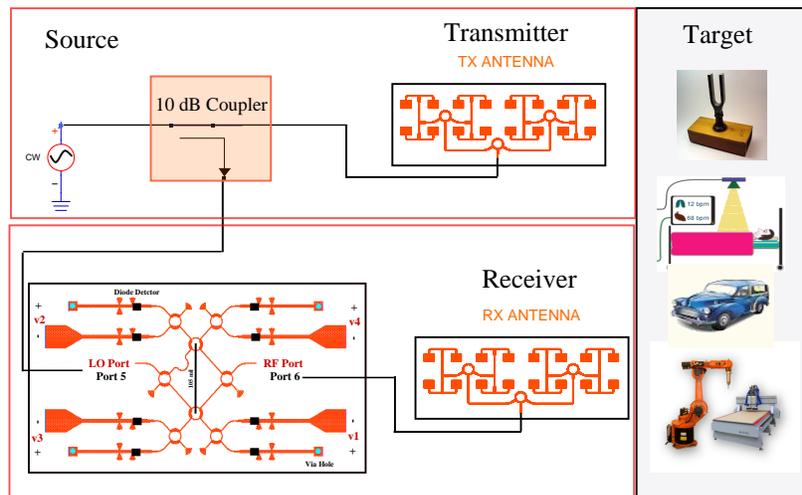


FIGURE 5.14 – Block diagram of a  $77 \text{ GHz}$  sensor.

To validate the proposed schematic, the measurement results of the six-port circuit, and the designed antenna, which are presented in Section II-A and Section II-D, are imported in the ADS

simulator. The radar attenuation ratio simulated based on the Friis equation as:

$$A_{radar} = \sqrt{\frac{P_r}{P_t}} = \sqrt{G_r G_t} \cdot \frac{\lambda}{4\pi R^2} \sqrt{\frac{\sigma}{4\pi}} \quad (5.16)$$

where  $\sigma$  represent radar cross section,  $G_r$  is receiver gain,  $G_t$  is transmitter gain,  $P_r$  is received power, and  $P_t$  is transmitted power.

Radar equation is for a point target where RCS is significantly smaller than range. For short range sensor, the near field RCS of the metallic plate ( $\frac{4\pi w^2 h^2}{\lambda^2}$ ) is considered [39]. This approximation will give accurate results in comparison to experimental measurement results. On the other point of view, the received signal power is reduced by 12 dB as the range between the sensor and the target doubles. For having enough signal at the baseband output, a low noise amplifier is beneficial for medium and long range sensor applications.

As a target, an aluminium plate with cross-section of  $0.01 m^2$  is moved over a displacement range of 15 to 20 cm. Amplifiers with 20 dB gain are used at two IF output ports of the circuit. It creates spiral shaped complex representations for displacements near the antenna which are shown in Fig.5.15. The I/Q signals for four different input power levels from 0 dBm to -15 dBm and 1.95 mm ( $\lambda/2$ ) displacement are depicted in Fig. 5.16.

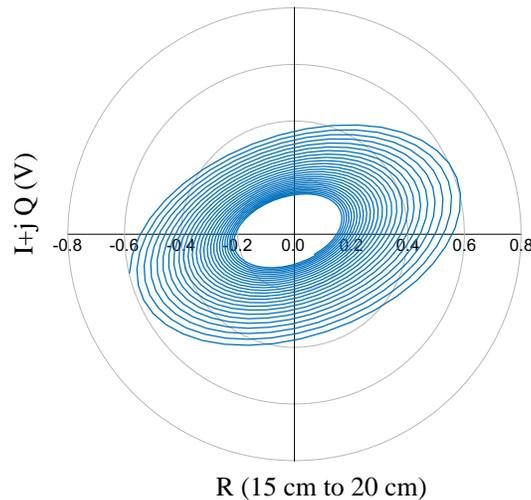


FIGURE 5.15 – Simulation results for displacements near the antenna.

The simulation results show a closed loop, which is ideally a circle, according to six-port theory. The distortion is due to the use of raw six-port output signals, without any calibration. The sensor

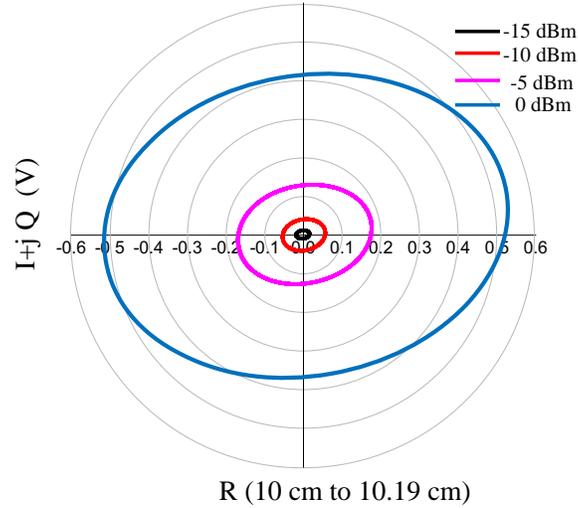


FIGURE 5.16 – Simulation results for target movement at different input powers.

accuracy is not affected due to the fact that the beat frequency measurements are depend on the number of turning in I/Q plane and are not depend on amplitude distortions. In addition, the signal level is low which keep diodes to work in the square law region and AM/PM distortion will not appear at the output of power detectors.

It also demonstrates the suitability of this architecture for short range distance sensing. It is worth mentioning that, range measurement is ambiguous due to the ambiguity in the obtained phase shift  $\Delta\phi$  by  $2\pi$ . Therefore, an unambiguous displacement can only be detected within the range of  $\lambda/2$ . However, a specific target with defined movement and range is needed for validating measurement results with the results obtained through simulation. For this aim, tuning forks with four different frequencies are used. The forks are place at a distance of  $R=25\text{ cm}$  from the sensor and tuning fork frequency, its range from target and the small oscillation of forks is modelled in ADS simulator. In order to model the target, a phase modulator excited by a voltage source having the frequency equal to fork oscillation frequency is used. A phase shifter is used to simulate the mechanical vibration within unambiguous range of  $\pm\lambda/4$  based on equation:

$$\Delta\phi = \frac{4\pi\Delta R}{\lambda}. \quad (5.17)$$

The vibration of the fork is modelled as [19]:

$$m \frac{d^2 x}{dt^2} + \gamma m \frac{dx}{dt} + kx = F, \quad (5.18)$$

where factor  $m$  represents the effective mass,  $\gamma$  is the drag coefficient,  $k$  is the spring constant, and  $F$  is the amplitude of the driving force. The constant  $k$  depends on the geometry and material of the forks ( $k = \frac{ET}{4}(\frac{w}{L})^3$ ). The  $k$  constant for the four selected frequencies are presented in Fig. 5.17.

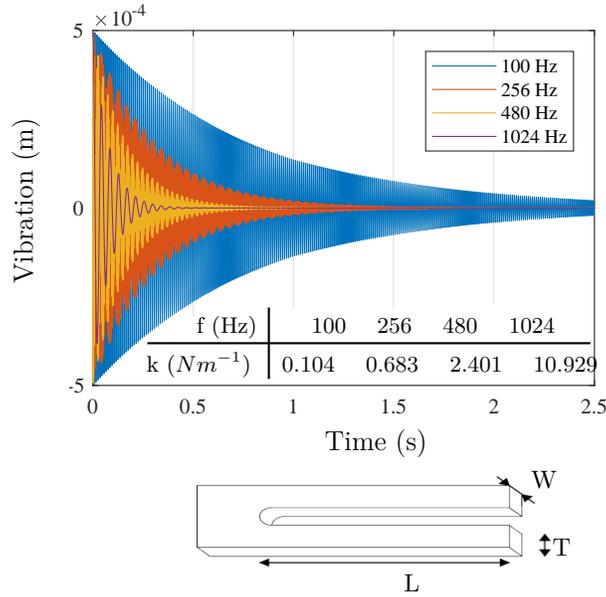


FIGURE 5.17 – Vibration of the forks for different frequencies and consequently different  $k$ .

As shown in Fig. 5.17, the transient solution of the fork vibration is an exponentially damped sinusoidal function. However, if the fork is steadily driven sinusoidally by force  $F \cos(\omega t)$  then the solution to (18) becomes sinusoidal.

$$x(t) = B \sin(\omega t) \quad (5.19)$$

$$B = \frac{F}{k} Q \frac{\omega_0}{\omega} \frac{1}{\sqrt{1 + Q^2 \left( \frac{\omega_0}{\omega} - \frac{\omega}{\omega_0} \right)^2}} \quad (5.20)$$

$$\tan(\theta) = \left[ Q \left( \frac{\omega_0}{\omega} - \frac{\omega}{\omega_0} \right) \right]^{-1} \quad (5.21)$$

where  $Q$  and  $\omega_0$  are defined in term of  $m, \gamma, k$  ( $\omega_0^2 = \frac{k}{m}$  and  $Q = \frac{m}{\gamma}$ ). As discussed, this non-linear phase modulation will generate harmonic on baseband signal. Fig. 5.18 shows the spectra of the IF signal for two different fork frequencies (100 Hz and 1024 Hz).

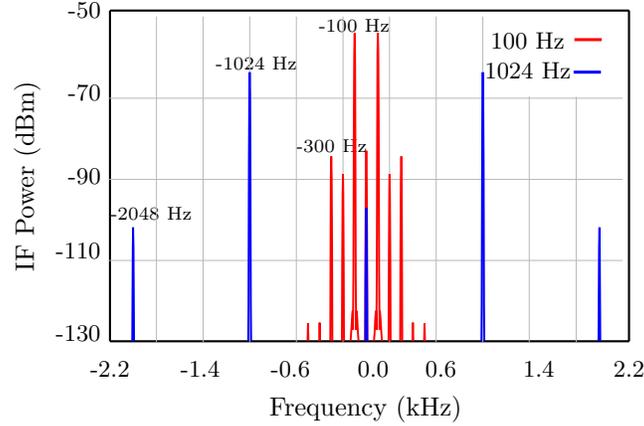


FIGURE 5.18 – Simulation results for the spectra of the IF signal for 100 Hz and 1024 Hz tuning forks.

The produced harmonics on baseband signal can be expanded as a first kind Bessel function as:

$$B(t) = \cos\left[\frac{4\pi R}{\lambda} + \frac{4\pi B \sin(\omega t)}{\lambda}\right] \quad (5.22)$$

$$B(t) = \operatorname{Re}\left[e^{j\frac{4\pi B \sin(\omega t)}{\lambda}} + e^{j\frac{4\pi R}{\lambda}}\right] \quad (5.23)$$

The exponential sinusoidal term can be extended using Fourier series as:

$$\operatorname{Re}\left[e^{j\frac{4\pi B \sin(\omega t)}{\lambda}}\right] = \sum_{n=-\infty}^{\infty} J_n\left(\frac{4\pi B}{\lambda}\right) \cdot e^{jn\omega t} \quad (5.24)$$

A linear approximation of the Bessel function is applicable due to the small value of fork vibration ( $\frac{4\pi B}{\lambda} \ll 1$ ). Then we have:

$$J_n\left(\frac{4\pi B}{\lambda}\right) = \frac{1}{2n!} \left(\frac{4\pi B}{\lambda}\right)^n \quad (5.25)$$

These parameters of mechanical vibrations of the target are modelled in ADS simulator by using phase modulator. The amplitude of the movement is less than  $\lambda/8$  which create less than  $90^\circ$  phase shift. The simulation results for I signals are shown in Fig. 5.19; the results for Q signal are the same with  $90^\circ$  phase shift phase shift.

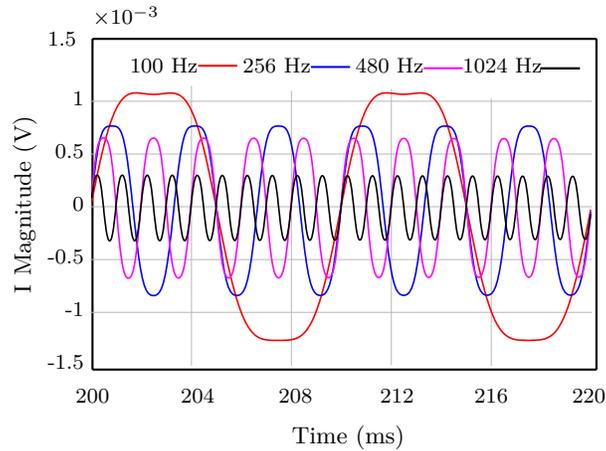


FIGURE 5.19 – Magnitude of the IF signals (I).

It can be clearly observed that the simulated results match very well with theoretical results and the vibration of forks are modelled accurately. The fundamental frequency of tuning forks can be read with high accuracy. The photograph of the fabricated sensor is depicted in Fig. 5.20

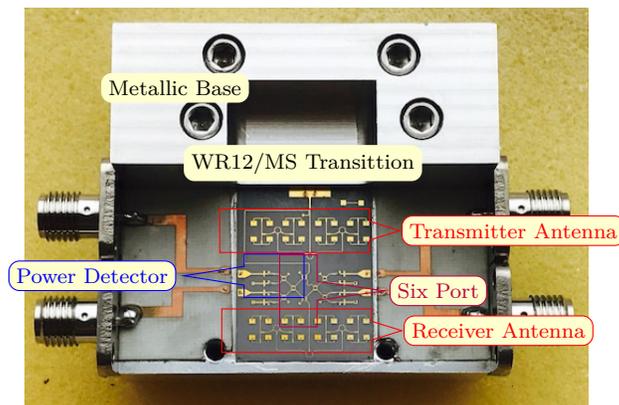


FIGURE 5.20 – Photo of the manufactured hardware prototype.

The measurement set-up includes the HP-83550 series mm-wave source, the mm-wave active multiplier from OML (X6), and the Tektronix DPO 7054 digital phosphor oscilloscope. The mm source frequency is set to 12.83 GHz and 10 dBm input power, then the multiplier will generate 77 GHz signal with 0 dBm power at the input of the parallel line coupler. The die is mounted and power detectors are wire-bonded to the PCB using ribbon bonds to ensure good matching over a broad bandwidth. Preliminary experimental distance and frequency measurements were performed in our laboratory. In Fig.5.21, one can observe the tuning fork experiment.

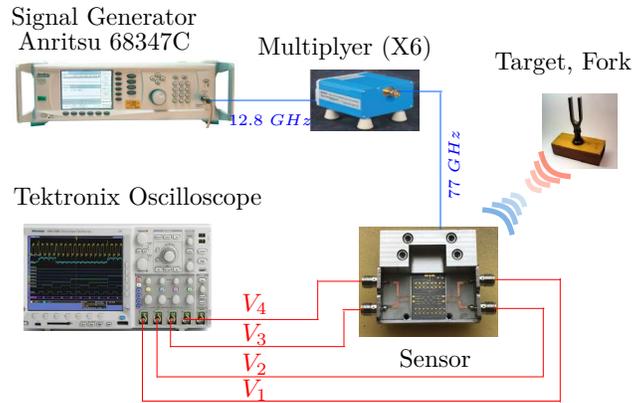


FIGURE 5.21 – Short distance measurement set-up.

The displayed images on the oscilloscope screen are captured in the initial part of the fork vibration showing also the fork frequency modulated by the inherent hand displacement. In the other measurement the fork was mounted on a stand to avoid this secondary amplitude modulation due to hand movements. The experimental set-up is developed according to the block diagram of Fig.5.14, as shown in Fig.5.22.

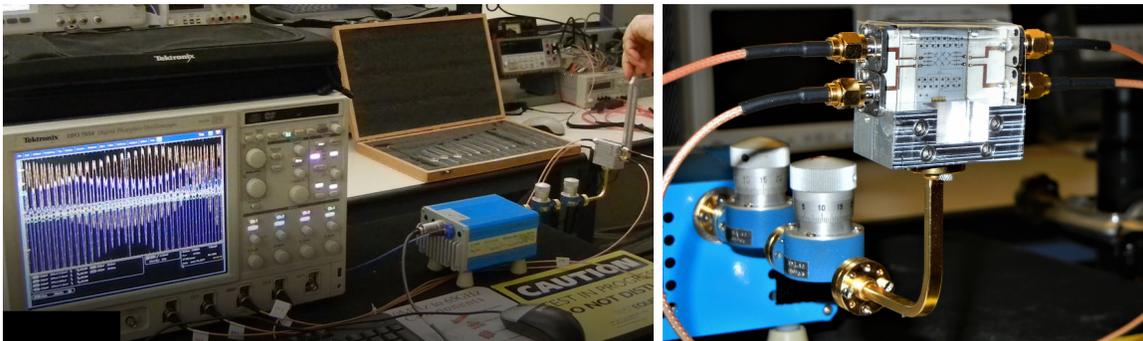


FIGURE 5.22 – Picture of the tuning fork experiment set-up.

The measurement results for I and Q are presented in Fig. 5.23. These results are extracted from 20ms screen data of the oscilloscope display. The screen shots are not taken exactly at the same time and there are still distortion in sinusoidal output signals. These distortions are due to harmonics produced by fork oscillations in the reflected signal, as also seen in simulated results. For bigger forks, having lower oscillation frequencies and bigger oscillation movements, more harmonics are generated in the beginning and, therefore, distortions of the measured signal are observed on the oscilloscope screen. The measurement results clearly present the expected frequency values for different tuning forks.

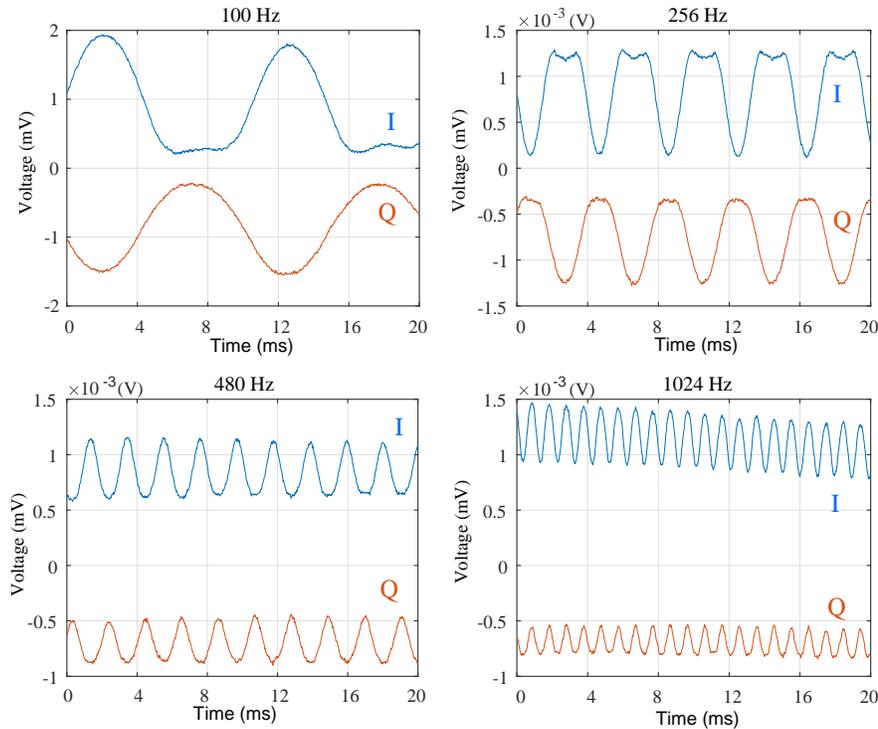


FIGURE 5.23 – Measurement results for four tuning forks with different frequencies (Blue line for I and red line for Q).

## 5.5 Conclusion

A mm-wave CW short range sensor was presented in this paper. It was integrated in MHMIC technology and mounted in a metallic fixture for laboratory measurement purposes. It consists of a wide-band six-port interferometer and two antenna arrays of 16 patch elements used for transmitter and receiver. The interferometer has a wideband of 12 GHz, and operates at 77 GHz in this experiment. To obtain quadrature differential signals, it uses four high sensitivity power detectors. Each one is fabricated with a pair of HSCH-9161 Schottky diodes and a hybrid coupler, to improve matching over the whole operating band. The reflected signal at the target is compared into the interferometer with the reference signal obtained using a directional coupler from the mm-wave oscillator. A tuning fork experiment is performed to prove the frequency measurement accuracy of the proposed sensor. Indeed, the measured frequency with the oscilloscope of both quadrature signals generated by the six-port is equal with the audio frequency marked on the fork, for all tested forks, from 100 Hz to 1024 Hz. If a FMCW signal is applied at this input it can be used to measure range

and speed of the target without ambiguity. The proposed sensor, simple, robust and low-cost, can therefore be used in various industrial or biomedical applications.

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## Article 6

# Accurate and Robust CW-LFM Radar Sensor: Transceiver Front-End Design and Implementation

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### Abstract

Cet article présente la conception et la mise en application d'un capteur à onde continue modulée linéairement en fréquence (CW-LFM) pour les applications à courte portée. Un démodulateur six-port est utilisé pour convertir à la baisse les signaux reçus. Il utilise quatre détecteurs de puissance à large gamme dynamique fabriqués avec des diodes Schottky HSCH 9161. Deux réseaux de  $8 \times 2$  antennes patch avec un gain de 16 *dBi* sont mis en application dans les modules du transmetteur et du récepteur. Le capteur homo-dynamique proposé est fabriqué sur un substrat céramique et sa performance liée à la détection de la cible et de la vitesse est évaluée par des systèmes de simulation et de mesure.

## Abstract

This paper outlines the design and implementation of a continuous wave linear frequency modulated (CW-LFM) sensor for short-range applications. A six-port demodulator is used to down-convert the received signals. It uses four high dynamic range power detectors fabricated with HSCH 9161 Schottky diodes. Two 16 *dBi* gain  $8 \times 2$  patch antenna arrays are implemented in transmitter and receiver modules. The proposed homo-dynamic sensor is fabricated on a ceramic substrate and its performance to detect of a target range and velocity is evaluated through simulation and measurement systems.

## 6.1 Introduction

Millimeter-wave radar based on a frequency modulated continuous waveform (FMCW) is a technology has expanded in the recent years in terms of its technical evolution and spreading of applications [1]-[5]. FMCW radar using LFM modulation provide high precision information about target range and relative. It also can avoid the DC offset problem and recover the range information which is ambiguous by using unmodulated CW radar [6]-[9]. It can also avoid high peak-to-average power ratio (PAPR) in transmission, which simplifies the design process for antennas, power amplifiers and power detector in comparison to pulse radar [10, 11].

Six-port reflectometer is used to give the capability to perform accurate phase measurement through simple scaler measurement. The six-port circuit has been known since the 20th century by F. Engen [12]. For 28 years from its first beginnings, it has been used as a two-port vector network analyzer (VNA) [13]. Recently, the six-port theory has made its way into other topics like material characterization, receiver, and radar [14]- [18]. The designed six-port reflectometer is the combination of four  $90^\circ$  hybrid couplers and a phase shifter which is experimentally characterized and validated for millimeter-wave signal quadrature down-conversion. Miniaturized Hybrid Microwave Integrated Circuit (MHMIC) technology is used to fabricate the proposed sensor.

The sensor can measure phase, frequency or relative amplitude variation of the reflected signal to the target, compared to a reference signal derived through a -10 *dB* parallel line coupler from the transmitted LFM-CW signal. In this prototype, two 16 *dBi* gain 16-elements patch antenna arrays

have been used in transmitter and receiver modules. Patch antenna array are used because they are very economical, compact, and easy for fabrication, installation. The commercially available millimeter-wave GaAs Schottky diodes, Agilent HSCH-9161, are used to convert the output power of six-port to baseband voltages.

In this research, the entire millimeter-wave RF front-end and T/R-modules of LFM-CW radar are designed, fabricated and measured over a bandwidth of 70-82 GHz. In the following, an overview and its benefit and limitations of this LFM-CW sensor will be explained by system simulations and an appropriate measurement set-up.

## 6.2 Theory and Basic Equations

This section explains the FMCW sensor based on six-port for determining distance to target using a multi-tone radar system. There are several different modulations that are used in FMCW signals such as sawtooth, triangle and sinusoidal. In our case, we will consider a CW-LFM model of the FMCW signal as shown in Fig.6.1.

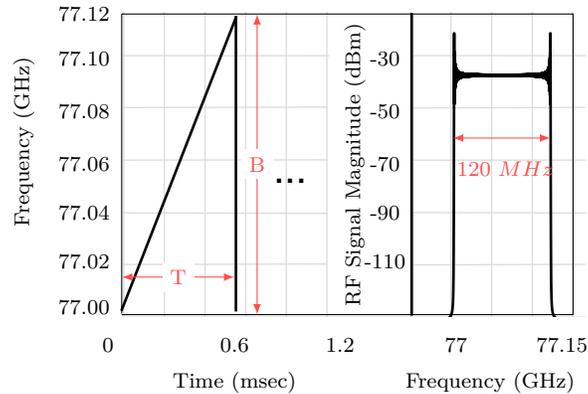


FIGURE 6.1 – Transmitted signal chirp modulation.

As it can be seen, transmitted frequency increases linearly (in bandwidth of  $B$ ) as a function of time during sweep time ( $T$ ). For short range radar application, maintaining the wide bandwidth for good range-resolution is critical. However, the wider the bandwidth, the greater the degree of noise that will be input to the receiver. The frequency is a linear function of time, with a starting

frequency of 77 GHz, as seen in previous figure. Frequency at any given time  $t$  can be found by:

$$f(t) = f_0 + \alpha t, \quad (6.1)$$

where  $\alpha$  is the chirp rate ( $\alpha = B/T$ ) and can be thought as a speed of changing the frequency. By using frequency change over time, we can find the instantaneous phase:

$$\phi_{Tx}(t) = 2\pi \int_0^t f(t)d(t) + \phi_0 = 2\pi \left( f_0 t + \frac{\alpha}{2} t^2 \right) + \phi_0, \quad (6.2)$$

where  $\phi_0$  is initial phase of the signal. Therefore, the transmitted signal can be written as:

$$x_{Tx}(t) = a \cos(\phi_t(t)). \quad (6.3)$$

If we want to describe the transmitted signal in the  $n^{th}$  sweep we have to define  $t = nT + t_s$ . where  $t_s$  is the time from the start of  $n^{th}$  sweep. Therefore, the transmitted signal is:

$$\phi_{Tx}(t) = 2\pi \left( f_0 (nT + t_s) + \frac{\alpha}{2} t_s^2 \right) + \phi_0. \quad (6.4)$$

The returned signal from the object will have the same form, but with some delay  $\tau$  which can be defined as:

$$\tau = \frac{2(R + v(nT + t_s))}{c}. \quad (6.5)$$

Considering the delay  $\tau$ , we can describe the returned signal as:

$$\phi_{Rx}(t) = 2\pi \left( f_0 (nT + t_s - \tau) + \frac{\alpha}{2} (t_s - \tau)^2 \right) + \phi_0, \quad (6.6)$$

$$x_{Rx}(t) = a(t) \cos(\phi_{Rx}(t)). \quad (6.7)$$

According to the six-port reflectometer principle, the returned signal is mixed with the transmitted signal. As shown in Fig. 6.2, by injecting the transmitted signal at port 5, as a local signal, and the received signal at port 6, the normalized wave at the four output ports of six-port circuit are:

$$b_i = a_5 S_{5i} + a_6 S_{6i} \quad \text{for } i = 1, 2, 3, 4. \quad (6.8)$$

Four output ports of the six-port circuit are connected to power detectors that deliver a voltage linearly related to the power of the RF signal. As known, the output voltage of four identical power detector is proportional to the square magnitude of the RF input signal.

$$V_i = k|b_i|^2 \quad \text{for } i = 1, 2, 3, 4. \quad (6.9)$$

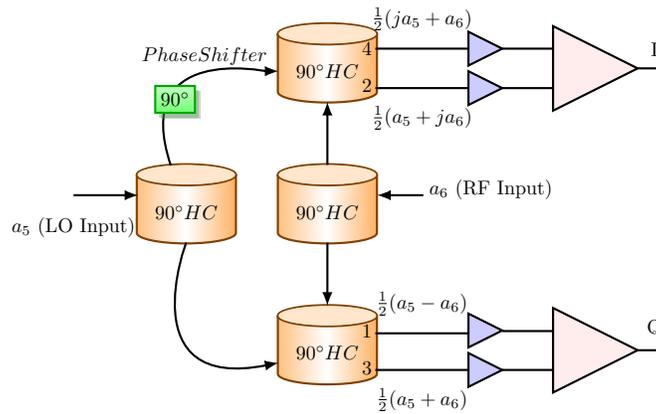


FIGURE 6.2 – Layout of six-port interferometer.

The output voltages can be expressed as follows:

$$V_{1,3}(t) = k \frac{a^2}{4} \left( 1 + \alpha(t)^2 \pm 2\alpha(t)^2 \cos(\Delta\phi(t)) \right), \quad (6.10)$$

$$V_{2,4}(t) = k \frac{a^2}{4} \left( 1 + \alpha(t)^2 \pm 2\alpha(t)^2 \sin(\Delta\phi(t)) \right). \quad (6.11)$$

In the previous equations,  $\Delta\phi = \phi_r - \phi_t$  is the instantaneous phase difference between the six-port inputs (LO and RF).

Using equations (10) and (11), and considering the differential approach, the output  $i$  and  $q$  signals are:

$$I(t) = V_3(t) - V_1(t) = k|a|^2 a(t) \cos \left( 2\pi \left( f_0\tau + \alpha\tau t_s - \frac{\alpha\tau^2}{2} \right) \right), \quad (6.12)$$

$$Q(t) = V_4(t) - V_2(t) = k|a|^2 a(t) \sin \left( 2\pi \left( f_0\tau + \alpha\tau t_s - \frac{\alpha\tau^2}{2} \right) \right). \quad (6.13)$$

By replacing  $\tau$  with its equivalent from equation 5, we will get:

$$I(t) = k|a|^2 a(t) \cos \left( 2\pi \left( \frac{2f_0R}{c} + \frac{2f_0vnT}{c} + \frac{2f_0t_s}{c} + \frac{2\alpha Rt_s}{c} + \frac{2\alpha vnTt_s}{c} + \frac{2\alpha vt_s^2}{c} - \frac{2\alpha R^2}{c^2} - \frac{2\alpha v^2 n^2 T^2}{c^2} - \frac{2\alpha v^2 t_s^2}{c^2} - \frac{4\alpha vnTt_s}{c^2} - \frac{4\alpha vR(nT + t_s)}{c^2} \right) \right). \quad (6.14)$$

The values of chirp parameters are shown in Table.6.1. These parameters are chosen based on INRS laboratory instrument resolution and their finite precision for short range measurement.

Tableau 6.1 – Parameters of chirp.

<i>Parameter</i>	<i>Value</i>
<b>B</b>	120 MHz
<b>T</b>	650 msec
<b>f<sub>0</sub></b>	77 GHz
<b>Number of chirps</b>	5
<b>Number of samples per chirp</b>	1024

Based on the parameters in Table (1) and equation (14), the values of some expressions are very small and can easily be neglected. For an object in short distance (less than 1 *m*) which is moving with a velocity of less than 10 *m/sec*, the equation (14) can be approximated as:

$$I(t) = k|a|^2 a(t) \cos \left( 2\pi \left( \frac{2\alpha R t_s}{c} + \frac{2f_0 v n T}{c} + \frac{2f_0 R}{c} \right) \right), \quad (6.15)$$

The first term in equation (15) is the beat frequency, the second term represents the Doppler frequency, and the last term is the constant phase shift related to the range from a target. The theoretical study of the FMCW radar gave the computational requirements of the algorithm. Based on this requirements a platform for the circuit will be simulated and implemented in next section.

### 6.3 Circuit Design and Results

The six-port interferometer has various architectures consisting of power divider, coupler and phase shifter [19, 20, 21]. A six-port with four hybrid coupler and a 90° phase shifter is experimentally characterized and validated for RF signal demodulation. The six-port circuit have been fabricated on a 127  $\mu\text{m}$  ceramic substrate with relative permittivity  $\epsilon_r$  of 9.8 (size 2.54 *cm*  $\times$  2.54 *cm*). The six-port output ports are well matched and transmission between input RF port and the four outputs is close to the theoretical value of -6 *dB* over a wide frequency band of 12 *GHz* [20, 21, 22].

Moreover, a successful six-port operation needs the ability to measure high-frequency power ratios accurately. HSCH-9161 Schottky diodes are used in the designed sensor to extract both magnitude and phase information of the reflected signal to the target. In addition, a 16 *dBi* gain 77 *GHz*  $8 \times 2$  micro-strip patch antenna array is designed and fabricated for transmitter and receiver. In order to reduce the size of the whole prototype and facilitate the integration with other integrated passive devices, the proposed antenna array has been designed on a same ceramic die. The simulated peak gains are 6.3 *dBi* for the element and 16.2 *dBi* for the array.

Fig. 6.3 shows a detail of the fabricated six-port reflectometer, power detectors and transceiver antennas (all fabricated on  $16.83 \text{ mm} \times 13.94 \text{ mm}$  ceramic substrate) [23, 24]. To validate the proposed schematic, different parts of circuit are fabricated separately and measurement results are imported in the Advanced Design Systems (ADS) software of Keysight Technologies simulator. As a target, an aluminium plate with cross-section of  $0.01 \text{ m}^2$  is placed in the range of 0.3, 0.6, and 0.9 *m*.

Magnitude and spectrum of baseband signal are shown in Fig.6.4. In system simulations, amplifiers with 20 *dB* gain are used at two IF output ports of the circuit.

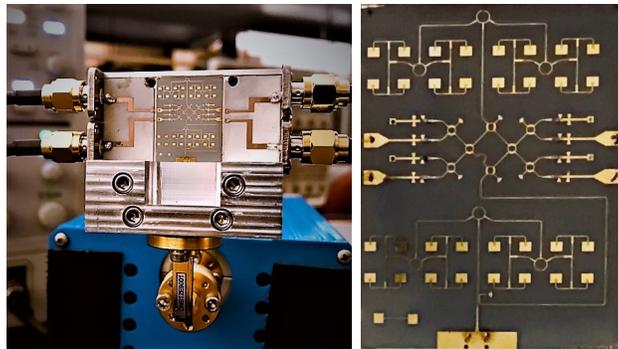


FIGURE 6.3 – Photo of the manufactured hardware prototype.

The simulation results for different ranges demonstrate that the baseband signal frequencies agree with the expected values which can be calculated based on the equation (15). The simulation results for different velocities of the target are shown in Fig. 6.5.

It can be seen that the simulated results for different Doppler frequencies also match very well with the expected values and all the parts are modelled accurately.

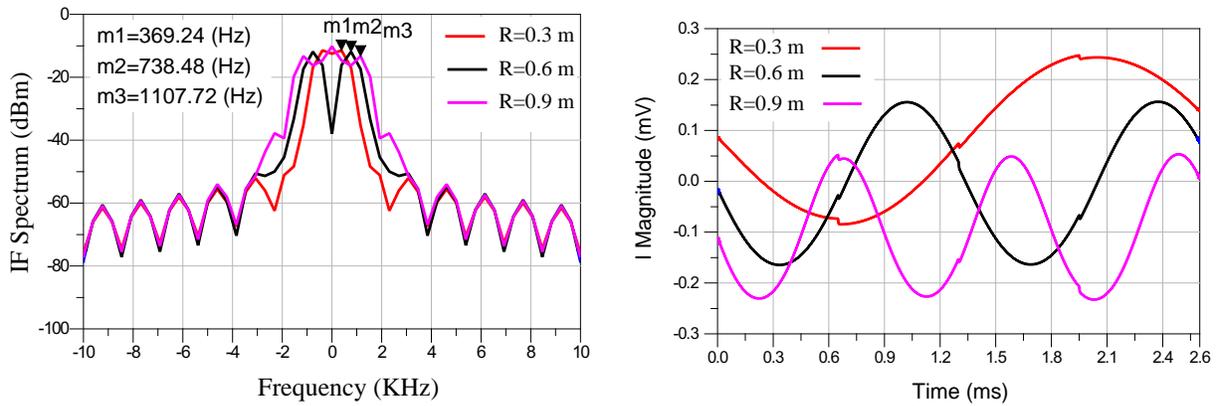


FIGURE 6.4 – Simulation results for different ranges.

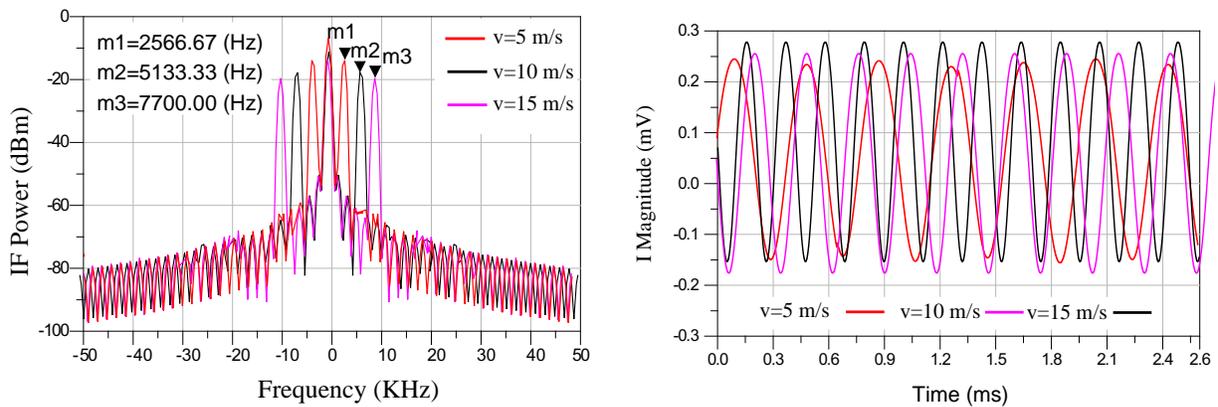


FIGURE 6.5 – Simulation results for different velocities.

Because the front-end is optimised at a central frequency, the output signal voltage amplitudes slightly decreases if frequency is shifted. Therefore, the circuit acts also as a frequency demodulator (FM to AM converter). Measurements are shown in Fig. 6.6. for different beat frequencies. This additional feature can be used to extract information more accurately specially at higher beat or Doppler frequencies.

The measurement set-up includes the HP-83550 series millimeter-wave source, the millimeter-wave active multiplier from OML (X6), and the Tektronix DPO 7054 digital phosphor oscilloscope. Arbitrary waveform generator (AWG) Agilent N8241-A is used to generate chirp waveforms, based on information in Table.1, for creating LFM-CW signal using Matlab interface. Matlab is one of the programmatic interfaces supported by the N8241A which can easily control and generate data to be output. AWG has capability of creating high-resolution waveforms for proposed millimeter-wave radar sensor applications.

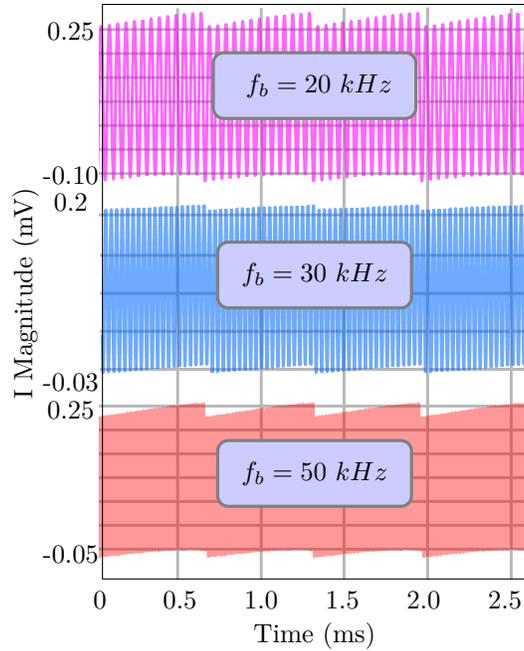


FIGURE 6.6 – Simulation results for magnitude of I signal for different beat frequencies.

The millimeter source frequency is set to  $12.83\text{ GHz}$  and  $10\text{ dBm}$  input power, then the multiplier will generate  $77\text{ GHz}$  signal with  $0\text{ dBm}$  power at the input of the parallel line coupler. The die is mounted and power detectors are wire-bonded to the PCB using ribbon bonds to ensure good matching over a broad bandwidth. Preliminary experimental distance and frequency measurements were performed in our laboratory. In Fig. 6.7 one can observe the experiment set-up.

Range measurement test includes two parts. In the first part, a target (aluminium plate with cross section of  $0.09\text{ m}^2$ ) is placed  $15\text{ cm}$  far from the fabricated sensor and the phase shift for different frequencies ( $\Delta f=30\text{ MHz}$  step from  $69.5\text{ GHz}$  to  $77.5\text{ GHz}$ ) are measured. The expected phase shift for each step is [15]

$$\Delta\phi = \phi_{Tx} - \phi_{Rx} = \frac{4\pi R\Delta f}{c}. \quad (6.16)$$

The measurement results for different frequencies are shown in Fig. 6.8. As expected, all the points move around a circle with the specific phase shift ( $10.8^\circ$ ) which is related to the target range based on equation (16).

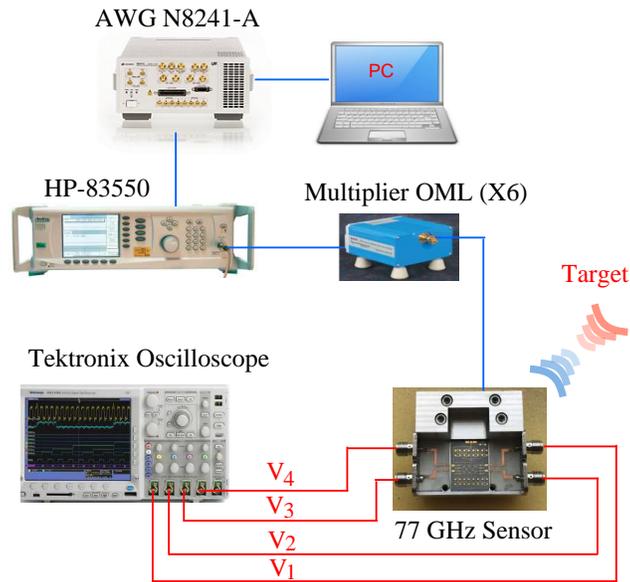


FIGURE 6.7 – Short distance measurement set-up.

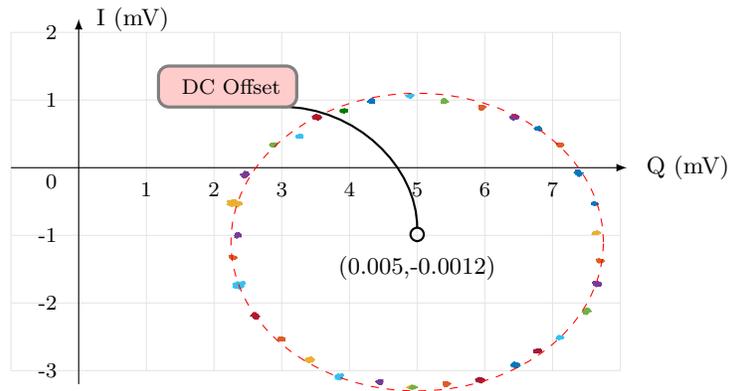


FIGURE 6.8 – Measurement results for target at  $R = 15 \text{ cm}$  for different frequencies.

The center of circle represents the circuit DC-offset. DC-offset due to the characteristics of the six-port circuit, differences between the four power detectors at output ports, and oscilloscope settings if DC coupling is used.

In the second part, the phase difference for different ranges and different frequencies are measured. In fig. 6.9, the frequency changed in bandwidth of  $120 \text{ MHz}$  with step of  $30 \text{ MHz}$ . The phase difference between two points give us information about target ranges.

For having better accuracy, the step frequency must be chosen higher for small ranges, and the maximum phase difference must not exceed  $360^\circ$ .

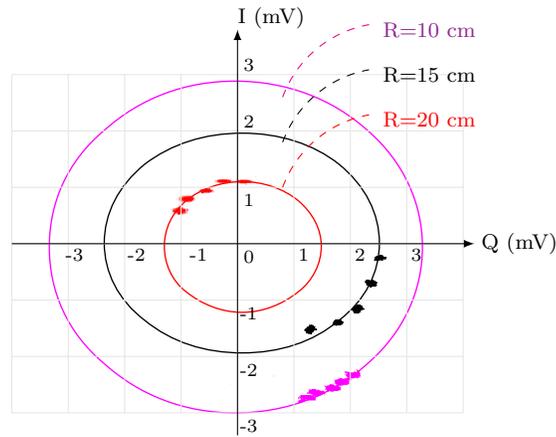


FIGURE 6.9 – Magnitude of I signal for different ranges while frequency sweep over 120 MHz.

In Fig. 6.8 DC-offset are removed to make comparison easier which will not have effect on target range and velocity measurements.

Tableau 6.2 – Measurement results for different ranges.

Range (cm)	Phase shift (deg)	Radius (mV)
10	$7.22^\circ$	3.09
15	$10.79^\circ$	2.17
20	$14.45^\circ$	1.31

The circumference of the ellipse (in theory a perfect circle) is direct proportional with the received power. The ration of received power to transmitted power can be calculated based on radar equation as:

$$\frac{P_r}{P_t} = \frac{\lambda G_r G_t}{(4\pi R^2)^2} \cdot \frac{\sigma}{4\pi}, \quad (6.17)$$

where  $\sigma$  represent radar cross section (RCS),  $G_r$  is receiver gain,  $G_t$  is transmitter gain,  $P_r$  is received power, and  $P_t$  is transmitted power. This equation is for a point target where RCS is significantly smaller than range [25]. For short range sensor and relatively big target sizes, the radar equation will not give accurate results in comparison to experimental measurement results. Based on equation (17) , the power has to increase 16 times when radius is doubled. However the results in table 6.2 show that the received power is proportional to  $1/R \exp(2.47)$  for near field target. Therefore, the

measurement concludes that for near field and important RCS, the use of Friis equation, where the received power is proportional with  $1/R^2$ , is a better approximation as the radar one. An empirical coefficient was obtained in our experiment.

For velocity measurement, same plate are moved in front of the sensor with three different speeds. The results shown in Fig.6.10 are extracted from 50 ms screen data of the oscilloscope display. The screen shots are not taken exactly at the same time and there are still distortion in sinusoidal output signals. These distortions are due to modulation produced at output of six-port circuit, as also seen in simulated results. The measurement results clearly present the expected Doppler frequency values for different target velocities.

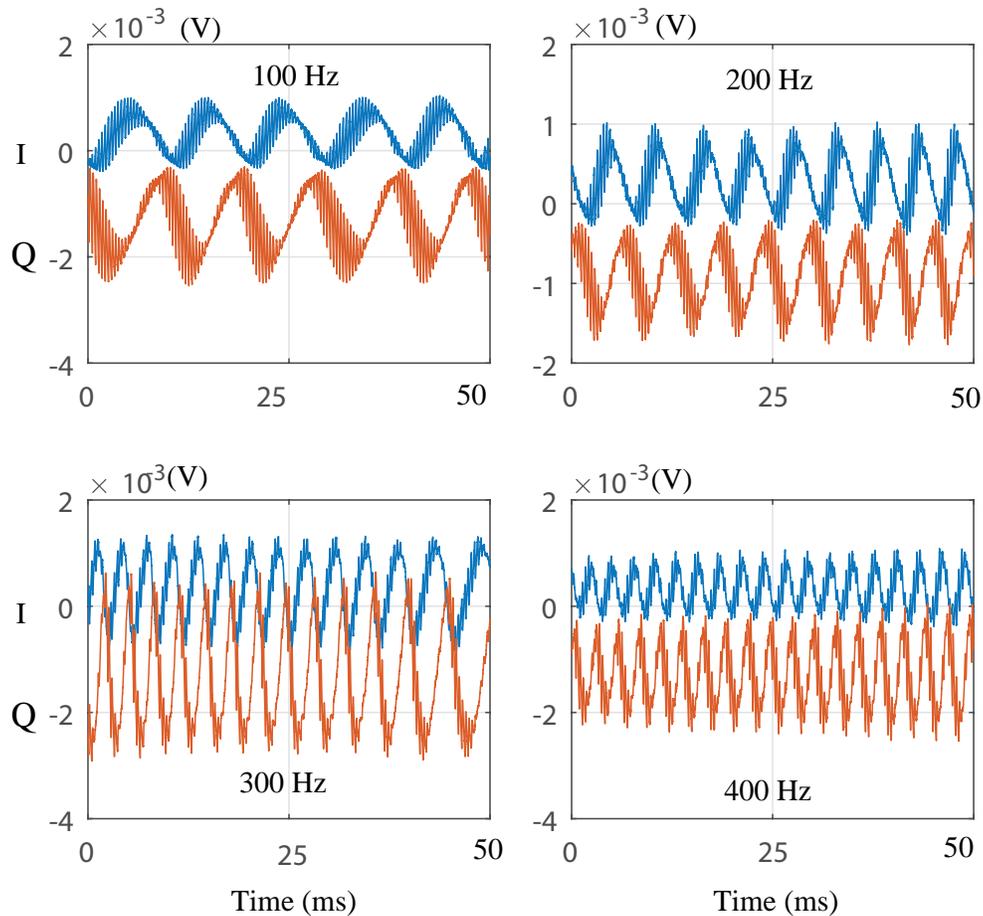


FIGURE 6.10 – Measurement results for different velocity.

## 6.4 Conclusion

A millimeter-wave integrated radar sensor is presented in this paper. It can be used in FMCW or multi-tone configurations to precisely measure range and speed of a target. Because of the very low millimeter-wave power used in the experiment the results are done in short range. The use of a low noise amplifier in the receiver front-end will considerably increase the operating range. Taking benefit of this robust and low-cost schematic and manufacturing process, such sensors can be used in various industrial and biomedical applications.

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## Chapter 7

# Conclusions et Travaux Futurs

Le capteur six-port s'avère un candidat prometteur pour diverses applications, tant pour les mesures de la distance, que pour les mesures de la vitesse relative. Quelques applications peuvent bénéficier des aspects positifs des nouvelles techniques de mesure de vitesse relative et distance. Cette thèse présente un capteur CW et un capteur LFM-CW à courte portée. L'entier prototype du capteur six-port a été intégré dans la technologie MHMIC et assemblé dans une boîte métallique prévue avec des connecteurs standard en ondes millimétriques et en bande de base aux fins de mesures en laboratoire. L'utilisation de cette technologie permet des systèmes de capteurs moins chers, plus précis et plus compacts, pour de diverses applications industrielles et pour le grand public.

Le capteur radar proposé comprend un interféromètre six-port large-bande et deux réseaux d'antennes patch à 16 éléments utilisés pour le transmetteur et le récepteur. Malgré que l'interféromètre six-port ait une largeur de bande de 12 GHz (fonctionne à une fréquence centrale de 77 GHz), l'utilisation des réseaux d'antennes intégrés réduit la bande d'opération du capteur, tel qu'explique en détails dans la thèse. Pour obtenir des signaux différentiels en quadrature, il utilise quatre détecteurs de puissance à haute sensibilité. Chacun est fabriqué avec une paire de diodes Schottky HSCH-9161 et un coupleur hybride, afin d'améliorer l'adaptation sur toute la bande passante. Le signal réfléchi sur la cible est comparé dans l'interféromètre avec le signal de référence obtenu à l'aide d'un coupleur directionnel de l'oscillateur à ondes millimétriques.

Les mesures ont été réalisées dans deux scénarios de système différents, prouvant un accord excellent avec les simulations du système en ADS. Dans le premier scénario, des diapasons à différentes fréquences acoustiques ont été utilisés comme cible. Un essai avec le diapason est réalisé pour démontrer la précision du capteur proposé dans de la mesure de la fréquence audio. Vraiment, la fréquence mesurée avec l'oscilloscope des deux signaux en quadrature générés par le six-port est égale avec la fréquence audio marquée sur le diapason, pour tous les diapasons mis à l'essai, de 100 Hz à 1024 Hz. Dans le deuxième scénario, un signal modulé en fréquence est transmis vers une plaque en aluminium, sur une distance connue ou déplacé avec une certaine vitesse. Le capteur peut mesurer la phase, la fréquence ou la variation relative d'amplitude du signal réfléchi sur la cible, par rapport à un signal de référence obtenu par un coupleur à lignes parallèles de -10 dB.

Le radar proposé est un radar monostatique de point de vue construction, dont le transmetteur et le récepteur sont fabriqués sur la même monture. De point de vue architectural il est bistatique, car on utilise des antennes séparées d'émission et de réception. Il est moins cher et plus compact et il ne pose aucun problème pour la synchronisation de l'oscillateur local. Tel que mentionné, son principal inconvénient est l'exigence d'avoir une puissance de sortie du transmetteur élevée, ainsi qu'un récepteur sensible pour les systèmes radar à longue portée et à moyenne portée. La sensibilité du capteur impose des exigences rigoureuses relatives à la linéarité et à la plage dynamique du système. Comme spécifié auparavant, le capteur radar proposé utilise un coupleur à lignes parallèles connecté avec le réseau d'antennes de transmission pour générer le signal de référence pour le récepteur. Parce qu'il n'y a pas un amplificateur RF après ce coupleur, la puissance transmise est réduite pour empêcher le couplage parasite des signaux dans le substrat commun. De même, parce que on n'utilise pas un amplificateur à faible bruit à la réception, le rapport signal bruit est aussi légèrement dégradé. Par contraste, les systèmes bistatiques de point de vue construction ne posent pas ces problèmes et présentent un SNR supérieur si un récepteur plus performant est utilisé. Toutefois, à cause des différentes exigences des systèmes radar, la conception d'un système radar compact bistatique (de tous les points de vue construction et architectural) peut s'avérer plus difficile et plus chère et exige une attention particulière au niveau de la conception.

Dans l'opinion de l'auteur, le capteur radar six-port à faible cout pour des mesures précises de distance et de vitesse est très utile et, par conséquent, il y a beaucoup de possibilités de travaux futurs. Par exemple:

- Concevoir et mettre en application une antenne à ondes millimétriques, qui respecte les exigences relatives à un gain élevé et à une faible perte, ainsi qu'à la dimension réduite pour les capteurs spéciaux à moyenne et longue portée.
- Analyser et comparer les différentes formes d'onde en dents de scie et triangulaires du radar FMCW, y compris la forme d'onde et les paramètres tels que la pente de la rampe et la durée de temps, et trouver les points optimaux entre la résolution et la largeur de bande, ce qui est plus essentiel pour les radars de haute fréquence. En fait, même si la résolution spatiale est améliorée en utilisant des fréquences supérieures, l'atténuation atmosphérique augmente et, pour une portée de détection donnée, une puissance de sortie supérieure est nécessaire.
- Faire une comparaison plus précise entre le récepteur six-port et le mélangeur conventionnel à diodes ; cette recherche ne vise que la consommation d'énergie. Il est intéressant de faire une comparaison entre plusieurs paramètres techniques tels que la sensibilité, SNR, l'offset LO, etc.
- Améliorer la performance du modulateur six-port et concevoir des commutateurs rapides en haute fréquence ; il serait peut-être intéressant d'étudier la possibilité de concevoir un réseau passif qui puisse transférer plus d'informations pour la poursuite de cibles multiples ou pour les fréquences multi-tonales sans utiliser un VCO ou un PLL.
- Prendre en considération l'effet de l'environnement dans le comportement des capteurs radar. Tous les essais sont réalisés dans le laboratoire INRS, dans des atmosphères environnementales spécifiques. Il est intéressant d'étudier le comportement du radar à base de six-port dans différents environnements.

En conclusion, cette thèse ouvre un vaste domaine de recherche dans la conception des capteurs radar à faible coût avec des applications pratiques en industrie, domaine biomédical, le domaine de la sécurité et surveillance, etc.

## Liste des publications

### Jounaux

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