High Frequency solutions for Internet of Things connectivity

Ing. Giovanni Collodi
Prof. Stefano Selleri

Università degli Studi di Firenze
Dipartimento di Ingengeria dell'Informazione

INTERNET OF THINGS

The Internet of Things (IoT) is a novel paradigm that is rapidly gaining ground in the scenario of modern wireless telecommunications.

The basic idea of this concept is:

"*A pervasive presence around us of a variety of things or objects – such as Radio-Frequency IDentification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals*"

IOT TERMS AND DEFINITION

Internet of Things: A network of internet-connected objects able to collect and exchange data using embedded sensors.

Internet of Things device: Any stand-alone internet-connected device that can be monitored and/or controlled from a remote location.

Internet of Things ecosystem: All the components that enable businesses, governments, and consumers to connect to their IoT devices, including remotes, dashboards, networks, gateways, analytics, data storage, and security.

Physical layer: The hardware that makes an IoT device, including sensors and networking gear.

Network layer: Responsible for transmitting the data collected by the physical layer to different devices.

Application layer: This includes the protocols and interfaces that devices use to identify and communicate with each other.

IOT TERMS AND DEFINITION

Remotes: Enable entities that utilize IoT devices to connect with and control them using a dashboard, such as a mobile application. They include smartphones, tablets, PCs, smartwatches, connected TVs, and nontraditional remotes.

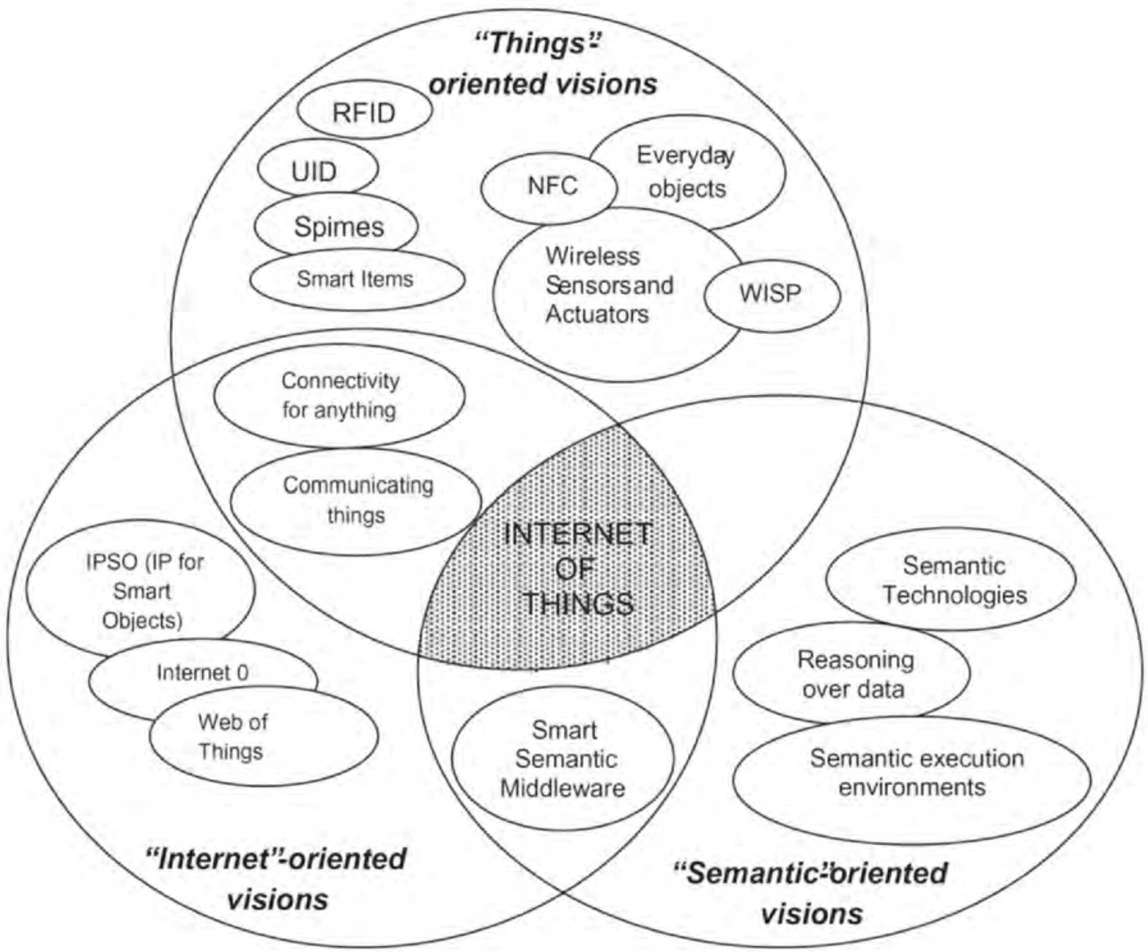
Dashboard: Displays information about the IoT ecosystem to users and enables them to control their IoT ecosystem. It is generally housed on a remote.

Analytics: Software systems that analyze the data generated by IoT devices. The analysis can be used for a variety of scenarios, such as predictive maintenance.

Data storage: Where data from IoT devices is stored.

Networks: The internet communication layer that enables the entity to communicate with their device, and sometimes enables devices to communicate with each other.

INTERNET OF THINGS



INTERNET OF THINGS

The IoT enables physical objects to see, hear, think and perform jobs by letting them "talk" together, to share information and to coordinate decisions.

The IoT transforms physical objects from being traditional to smart by exploiting such as

- Ubiquitous and pervasive computing
- Embedded devices
- Communication technologies,
- Sensor networks
- Internet protocols and applications.

INTERNET OF THING VISION

The concept of the IoT

Every domain specific application is interacting with domain independent services, whereas in each domain sensors and actuators communicate directly with each other.

IoT APPLICATION

IoT is expected

- To have significant home and business applications
- To contribute to the quality of life
- To grow the world's economy.

In order to realize this potential growth, *emerging technologies and innovations, and service applications need to grow* proportionally to match market demands and customer needs.

Furthermore, *devices need to be developed to fit customer requirements* in terms of availability anywhere and anytime.

Also, *new protocols are required for communication compatibility* between heterogeneous things (living things, vehicles, phones, appliances, goods, etc.)

IoT APPLICATION

Smart-homes

Smart-homes enable their residents to automatically open their garage when reaching home, prepare their coffee, control climate control systems, TVs and other appliances.

IoT APPLICATION

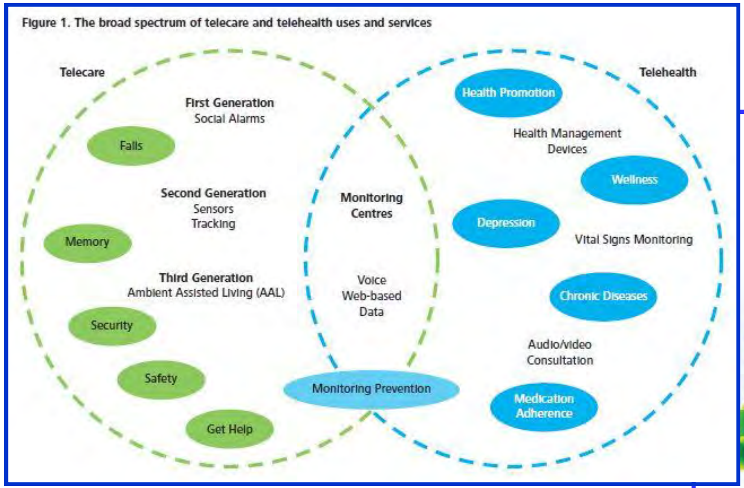


Figure 1. The broad spectrum of telecare and telehealth uses and services

Healthcare applications and related IoT-based services such as mobile Health (m-Health) and telecare that enable medical wellness, prevention, diagnosis, treatment and monitoring services to be deliveredefficiently through electronic media

IoT APPLICATION

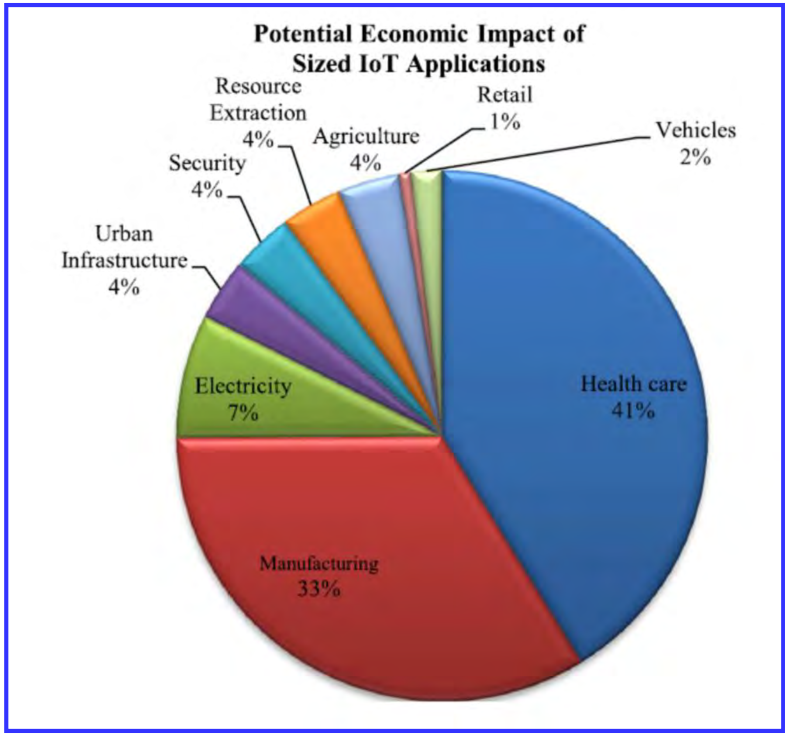
The application of the IoT paradigm to an urban context is of particular interest, as it responds to the strong push of many national governments to adopt ICT solutions in the management of public affairs, thus realizing the so-called Smart City concept

IoT MARKET OPPORTUNITY

The IoT offers a great market opportunity for equipment manufacturers, Internet service providers and application developers.

The IoT smart objects are expected to reach 212 billion entities deployed globally by the end of 2020 and by 2022, M2M (Machine to Machine) traffic flows are expected to constitute up to 45% of the whole Internet traffic.

All these point to a potentially significant and fast-pace growth of the IoT in the near future, related industries and services.



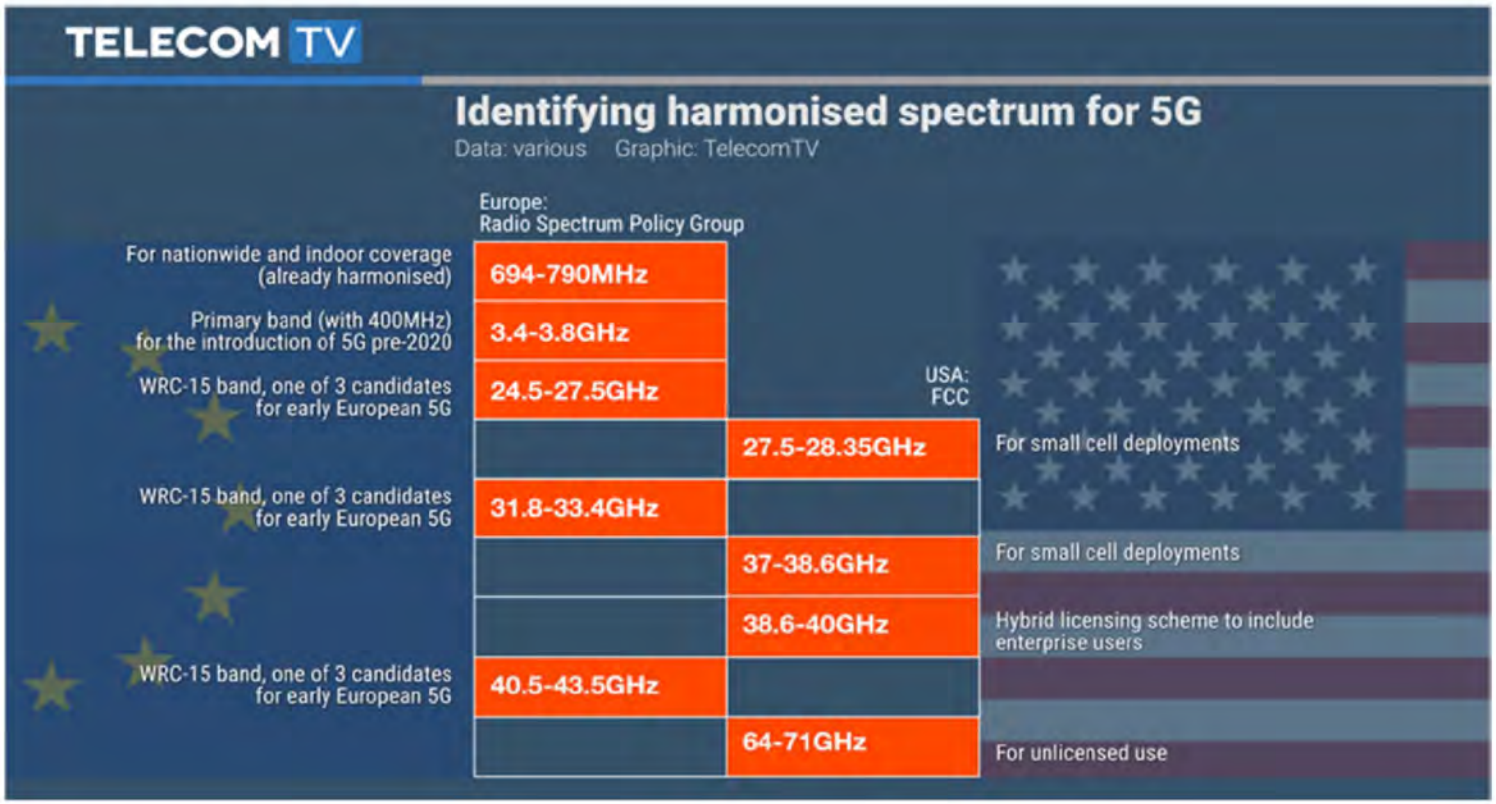
This progression provides a unique opportunity for traditional equipment and appliance manufacturers to transform their products into “smart things.”

5G REVOLUTION IN THE IoT

5G mobile networks capability to transmit data about 10 times faster than 4G LTE could transfigure IoT application:
Faster data transmission could simplify connected device management, which means 5G could lead to significant growth in the IoT.

Right now, many IoT solutions use 4G LTE network to connect the IoT devices, but the devices produce so much data that's hard to process quickly. That creates high latency which in turn limits IoT solutions' effectiveness.
Since 5G is able to transmit data drastically faster, companies could deploy more connected devices without latency issues. That'll gives the overall number of connected devices deployed a boost right after 5G arrives,

5G HARMONIZED SPECTRUM



5G MILLIMETER WAVE

About 5G:

Target: achieve higher data rate requirement in the order of 10 Gbps,

The specifications are published in the 3GPP Release 15 and beyond.

5G has different frequency ranges

- sub 6 GHz (5G macro optimized),
- 3-30 GHz (5G E small cells)
- 30-100 GHz (5G Ultra Dense).

About millimeter wave: The frequency bands which lies between 30 GHz to 300 GHz is known as millimeter wave. This is due to the fact that wavelength of electro-magnetic wave will be in millimeter range at these frequencies. There are many advantages and disadvantages of mm wave.

5G MILLIMETER WAVE

Due to growth of large number of mobile data subscribers, need for larger bandwidth arises.

The fact is bandwidth is limited in the available mobile frequency spectrum which is below the mm wave band.

Due to this millimeter wave band has been explored as mobile frequency spectrum by operators due to its support for larger bandwidth.

Though penetration loss is higher at these mm wave frequencies as these frequencies can not penetrate walls and certain objects in the buildings. Moreover mm wave frequencies get attenuated due to rain.

After careful inclusion of all these factors in the RF link budget calculation, mm wave can be strong future for the mobile data broadband market.

About 5G millimeter wave: The millimeter wave frequencies which are used for 5G mobile technology is known as 5G millimeter wave.

5G MILLIMETER WAVE

Features	Description
Data rate	10 Gbps or higher
Frequency Bands	The bands are split into <40 GHz and >40GHz upto 100 GHz frequency
Bandwidths	• 10 subcarriers of 100 MHz each can provide 1GHz BW due to carrier aggregation at <40 GHz • 500 MHz to 2 GHz BW can be achieved without carrier aggregation at >40GHz
Distance coverage	2 meters (indoor) to 300 meters (outdoor)
Modulation types	CP-OFDMA <40GHz SC >40GHz
Frame topology	TDD
latency	About 1 ms
MIMO type	Massive MIMO is supported. Antennas are physically small and hence there will be approx. 16 antenna array available in 1 square inch. Hence 5G mm wave compliant eNBs support 128 to 1000 antenna arrays. These are used to increase the capacity and coverage both.

ADVANTAGE OF 5G MILLIMETER WAVE

- Provides larger bandwidth more number of users can be accommodated.
- it is more favourable for smaller cell deployment.
- Coverage is not limited to line of sight as first order scatter paths are viable.
- Channel sounding feature is employed to take care of different types of losses at mm wave frequencies (*).
- Antenna size is physically small and hence large number of antennas are packed in small size. This leads to use of massive MIMO to enhance the capacity.
- Dynamic beamforming is employed and hence it mitigates higher path loss at mm wave frequencies.
- 5G millimeter wave networks support multi-gigabit backhaul upto 400 meters and cellular access upto 200-300 meters.

(*) Channel sounding refers to measurement or estimation of channel characteristics which helps in successful design, development and deployment of 5G network with necessary quality requirements.

DISADVANTAGE OF 5G MILLIMETER WAVE

- Millimeter wave goes through different losses such as penetration, rain attenuation etc. This limits distance coverage requirement of mm wave in 5G based cellular mobile deployment.
- Path loss at mm is proportional to square of the frequency. It supports 2 meters in indoors and about 200-300 meters in outdoors based on channel conditions and AP/eNB height above the ground.
- Supports only LOS (Line of Sight) propagation.
- Foliage loss is significant at such mm wave frequencies.
- Power consumption is higher at millimeter wave due to more number of RF modules due to more number of antennas (*).

(*) To avoid this drawback, hybrid architecture which has fewer RF chains than number of antennas need to be used at the receiver. Moreover low power analog processing circuits are designed in mm wave hardware.

5G CHANNEL SOUNDING

About channel: The path between transmitter and receiver through which information flows in various forms (electrical, electromagnetic, binary etc.) is known as channel. We will refer here wireless channel or RF channel.

During wireless system development mathematical model of channel is designed and used during system simulation to achieve desired BER/PER results at various SNR.

The different wireless systems have different channel models based on frequency, terrain, mobility, path loss etc.

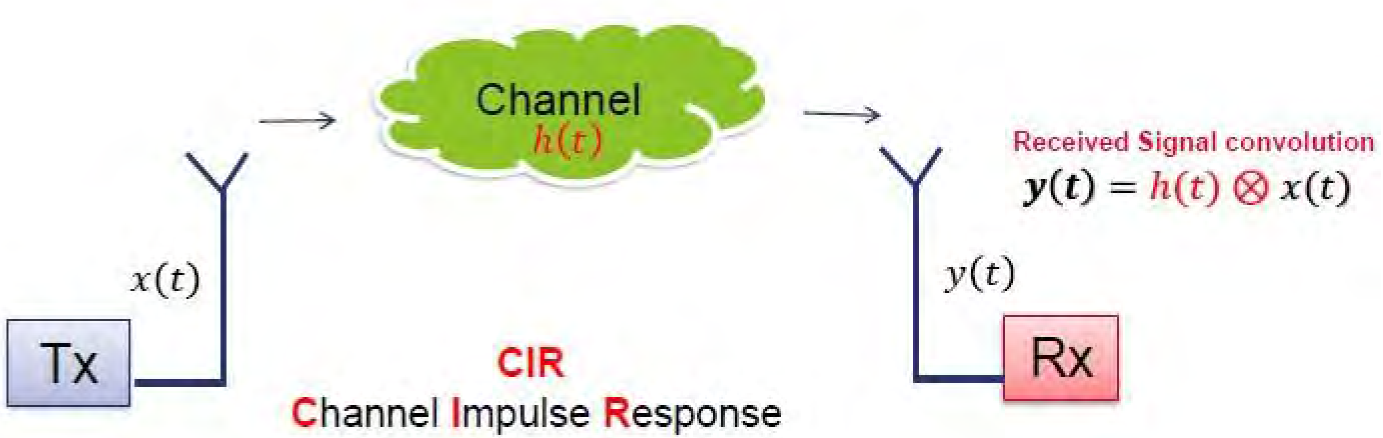
During RF channel model development various parameters have to be considered :

- delay,
- path loss,
- absorption,
- multipath,
- reflection,
- fading,
- doppler effect

5G CHANNEL SOUNDING

Function of channel sounding: The purpose of channel sounding is to understand various characteristics of RF channel. In other words channel sounding refers to measurement or estimation of channel characteristics. The channel sounding technique employed in 5G network is known as 5G channel sounding.

This will help in channel model development. This also helps in channel estimation and channel equalization algorithms used at complex wireless receivers in 4G and 5G based standards.



CHANNEL SOUNDING TECHNIQUES

Preamble or pattern Based:

Using known symbols or patterns available at the receiver. This technique uses corrupted symbol or pattern and reference pattern already available to determine channel characteristics for channel sounding.

Reference symbols such as pilots inserted between the OFDM symbols can also be used for channel estimation.

Rusk sounding:

It generates frequency tones at all the frequencies available in desired bandwidth.

These tones are transmitted across the path between the transmitter and receiver to determine channel behaviour at all the frequencies.

5G CHANNEL SOUNDING MEASUREMENTS

For 5G channel sounding following parameters are used to determine CIR (Channel Impulse response) at different millimeter wave frequencies such as 28 GHz, 38 GHz and 72 GHz.

Instantaneous parameters:

- Power delay profile,
- Path loss and path delay,
- AoA (Angle of Arrival),
- AoD (Angle of Departure),
- Doppler frequency shift

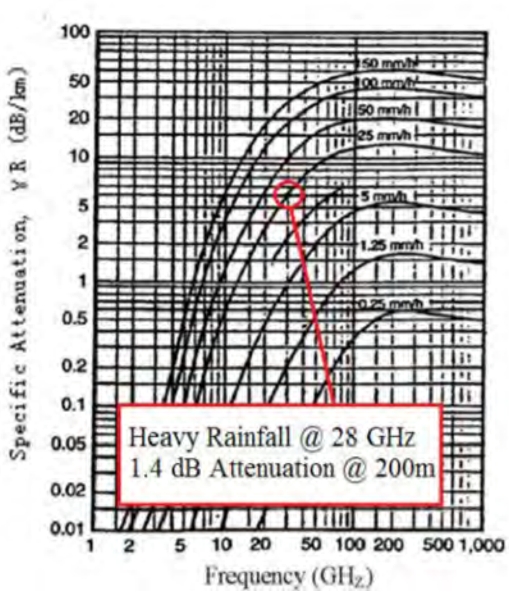
Statistical parameters :

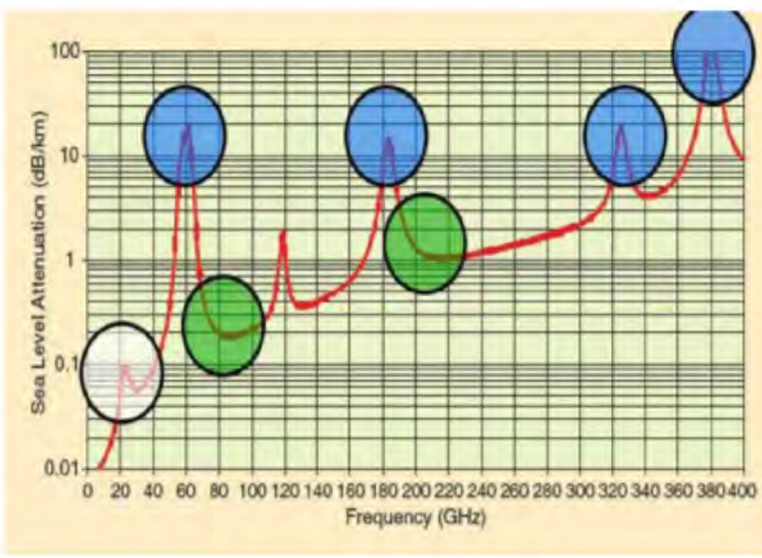
- Angular speed of AoA and AoD,
- Power angular spectrum,
- Correlation matrix,
- Rician factor (K),
- Doppler spectrum etc.

5G CHANNEL PROPAGATION DRAWBACK

One of the major hurdles in implementing radio access at microwave frequency is overcoming the unfavorable propagation characteristics.

Radio propagation at these frequencies is highly affected by atmospheric attenuation, rain, blockage (buildings, people, foliage), and reflections.

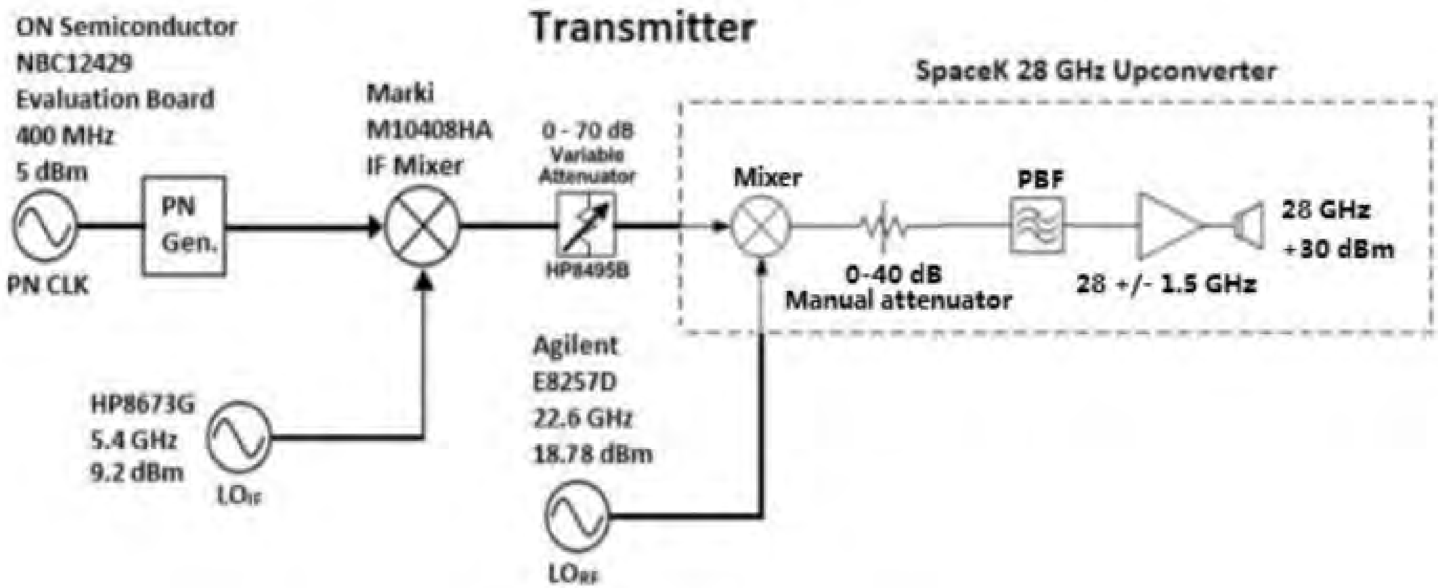




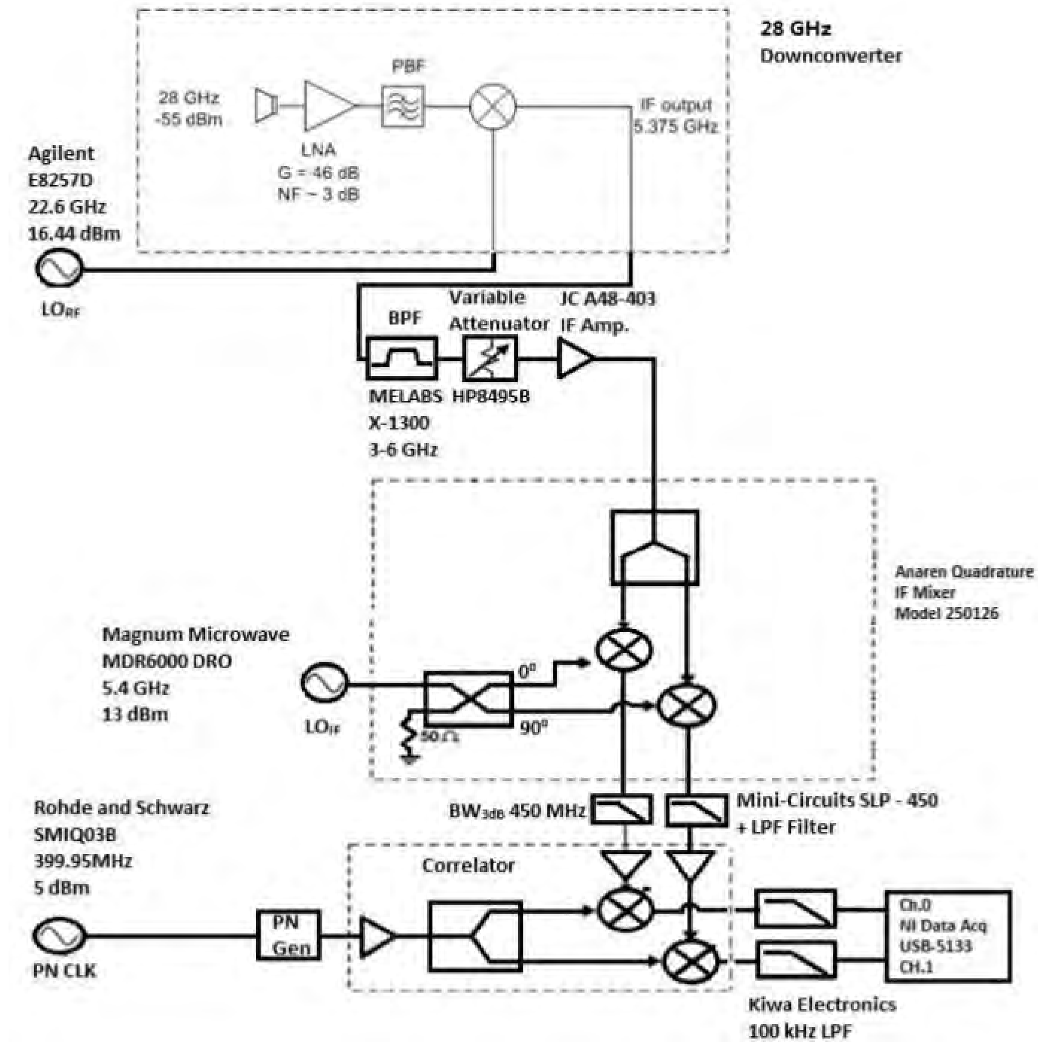
5G CHANNEL MEASUREMENTS SET UP

Transmitter:

A pseudo-random noise(PN) sequence sliding correlator was utilized as the probing signal, which was modulated to a 5.4 GHz intermediate frequency (IF) and upconverted to 28 GHz after mixing with a 22.6 GHz local oscillator (LO). The transmitter power was +30 dBm (a typical value for lower power femtocells), fed to a steerable 10◦ beamwidth 24.5 dBi horn antenna or a 30◦ beamwidth 15 dBi horn antenna that was mechanically rotated



5G CHANNEL MEASUREMENTS SET UP



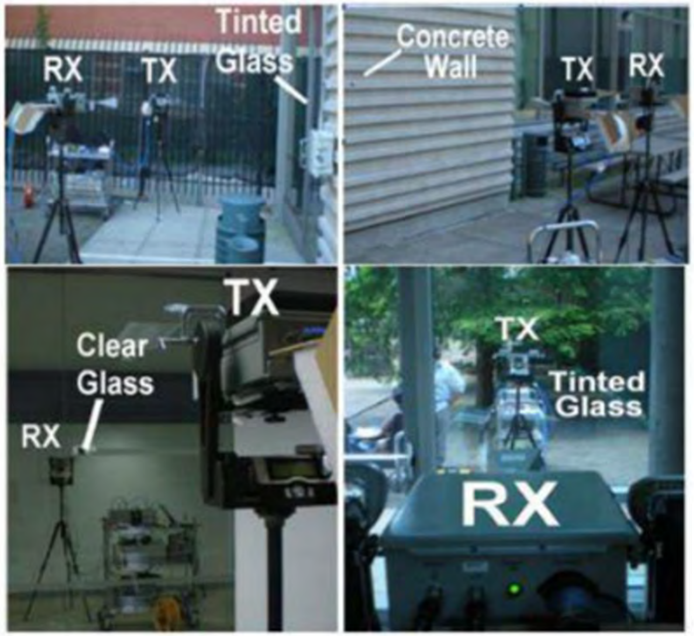
The receiver used the same type of horn antennas as the transmitter.

In order to achieve increased measurement dynamic range for increased coverage distance, a sliding correlator spread spectrum system is used.

Total measured dynamic range was approximately 178 dB between the transmitter and receiver using the most directional horn antennas in order to obtain an SNR of 10 dB, on the order of future small cells.

5G CHANNEL MEASUREMENTS

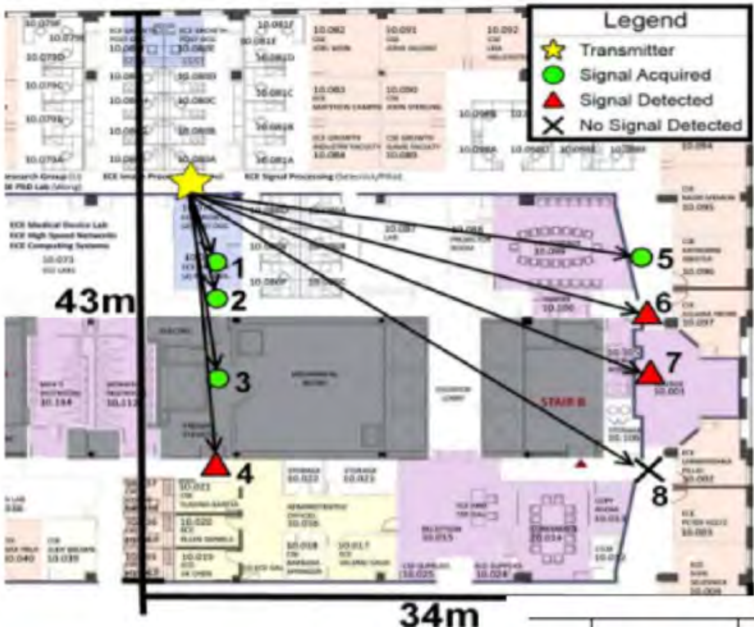
Environment	Location	Material	Thickness (cm)	Received Power - Free Space (dBm)	Received Power - Material (dBm)	Penetration Loss (dB)
Outdoor	ORH	Tinted Glass	3.8	-34.9	-75.0	40.1
	WWH	Brick	185.4	-34.7	-63.1	28.3
Indoor	MTC	Clear Glass	<1.3	-35.0	-38.9	3.9
	WWH	Tinted Glass	<1.3	-34.7	-59.2	24.5
		Clear Glass	<1.3	-34.7	-38.3	3.6
		Wall	38.1	-34.0	-40.9	6.8



28 GHz reflection measurement for outdoor tinted glass at ORH and outdoor concrete wall at ORH,

penetration loss measurement for indoor clear non-tinted glass at MTC and tinted glass at ORH

5G CHANNEL MEASUREMENTS



Map of the penetration measurements through multiple obstructions in an office environment located at the 10th floor of 2 MetroTech Center in Brooklyn, New York

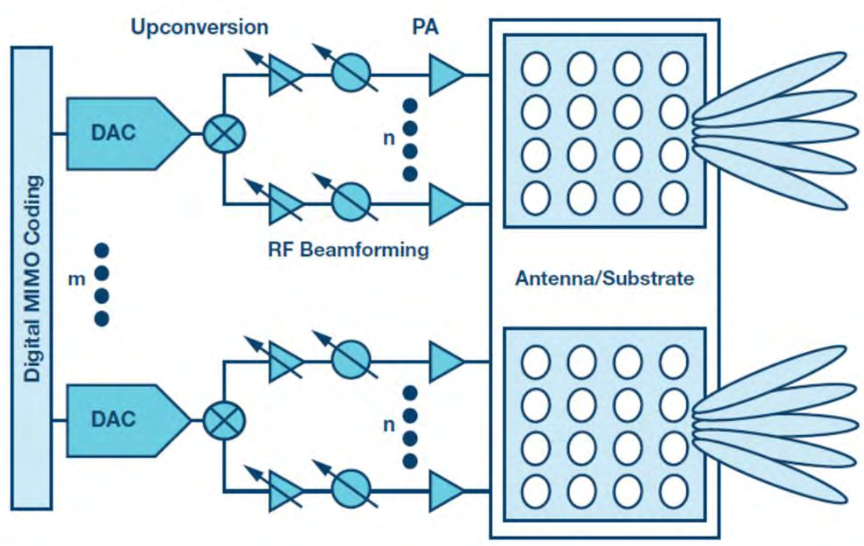
RX ID	TX-RX Separation (m)	# of Partitions				Transmitted Power (dBm)	Power Received – Free Space (dBm)	Received Power – Test Material (dBm)	Penetration Loss (dB)
		Wall	Door	Cubicles	Elevator				
1	4.7	2	0	0	0	-8.6	-34.4	-58.8	24.4
2	7.8	3	0	0	0	-8.6	-38.7	-79.8	41.1
3	11.4	3	1	0	0	11.6	-21.9	-67.0	45.1
5	25.6	4	0	2	0	21.4	-19.0	-64.1	45.1
4	30.1	3	2	0	0	21.4	-30.4	Weak Signal Detected	
6	30.7	4	0	2	0	21.4	-30.5		
7	32.2	5	2	2	0	21.4	-30.9		
8	35.8	5	0	2	1	21.4	-31.9	No Signal Detected	

5G TX- RX MIMO SOLUTION

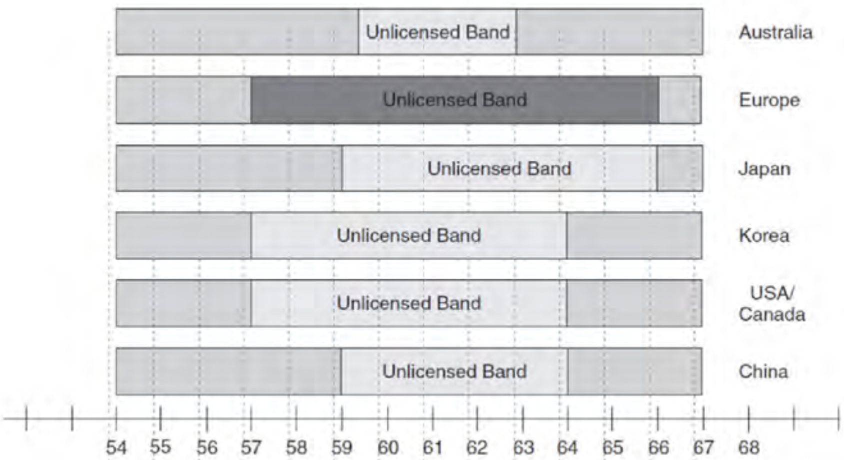
it has been acknowledged that adaptive beamforming will be required to overcome the propagation challenges for 5G systems.

Unlike point-to-point systems, the beamforming will need to adapt to the users and the environment to deliver the payload to the user.

It is generally agreed in the industry that hybrid MIMO systems will be used in the microwaveand low millimeter wave bands, while in V bands and E bands—where bandwidth is plentiful—the systems will likely only employ beamforming to reach the required throughput goals.



60 GHz CHOICE



60 GHz technology offers various advantages over current or existing communications Systems. One major reason for the recent interest in 60 GHz technology is the huge unlicensed bandwidth

60 GHz enables a 5 GHz of continuous bandwidth and is available in many countries worldwide.

Technology	Frequency (GHz)	PA output (dBm)	Antenna gain (dBi)	EIRP output (dBm)
60 GHz	57.0–66.0	10.0	25.0	35.0
UWB	3.1–10.6	−11.5	1.5	−10.0
IEEE 802.11n	2.4/5.0	22.0	3.0	25.0

This bandwith is comparable to the unlicensed bandwidth allocated for ultra-wideband (UWB) but, the 60 GHz bandwidth is continuous and less restricted in terms of power limits.

60 GHz technology particularly attractive for gigabit wireless applications

60 GHz CHOICE

60 GHz regulation allows much higher transmit power or EIRP (equivalent isotropic radiated power) compared to other existing WLAN and WPAN systems.

The output power of a power amplifier for 60 GHz is typically limited to 10 dBm because the implementation of efficient power amplifiers at this frequency is very challenging though FCC regulations allow up to 27 dBm.

the huge antenna gain up to 40 dBi has significantly boosted the allowable EIRP limits.

The higher transmit power is necessary to overcome the higher path loss at 60 GHz.

The high path loss seems to be a disadvantage at 60 GHz, it confines the 60 GHz operation to within a room in an indoor environment. Hence, the effective interference levels for 60 GHz are less severe than those systems located in the congested 2.0–2.5 GHz and 5.0–5.8 GHz regions

60 GHz CHOICE

The huge bandwidth available for 60 GHz and UWB systems simplifies the system design of these technologies.

A system with much lower spectral efficiency can be designed to deliver a Gbps transmission to provide low cost and simple implementation.

A typical 60 GHz system requires only 0.4 bps/Hz to achieve 1Gbps, making it an ideal candidate to support very high data rate applications using simple modulation.

Technology	Bandwidth (MHz)	Efficiency@ 1 Gbps (bps/Hz)	Target data rate (Mbps)	Efficiency required (bps/Hz)
60 GHz	2000	0.5	4000	2.0
UWB	528	2.0	480	1.0
IEEE 802.11n	40	25.0	600	15.0

The spectral efficiency required by the 60 GHz, UWB and IEEE 802.11 systems to achieve 1Gbps transmission as well as spectral efficiency of the actual deployment of such systems.

60 GHz IN WORLD

The combination of high EIRP limit, huge bandwidth, and harmonized regulation and frequency allocation globally has positioned 60 GHz in the forefront of Gbps wireless communications.
This can be demonstrated by the immense standardization effort and industry alliance formation to promote 60 GHz technology.

Region	Unlicensed bandwidth (GHz)	Transmit power	EIRP (dBm)	Maximum antenna gain (dBi)
USA/Canada	7.0	500 mW or 27 dBm (max)*	40.0 (ave)+ 43.0 (max)#	33.0 (max) when 10.0 dBm TX power is used
Japan	7.0†	10 mW or 10 dBm (max)	58.0 (max)	47.0
Korea	7.0	10 mW or 10 dBm (max)	27.0 (max)	17.0‡
Australia	3.5	10 mW or 10 dBm (max)	51.7 (max)	41.8
Europe◇	9.0	20 mW	57.0 (max)	30.0

Despite the tremendous progress made in 60 GHz technology in the past decade, the challenges of full-scale commercialization still remain, particularly in providing low-cost, low-power and robust 60 GHz products.

60 GHz FRONT-END

One of the key technical challenges for the widespread commercial use of 60 GHz based wireless end-user products is their cost-effective implementation.

This has provided the motivation for a great deal of work on silicon-based millimeter-wave technologies capable of providing higher integration and lower power consumption than the III-V compound semiconductor technologies used in 60 GHz bands even a few years ago.

The challenging 60 GHz radio frequency (RF) front-ends induce several critical RF non-idealities that must be addressed in 60 GHz system design.

This problem becomes even more critical in mobile or handheld device related applications in which an aggressive RF circuit design for low power consumption and small form factors is a must

60 GHz Radio Implementation in Silicon

In recent years, the design of active and passive mm-wave components in general – and in the 60 GHz band in particular – has become a center of gravity for academic and industrial research.

Within a period of six years, from the first 60 GHz building blocks integrated in silicon introduced in 2004 to today, this field of research has quickly expanded, resulting in multiple examples of fully integrated radios and phased arrays.

<u>The availability of silicon processes that allow radio implementation at 60 GHz (45 nm CMOS and 0.13 μm SiGe BiCMOS) is arguably the single most important factor in fueling 60 GHz standardization and investment activities.</u>

This part of the course presents an overview of the current solutions, techniques and tradeoffs involved in the implementation of a high-data-rate 60 GHz radio in silicon from the radio frequency (RF) front-end to the mixed-signal (analog/digital) interface with a digital baseband chip

Semiconductor Technologies for 60GHz Radios

In early 1990s:

the cutoff frequencies for silicon transistors (CMOS FETs and SiGe HBTs) were below 100 GHz and about an order of magnitude smaller than those achieved by the III-V semiconductor devices which dominated the RF and mm-wave regime.

In 2005:

both SiGe and CMOS transistors had cutoff frequencies exceeding 200 GHz. During this period the foundations for RF integrated circuit design were laid, multiple new design techniques and circuit topologies were constantly introduced, and the manufacturing of integrated passivecomponents (RF inductors, capacitors and transmission lines) matured.

Actually:

SiGe and CMOS tecnolgy is mature for implementation of 60 GHz solutions

Semiconductor Technologies for 60GHz Radios

Evolution of high performance RF CMOS characteristics:

Year of production	2010	2011	2012	2013	2014
Physical L_{gate} [nm]	29	27	24	22	20
Supply voltage [V]	1	1	1	0.95	0.9
Peak f_T [GHz]	310*	330*	370**	400**	440**
Peak f_{MAX} [GHz]	380*	410*	460**	510**	560**
NF_{min} at 60 GHz [dB]	3.3	3.2	3.0	3.0	2.9

Lgate. This refers to the actual minimum gate length that a FET can have in a given process

Supply voltage. This value is specified to ensure reliability of digital circuits.

Peak f_T. Is the highest f_T in a given technology for an optimum device size and bias conditions (f_T frequency at which the current gain of a transistor with an AC short circuit as a load reaches unity)

Peak f_{MAX}. The frequency at which the power gain of a transistor (for power matched source and load impedances) reaches unity is known as the power-gain cutoff frequency.

NFmin at 60GHz. The minimum 60 GHz noise figure that can be obtained for a device under optimum impedance matching and bias conditions.

Semiconductor Technologies for 60GHz Radios

RFCMOS advantage

One of the key advantages of using CMOS technology for a 60 GHz radio is that it makes a single-chip implementation possible, which is desirable from at least two perspectives:

- Reduce the form factor of the complete 60 GHz solution.
- The performance of the digital baseband benefits from the use of the latest technology

The availability of devices with higher cutoff frequencies implies a certain level of performance can be obtained at a relatively lower bias current.

The expected reduction in power consumption is (without significant circuit design and/or device innovations) less than 20%.

Semiconductor Technologies for 60GHz Radios

Evolution of high performance SiGe HBT characteristics:

Year of production	2010	2011	2012	2013	2014
Emitter width [nm]	100	100	100	90	90
BV_{ceo} [V]	1.6	1.55	1.5	1.45	1.4
Peak f_T [GHz]	320	340	360*	380*	395*
Peak f_{MAX} [GHz]	350	370*	390*	410*	425**
NF_{min} at 60 GHz [dB]	1.9	1.7	1.5	1.4	1.3

BV_{CEO} Breakdown Voltage base open
Peak f_T. Is the highest f_T in a given technology for an optimum device size and bias conditions (f_T frequency at which the current gain of a transistor with an AC short circuit as a load reaches unity)
Peak f_{MAX}. The frequency at which the power gain of a transistor (for power matched source and load impedances) reaches unity is known as the power-gain cutoff frequency.
NFmin at 60GHz. The minimum 60 GHz noise figure that can be obtained for a device under optimum impedance matching and bias conditions.

SiGe bipolar transistors maintain an advantage of about 1.5 dB in NF_{min} with a comparable increase in cutoff frequencies.

Semiconductor Technologies for 60GHz Radios

RFCMOS SiGe HBT and III-V Semiconductor Comparison

Technology	CMOS HP	SiGe	GaAs Low noise	GaAs Power	InP Low noise	InP Power
Device type	FET	HBT	MHEMT		HEMT	
Gate length/Emitter width [nm]	20	90	50		35*	
Peak f_T [GHz]	440**	395*	350*	–	420	–
Peak f_{MAX} [GHz]	560**	425**	–	325*	–	450*
NF_{min} at 60 GHz [dB]	2.9	1.3	0.6*	–	0.6*	–
P_{out} at 60 GHz [mW/mm]	–	–	–	600*	–	400*

III-V semiconductors (GaAs and InP) dominated mm wave applications until recently.

Performance comparisons show:

- SiGe and CMOS have cutoff frequencies comparable to GaAs and InP,
- GaAs and InP devices outperform silicon devices in terms of noise and output power performance.

Semiconductor Technologies for 60GHz Radios

60 GHz Front-End components

60 GHz radios can be highly complex integrated systems, and their overall performance depends on a careful balance of different component specifications.

Basic elements in radio Transceiver design are :

- LNA – Low Noise amplifier
- PA – Power Amplifier
- Frequency synthesizer
- ADCs and DACs for Wide Bandwidth Signals

Semiconductor Technologies for 60GHz Radios

LNA – Low Noise amplifier

It can be observed that the transition from 0.13 μm CMOS to 90 nm CMOS offered a performance advantage, but that the reported results from 65 nm and 90 nm CMOS are in general comparable.

Technology	NF [dB]	Gain [dB]	$IP_{1\,dB}$ [dBm]	Power consumption [mW]	Reference
0.13 μm SiGe	5	>12	−12	8.1	[6]
0.13 μm SiGe	4.5	14.7	−20	10.8	[7]
0.13 μm CMOS	8.8	12	–	54	[8]
0.13 μm CMOS	8	25	−22	79	[9]
90 nm CMOS	5.5	14.6	−14.1	24	[10]
90 nm CMOS	6.5	12.2	−7.2	10.5	[11]
90 nm CMOS	4.4	15	−18	4	[12]
65 nm CMOS	6.2	19	−16	35	[13]
65 nm CMOS	5.6	11.5	–	72	[14]
65 nm CMOS	5.9	15	−15.1	31	[15]

Another observation that follows from these results is that while the noise performance of LNAs in 65 nm and 90 nm CMOS approaches that of 13 μm SiGe BiCMOS, this is frequently achieved at the expense of higher power consumption.

In general, for both LNAs and PAs, a tradeoff exists between operating bandwidth and power consumption. By using high-impedance inter-stage matching techniques, a higher gain (and potentially lower NF) can be obtained with a lower bias current.

Semiconductor Technologies for 60GHz Radios

PA – Power Amplifier

Due to the availability of both a higher supply voltage as well as typically higher achievable voltage gain for a given amplification stage, PAs in SiGe exhibit, higher efficiency and output power than their CMOS counterparts. The differences in performance among reported PA designs in SiGe reflect the fact that PAs have a wide design space and face multiple tradeoffs.

Technology	Supply voltage [V]	Frequency [GHz]	Gain [dB]	OP1dB [dBm]	Saturated output [dBm]	Peak PAE [%]	Reference
0.25 µm SiGe	3.3	61	18.8	14.5	15.5[1]	19.7	[16]
0.18 µm SiGe	1.8	60	11.5	11.2	15.8[3]	16.8	[17]
0.13 µm SiGe	1.2	58	4.5	–	11.5[1]	20.9	[18]
0.13 µm SiGe	4	60	18	13.1	20[3]	12.7	[19]
0.13 µm CMOS	1.6	60	13.5	7	7.8[1]	3	[20]
90 nm CMOS	1.5	60	5.2	6.4	9.3[1]	7.4	[10]
90 nm CMOS	1.0 0.7	60	13.9 14.3	10 5.2	11[2] 8.3[2]	8.2 6.7	[21]
90 nm CMOS	1.0	60	5.6	9	12.3[2]	8.8	[22]
90 nm CMOS	1.2	63	15	–	10–12.5[3,4]	10–19[4]	[23]
65 nm CMOS	1.2	62	4.5	5.5	9[1]	8	[24]
65 nm CMOS	1.2	60	12.8	1.5	7[1]	–	[13]
65 nm CMOS	1.0	62	15.5	5	11.5[2]	15.2	[25]
45 nm CMOS	1.1	60	6 5.6	11 8.4	13.8[2] 10.6[1]	7 6.5	[26]

All of the 60 GHz PAs in CMOS reported operate in linear mode (class A) or with moderate nonlinearity (class AB).

It can be observed that 60 GHz CMOS PAs are capable of delivering 7–10 dBm maximum output power when using a single device at the output and 10–13 dBm when employing two devices at the last amplification stage

Semiconductor Technologies for 60GHz Radios

PA – Power Amplifier

While future advances in silicon technologies are expected to moderately increase 60 GHz PA efficiency (mainly due to improvements in f_{MAX}), significant advances in output power depend on further innovations in mm-wave PA architecture and implementation.

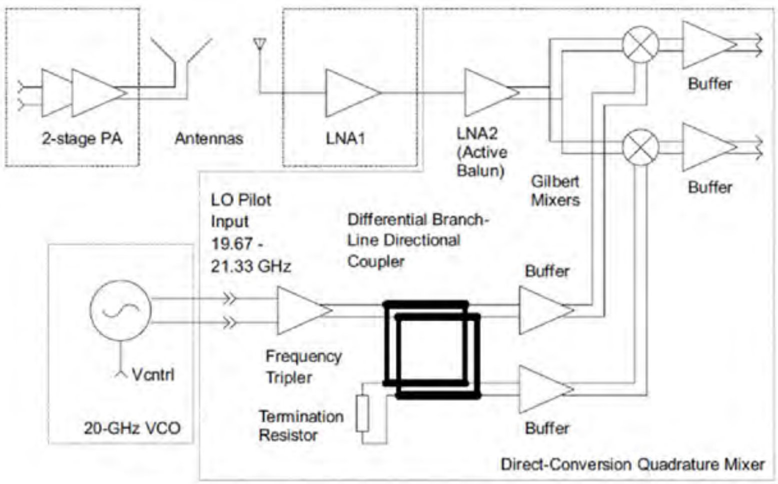
To understand this trend better, it is necessary to look at the impact of technology scaling in more detail. The continuous down-scaling of transistor dimensions that is required to increase the cutoff frequencies implies higher electric fields across materials and, in turn, lowers the maximum operating voltages for reliable operation.

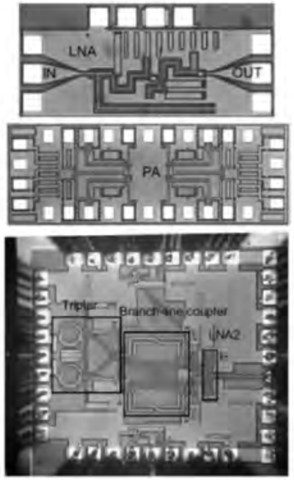
Note that during normal operation, the devices in the final stage of the PA will experience voltage swings that exceed the supply voltage.

The longterm degradation mechanisms in CMOS PAs operating at mm-wave frequencies are yet to be understood.

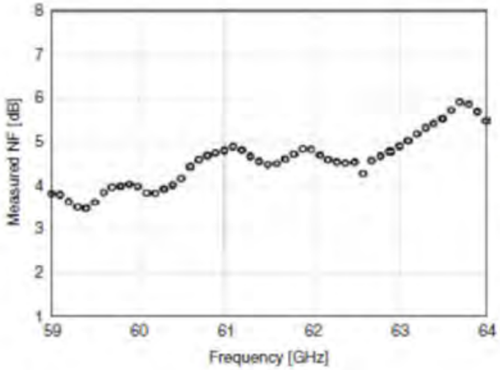
Semiconductor Technologies for 60GHz Radios

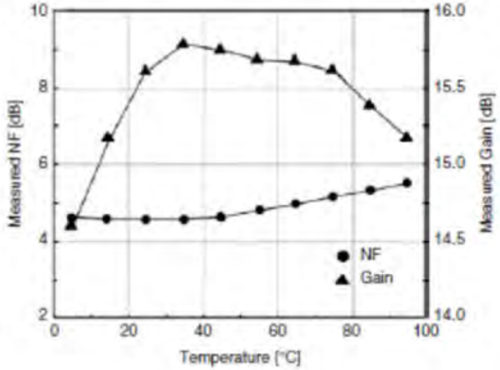
SiGe 60 GHz Transceiver





	LNA	PA	Downconverter
Freq.	61.5 GHz	61.5 GHz	61.5 GHz
Gain	17 dB	10.7 dB	16 dB
NF	4.2 dB	-	14.8 dB
P1dB	-20 dBm (in)	+8.7 dBm (out)	-17 dBm (in)
IIP3	-8.5 dBm	+1.4 dBm	-7 dBm
IIP2	-	-	+13 dBm
Psat	-	> +11.8 dBm	-
LO leakage to LNA2 input	-	-	< -50 dBm
S11	-14 dB	-14.5 dB	-12 dB
S22	-12 dB	-24 dB	-
S12	-40 dB	-40 dB	-
Supply Current	6 mA @ 1.8V	130 mA @ 1.1V	112 mA @ 2.7V (entire chip) 55 mA @ 2.7V (w/o output buffers)





Semiconductor Technologies for 60GHz Radios

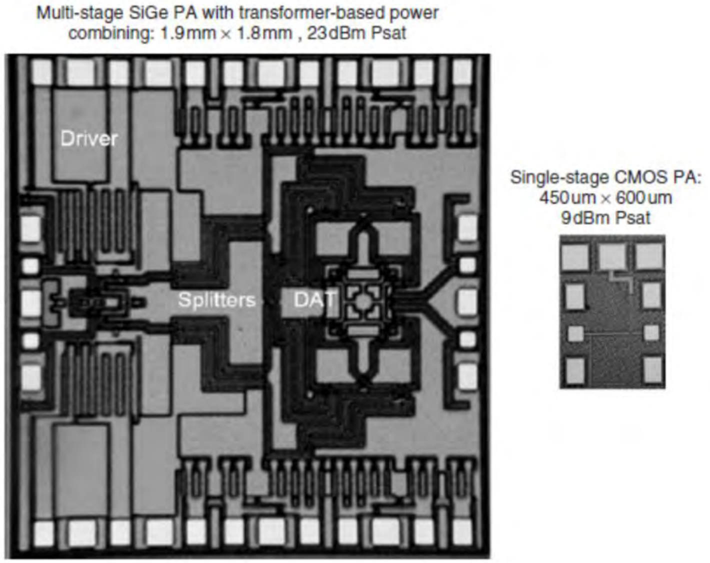
PA – Power Amplifier

Since the amount of RF power that can be obtained from a single device is essentially limited by technology, increased output power must come from the aggregation of the energy originating from different devices.

This is achieved through the use of power combining techniques. Combine the output of more than two devices requires the implementation of customized complex passive networks.

At mm-wave frequencies, these power combiners must be carefully designed leveraging EM simulation and their area overhead may become an important drawback.

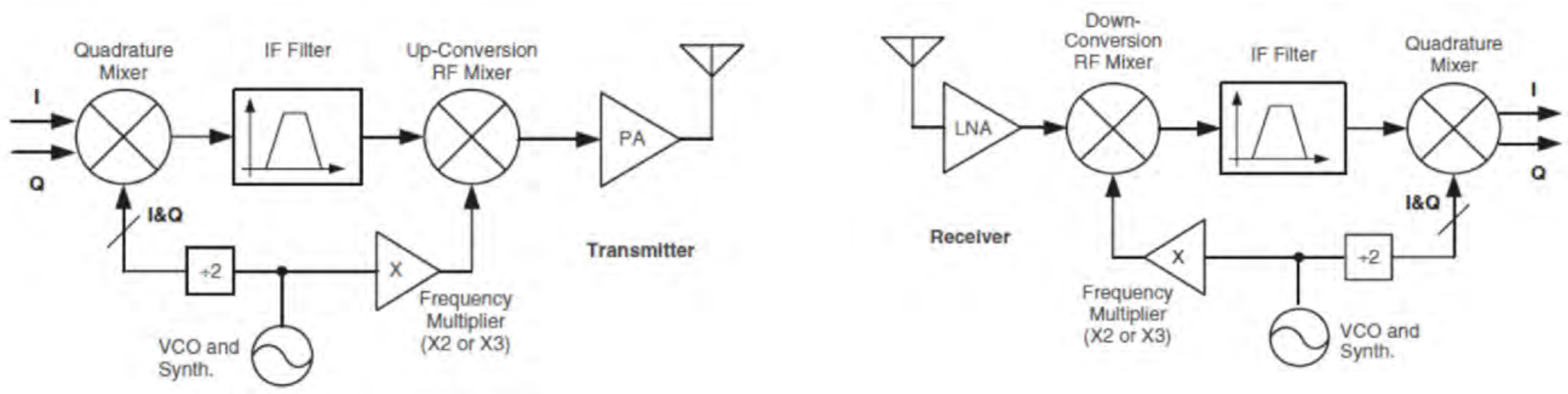
The PA is implemented in SiGe 0.13 μm technology, combines a total of four differential outputs (8 HBT devices in total), and delivers a maximum output power of 23 dBm at 60 GHz using a 4V



Semiconductor Technologies for 60GHz Radios

Frequency Synthesis

The overall architecture of a 60 GHz radio is closely related to its frequency planning and frequency synthesis strategy.



Generic super-heterodyne architecture for a 60 GHz transceiver chipset.

A two-step conversion architecture for 60 GHz applications has two main advantages from a local oscillator (LO) signal generation viewpoint

Semiconductor Technologies for 60GHz Radios

Frequency Synthesis

A two-step conversion main advantages :

- The VCO can operate at frequencies below 30 GHz where wider frequency tuning range and phase noise can be obtained, especially considering process and temperature variations. This is particularly important for applications that target use of all of the frequency channels and at least some of the complex modulation schemes of standards such as IEEE 802.15.3c.

- The quadrature of the up-conversion and down-conversion signals is introduced at the first up/down-conversion step at a frequency below 15 GHz and through the use of a divider. SC and OFDM signaling schemes at Gbps data rates require very precise quadrature balance; this is very challenging to achieve over process and temperature variations as the frequency increases.

Semiconductor Technologies for 60GHz Radios

Frequency Synthesis

In principle, different combinations of frequency division and multiplication factors can be employed in a super-heterodyne architecture.
We focus on the use of a division factor of 2 since it is one of the best-known ways of obtaining quadrature signals.

Design techniques for implementing a divide-by-2 circuit are mature enough to allow different performance optimization tradeoffs among power consumption, phase noise, robustness, and other factors.

Frequency multipliers, are based on the inherent nonlinear properties of semiconductor devices. Fundamentally it is possible to implement frequency multiplication factors of 2, 3, 4 or more at mm-wave frequencies in both SiGe and CMOS.

The practical choices are limited since conversion efficiency and output power are critical for the use of a frequency multiplier in a 60 GHz radio. In particular, the conversion gain of the front-end down-conversion and upconversion mixers are strongly dependent on their input LO power.

Semiconductor Technologies for 60GHz Radios

Frequency Synthesis

IEEE 802.15.3c Channel #	RF center frequency [GHz]	IF frequency [GHz]	Doubler output [GHz]	RF image [GHz]	VCO frequency [GHz]
1	58.320	11.664	46.656	34.992	23.328
2	60.480	12.096	48.384	36.288	24.192
3	62.640	12.528	50.112	37.584	25.056
4	64.80	12.960	51.840	38.880	25.920

frequency doubler

IEEE 802.15.3c Channel #	RF center frequency [GHz]	IF frequency [GHz]	Tripler output [GHz]	RF image [GHz]	VCO frequency [GHz]
1	58.320	8.331	49.989	41.657	16.663
2	60.480	8.640	51.840	43.200	17.280
3	62.640	8.949	53.691	44.743	17.897
4	64.80	9.257	55.543	46.286	18.514

frequency tripler

Although a frequency multiplier degrades the LO phase noise with respect to that of the source VCO, solutions that employ a multiplication factor achieve an overall lower phase noise with respect to the direct synthesis of a 50 or 60 GHz LO carrier

It is also important to observe that two-step conversion solutions naturally enable coverage of a wider range of frequencies as compared to direct alternatives.

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals

With respect to previous wireless technologies, such as 802.11a/b/g/n, 60 GHz systems increase the employed channel bandwidth by a factor of 10 or more in order to enable data rates in excess of 1 Gb/s.

This increase demands a proportional increase in the sampling rate of analog-to-digital and digital-to- analog interfaces in the system.

To process the channel bandwidth of signaling schemes in the 802.15.3c standard (approx. 850MHz at baseband), a sampling rate of at least 1.7 Gsps is necessary.

Nevertheless, proper symbol synchronization requires some degree of oversampling, and sampling rates in excess of 2.5 Gsps will be required in most practical 60 GHz systems.

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals

Process [nm]	Design bits	ENOB	Max. sampling freq. [Gsps]	ERBW [GHz]	Power consumption [mW]	FOM [pJ/conv.]	Architecture	Reference
90	5	3.6	3.5	1.00	227	9.18	Flash	[34]
90	7	5.2	0.8	0.30	120	5.48	Folding-interpolation	[35]
90	6	5.1	10.7	5.00	1600	4.70	Time-interleaved pipeline	[36]
90	6	5.3	1.0	0.50	55	1.37	Two-step sub-ranging	[37]
90	4	3.7	1.3	0.63	2.5	0.16	Modified flash	[38]
90	6	4.9	0.6	0.33	10	0.52	Time-interleaved	[39]
90	11	8.7	0.8	0.40	350	1.07	Time-interleaved	[40]
90	9	7.0	0.4	0.16	139	3.35	Pipeline	[41]
90	7	6.0	1.1	0.30	46	1.18	Time-interleaved pipeline	[42]
90	6	4.9	3.5	1.75	98	0.94	Flash	[43]
90	5	4.3	1.8	0.88	2.2	0.06	Folding flash	[44]
90	5	4.6	1.8	0.88	7.6	0.18	Flash	[45]
90	8	6.9	1.3	0.63	207	1.44	Folding flash	[46]
90	6	5.3	2.7	1.35	50	0.47	Flash	[47]
65	5	2.9	0.5	0.25	7.5	2.06	Time-interleaved SAR	[48]
65	6	5.2	0.8	0.40	12	0.41	Flash	[49]
65	6	5.2	5.0	2.50	320	1.75	Flash	[50]
65	4.5	3.8	7.5	3.75	52	0.51	Flash	[51]
45	7	5.4	2.5	1.25	52	0.51	Time-interleaved	[52]
45	6	5.5	1.2	0.60	28.5	0.52	Flash	[53]

The table presents a summary of ADCs which feature sample frequencies greater than 400 MHz.

The designs are grouped by technology node to support analysis of performance trends.

Due to the high speed switching nature of data conversion operations (similar to those in digital circuits), CMOS is the clear technology of choice for data converters within this range of sampling frequencies.

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals

In addition to the designed number of bits and maximum sampling frequency previous table includes the *effective number of bits* (ENOB) and *effective resolution Bandwidth* (ERBW).

The ENOB is calculated from the measured signal-to-noise-and-distortion ratio (SNDR) that corresponds to an input signal with a frequency equal to the ERBW (usually the Nyquist frequency).

In other words, the ADC has at least x ENOB over the signal bandwidth ERBW.

To compare ADC conversion efficiencies, the following figure of merit (FOM) is generally employed in the literature:

$$FOM = \frac{\text{Power consumption}}{(2 \cdot \text{ERBW}) \cdot (2^{\text{ENOB}})} [\text{pJ/conv}].$$

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals

- It is important to note that in most ADC publications the reported power consumption corresponds exclusively to the ADC core; the unit that actually performs the conversion.

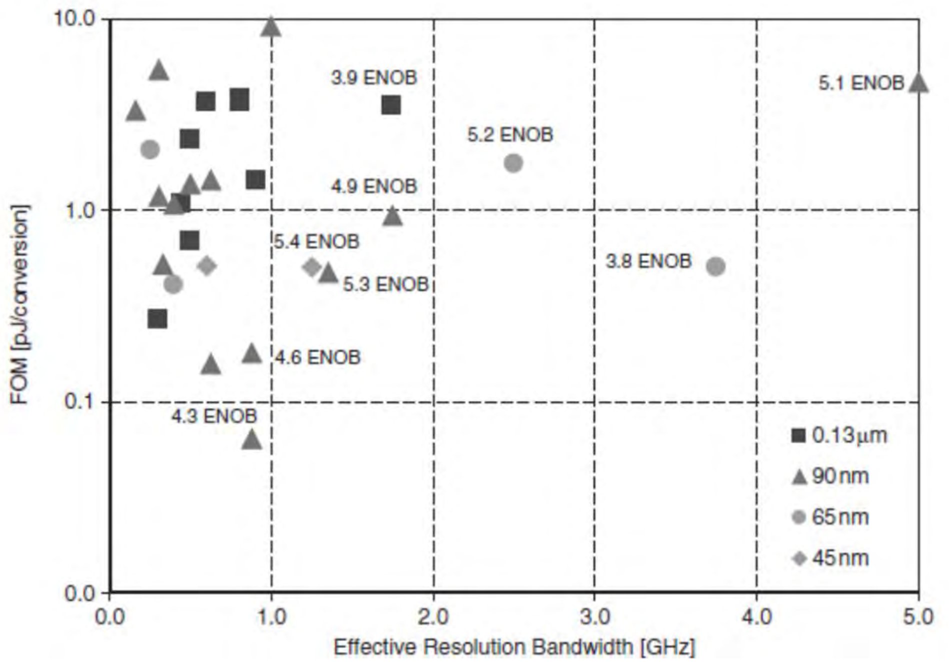
- In practice, high-speed ADCs require additional components such as clock buffers, drivers for analog and digital signals connected externally through 50 Ohm interfaces, and voltage regulators.

- The performance of this additional circuitry is vital not only to ADC operation but also to maintain the required ENOB overvoltage, process and temperature variations.

- The power and silicon area associated with these components is often comparable to that of the ADC core itself.

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals

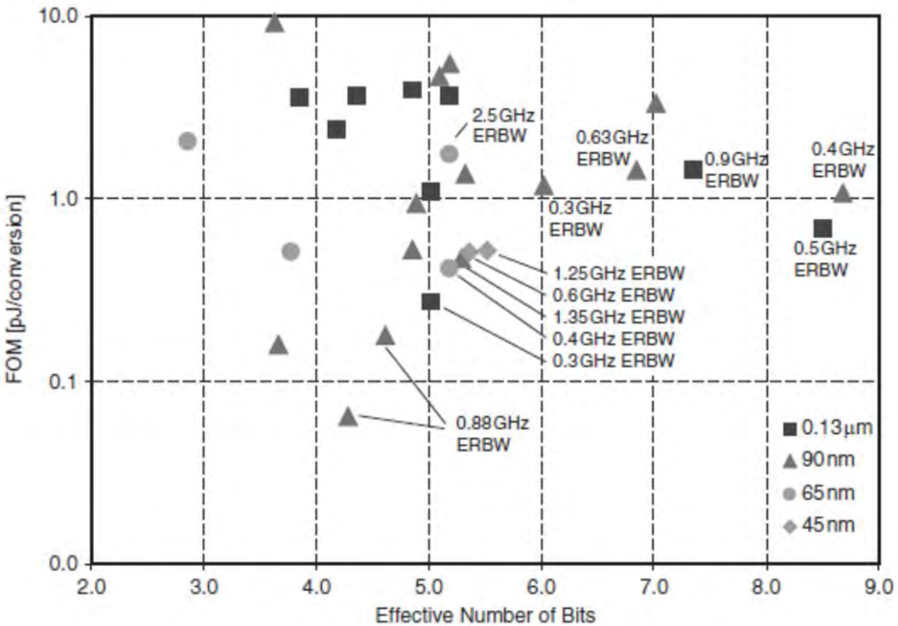


The transition from a 0.13 µm to a 90 nm process combined with innovations in ADC architecture and calibration algorithms, resulted in improved conversion efficiency versus ERBW.

The availability of a 65 nm technology enabled ADCs with higher sampling frequencies but so far has not demonstrated an increased efficiency for a given ERBW.

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals



The graphic compare conversion efficiency with respect to ENOB.
It can be observed that both 90 nm and 65 nm technologies offer an advantage with respect to 0.13 μm for ADCs with relatively low resolution but not for ENOB greater than 5.5 dB. These observations indicate that as technology scaling progresses, it is easier to achieve faster conversion speeds (due to higher f_T and f_{MAX}); nevertheless the associated reduction in voltage supply and increased device mismatch (detrimental to comparators and other ADC circuits) make it difficult to sustain the ENOB performance and/or to increase the overall conversion efficiency.

Semiconductor Technologies for 60GHz Radios

ADCs and DACs for Wide Bandwidth Signals

Technology	Design bits	Max. sample rate [Gs/s]	Measured SFDR at output frequency	Power [W]	Reference
0.25 µm BiCMOS	15	1.2	63 dB at 1.2 GHz	6	[54]
0.35 µm CMOS	10	1.0	61 at 490 MHz	0.11	[55]
0.18 µm CMOS	14	1.4	67 dB at 260 MHz	0.4	[56]
65 nm CMOS	12	2.9	60 at 550 MHz	0.19	[57]

The table list a small number of examples of high speed DACs

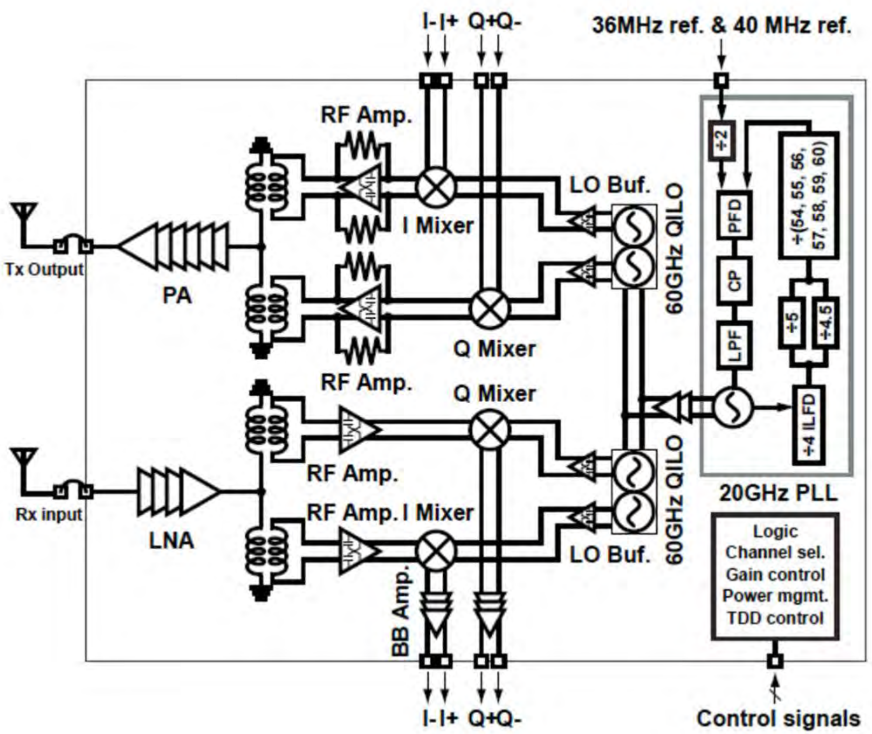
The required characteristics for a Gbps OFDM design in a 60 GHz system would be approximately 50 dB of spurious-free-dynamic range (SFDR, analogous performance metric to SNDR in ADCs) and a sample frequency greater than 2 GHz.

The DAC reported in [57] meets these specifications with a power consumption of 180 mW.

The performance trends of ADCs are expected to be similar in the case of DACs.

Semiconductor Technologies for 60GHz Radios

60 GHz CMOS Transciver



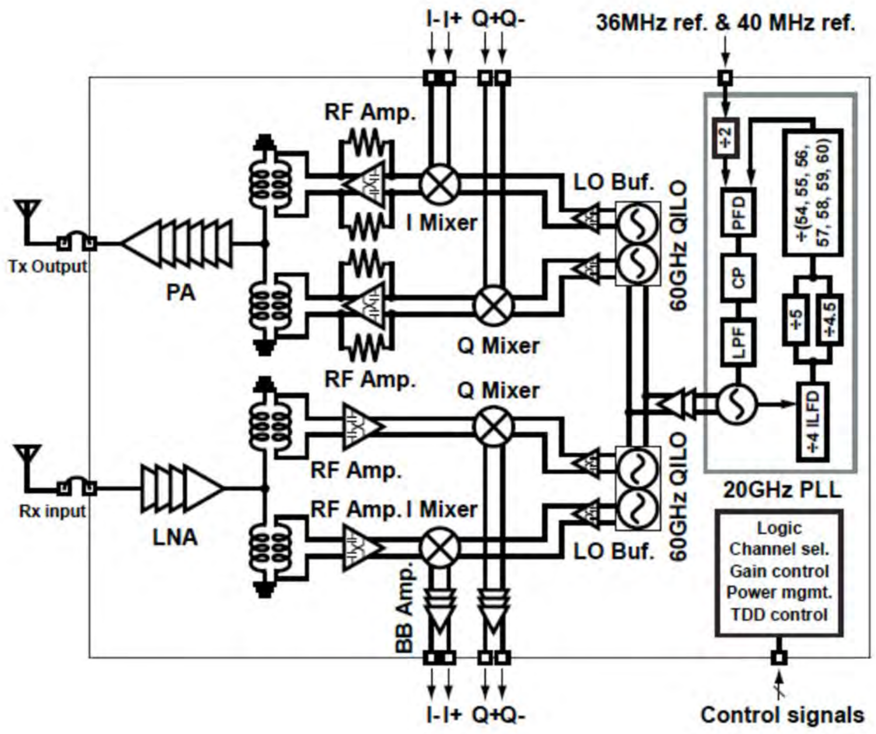
To realize 4-channel transceiver with high-order modulation like 64QAM, there are several challenges, such as:

- wideband gain characteristics,
- low local oscillator (LO) phase noise,
- fine and wideband I/Q mismatch calibration,
- small LO leakage

A direct-conversion architecture is widely used for the 60-GHz CMOS transceivers due to its low power consumption and wideband characteristic.

Semiconductor Technologies for 60GHz Radios

60 GHz CMOS Transciver



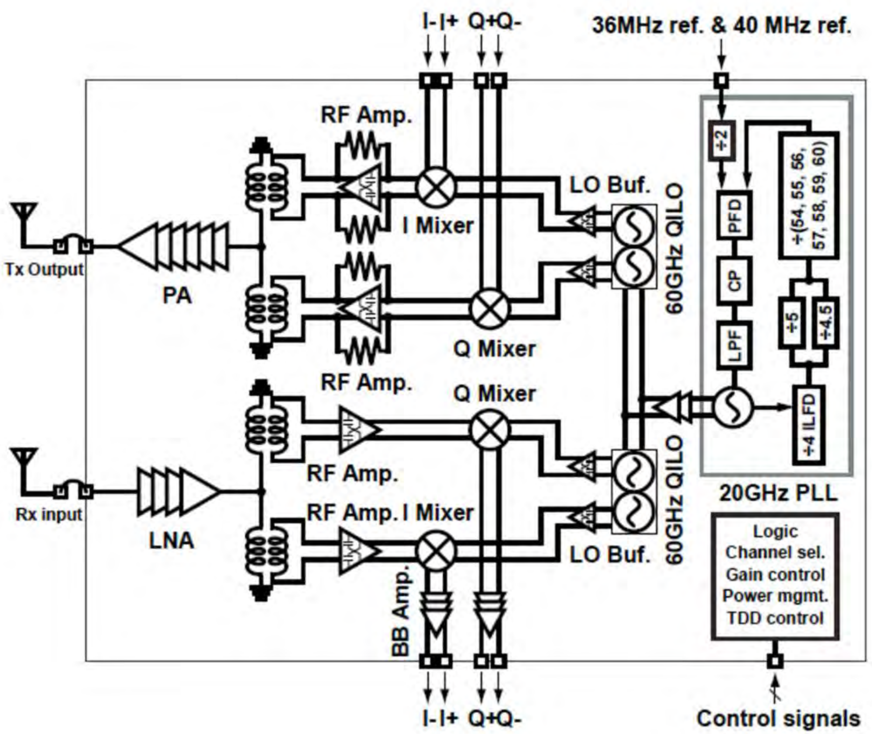
The Scheme shows the 60GHz direct-conversion front-end design.

The transmitter consists of a 6-stage PA, differential preamplifiers, I/Q passive mixers and a quadrature injection-locked oscillator (QILO).

The receiver consists of a 4-stage LNA, differential amplifiers, I/Q double-balanced mixers, a QILO, and baseband amplifiers.

Semiconductor Technologies for 60GHz Radios

60 GHz CMOS Transciver



The LO consists of the 60GHz QILO and a 20GHz PLL.

The 60GHz QILO works as a frequency tripler with the integrated 20GHz PLL.

It can generate 7 carrier frequencies with a 36MHz/40MHz reference:

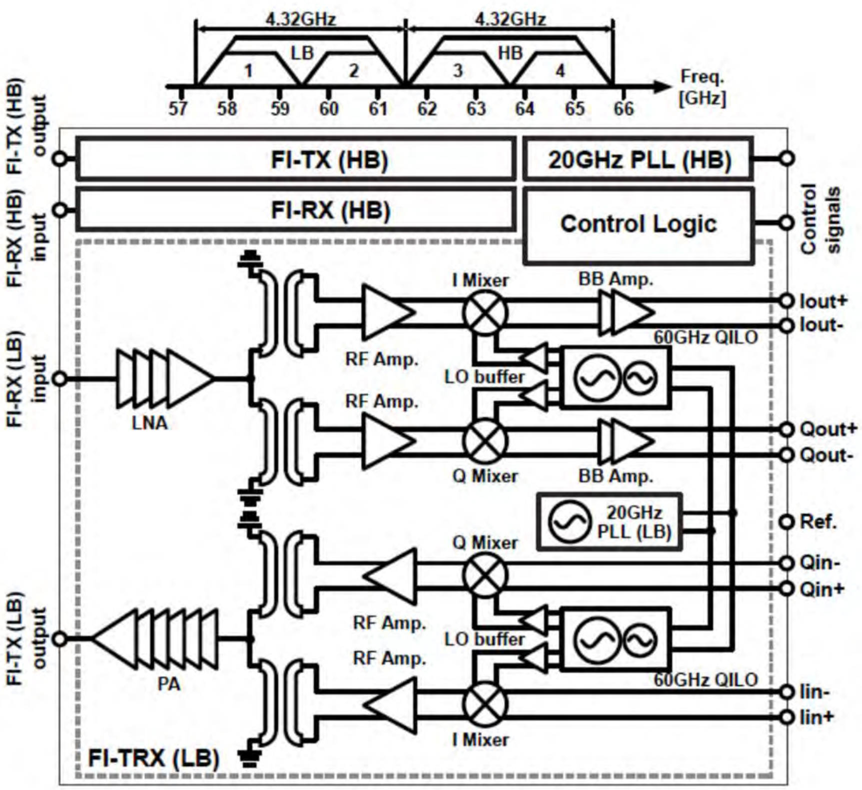
58.32GHz (ch.1),
60.48GHz (ch.2),
62.64GHz (ch.3),
64.80GHz(ch.4)

defined in IEEE802.11ad

-

Semiconductor Technologies for 60GHz Radios

60 GHz CMOS Transciver



The transceiver is composed of two direct-conversion FI transceivers. Each FI transceiver consists of an individual FI transmitter, FI receiver, and local oscillator.

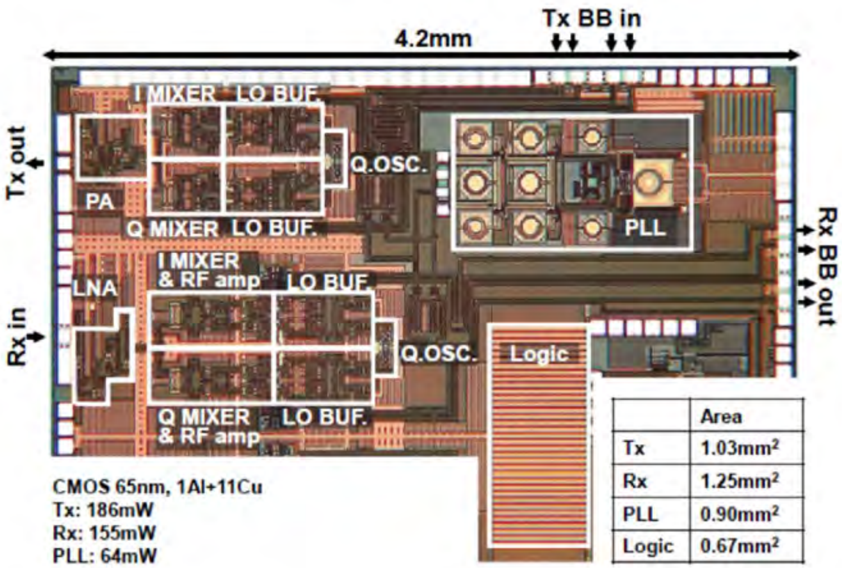
A control-logic block is integrated to manage the operation of both FI transceivers.

The two FI transceivers operate simultaneously within different frequency bands.

One of the TRX is working in the low band (LB, 57.24 GHz to 61.56 GHz), while the other one iband (LB, 57.24 GHz to 61.56 GHz), while the other one is working in the high band (HB, 61.56 GHz to 65.88 GHz).

Semiconductor Technologies for 60GHz Radios

60 GHz CMOS Transciver



60-GHz 1-stream transceiver.

Channel/ Carrier freq.	ch.1 58.32GHz	ch.2 60.48GHz	ch.3 62.64GHz	ch.4 64.80GHz	ch.1-ch.4 Channel bond
Modula-tion	64QAM				16QAM
Data rate*	10.56Gb/s	10.56Gb/s	10.56Gb/s	10.56Gb/s	28.16Gb/s
Constella-tion**					
Spec-trum**					
Tx EVM**	-27.1dB	-27.5dB	-28.0dB	-28.8dB	-20.0dB
Tx-to-Rx EVM***	-24.6dB	-23.9dB	-24.4dB	-26.3dB	-17.2dB

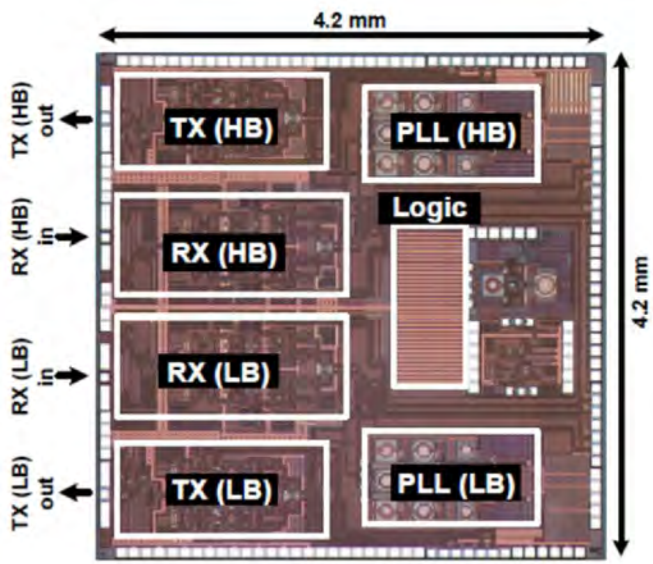
LO (20GHz PLL + 60GHz QILO)	
Frequency	58.32-64.80GHz (1.08GHz-step)
QILO range	58-66GHz
Phase noise @1MHz-offset	-95.3dBc/Hz (ch.1), -93.8dBc/Hz (ch.2), -92.1dBc/Hz (ch.3), -95.7dBc/Hz (ch.4) -96.5dBc/Hz (channel bond: 61.56GHz)

*The roll-off factor is 0.25. The bandwidth is 2.16GHz except for the channel bonding.
**Constellation, Spectrum, and Tx EVM are measured with an external down-converter.
***Tx-to-Rx EVM is measured through Tx and Rx, which is equal to –SNR(MER).

Measured constellation and performance summary of the 1-stream TRX front-end.

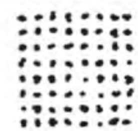
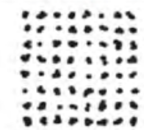
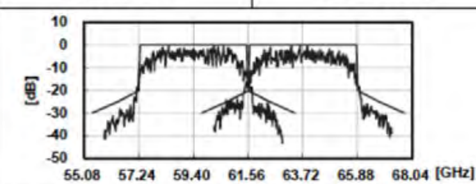
Semiconductor Technologies for 60GHz Radios

60 GHz CMOS Transciver



	2TX	2RX	2PLL	Logic
Area (mm^2)	2.03	2.56	1.93	0.66

60-GHz 2-stream transceiver.

Channel/ Carrier freq.	ch.1-2 (LB) 59.40GHz	ch.3-4 (HB) 63.72GHz
Modulation	64QAM	
Data rate*	21.12Gb/s	21.12Gb/s
Constellation**		
Spectrum**		
Back-off	6.0 dB	6.4 dB
TX EVM**	-27.6 dB	-27.2 dB
TX-to-RX EVM***	-24.1 dB	-23.0 dB

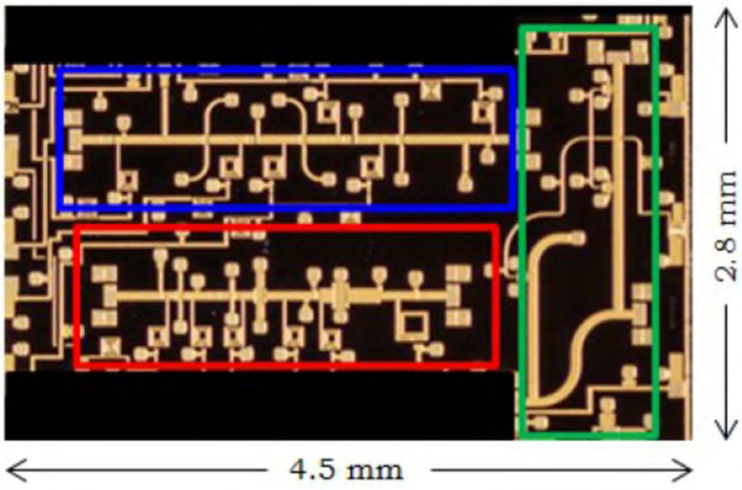
*The roll-off factor is 0.25. The bandwidth is 4.32GHz for the 2-channel bonding.
**Constellation, Spectrum, and TX EVM are measured with an external downconverter. The required TX EVMs is -26dB for 64QAM(MCS24).
***TX-to-RX EVM is measured through TX and RX, which is equal to –SNR(MER).

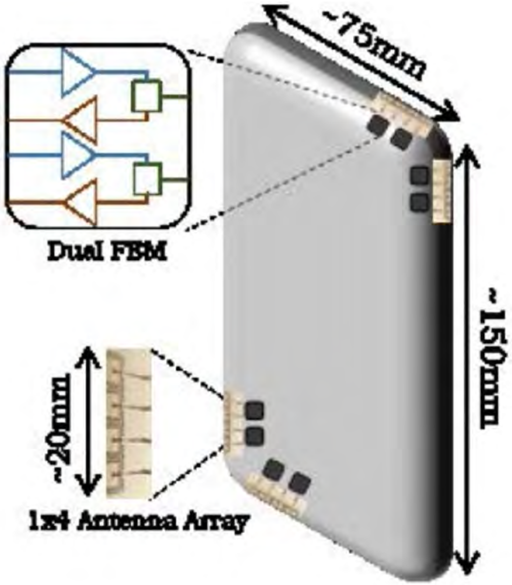
Measured constellation and performance summary of the 2-stream FI TRX front-end.

A FULLY INTEGRATED KA-BAND FRONT END FOR 5G TRANSCEIVER

The integrated front end includes a three stage power amplifier, three stage low noise amplifier, and single pole, double throw switch.

The integration of the front end is a crucial step to commercialize mm-Wave technology for 5G mobile communication.





DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER

5G application implement MIMO solutions or directly implement phased array antenna.

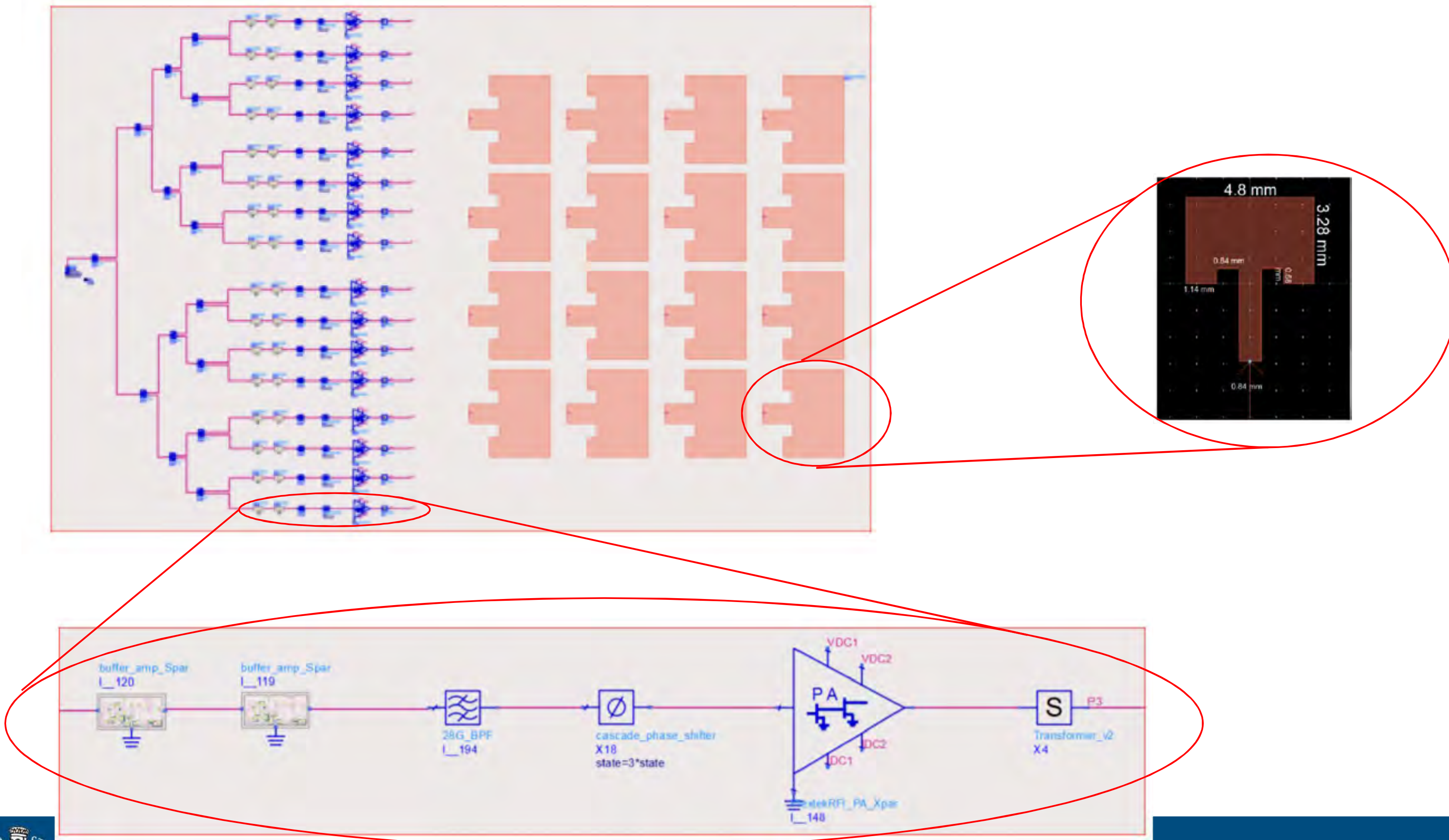
28GHz is one of the several candidate bands for the new 5G radio interface.

The design approach is based on integrating different type of simulation in order to foreseen the system behavior.

The approach involve

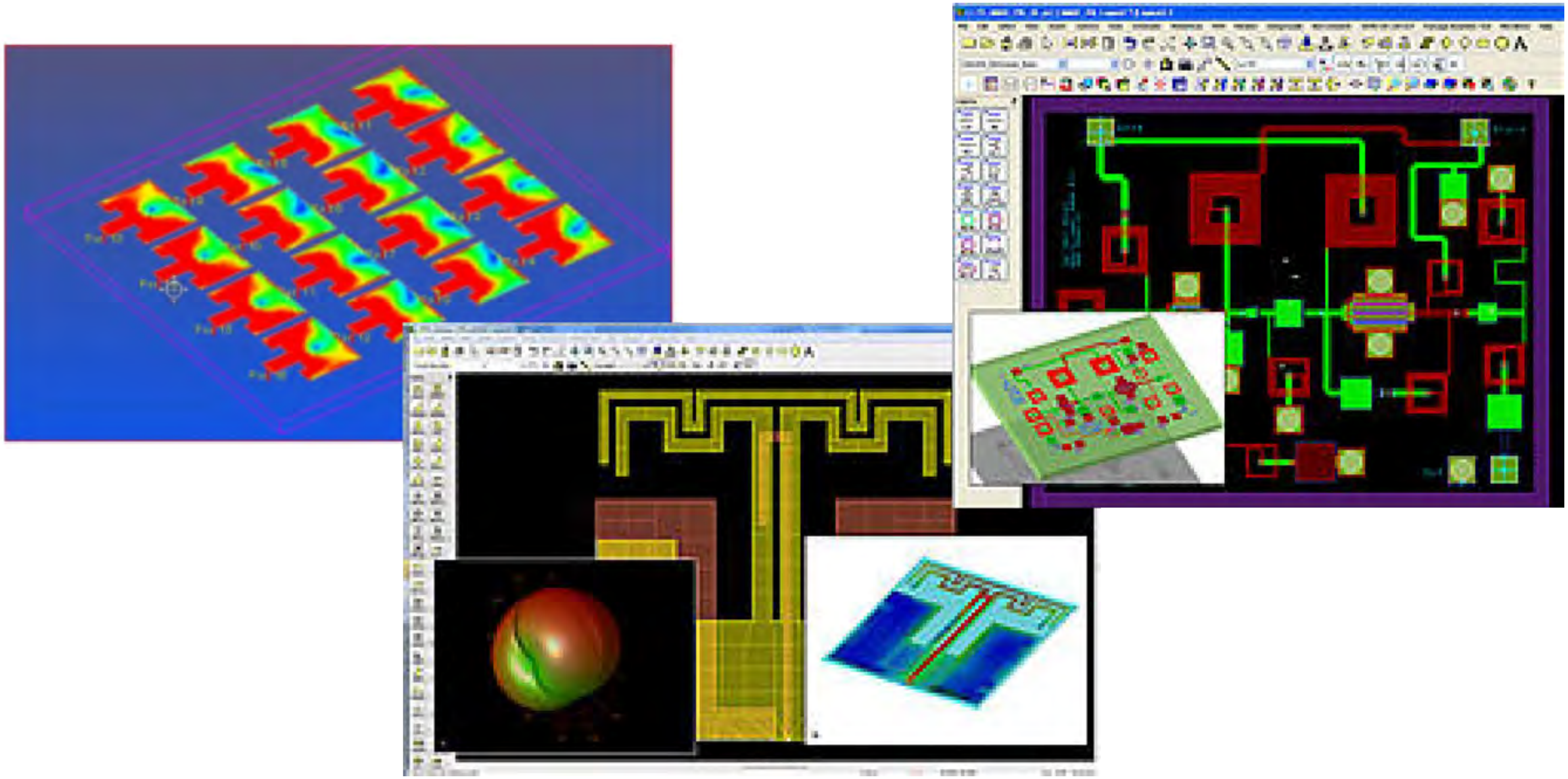
- EM simulation (for Antenna e passive components)
- S parameter modeling (for small Signal Amplifier)
- X parameter modeling for High Power Amplifier
- Harmonic Balance
- Cosimulation

DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER



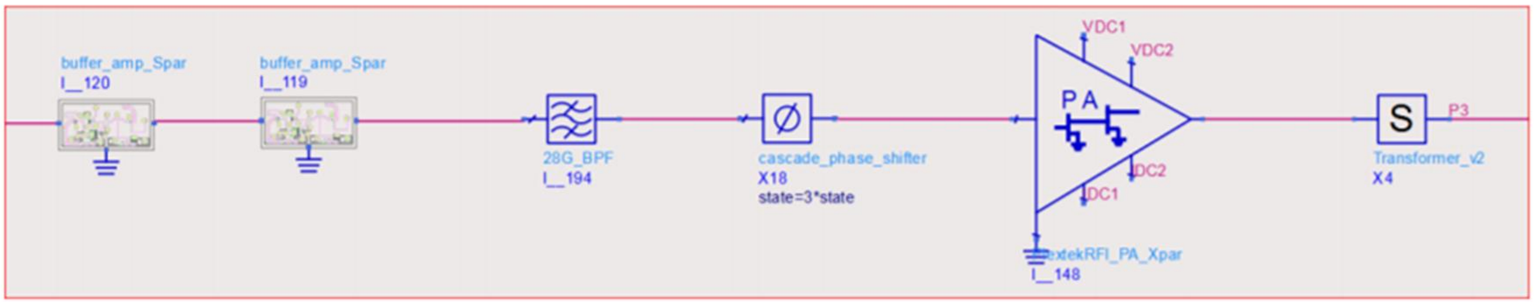
DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER

EM simulation (for Antenna e passive components)

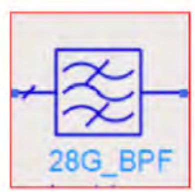


DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER

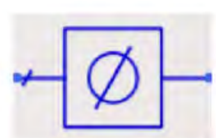
Transmit Chain



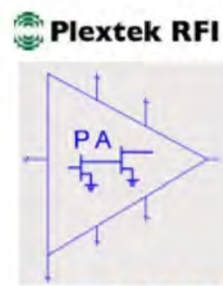
Plextek RFI Buffer Amp



28 GHz BPF

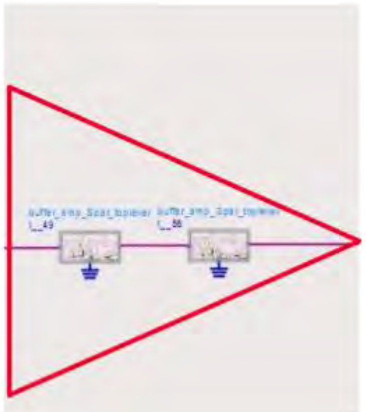


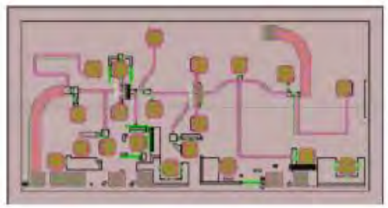
Phase Shifter



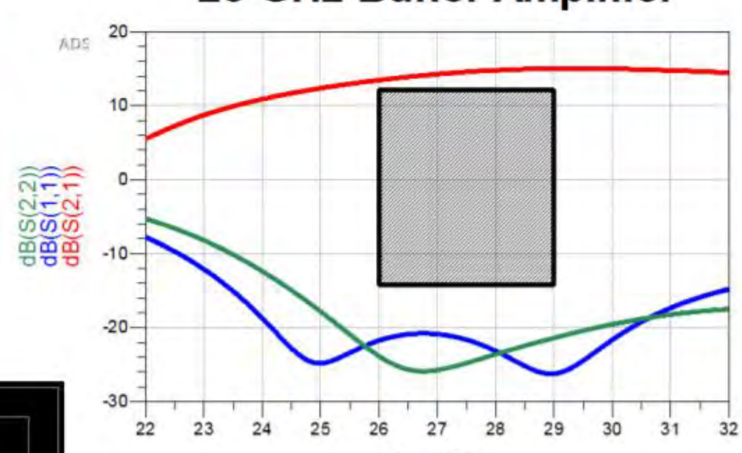
Plextek RFI PA

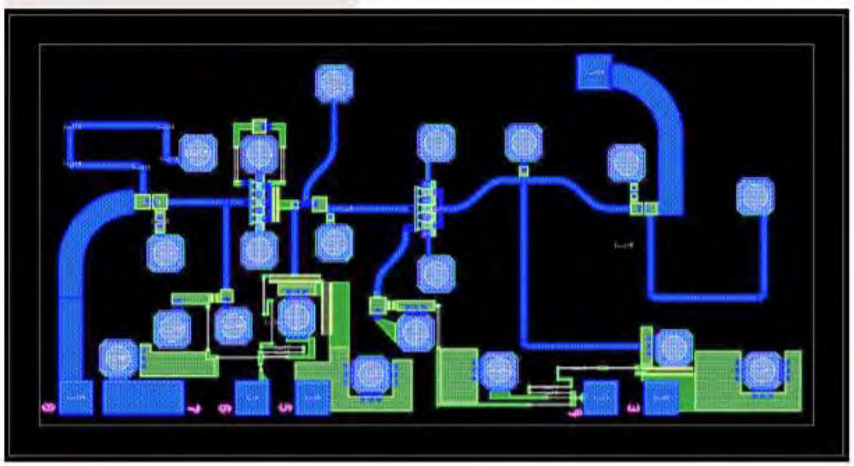
DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER





Plextek RFI



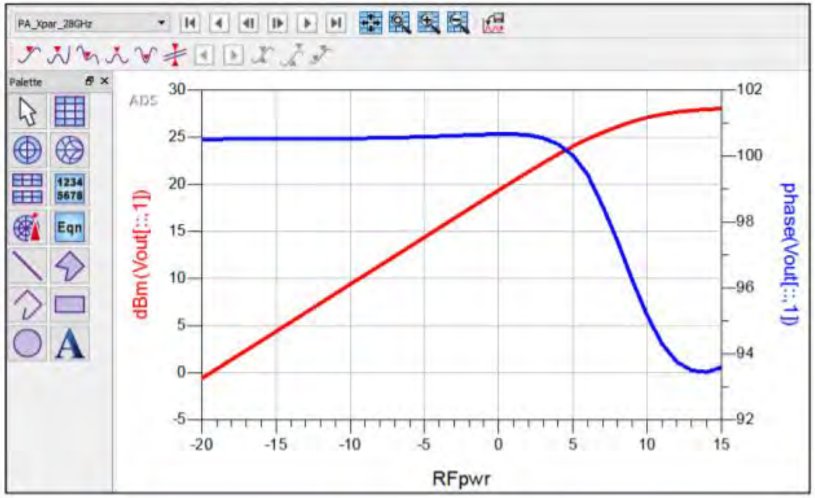


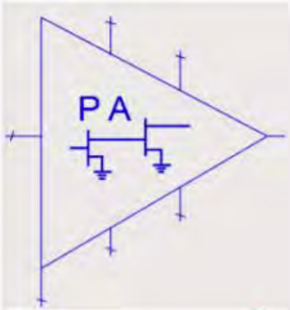
mm-Wave small signal Amp

Designed with:
TriQuint PHEMT process

DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER

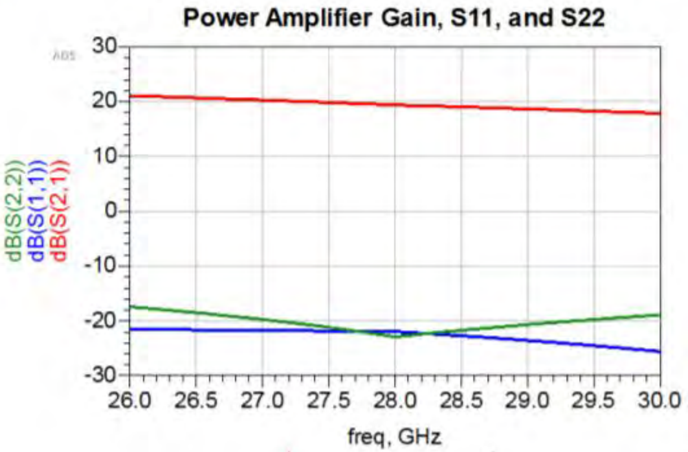
mm-Wave Power Amplifier





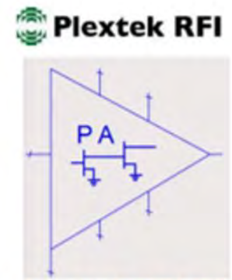
Plextek RFI PA
X-Parameter model

Plextek RFI



Designed with:
GCS InP_DHBT Process

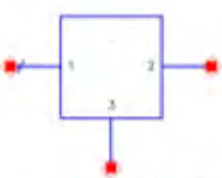
DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER



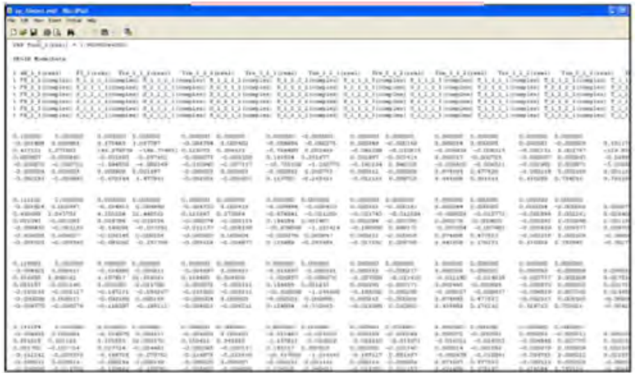
Plextek RFI PA

X-Parameters Power Amplifier Characterization

- Accurately captures all non-linearties
- Protects your IP
- Much faster simulation speed and trade-off analysis in hierarchical system design and verification.
- Accurate load pull modeling capability

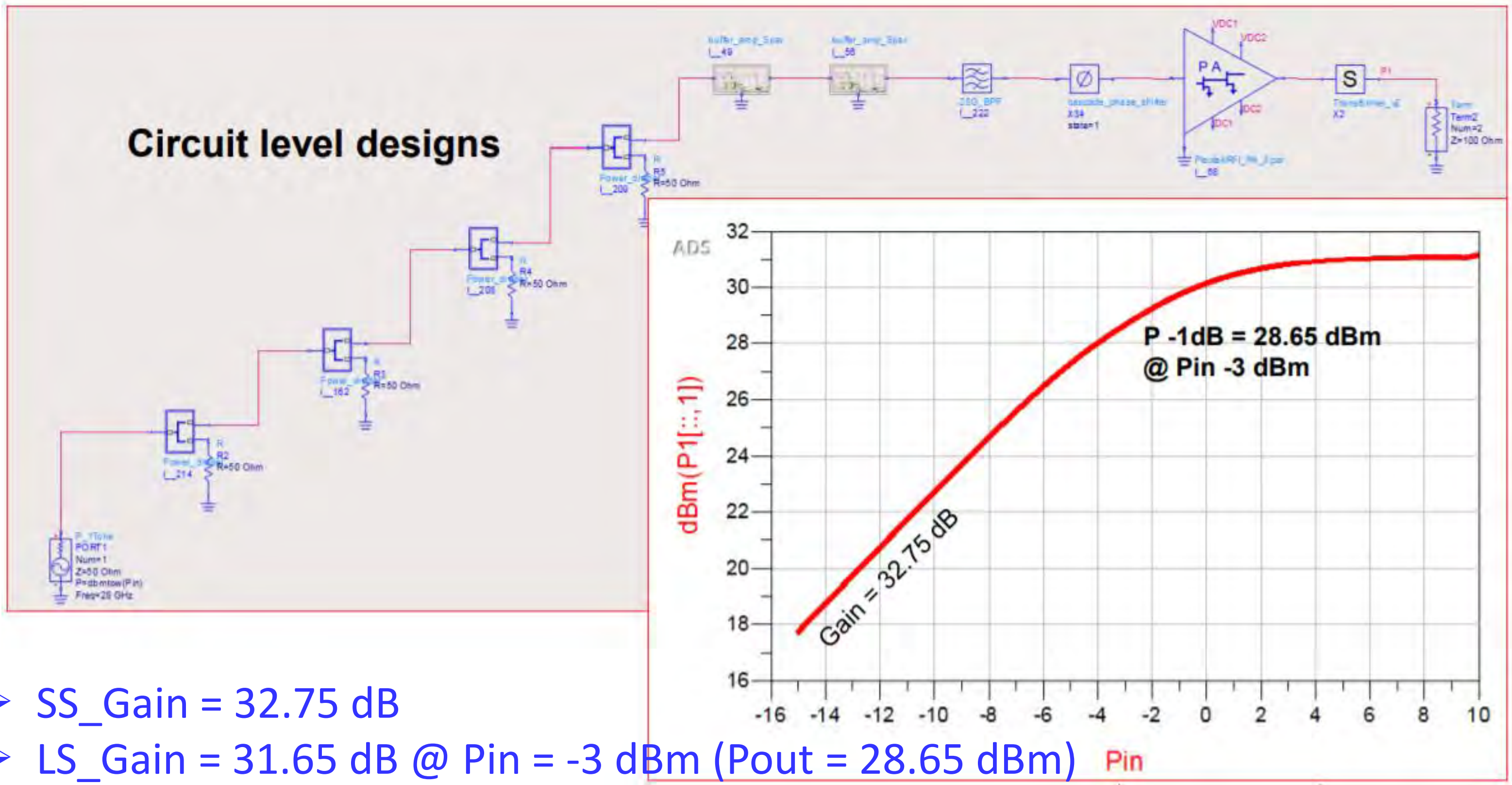


xp_filetest
xp_filetest_1
fundamental_1=_freq1



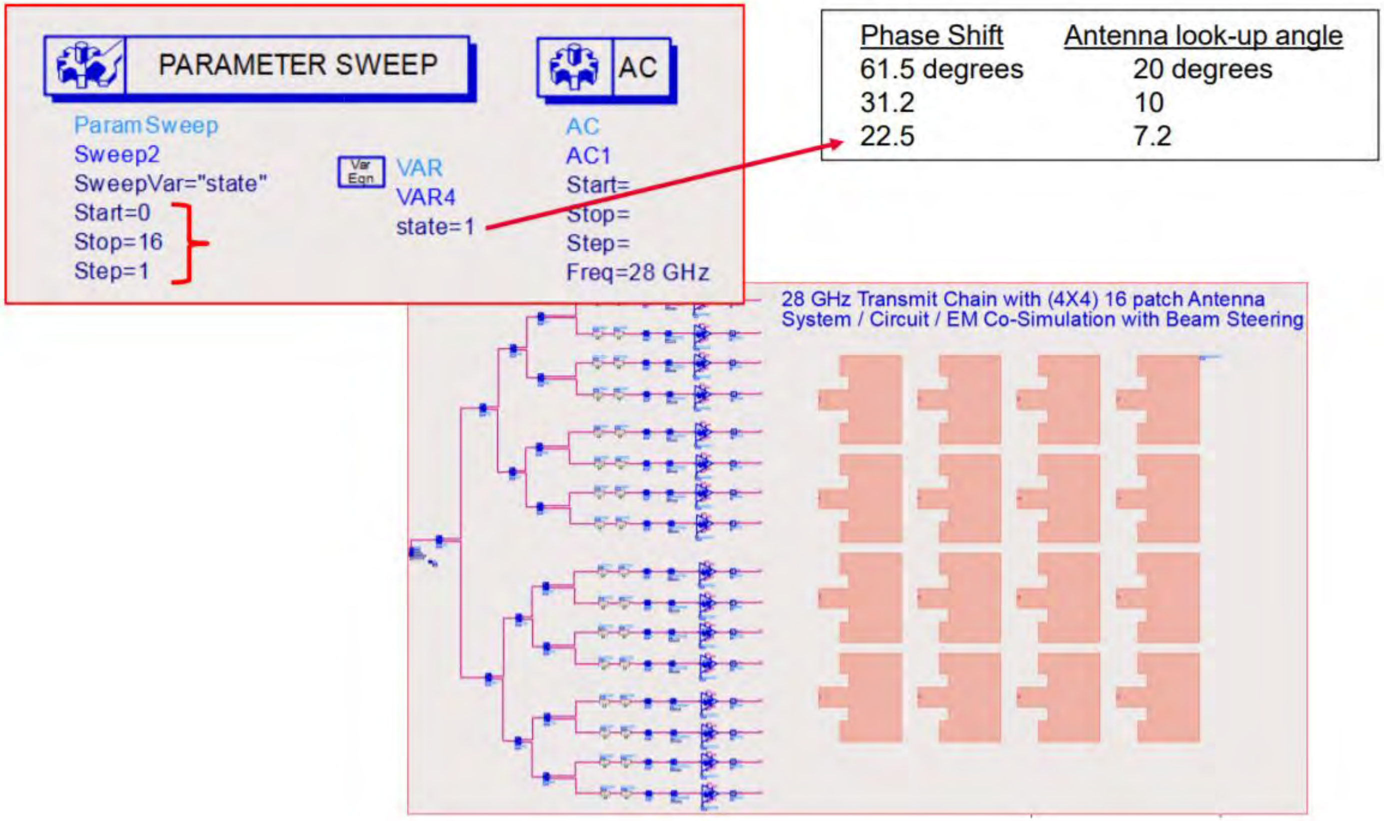
DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER

HB Simulation



- SS_Gain = 32.75 dB
- LS_Gain = 31.65 dB @ Pin = -3 dBm (Pout = 28.65 dBm)
- LS_Gain = 29.44 dB @ Pin = 1 dBm (Pout = 30.44 dBm

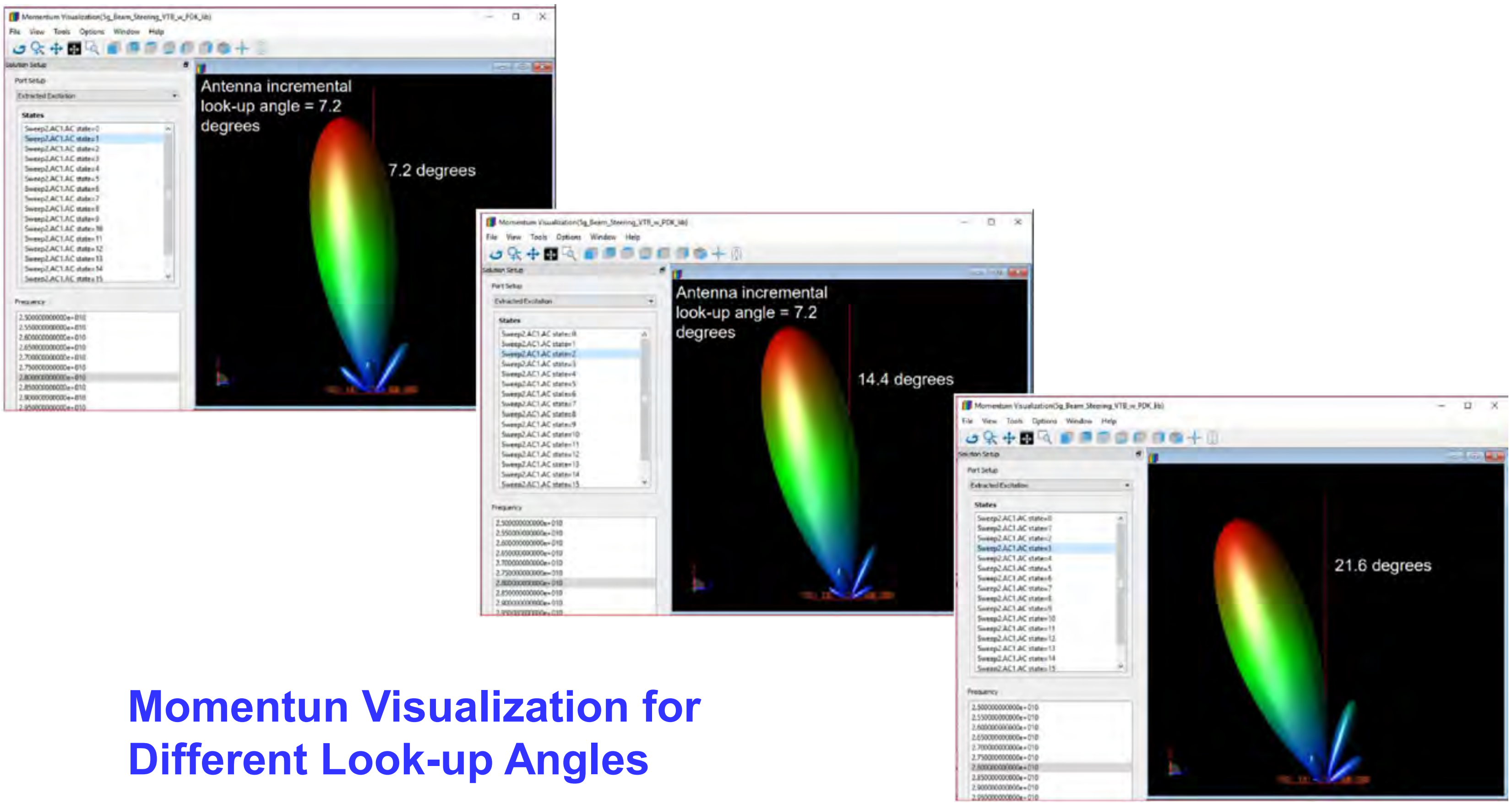
DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER



Phase Shift	Antenna look-up angle
61.5 degrees	20 degrees
31.2	10
22.5	7.2

Sweeping the Phase Shifter for Different Look-up Angles

DESIGN AND SIMULATION OF 5G 28-GHZ PHASED ARRAY TRANSCEIVER

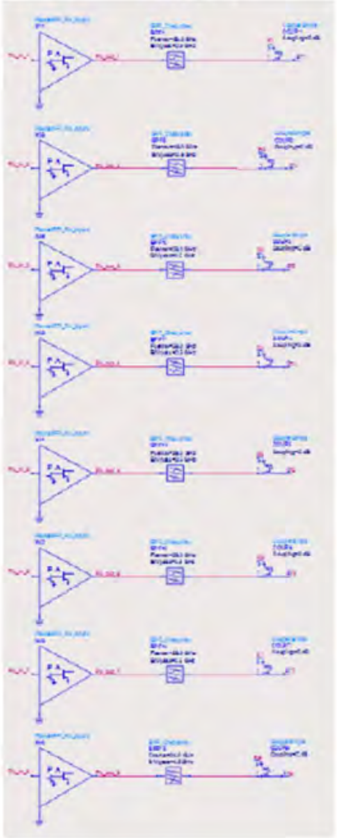


Momentun Visualization for Different Look-up Angles

5G 28 GHz TRANSCEIVER TRANSMITTER CHAIN

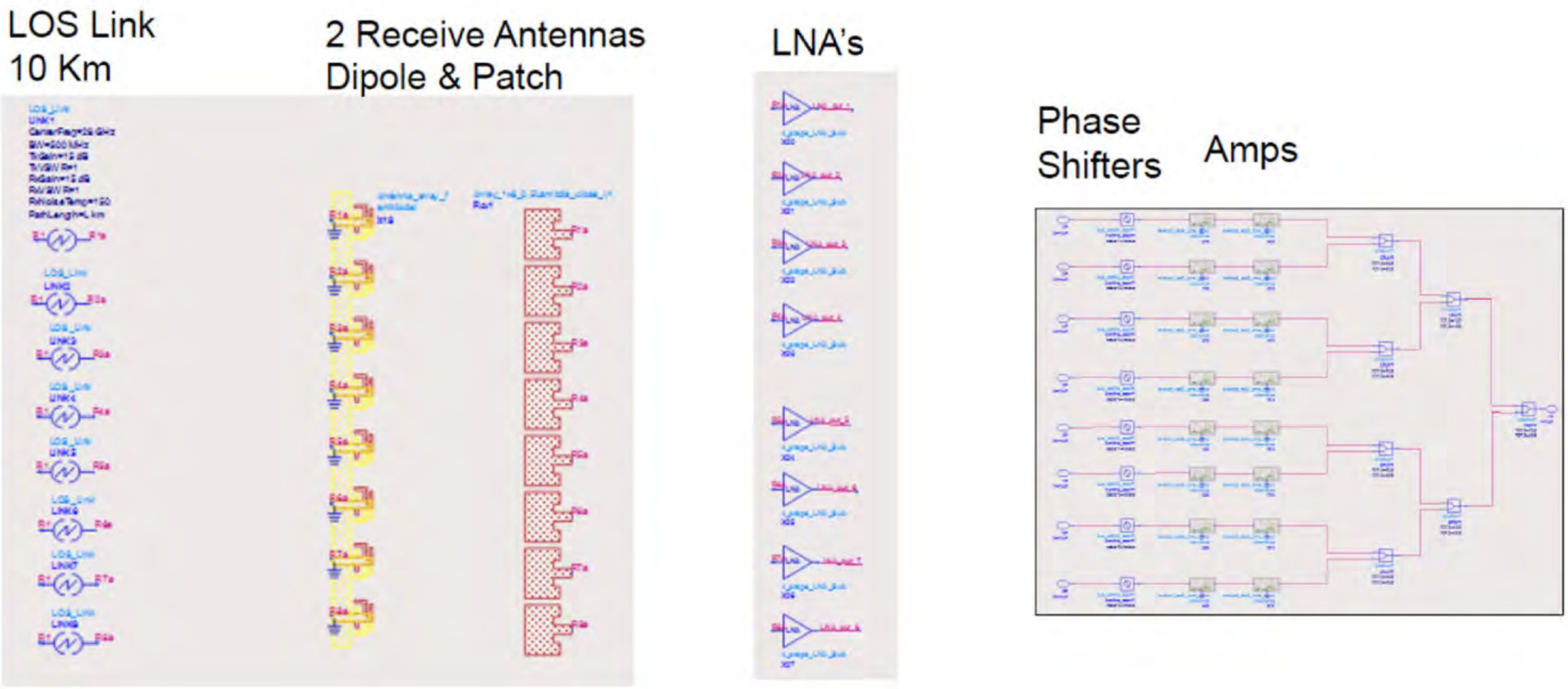
Amps Phase Shifters

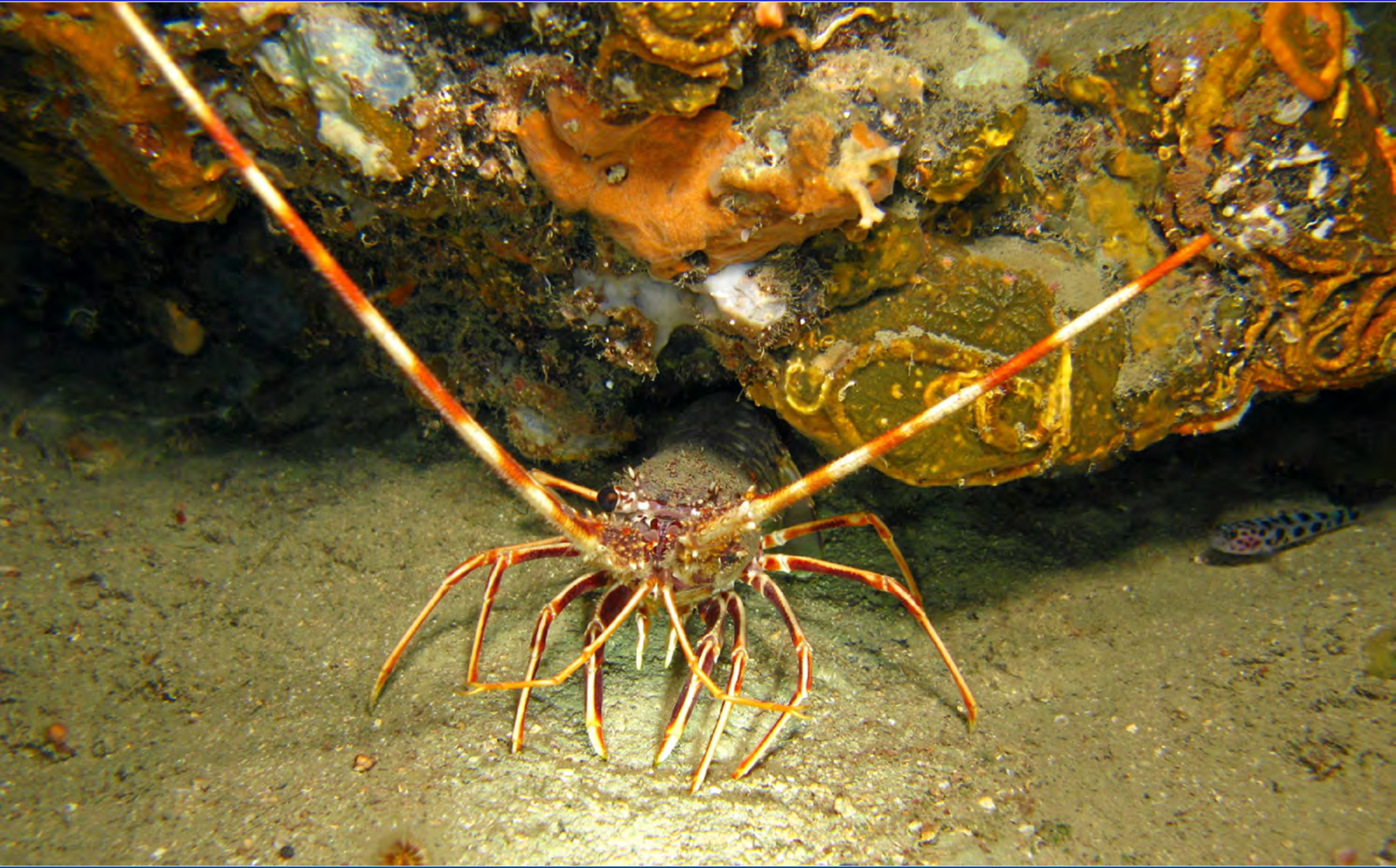
PA's Filters



Transmit Patch Antenna LOS Link: 10 Km

5G 28 GHz TRANSCEIVER RECEIVER CHAIN





Antenna problem(s)

OK, so you are wandering in the 60GHz Paradise 5G promised you, where data rate is measured in tens of Gb/s and anyone is connected with everything…

Antenna problem(s)

…yet customers are generally unsatisfacetd by wires

Antenna problem(s)

The problem is to deliver the signal… you might remember Friis formula

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

60GHz → λ = 5mm = 5×10^{-3} m

AT ONE METER

$P_r = 1.6 \times 10^{-7} G_t G_r P_t$

Forget of “dumb” antennas

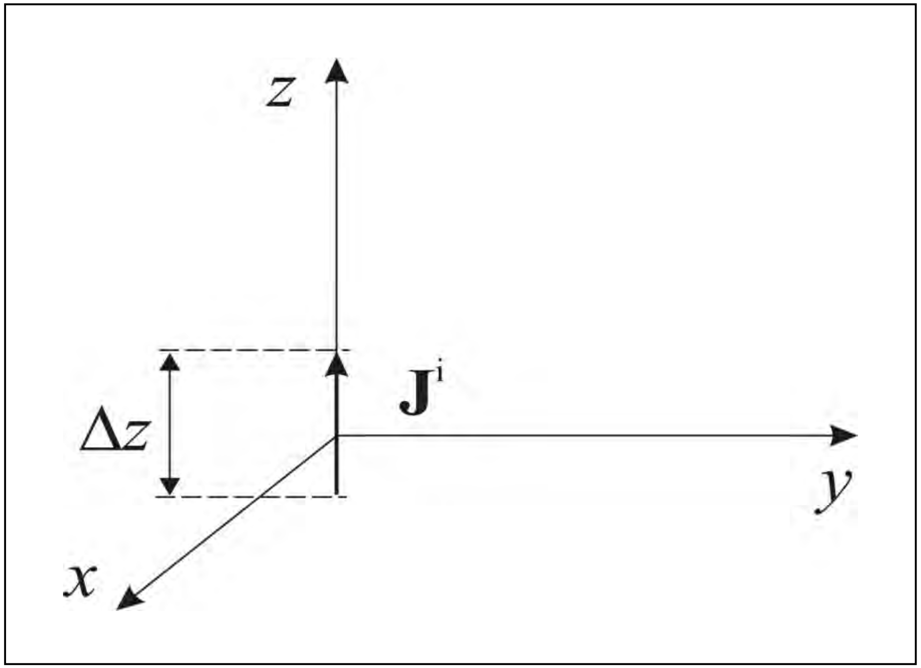
A few things you should already know

The basic brick to understand antennas is the elementary electric dipole

$$\mathbf{J}^{i} = I(z)\delta(x)\delta(y)\hat{z}$$

$$I(z) = \begin{cases} I & z \in \left[-\frac{\Delta z}{2}, \frac{\Delta z}{2}\right] \\ 0 & \text{elsewhere} \end{cases}$$

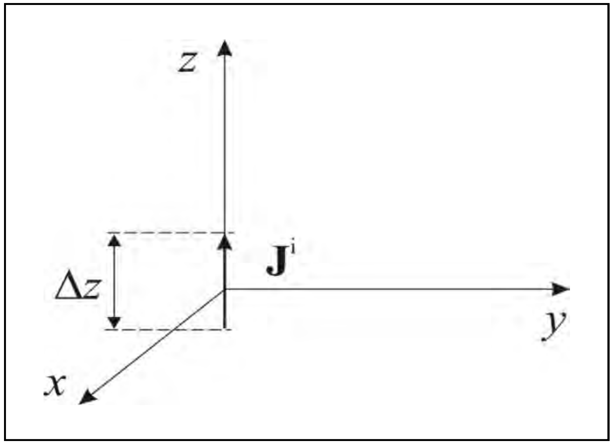
$$\Delta z << \lambda$$



A few things you should already know

$$\mathbf{E} = E_r\,\hat{r} + E_\vartheta\,\hat{\vartheta} + E_\varphi\,\hat{\varphi}$$

$$\mathbf{H} = H_r\,\hat{r} + H_\vartheta\,\hat{\vartheta} + H_\varphi\,\hat{\varphi}$$



$$\begin{cases} E_r = \zeta \dfrac{I\,\Delta z}{2\pi}\left(\dfrac{1}{r^2} + \dfrac{1}{jkr^3}\right)\cos\vartheta\, e^{-jkr} \\ E_\vartheta = \zeta \dfrac{I\,\Delta z}{4\pi}\left(\dfrac{jk}{r} + \dfrac{1}{r^2} + \dfrac{1}{jkr^3}\right)\sin\vartheta\, e^{-jkr} \\ E_\varphi = 0 \end{cases}$$

$$\begin{cases} H_r = 0 \\ H_\vartheta = 0 \\ H_\varphi = \dfrac{I\,\Delta z}{4\pi}\left(\dfrac{jk}{r} + \dfrac{1}{r^2}\right)\sin\vartheta \exp e^{-jkr} \end{cases}$$

$\zeta = \sqrt{\dfrac{\mu}{\varepsilon}}$ free space characteristic impedance

$\dfrac{1}{r^2}, \dfrac{1}{r^3} \rightarrow$ near, reactive, fields (neglectable as $r >> \lambda$)

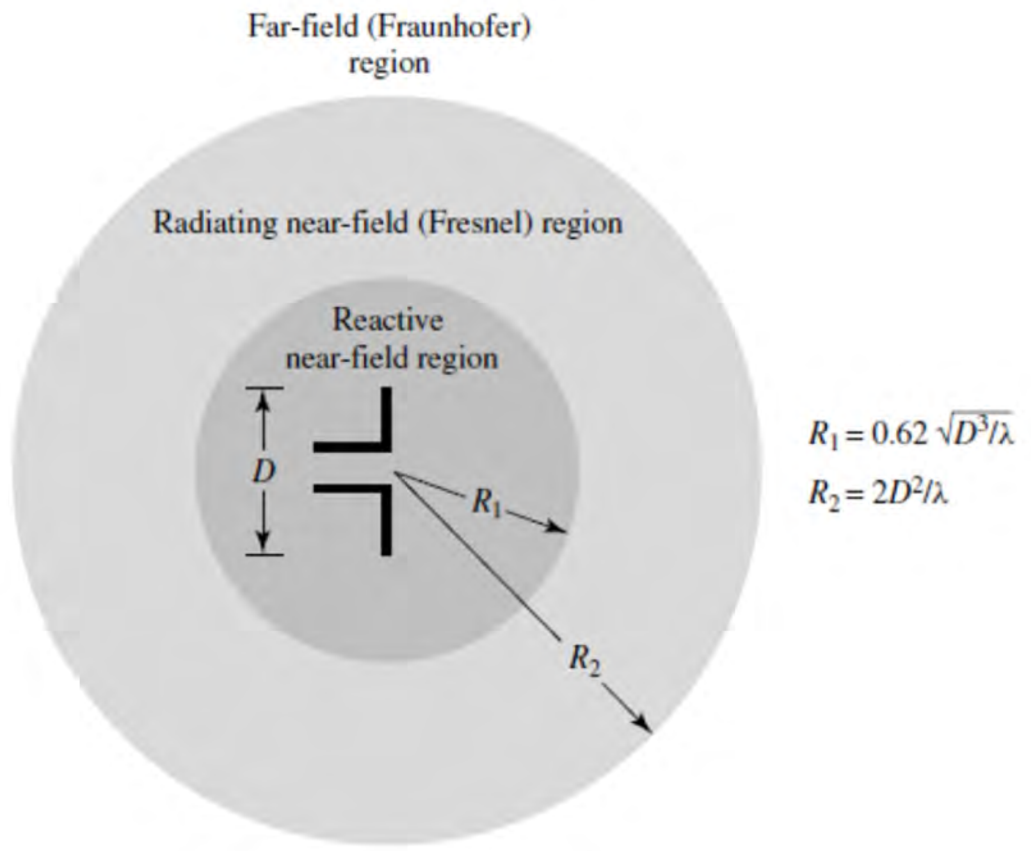
$\dfrac{1}{r} \rightarrow$ far, radiated, field

A few things you should already know

Far field expressions

$$E_\vartheta \approx j\zeta\, k \frac{I\,\Delta z}{4\pi r} \sin\vartheta\, e^{-jkr}$$

$$H_\varphi \approx \frac{E_\vartheta}{\zeta}$$



A few things you should already know

We define radiation intensity

$$U = \left|S\right| r^2 = \frac{1}{2}\frac{\left|\mathbf{E}\right|^2}{\zeta} r^2 \xrightarrow{\text{for a DEC}} \frac{1}{2} k^2 \zeta \frac{|I|^2 \Delta z^2}{(4\pi)^2} \sin^2 \vartheta$$

In this context the radiated power is

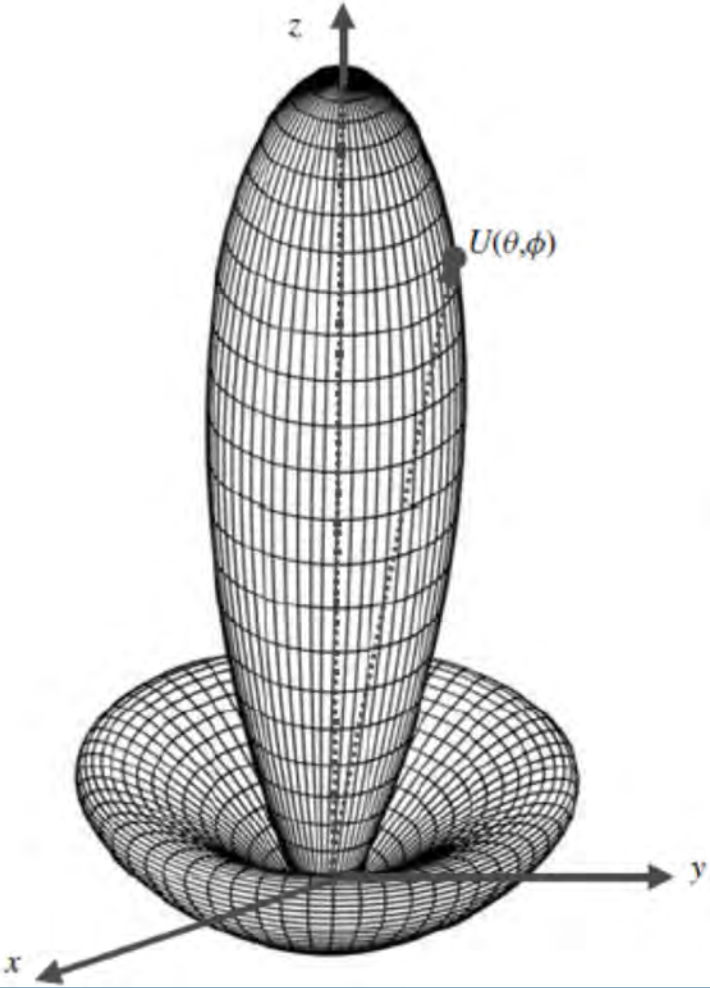
$$P_r = \iint_S U d\Omega \xrightarrow{\text{for a DEC}} \frac{1}{2} k^2 \zeta \frac{|I|^2 \Delta z^2}{(4\pi)^2} \int_0^{\pi} \int_0^{2\pi} \sin^2 \vartheta \sin\vartheta d\vartheta d\phi$$

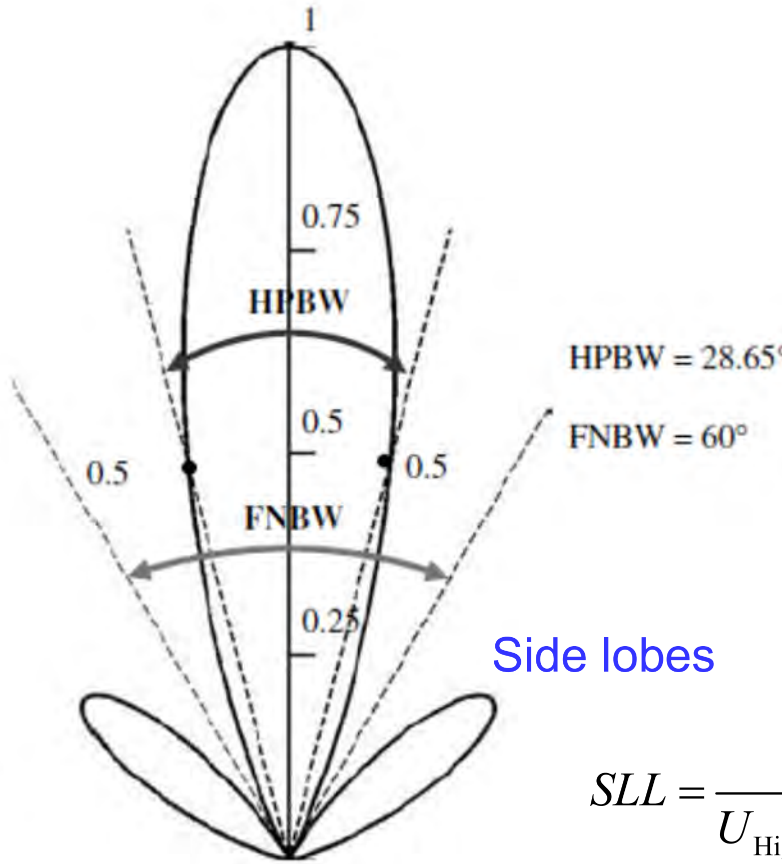
And we define an isotropic source as a source with

$$U(\vartheta,\phi) = U_0 = \frac{P_r}{4\pi}$$

A few things you should already know

For a generic antenna 3D representation of U is of great importance, as well as its cuts





Side lobes

$$SLL = \frac{U_M}{U_{\text{Higher side lobe}}}$$

A few things you should already know

IEEE Standard Definitions of Terms for Antennas: Directivity

"the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation intensity is implied."

$$D = \frac{U}{U_0} = \frac{U}{\frac{P_r}{4\pi}} = \frac{4\pi U}{P_r}$$

For an ISOTROPIC source it is plainly obvious that

$$D = 1$$

A few things you should already know

IEEE Standard Definitions of Terms for Antennas: Side Lobe

“A side lobe is “a radiation lobe in any direction other than the intended lobe.” (Usually a side lobe is adjacent to the main lobe and occupies the hemisphere in the direction of the mainbeam.) A back lobe is “a radiation lobe whose axis makes an angle of approximately 180◦ with respect to the beam of an antenna.” Usually it refers to a minor lobe that occupies the hemisphere in a direction opposite to that of the major (main) lobe.

Minor lobes usually represent radiation in undesired directions, and they should be minimized. Side lobes are normally the largest of the minor lobes. The level of minor lobes is usually expressed as a ratio of the power density in the lobe in question to that of the major lobe. This ratio is often termed the side lobe ratio or side lobe level.

A few things you should already know

IEEE Standard Definitions of Terms for Antennas: Gain

"the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π."

$$G = \frac{U}{\frac{P_a}{4\pi}} = \frac{4\pi U}{P_a}$$

Since the ratio between the input power and the radiated power is the antenna efficiency, it is:

$$G = \eta D$$

A few things you should already know

IEEE Standard Definitions of Terms for Antennas: Absolute (or Realized) Gain

"the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power provided by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π."

$$G_{abs} = \frac{U}{\frac{P_{in}}{4\pi}} = \frac{4\pi U}{P_{in}}$$

Since the accepted power is the incideent power minus the reflected power it is:

$$P_a = (1 - |\Gamma|^2) P_{in}$$

$$G_{abs} = (1 - |\Gamma|^2) G = \eta (1 - |\Gamma|^2) D$$

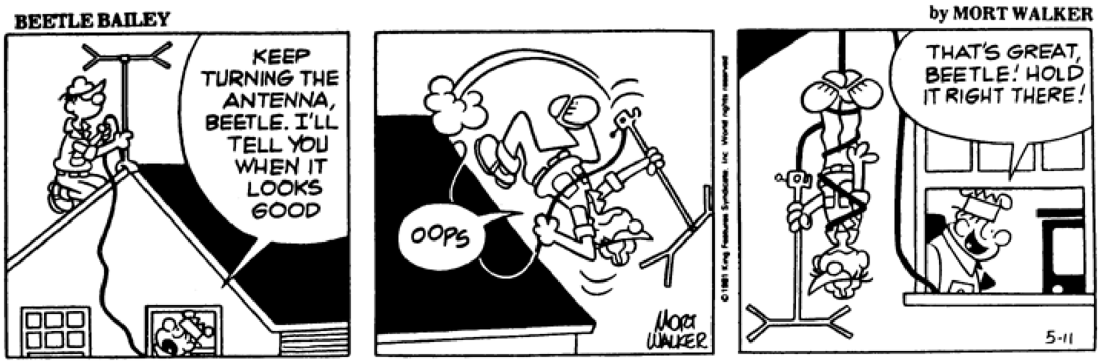
Antenna problem(s)

So we need high *gain* to have the link

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

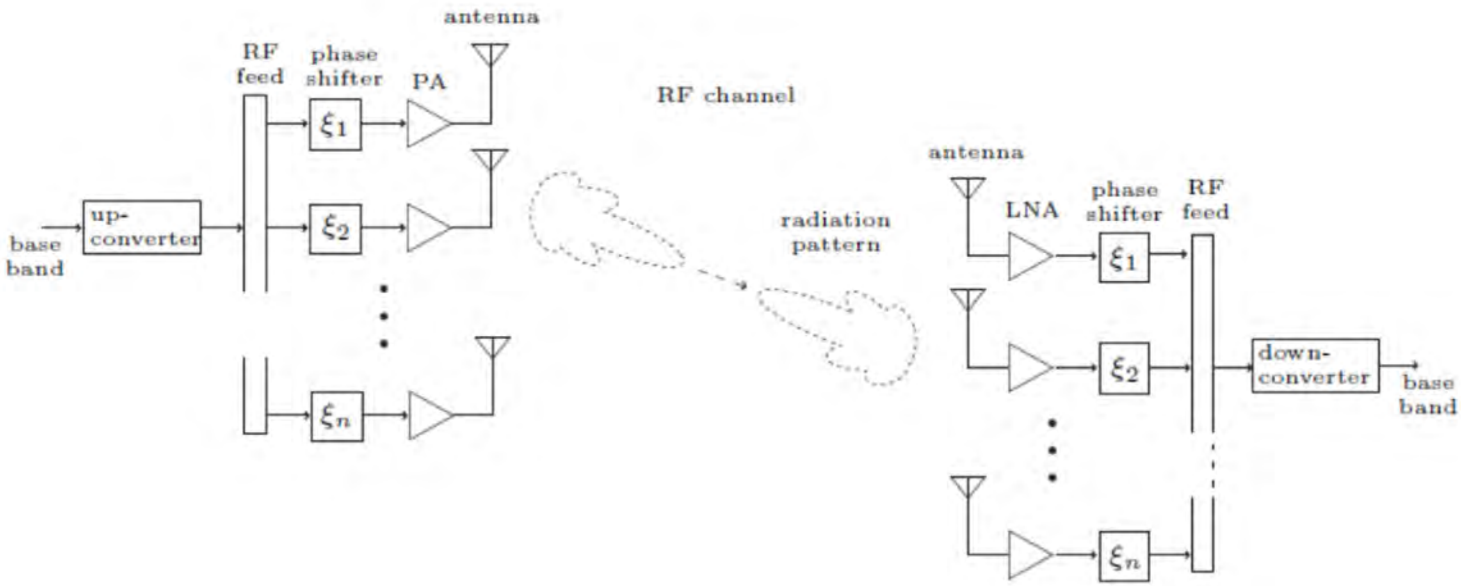
High GAIN means High DIRECTIVITY which means narrow MAIN LOBE…

… which means you have to precisely point the antennas



Antenna problem(s)

In a grandma-enabled environment it is the device who should, elettronically, take care of pointing the radiation diagram.



Antenna problem(s)

That's why we need SMART arrays, where elements are each backed by an amplifier and a phase shifter, the latter, at least, electronically controlled, if the former too much better.

Doing this at 60GHz is way challenging.

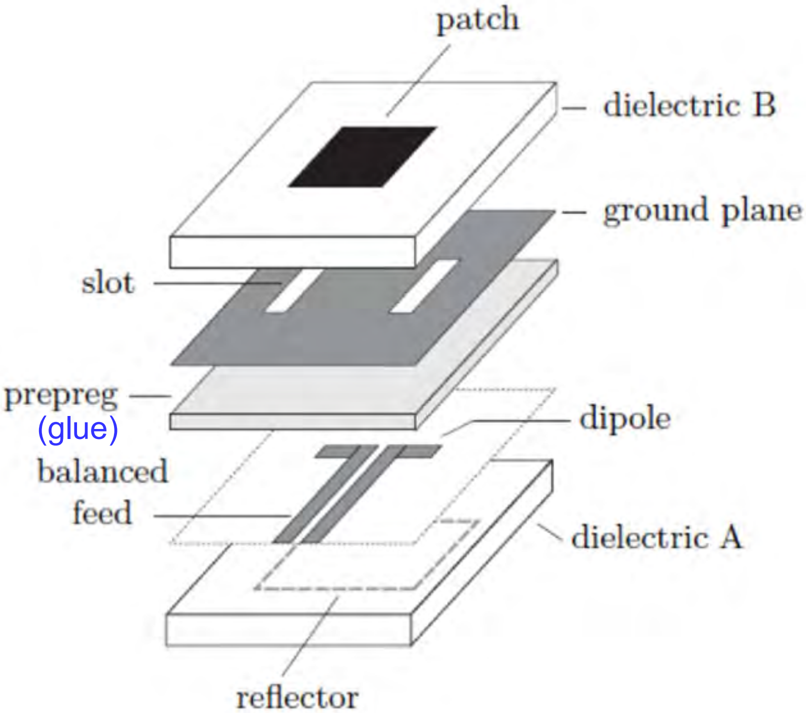
Let's start from the single element.

I will present few elements proposed quite recently in open literatuture,in printed technology

60GHz Radiating Elements

- Element should work at 60GHz with a 5GHz band
- Losses should be minimized
- Element should be small enough to allow its integration in an array
- Steerable
- Planar printed technology would permit immediate integration with the electronics

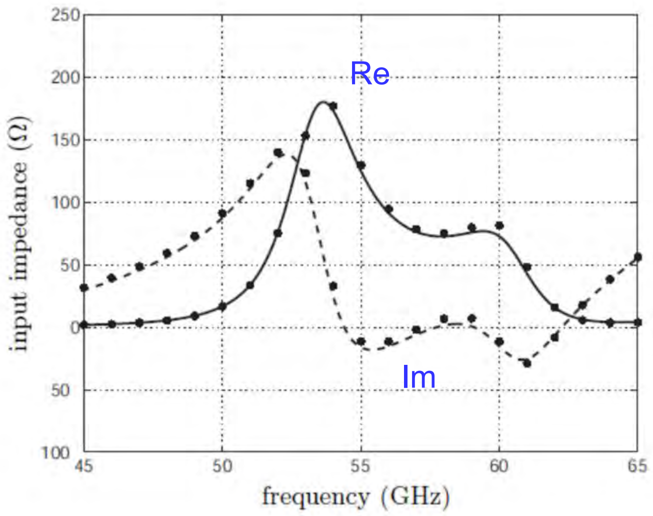
60GHz Radiating Elements

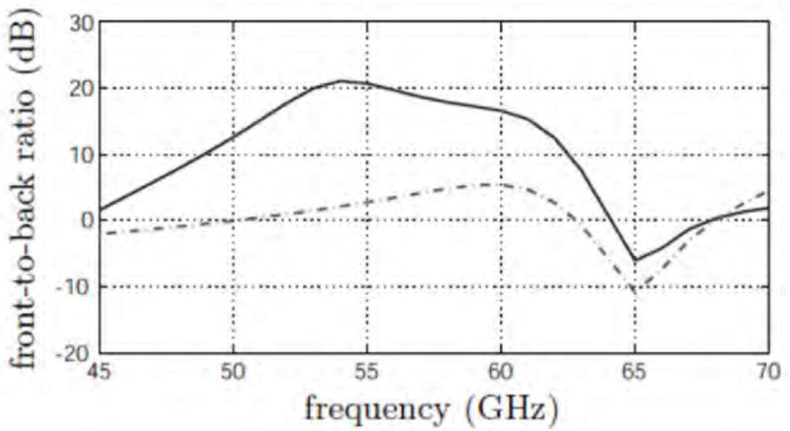


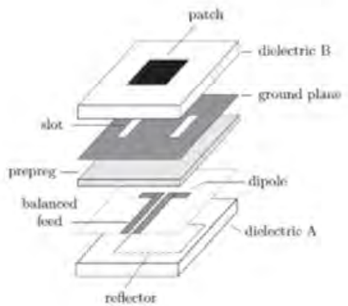
Element	Parameter	Value
dielectric A,B	ε_r	2.17
	thickness	0.25 mm
prepreg	ε_r	2.60
	thickness	0.11 mm
patch	length l	1.47 mm
	width w	1.45 mm
slots	length l	1.58 mm
	width w	0.23 mm
	spacing s	2.00 mm
reflector	length l	2.50 mm
	width w	1.80 mm
dipole	lenght l	2.31 mm
	width w	0.30 mm

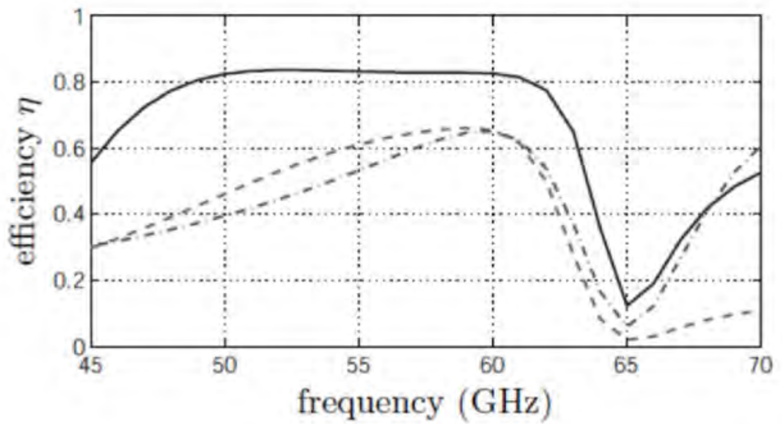
J.A.G. Akkermans, “Planar beam-forming antenna array for 60GHz broadband communication,” Ph.D. Thesis, Technishe Universiteit, Eindoven 2009

60GHz Radiating Elements

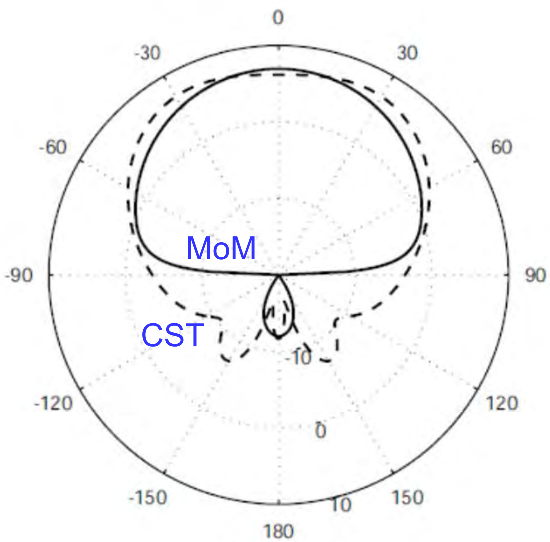




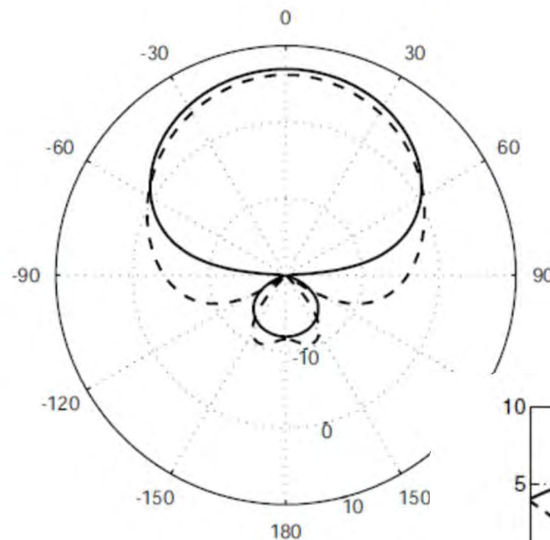




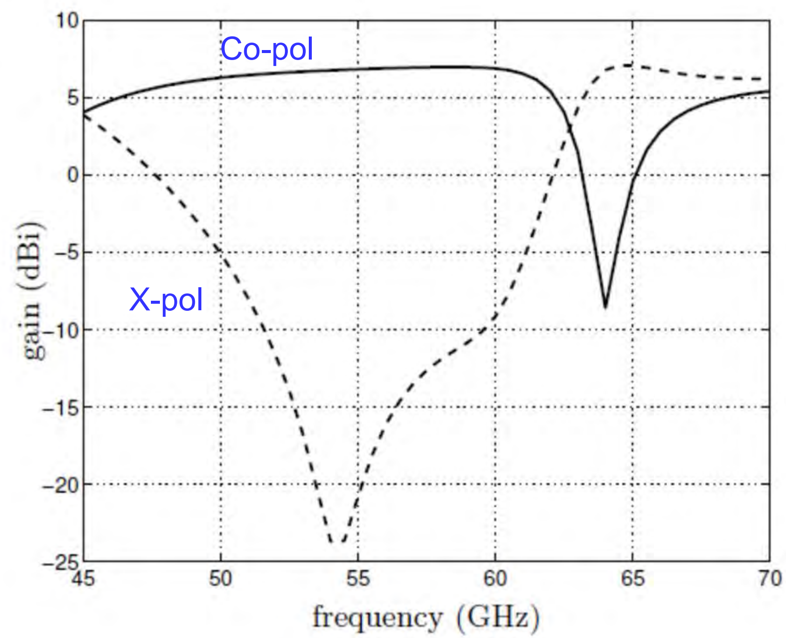
60GHz Radiating Elements



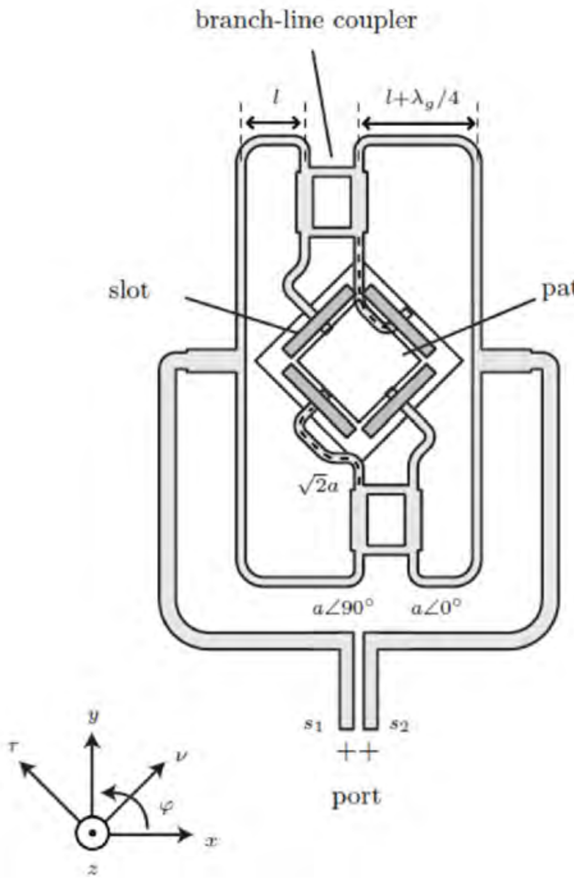
(a) E-plane

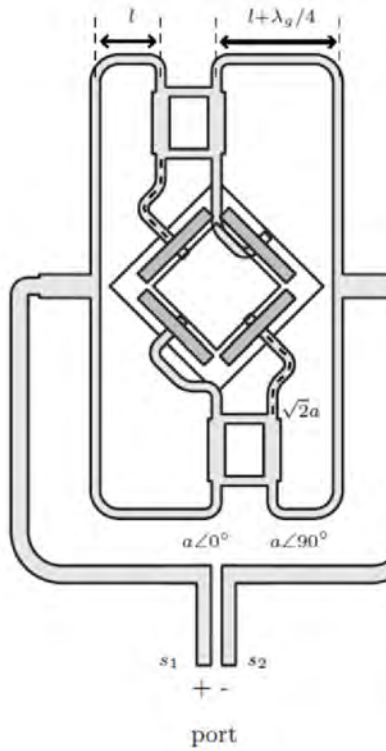


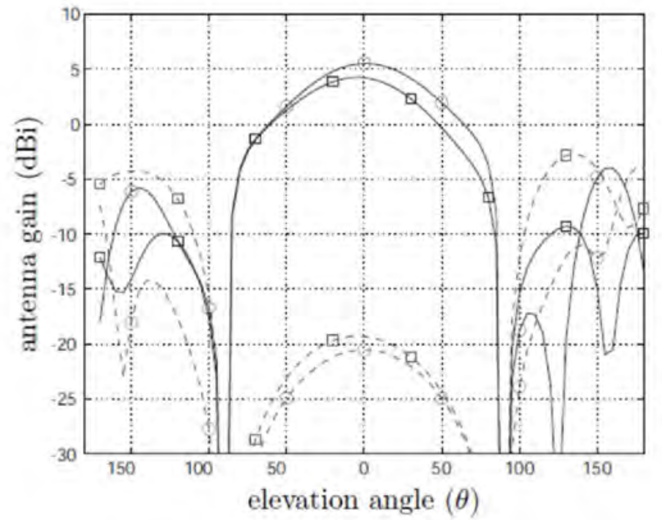
(b) H-plane



60GHz Radiating Elements

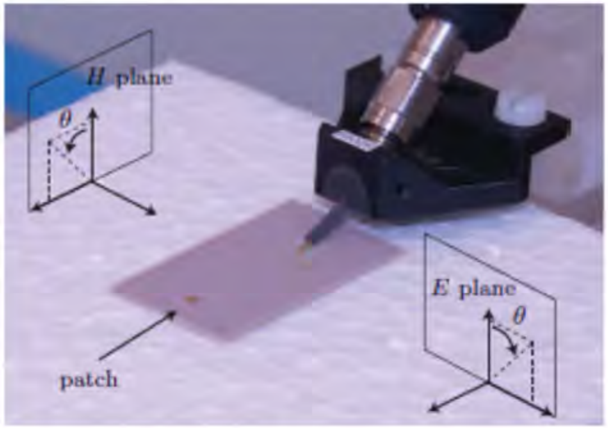






s_1	s_2	polarisation
$s\angle 0°$	$s\angle 0°$	linear, $\varphi = 45°$
$s\angle 0°$	$s\angle 180°$	linear, $\varphi = 135°$
$2s$	0	linear, $\varphi = 90°$
$s\angle 0°$	$s\angle 90°$	right-hand circular
$s\angle 90°$	$s\angle 0°$	left-hand circular

60GHz Radiating Elements



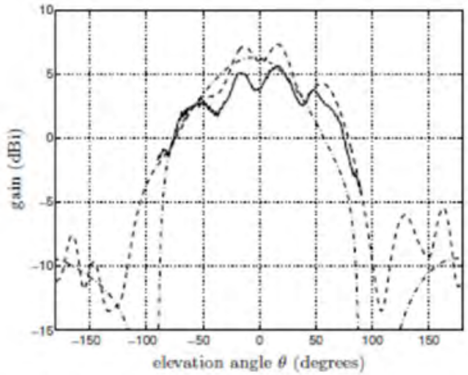
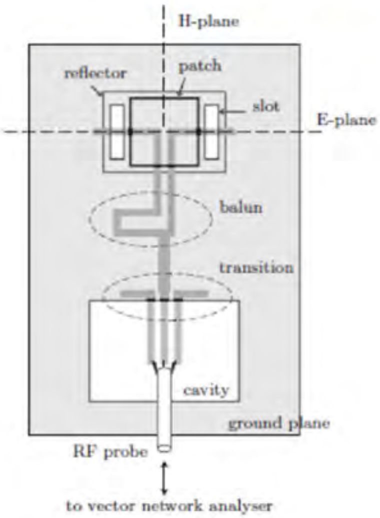


Figure 4.16: Radiation pattern. E-plane, $f = 54.2$ GHz. Measurement (solid), CST Microwave Studio (dash), Spark (dash-dot).



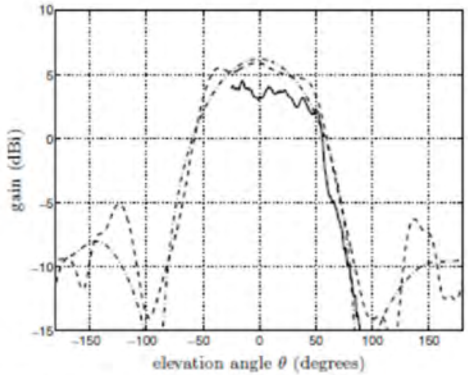
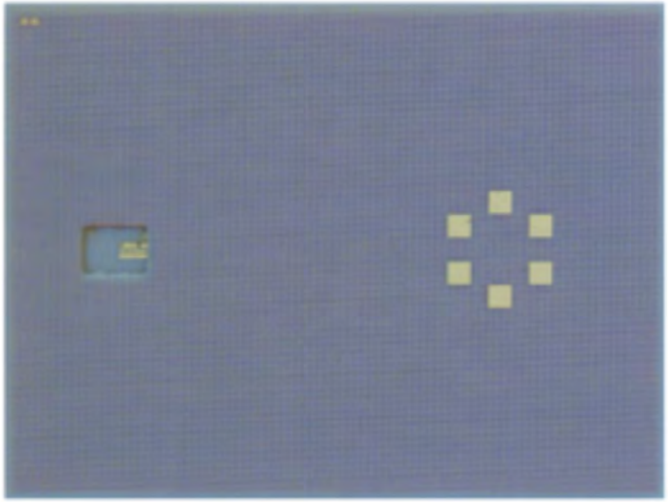
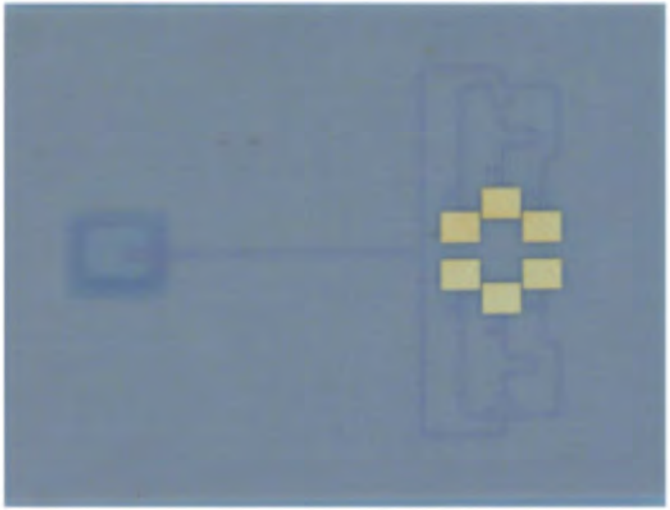
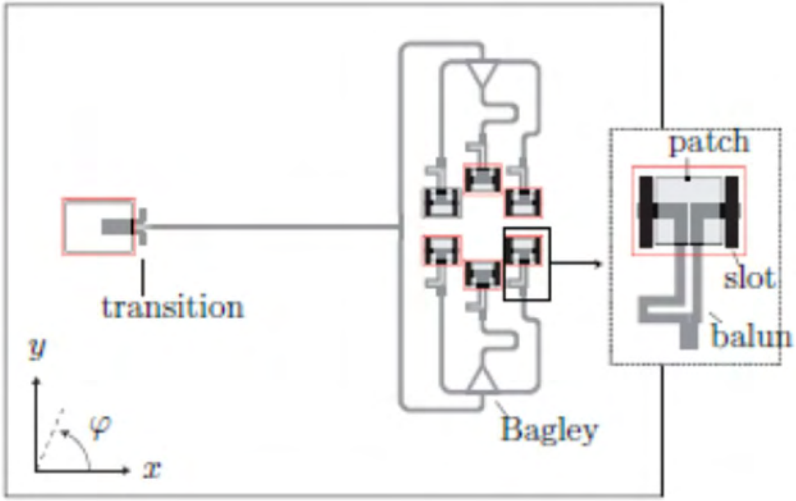


Figure 4.17: Radiation pattern. H-plane, $f = 54.2$ GHz. Measurement (solid), CST Microwave Studio (dash), Spark (dash-dot).

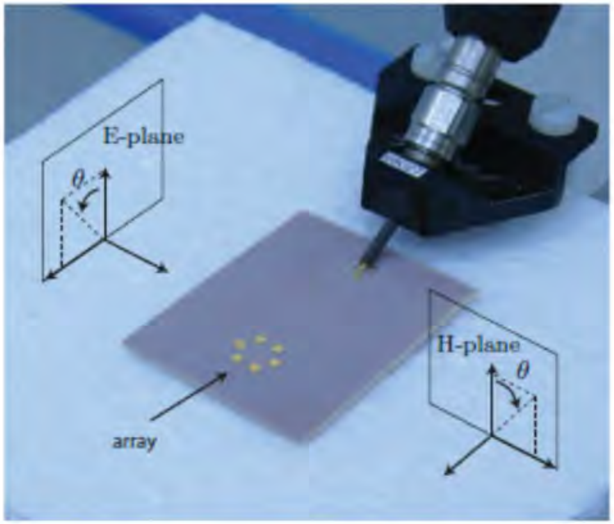
60GHz Radiating Elements in Array







60GHz Radiating Elements in Array



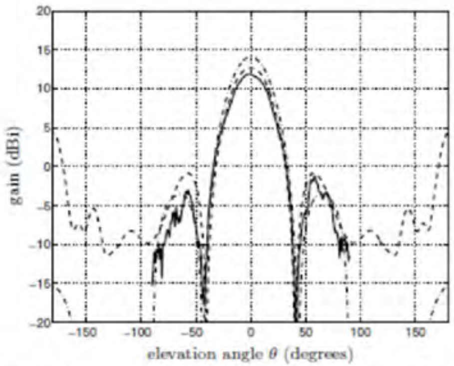


Figure 6.12: Radiation pattern of the circular 6-element array with broadside orientation. H-plane, f = 60.0 GHz. Measurement (solid), CST Microwave Studio (dash), Spark (dash-dot).

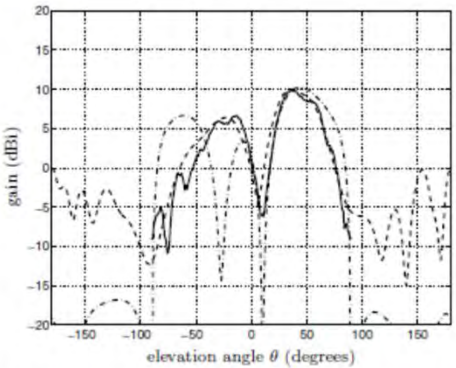


Figure 6.14: Radiation pattern of the circular 6-element array with $\theta_0 = 60°$. H-plane, f = 60.0 GHz. Measurement (solid), CST Microwave Studio (dash), Spark (dash-dot).

In realtà il nostro amico sta barando…

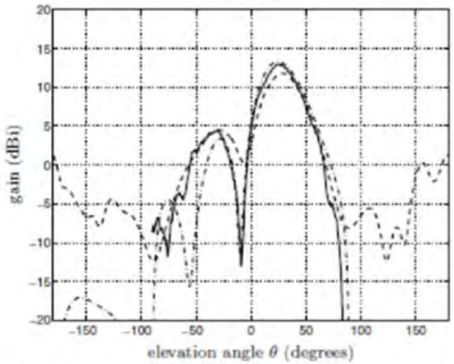
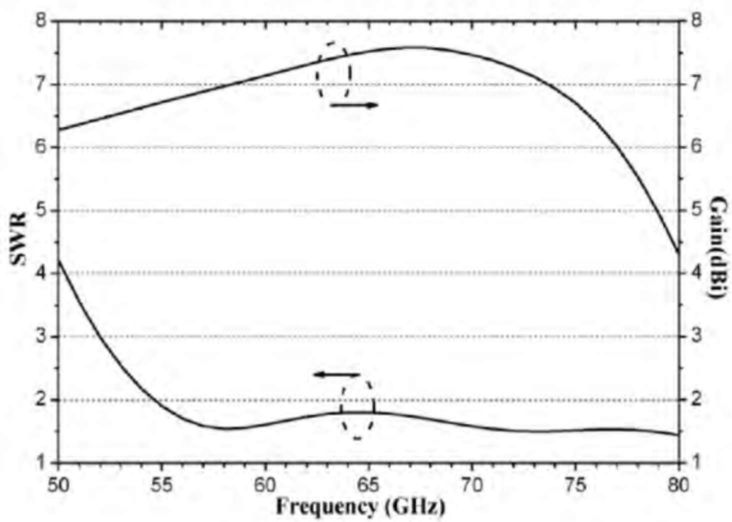
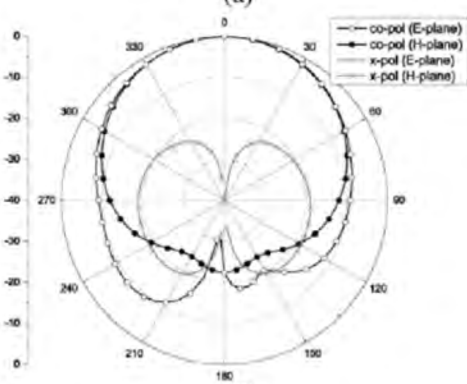


Figure 6.13: Radiation pattern of the circular 6-element array with $\theta_0 = 30°$. H-plane, f = 60.0 GHz. Measurement (solid), CST Microwave Studio (dash), Spark (dash-dot).

60GHz Radiating Elements in Array



(a)



(b)

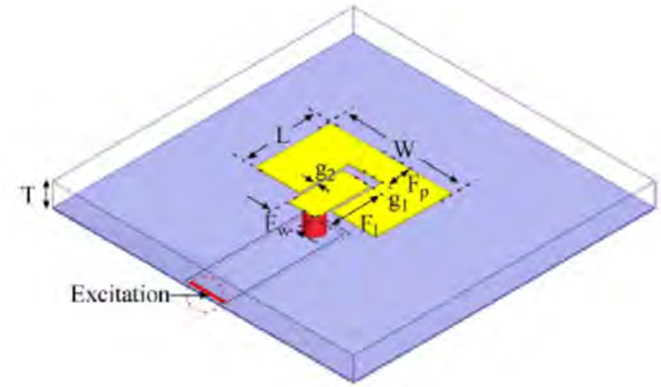


TABLE I
DIMENSIONS FOR THE ANTENNA ELEMENT

Parameter	F_l	F_w	F_p	T
Value(mm)	0.9 0.27λ	0.45 0.13λ	0.425 0.13λ	0.381 0.11λ
Parameter	g_1	g_2	L	W
Value(mm)	0.15 0.04λ	0.05 0.01λ	1.25 0.37λ	2 0.59λ

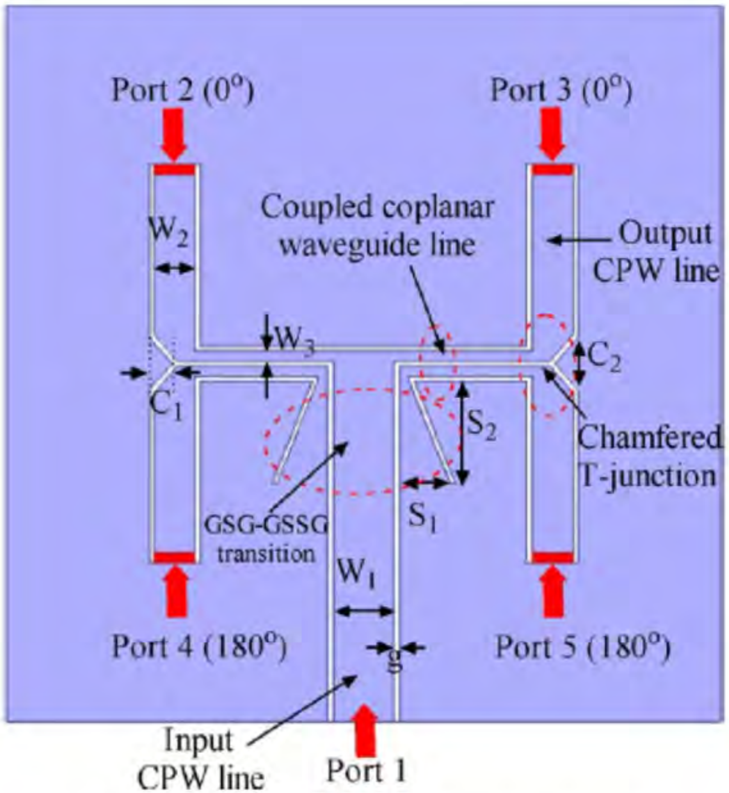
λ is one electrical wavelength in Duroid 5880 substrate referring to 60 GHz.

3012 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 62, NO. 6, JUNE 2014

Low-Cost Wideband Microstrip Antenna Array for 60-GHz Applications

Mingjian Li, *Student Member, IEEE*, and Kwai-Man Luk, *Fellow, IEEE*

60GHz Radiating Elements in Array



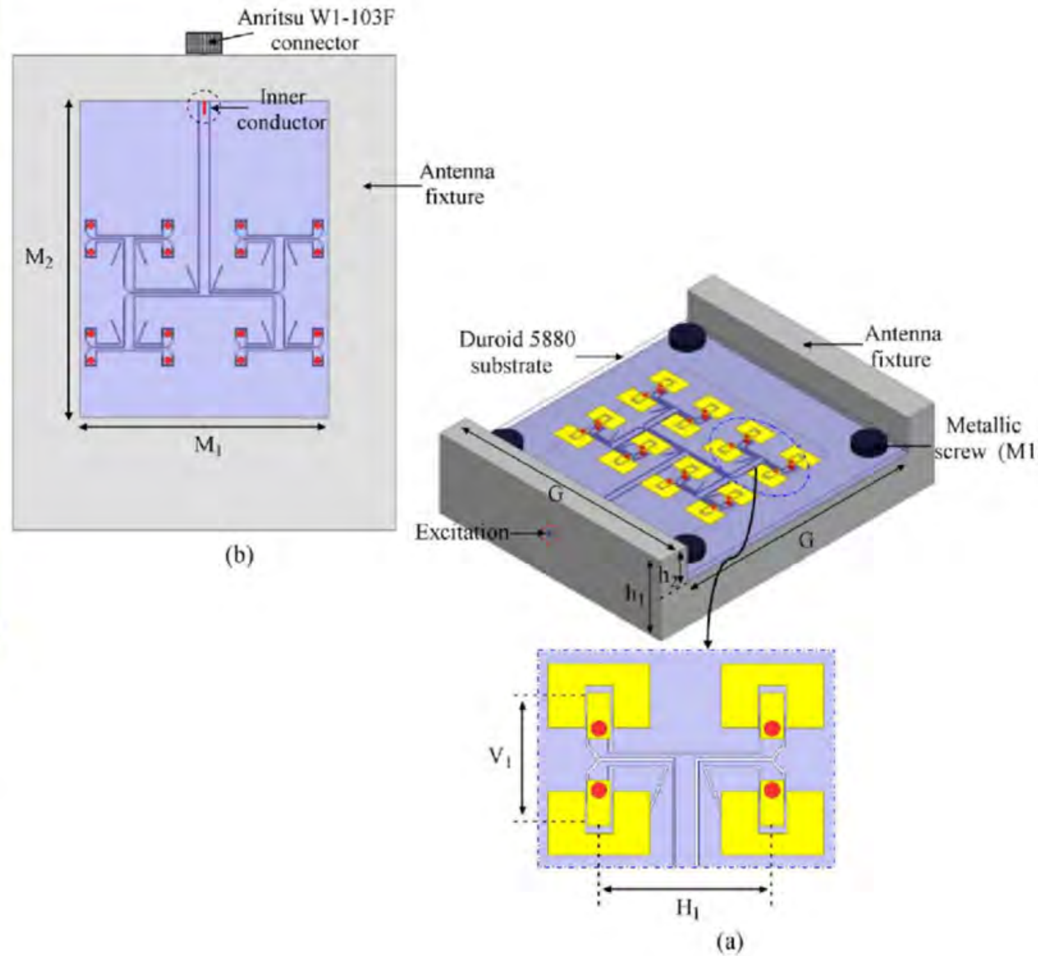


TABLE II

DIMENSIONS FOR THE 4-WAY POWER DIVIDER FEED NETWORK

Parameter	C_1	C_2	S_1	S_2
Value(mm)	0.18	0.5	0.7	1
Parameter	W_1	W_2	W_3	g
Value(mm)	0.6	0.4	0.05	0.05

60GHz Radiating Elements in Array

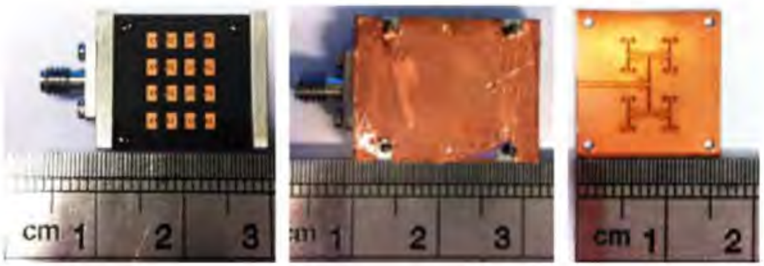


Fig. 6. Antenna prototype of the linearly polarized antenna array.

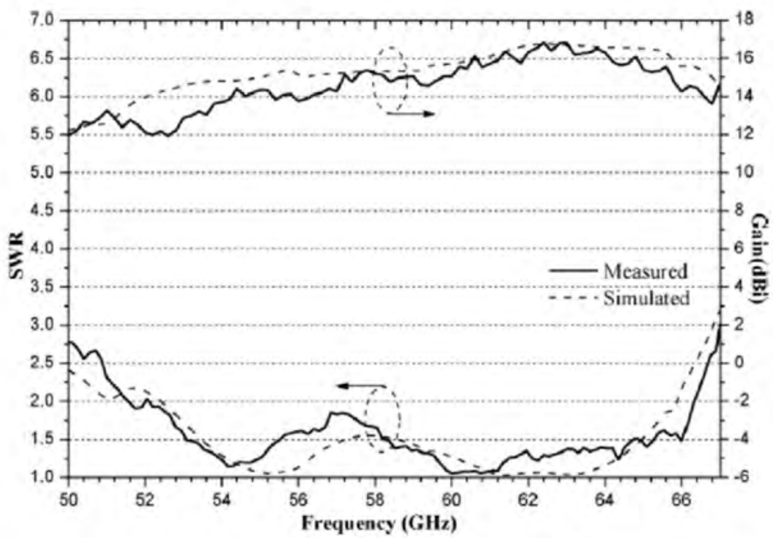


Fig. 7. Measured and simulated SWRs and gains of the linearly polarized antenna array.

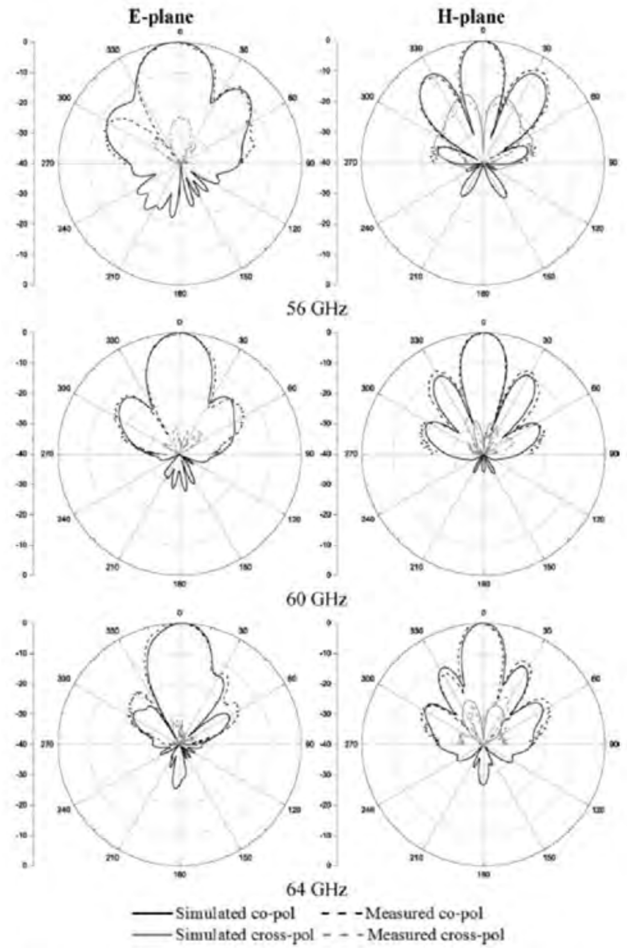
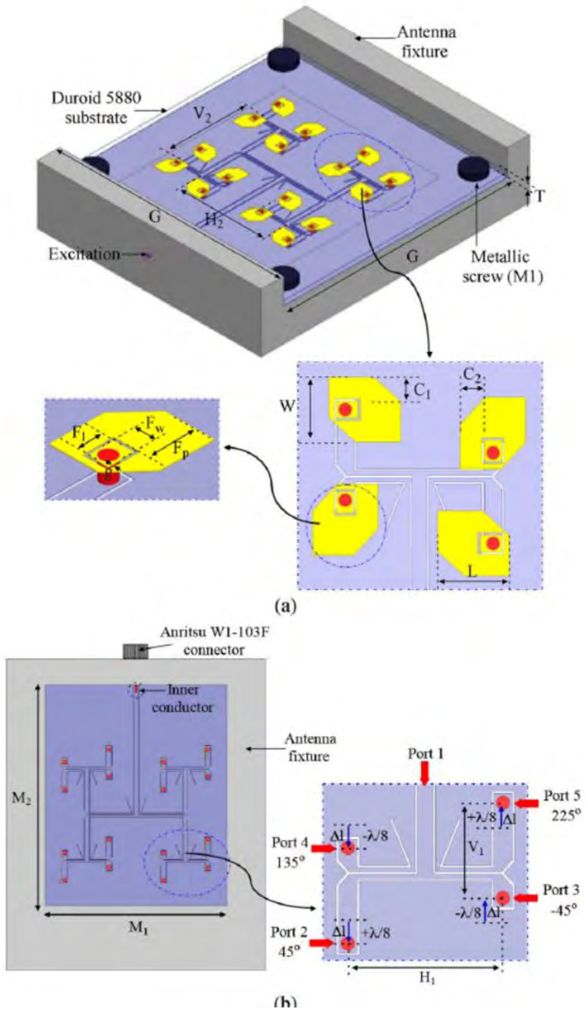


Fig. 8. Measured and simulated radiation patterns of the linearly polarized antenna array.

60GHz Radiating Elements in Array



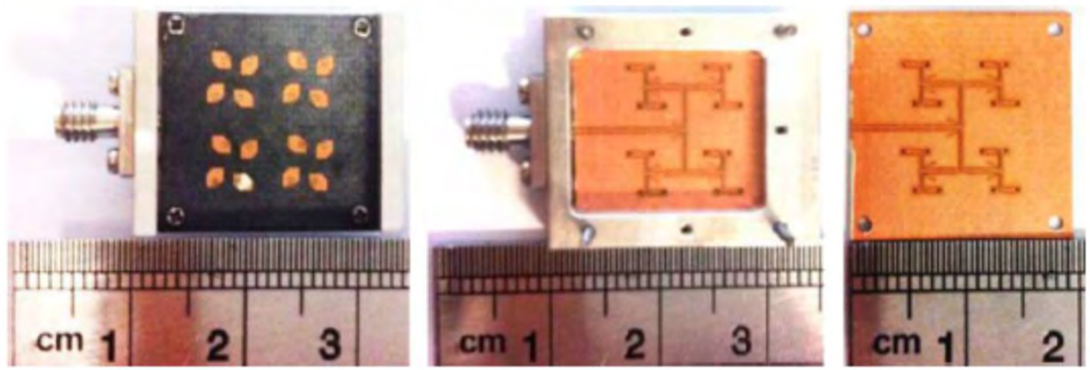


TABLE III
DIMENSIONS FOR THE CIRCULARLY POLARIZED ANTENNA ARRAY

Parameter	F_l	F_w	F_p	T
Value(mm)	0.5 0.15λ	0.4 0.12λ	0.925 0.27λ	0.381 0.11λ
Parameter	C_1	C_2	L	W
Value(mm)	0.56 0.17λ	0.62 0.18λ	1.65 0.49λ	1.5 0.46λ
Parameter	H_1	H_2	V_1	V_2
Value(mm)	3.4 1λ	7.6 2.2λ	2.1 0.62λ	7 2.1λ
Parameter	M_1	M_2	G	g
Value(mm)	14 4.15λ	17 5.04λ	20 5.93λ	0.05

λ is one electrical wavelength in Duroid 5880 substrate referring to 60 GHz.

60GHz Radiating Elements in Array

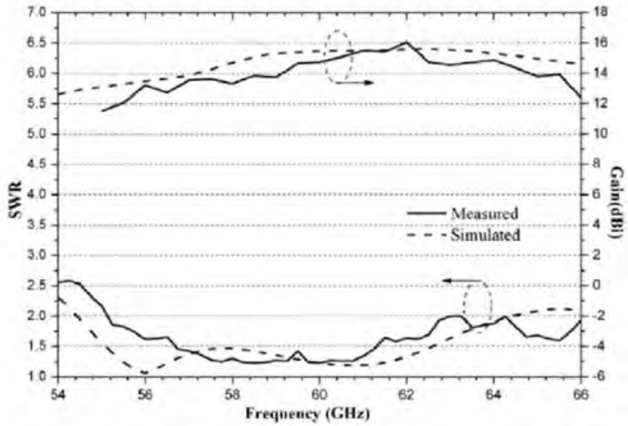


Fig. 11. Measured and simulated SWRs and gains of the circularly polarized antenna array.

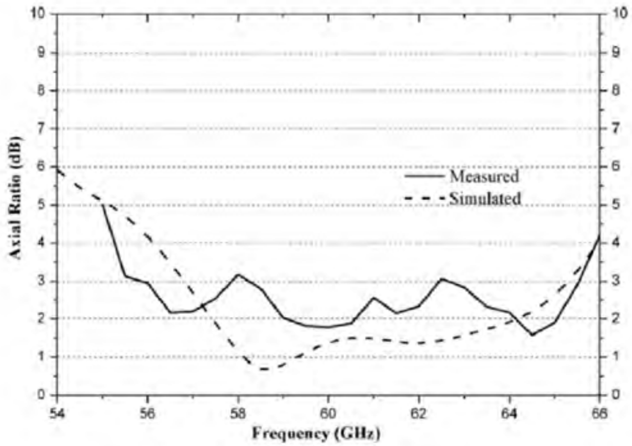


Fig. 12. Measured and simulated axial ratios of the circularly polarized antenna array.

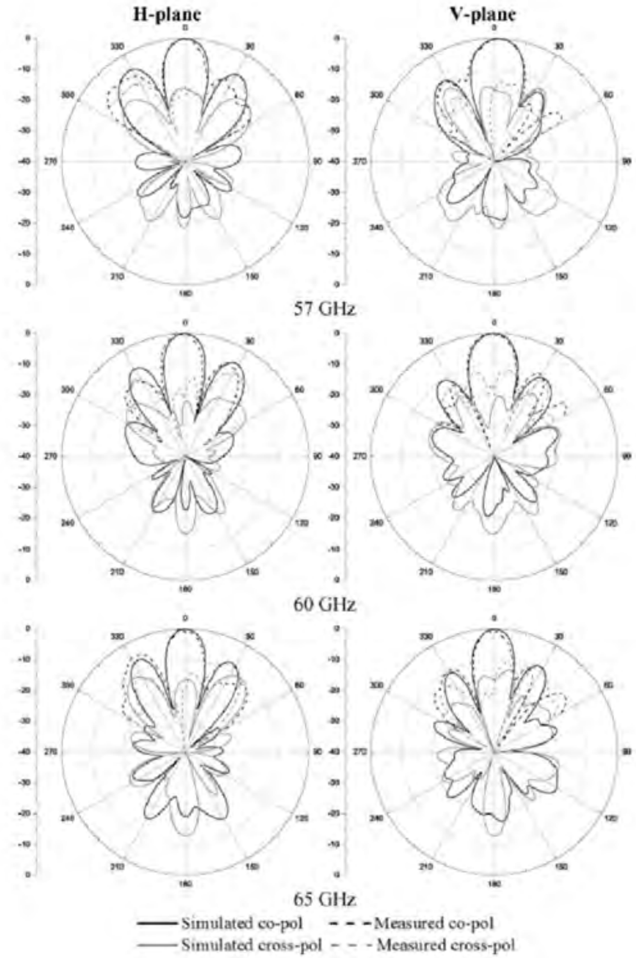
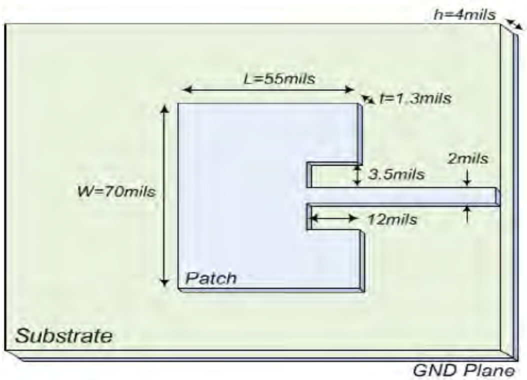


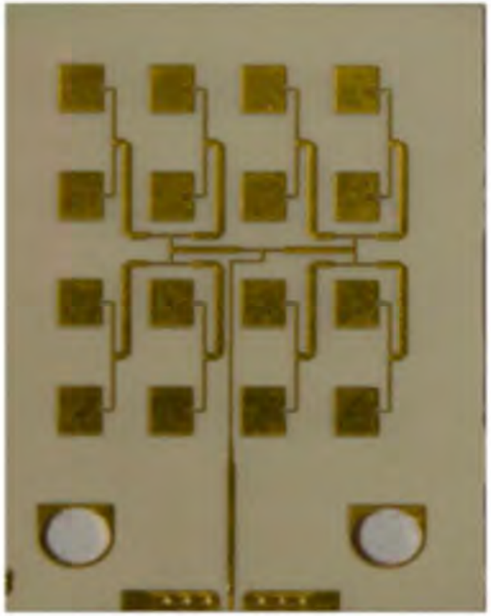
Fig. 13. Measured and simulated radiation patterns of the circularly polarized antenna array.

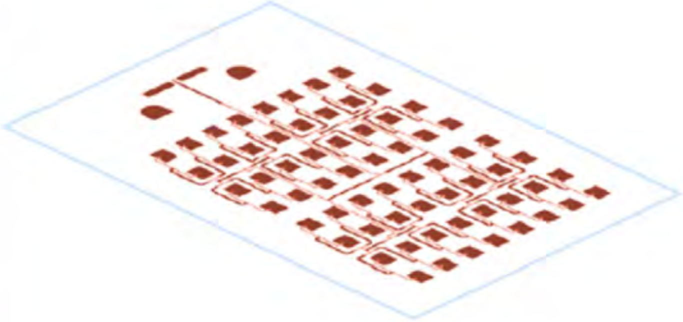
60GHz Radiating Elements in Array



STANDARD THICKNESS
0.001" (25µm)
0.002" (50µm)
0.004" (100µm)

Electrical Properties	
Dielectric Constant, 10 GHz, 23°C (Process)	2.9
Dielectric Constant, 10 GHz, 23°C (Design)	3.14
Dissipation Factor, 10 GHz, 23°C	0.0025





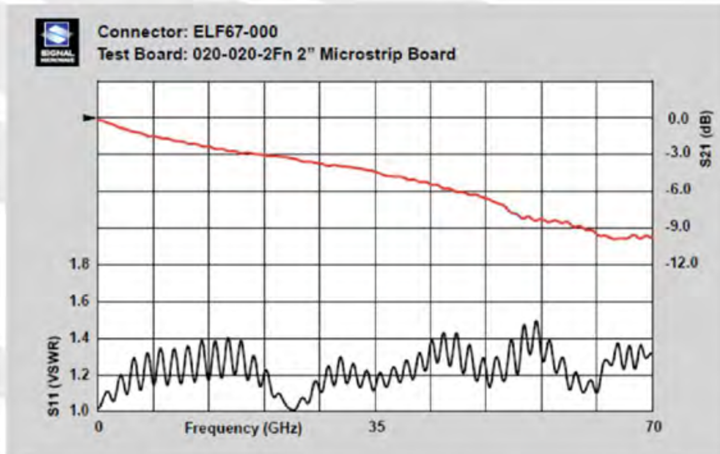
60 GHz Patch Antenna Array on Low Cost Liquid-Crystal Polymer (LCP) Substrate

Patrick Cabrol
InterDigital Communications, Inc.
Melville, New York
patrick.cabrol@interdigital.com

Philip Pietraski
InterDigital Communications, Inc.
Melville, New York
philip.pietraski@interdigital.com

60GHz Radiating Elements in Array

- 1.85 mm Interface
- Top Ground Only
- 70 GHz Bandwidth
- Board Design Support Available
- Edge Launch
- Test Boards Available
- No Soldering Required



2” microstrip test board with typical data through 70 GHz

Signal Microwave, LLC
Chandler, Arizona
info@signalmicrowave.com
www.signalmicrowave.com
(480) 322-4992

Unfeasible to solder connectors there...

60GHz Radiating Elements in Array

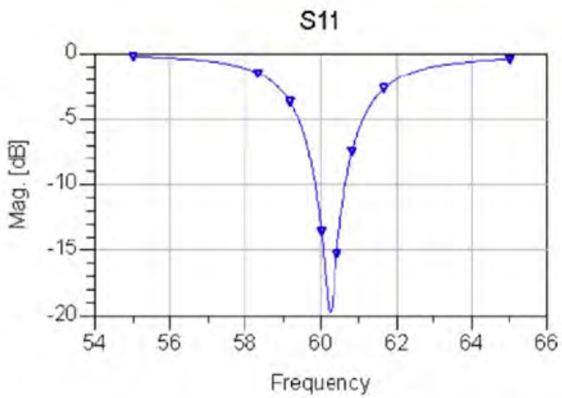


Figure 6. S11 for Single Patch Antenna Simulation.

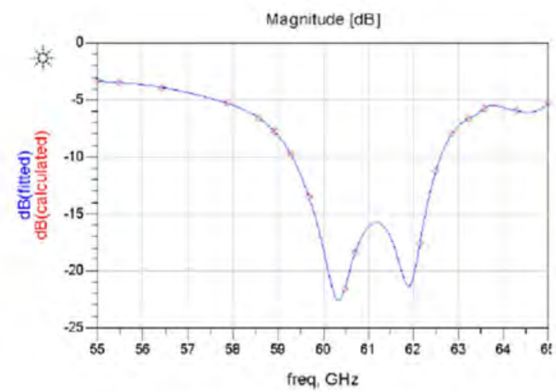


Figure 7. S11 for 4x4 Array Simulation.

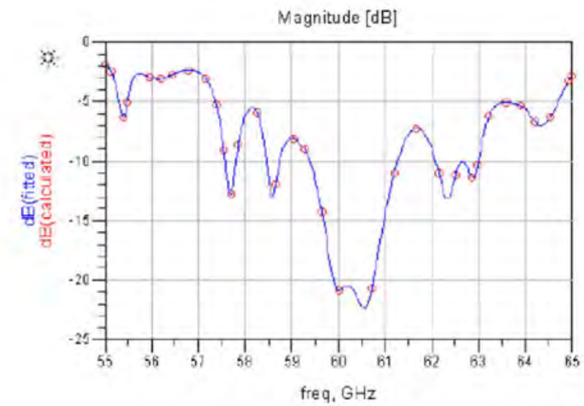


Figure 8. S11 for 8x8 Array Simulation.

TABLE I. ANTENNA ARRAYS SIMULATION RESULTS

Array Size	Simulation Results		
	Gain [dBi]	*Beamwidth [Deg]*	*Efficiency [%]*
1x1*	6.2	94	85
4x4*	18.5	24	77
8x8*	22.3	9	65
4x4**	18.1	24	71
8x8**	20.5	9	36

a. (*)$\varepsilon_r = 2.9$ and $\tan\delta = 0.0025$

b. (**)$\varepsilon_r = 3.16$ and $\tan\delta = 0.004$

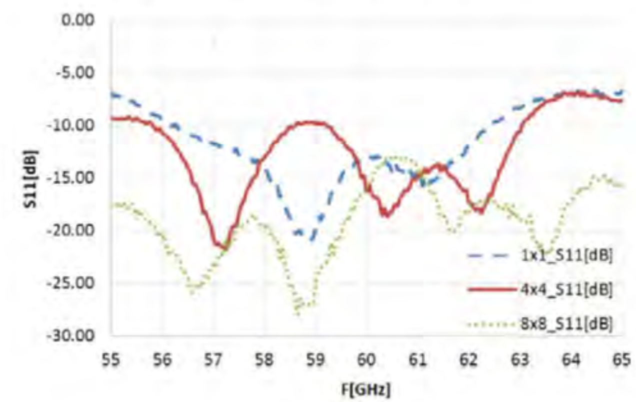


Figure 9. S11 Measured for All Arrays.

60GHz Radiating Elements in Array

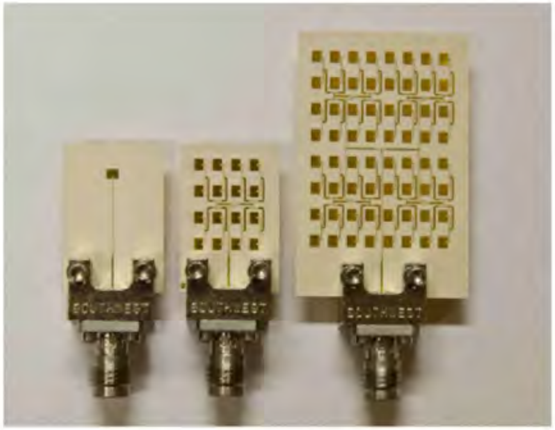


Figure 12. Patch Antenna Arrays and 1.85mm Connector assemblies.

TABLE II. ANTENNA ARRAYS MEASUREMENTS RESULTS

Array Size	Measurement Results		
	Gain [dBi]	*Beamwidth [Deg]*	*Efficiency [%]*
4x4	16.7	24	64
8x8	17.1	11	29

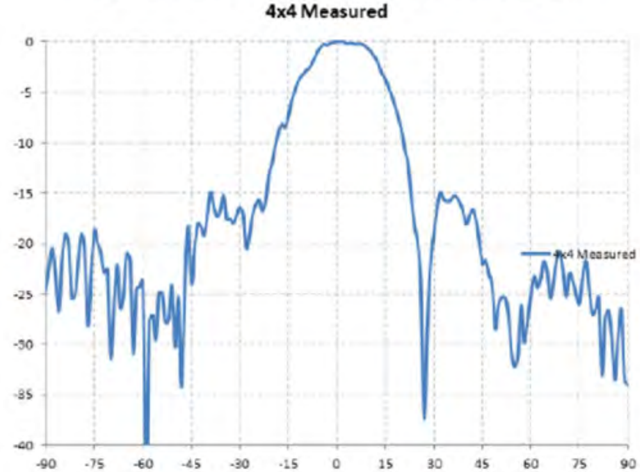


Figure 10. Radiation Characteristics for 4x4 Array.

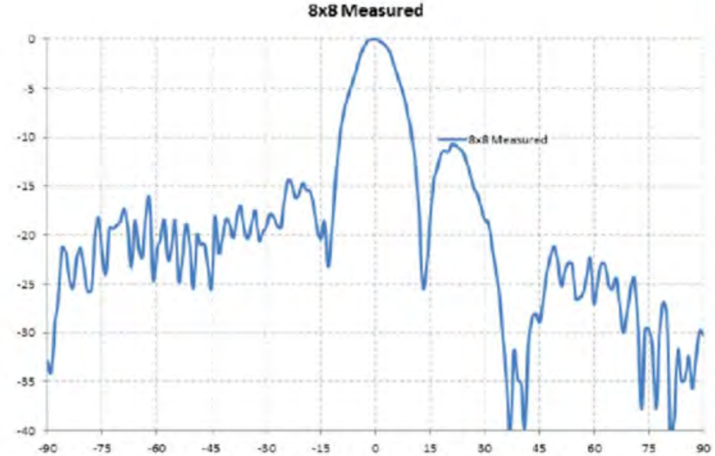


Figure 11. Radiation Characteristics for 8x8 Array.

60GHz Radiating Elements in Array

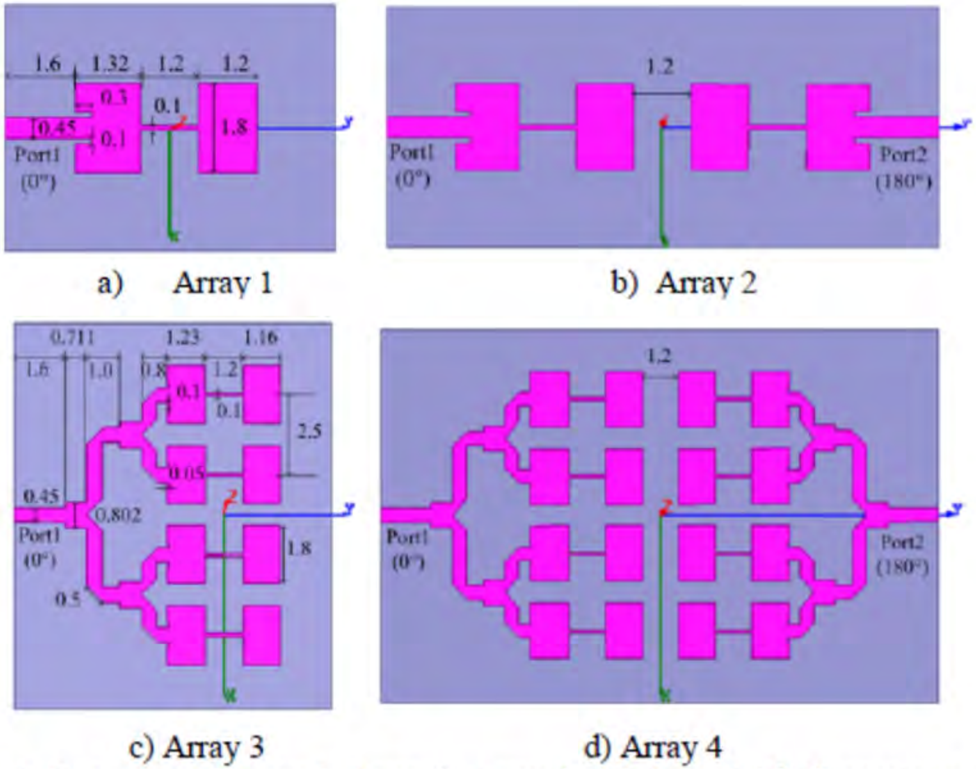


Fig. 1 Geometry of Array 1, Array 2, Array 3 and Array 4 (all dimensions are expressed in millimeters).

Property	Typic. RO4003C
Dielectric Constant, ε_r Process	3.38 ± 0.05
(2) Dielectric Constant, ε_r Design	3.55
Dissipation Factor tan, δ	0.0027 0.0021

A Compact High-Performance Patch Antenna Array for 60-GHz Applications

Wanlan Yang, Kaixue Ma, Senior Member, IEEE, Kiat Seng Yeo, Senior Member, IEEE, and Wei Meng Lim

60GHz Radiating Elements in Array

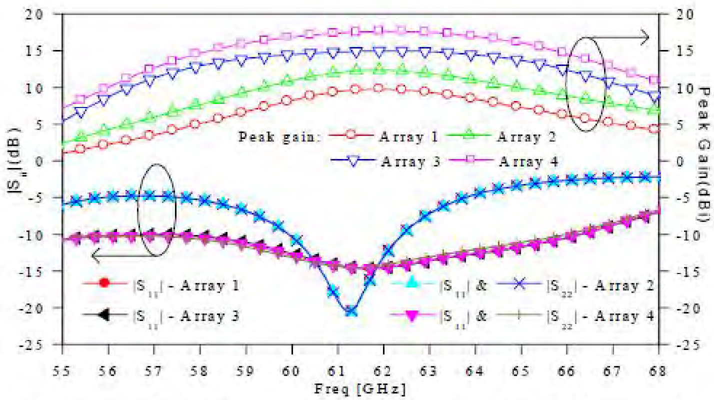
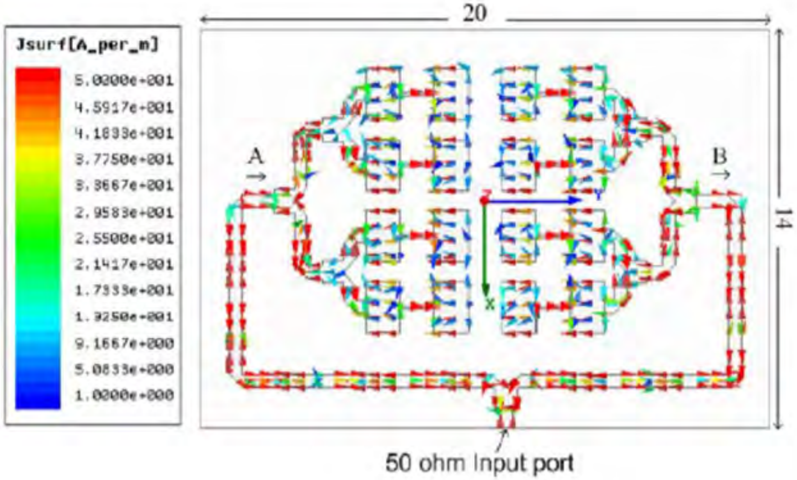


Fig. 2 Simulated reflection coefficients and peak gains of Array 1, Array 2, Array 3 and Array 4



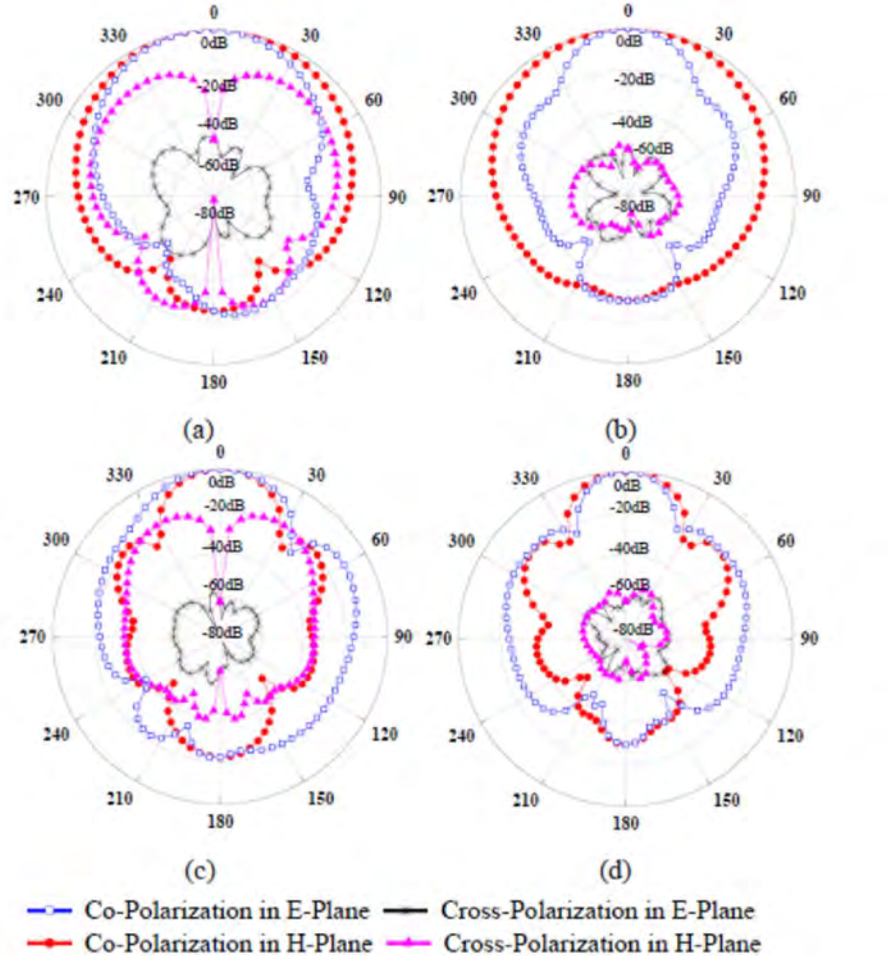
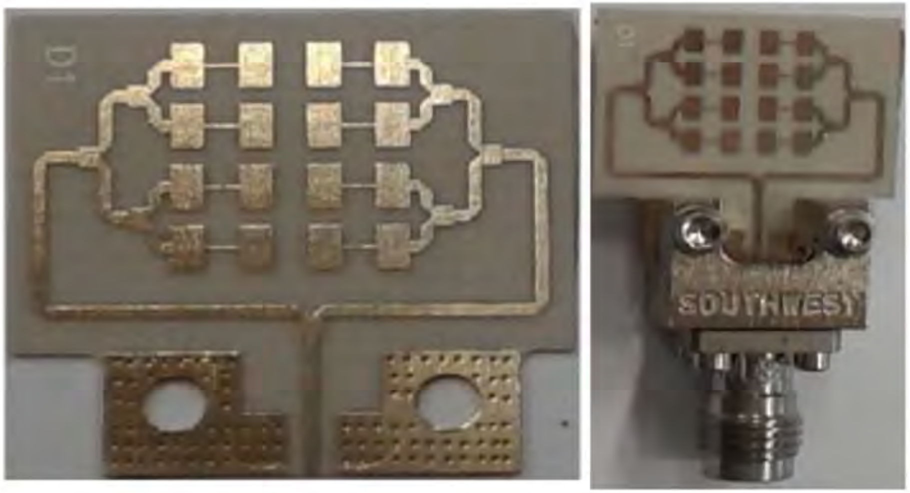


Fig. 3 Simulated radiation patterns of the designs in E- and H-planes @ 61.5 GHz for: (a) Array 1, (b) Array 2, (c) Array 3, (d) Array 4.

60GHz Radiating Elements in Array



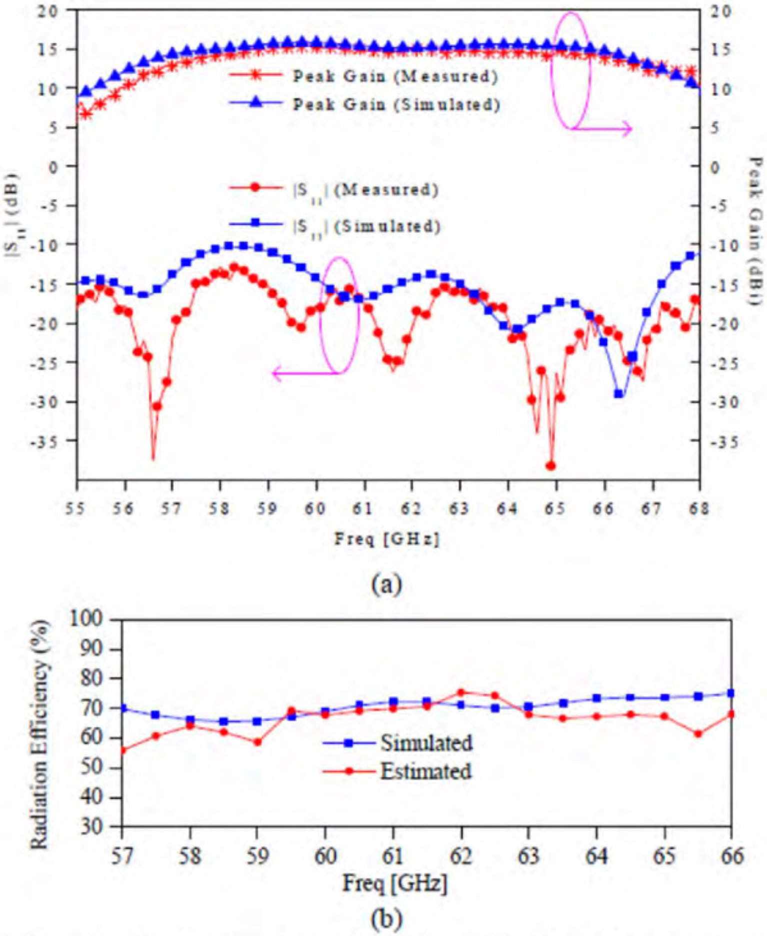
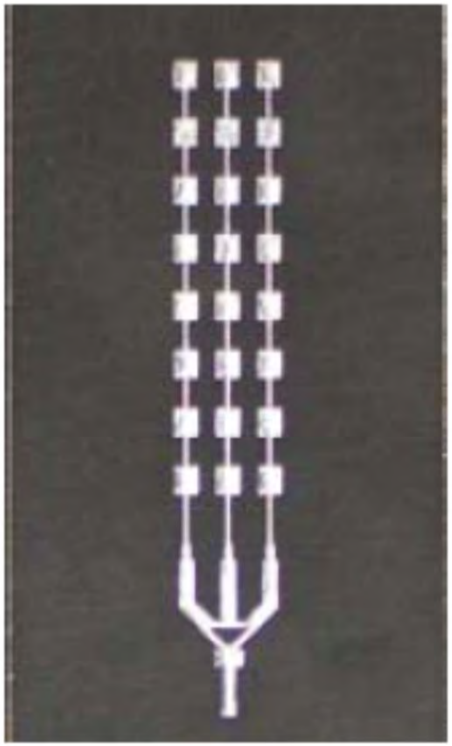
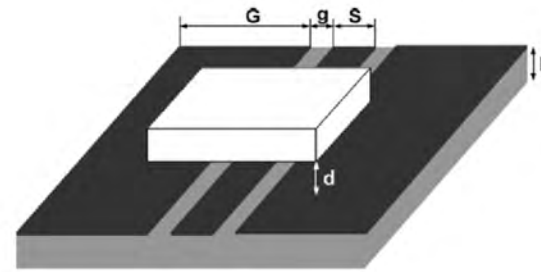


Fig. 6 Simulated and measured results of the proposed patch antenna array: (a) $|S_{11}|$ and Peak Gain, (b) radiation efficiencies.

60GHz (steerable) Array



(a)



A Steerable 60GHz array antenna using a reconfigurable dielectric phase shifter

Matthew Stoneback*, Charles Wolthausen, and Yasuo Kuga
Department of Electrical Engineering
University of Washington, Box 352500, Seattle, WA 98195

60GHz (steerable) Array

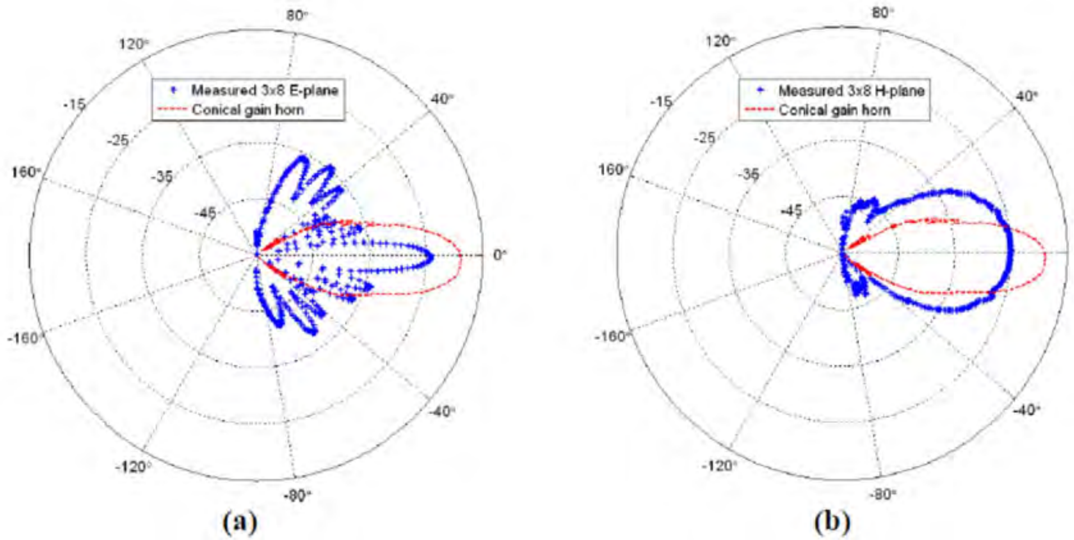
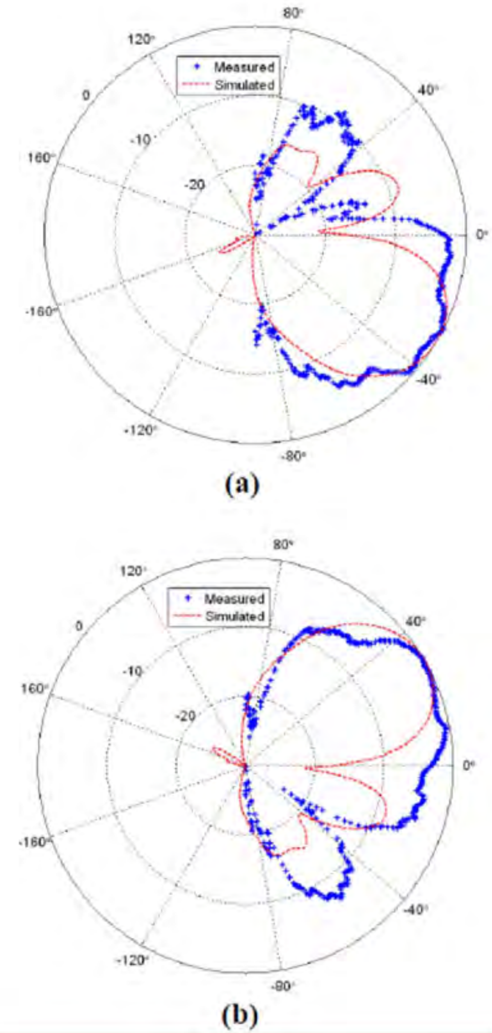
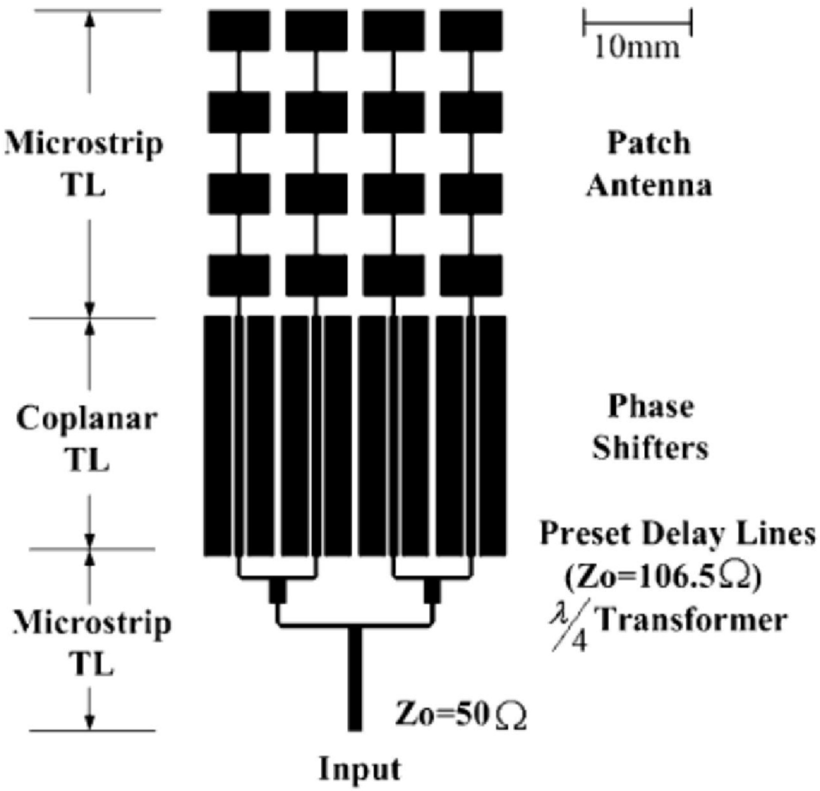


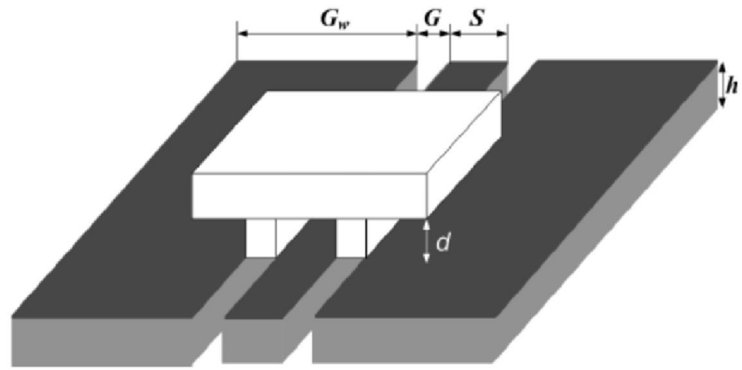
Fig. 3: (a) Measured E-plane radiation pattern of 3x8 array of Figure 2a plotted with V-band conical gain horn. (b) Measured H-plane radiation pattern of 3x8 array of Figure 2a plotted with V-band conical gain horn.



The central column has a 105° delay built in, the right or the left can be forced to have a 210° delay with the dielectric slab. Hence a +-30° steering is attained.

60GHz (steerable) Array





IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 55, NO. 2, FEBRUARY 2007

Theory →

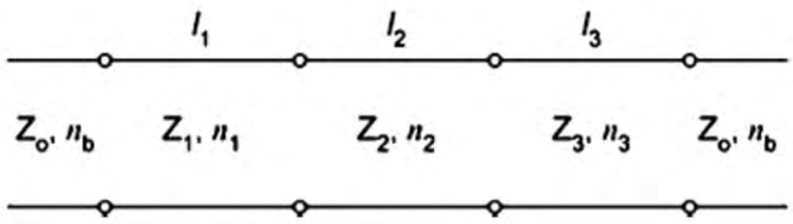
A 20 GHz Steerable Array Antenna Using 3-bit Dielectric Slab Phase Shifters on a Coplanar Waveguide

Junho Cha, *Member, IEEE*, Yasuo Kuga, *Fellow, IEEE*, Akira Ishimaru, *Life Fellow, IEEE*, and Sangil Lee

60GHz (steerable) Array

3bits → 45°, 90°, 180° sections

$$\underbrace{(n_i - n_b)k_0 l_i = \Delta\theta_i}_{\substack{\text{adds } \Delta\theta_i \text{ with respect to} \\ \text{equal length of uloaded line}}}, \qquad \underbrace{n_i k_0 l_i = m_i \pi}_{\text{reflectionless when inserted}}$$



TL model of a 3-bit phase shifter.

$$45° \Rightarrow (m_1 = 1) : n_1 = \frac{4}{3} n_b; \quad l_1 = \frac{3}{8}\frac{\lambda_0}{n_b}$$

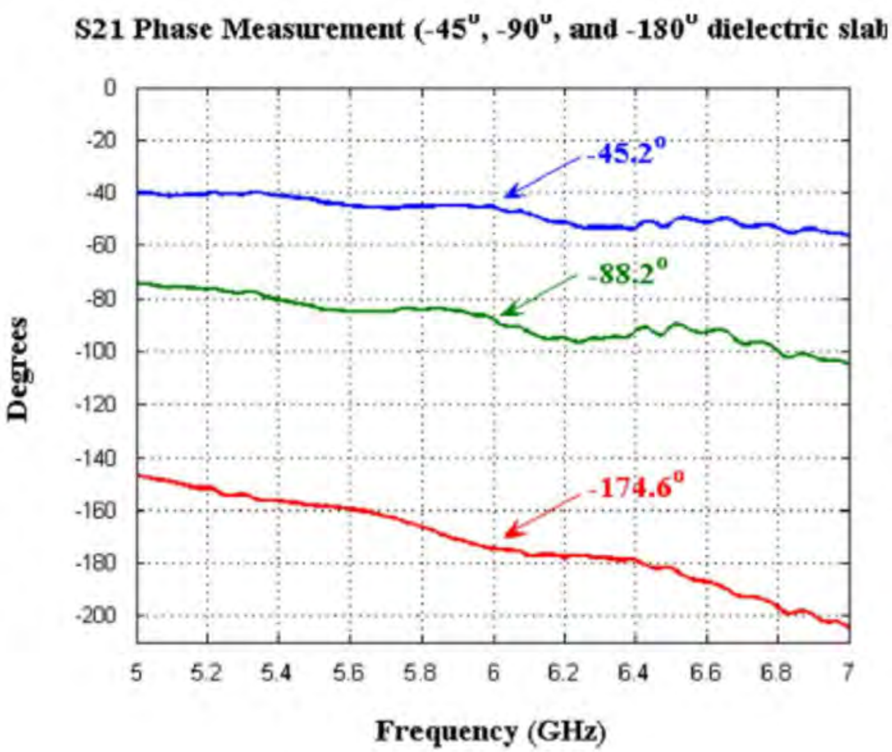
$$90° \Rightarrow \begin{cases} (m_2 = 1) : n_2 = 2n_b; & l_2 = \dfrac{\lambda_0}{4n_b} \\ (m_2 = 2) : n_2 = \dfrac{4}{3} n_b; & l_2 = \dfrac{3}{4}\dfrac{\lambda_0}{n_b} \end{cases}$$

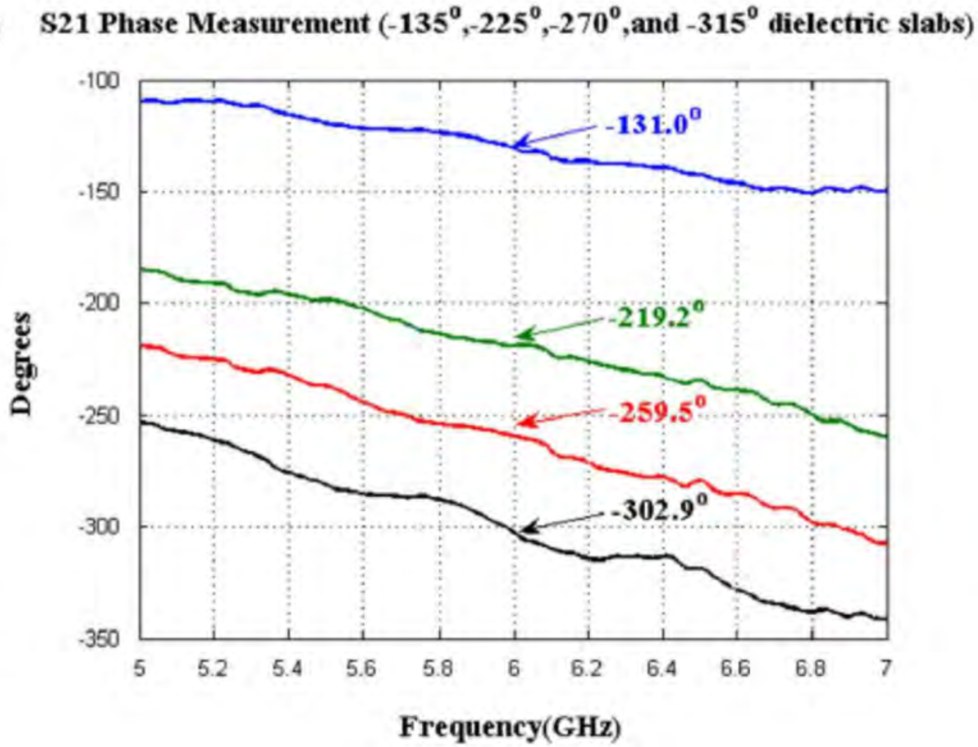
$$180° \Rightarrow \begin{cases} (m_3 = 2) : n_3 = 2n_b; & l_3 = \dfrac{\lambda_0}{2n_b} \\ (m_3 = 4) : n_3 = \dfrac{4}{3} n_b; & l_3 = \dfrac{3}{2}\dfrac{\lambda_0}{n_b} \end{cases}$$

n_b is the effective refractive index of the unloaded line

n_i is the effective refractive index of the loaded line

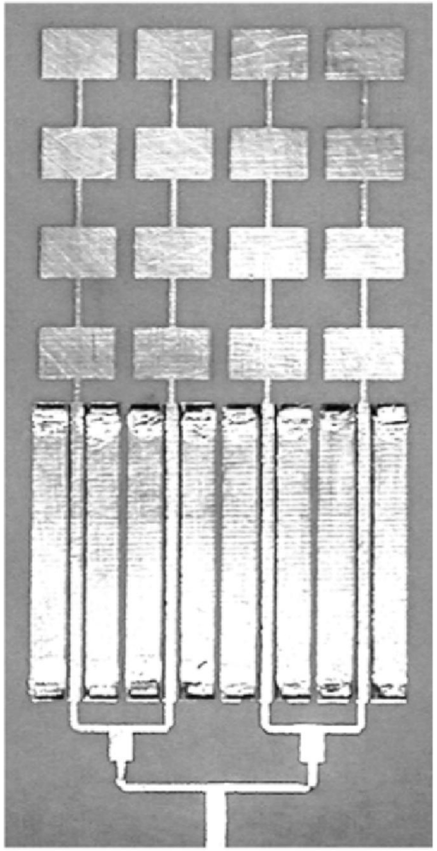
60GHz (steerable) Array

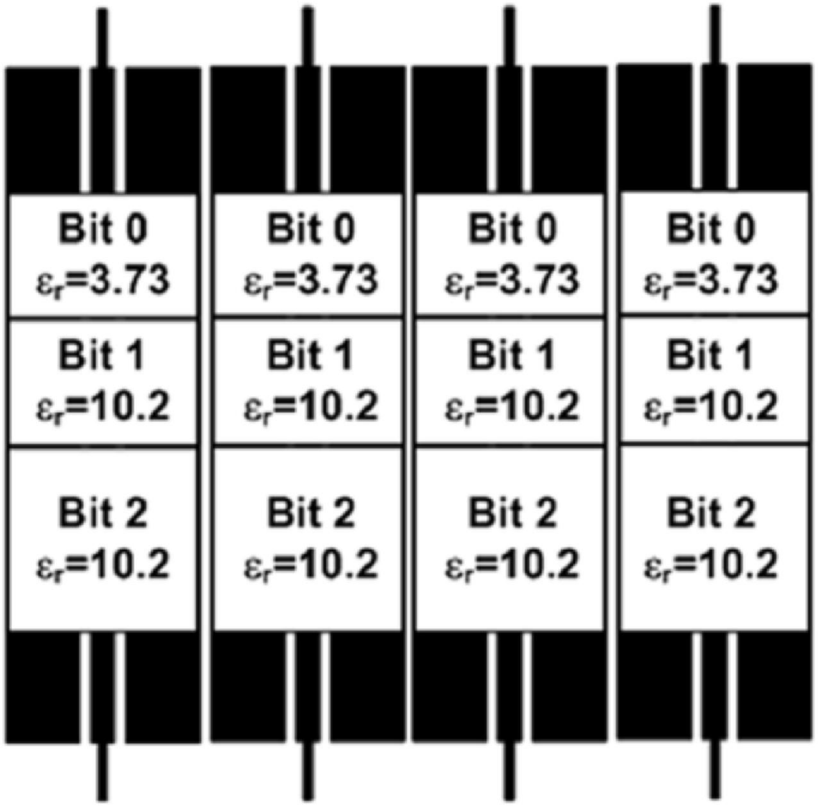




Measured results for m_1=1, m_2=2, m_3=4

60GHz (steerable) Array





Antenna designed for m_1=1, m_2=1, m_3=2

60GHz (steerable) Array

Unloaded CPW: line 0.8mm wide, grounds 2.5mm wide, gaps 0.4mm. Dielectric ε_r=3.38, h=0.508mm → ε_{eff}=1.33 (n_b=1.152)

45° section → (m_1=1) n_b=1.536, l_1=4.48mm → ε_{eff}=2.359, this can be done with a slab of ε_r=3.73 (by leaving a 10μm air gap)

90° section → (m_2=1) n_b=2.305, l_2=3.26mm → ε_{eff}=5.316, this can be done with a slab of ε_r=10.2

180° section → (m_3=2) n_b=2.305, l_3=6.52mm → ε_{eff}=5.316, this can be done with a slab of ε_r=10.2

60GHz (steerable) Array

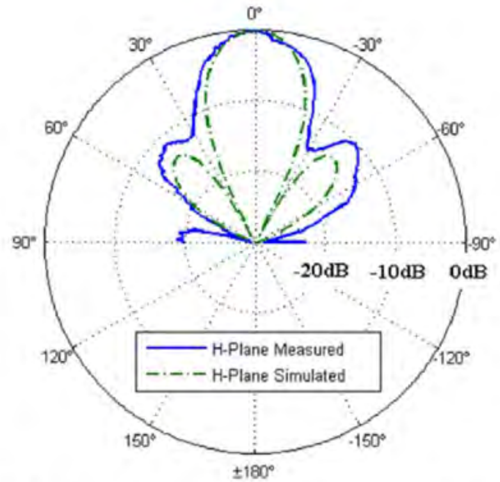


Fig. 9. Simulated and measured H-plane radiation patterns: No phase shift case. Slab positions are (000,000,000,000).

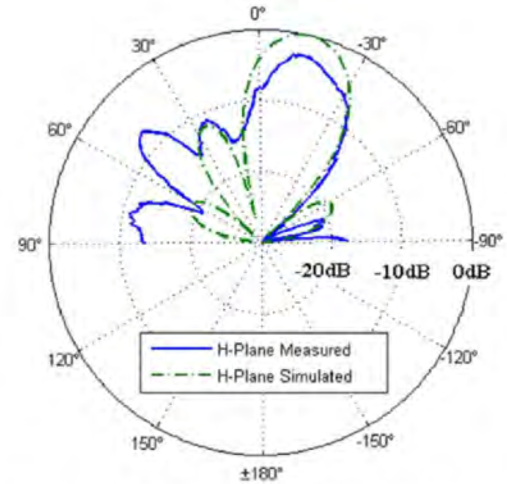


Fig. 11. Simulated and measured H-plane radiation patterns. The phase shift among elements is $-45°$ which corresponds to the beam angle of 15°. Slab positions are (110,010,100,000).

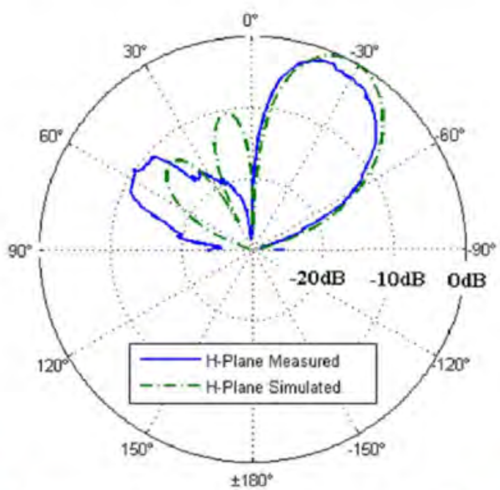


Fig. 12. Simulated and measured H-plane radiation patterns: The phase shift among elements is $-90°$ which corresponds to the beam angle of 30°. Slab positions are (011,001,010,000).

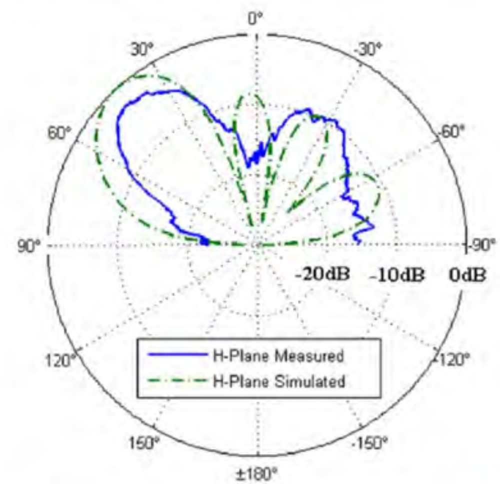
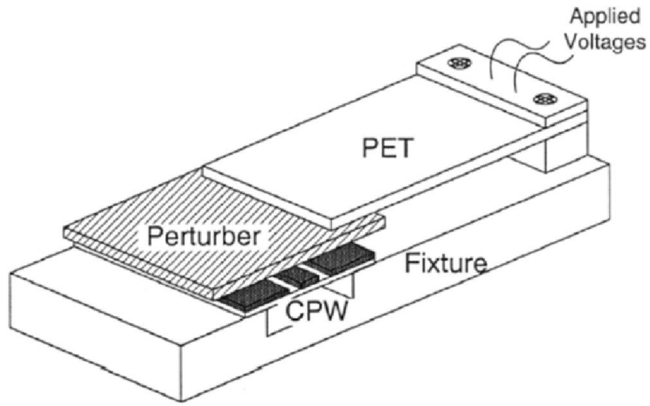
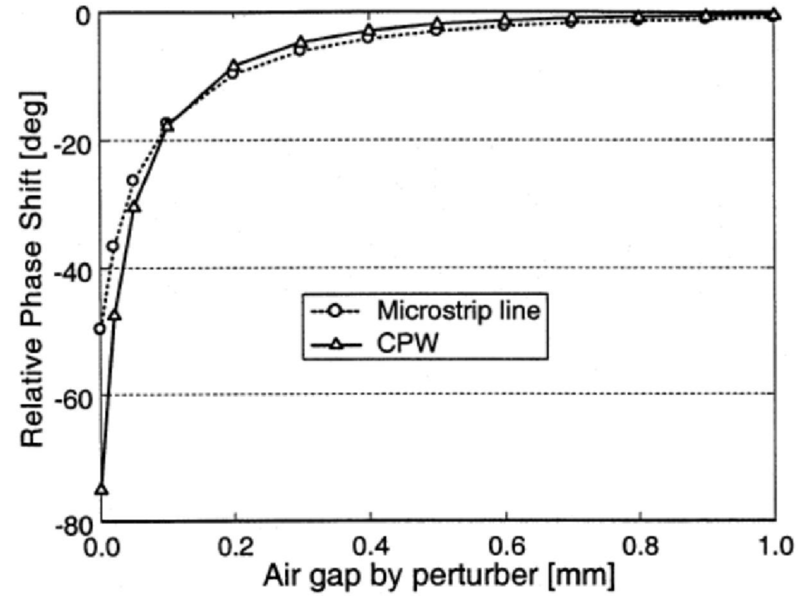
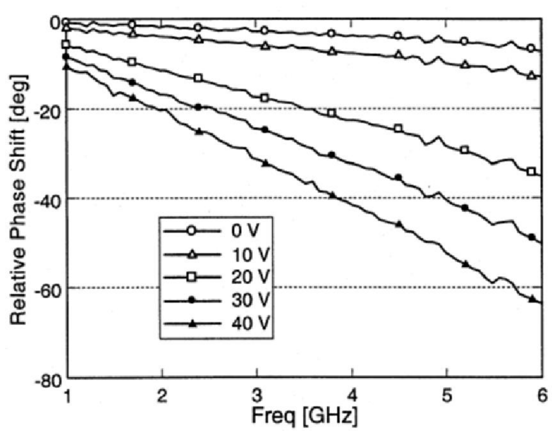


Fig. 13. Simulated and measured H-plane radiation patterns: The phase shift is $-135°$ which corresponds to the beam scan angle of 45°. Slab positions are (000,110,011,100).

60GHz (steerable) Array





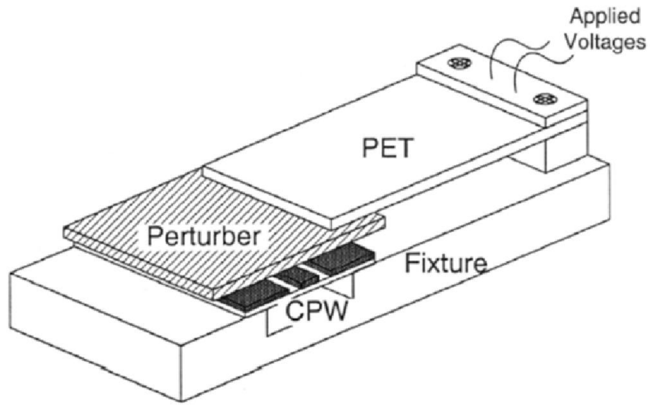


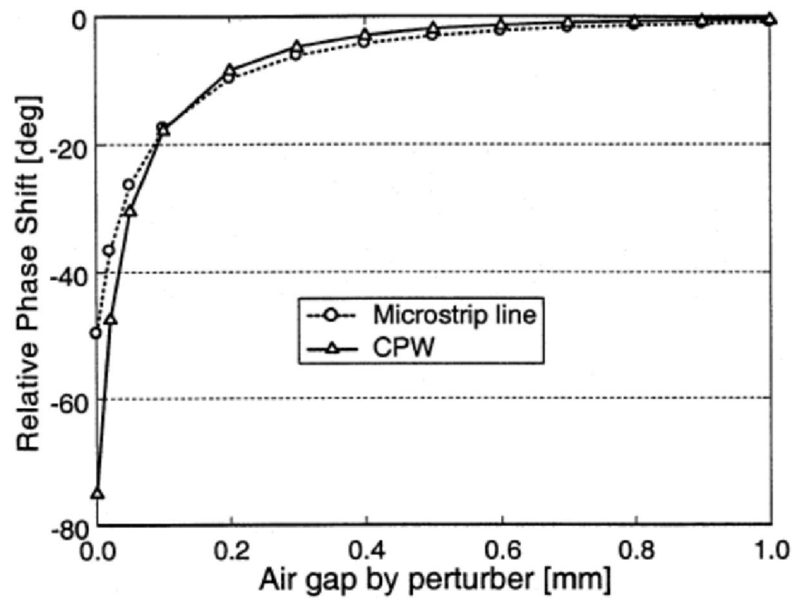
IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 13, NO. 1, JANUARY 2003 19

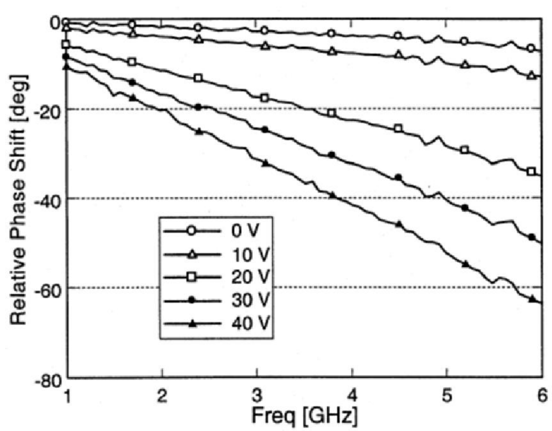
Time-Delay Phase Shifter Controlled by Piezoelectric Transducer on Coplanar Waveguide

Sang-Gyu Kim, Tae-Yeoul Yun, and Kai Chang, *Fellow, IEEE*

60GHz (steerable) Array





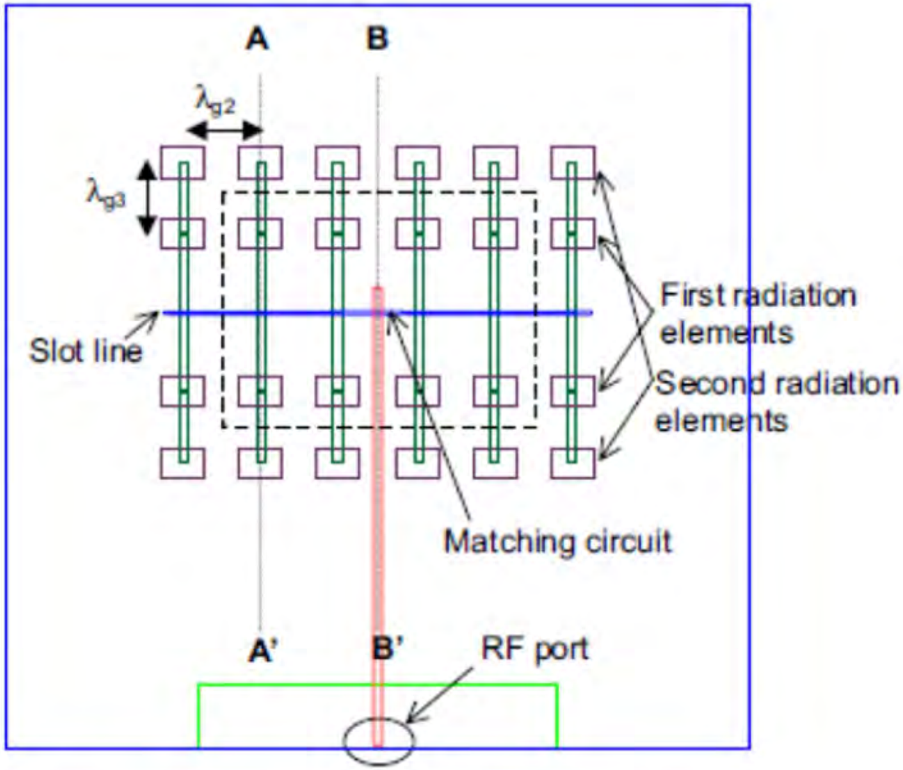


IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 13, NO. 1, JANUARY 2003 19

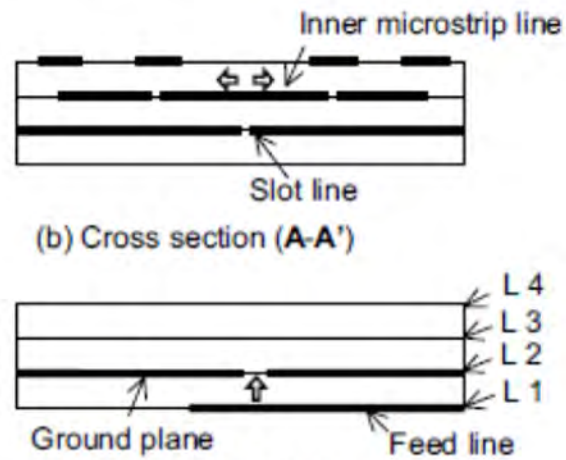
Time-Delay Phase Shifter Controlled by Piezoelectric Transducer on Coplanar Waveguide

Sang-Gyu Kim, Tae-Yeoul Yun, and Kai Chang, *Fellow, IEEE*

60GHz (steerable) Array



(a) Configuration of 24 (4x6)-element antenna



(b) Cross section (**A-A'**)

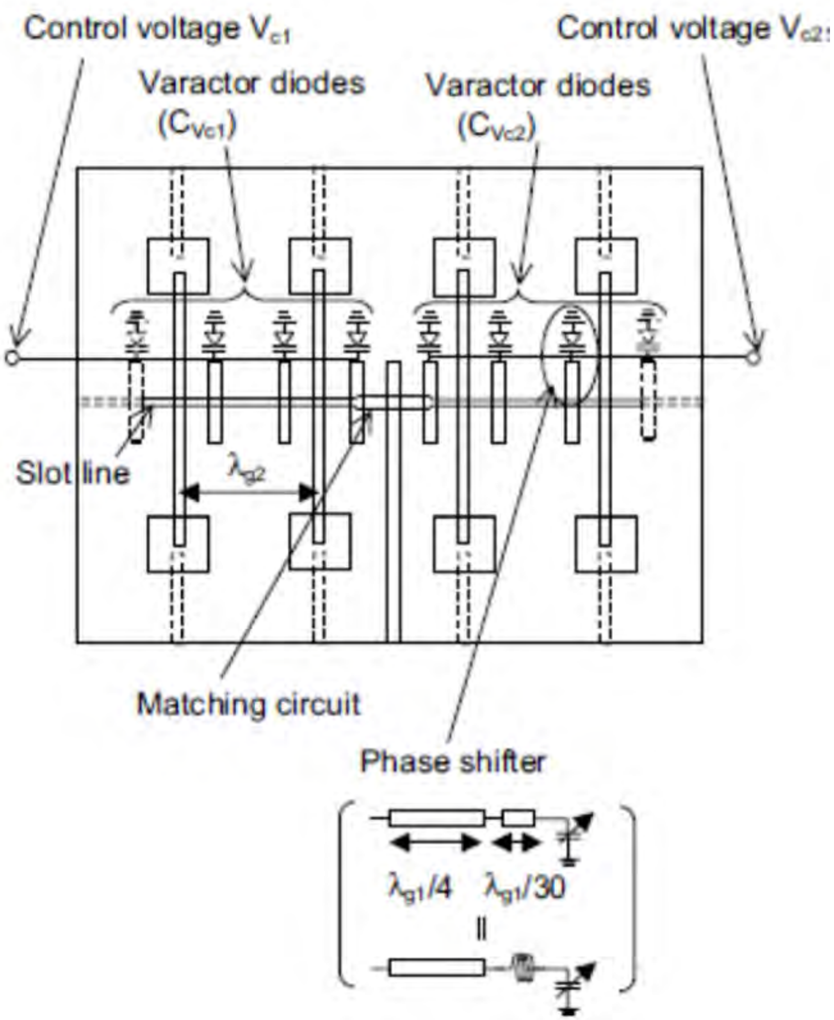
(c) Cross section (**B-B'**)

Fig. 2. Antenna structure
(Substrate: $\varepsilon_r = 2.2$, $\tan\delta = 0.002$, Conductor: copper).

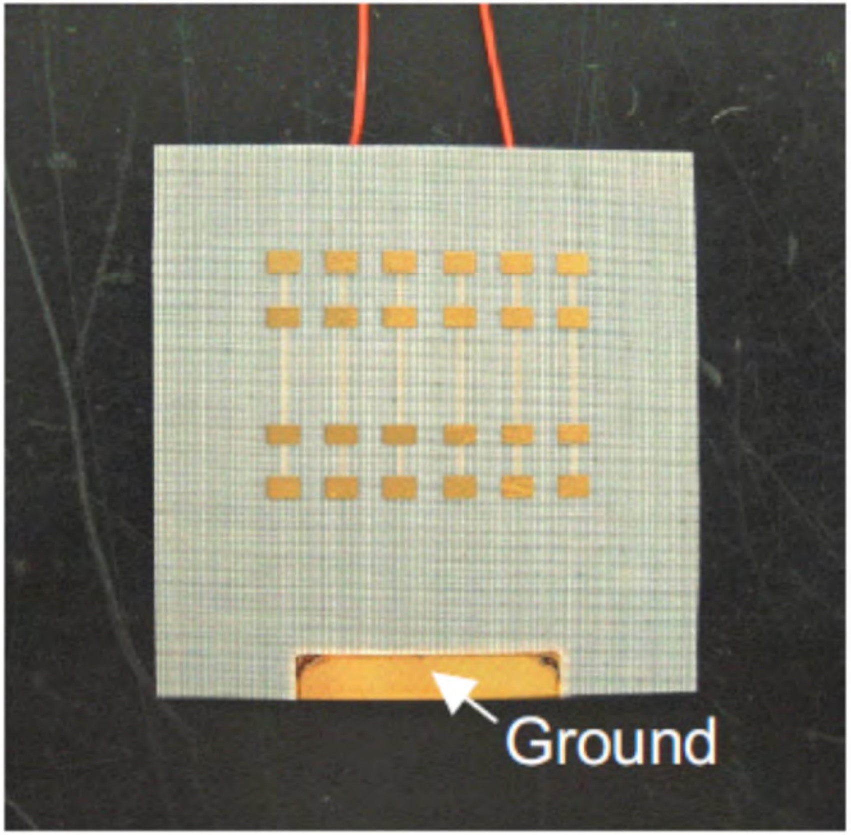
Beam-steerable Planar Array Antennas Using Varactor Diodes for 60-GHz-band Applications

Hiroki Tanaka and Takashi Ohira

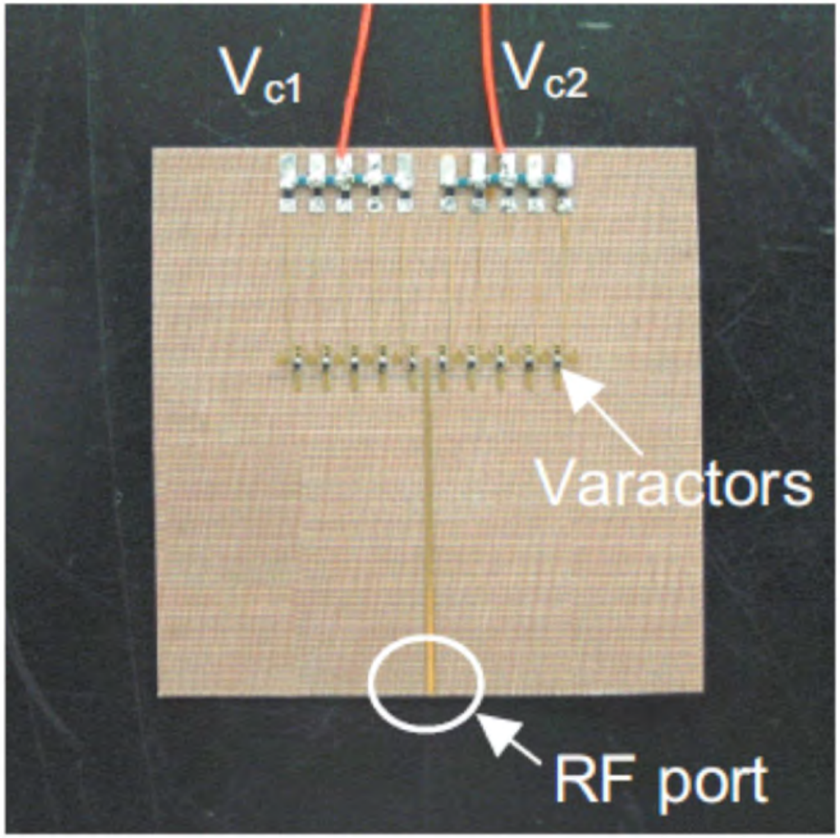
60GHz (steerable) Array



60GHz (steerable) Array

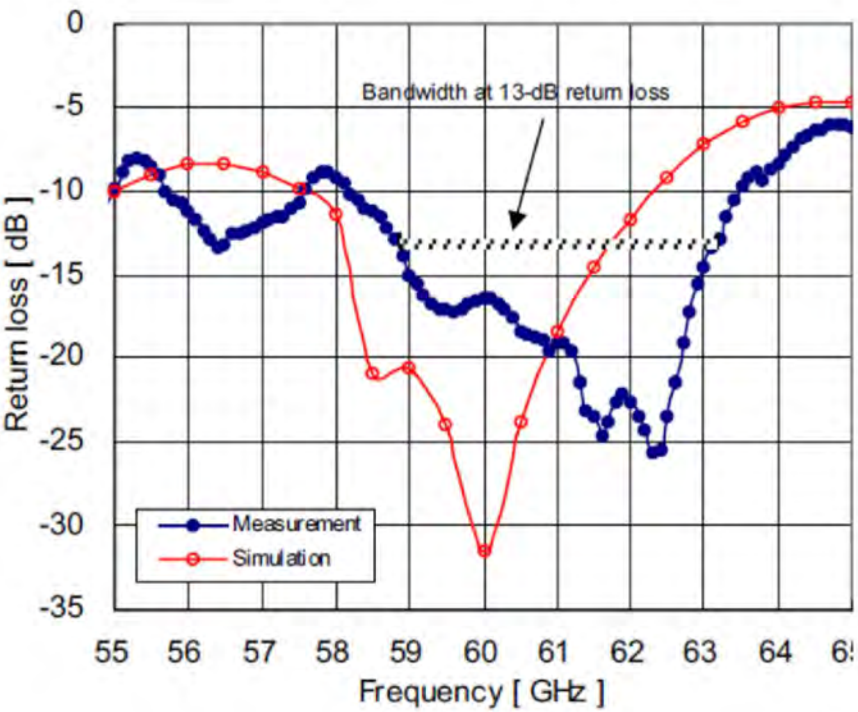


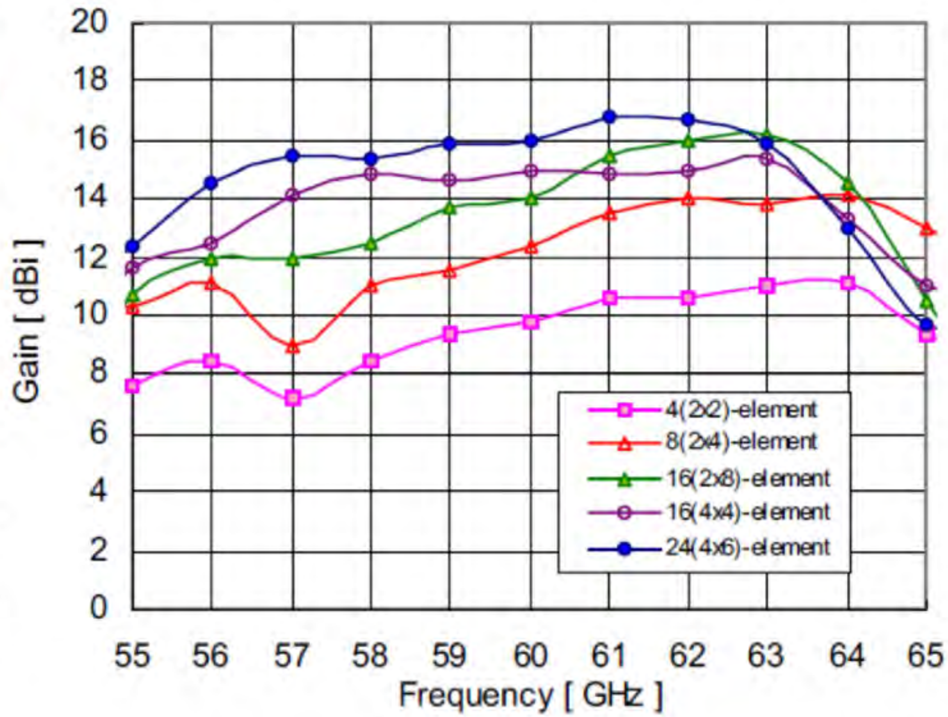
(a) Top side



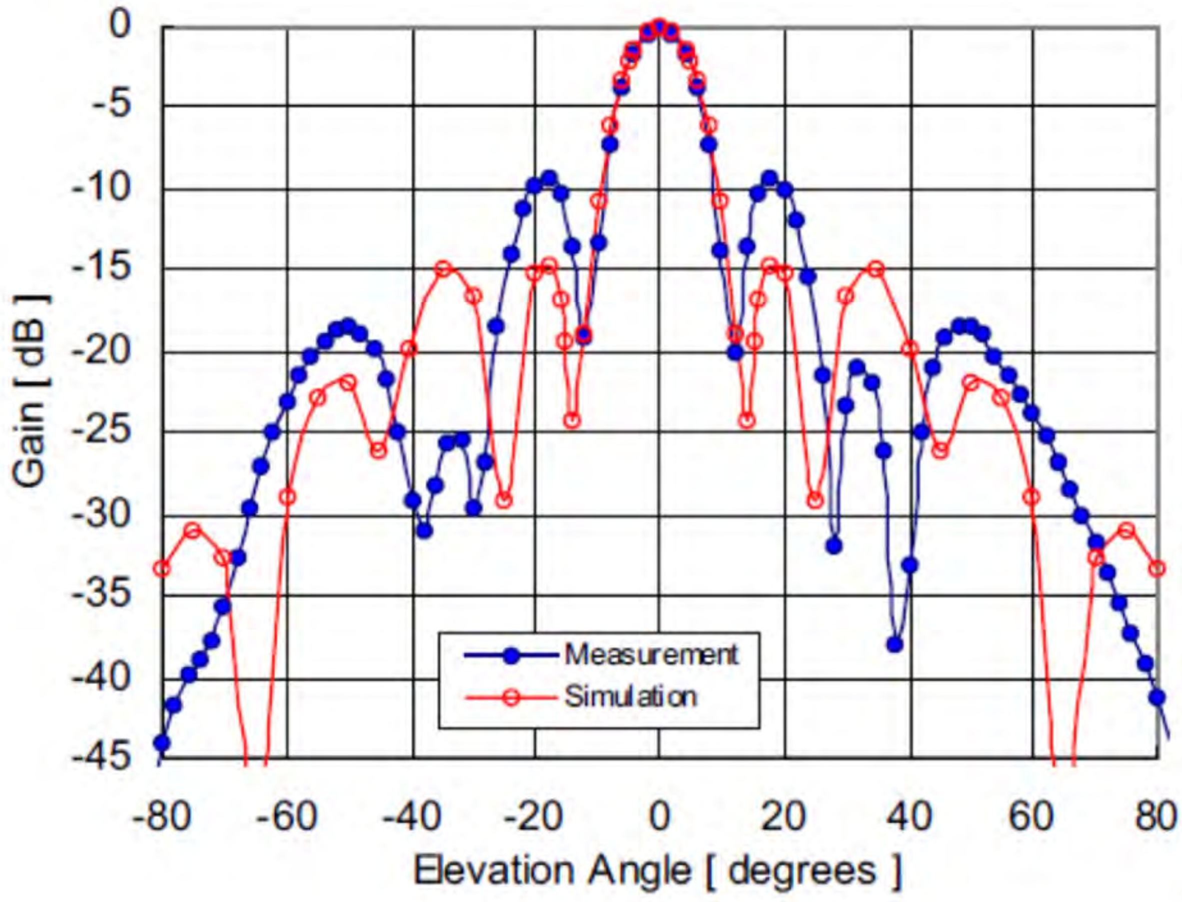
(b) Bottom side

60GHz (steerable) Array

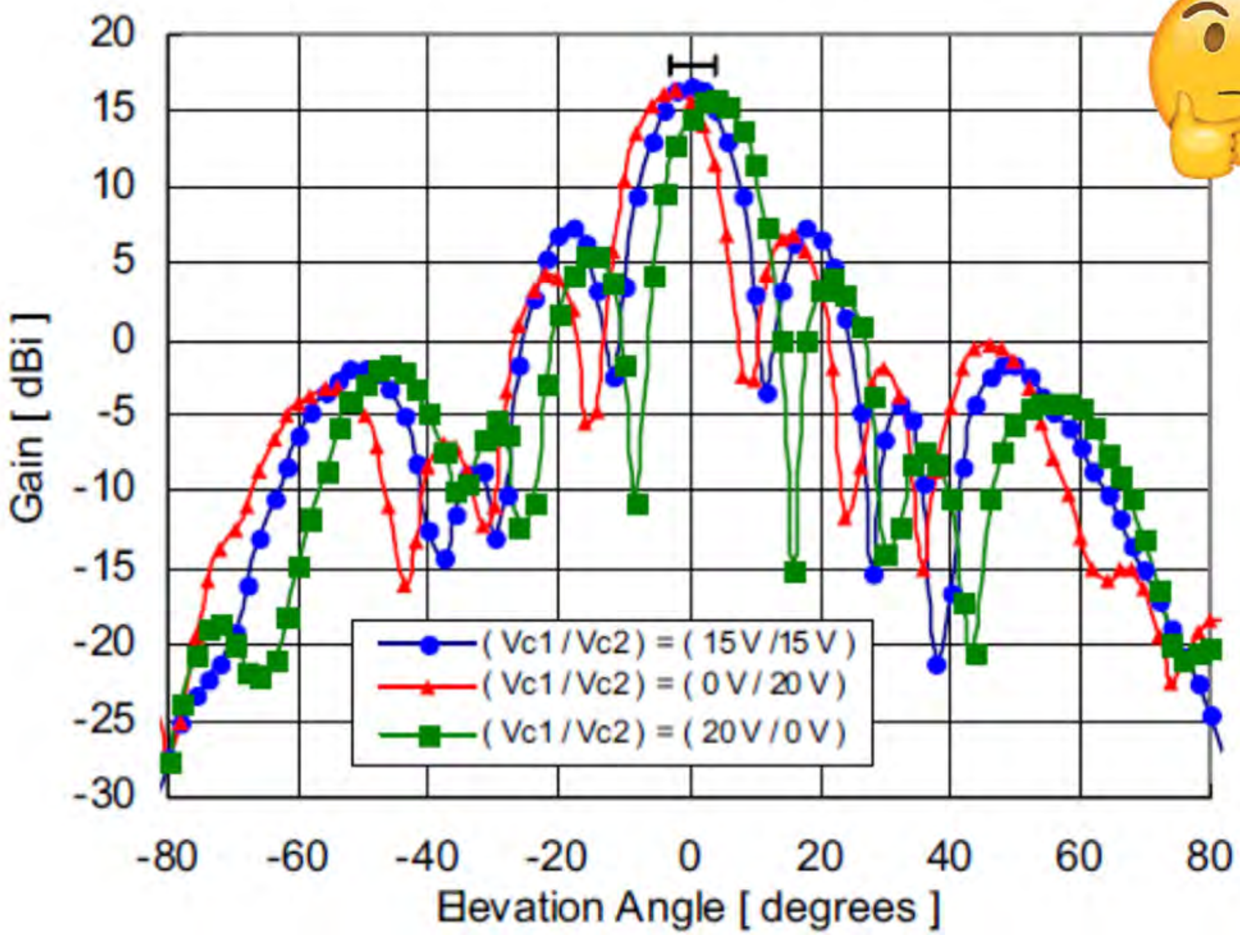




60GHz (steerable) Array



60GHz (steerable) Array



…60GHz Antennas?

- Element should work at 60GHz with a 5GHz band
- Losses should be minimized
- Element should be small enough to allow its integration in an array
- Steerable
- Planar printed technology would permit immediate integration with the electronics

And that’s all Folks….