

# Multi-Dimensional and Multi-Functional Substrate Integrated Waveguide Antennas and Arrays for GHz and THz Applications: An Emerging Disruptive Technology

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## Outline

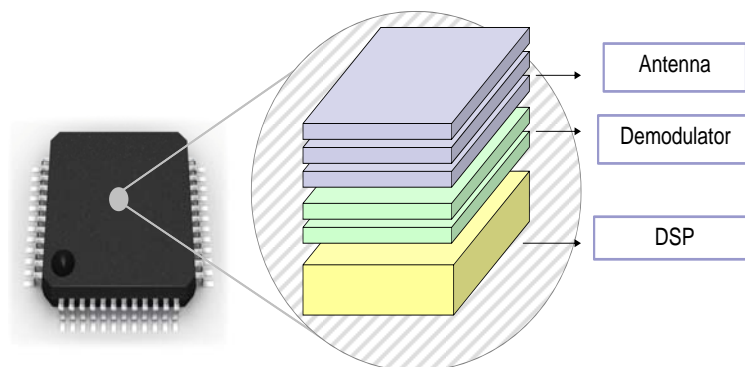
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- Introduction
- Substrate Integrated Waveguide (SIW) Techniques
- Integrated SIW Antennas and Arrays
- Multi-Dimensional Lego-Style Design
- Multi-Functional & Multi-Format Schemes
- Conclusion and Future Outlook

## Introduction

Sketched high-density fully Integrated GHz/THz platform for Machine-to-Machine (M2M) and Internet of Things (IoT)

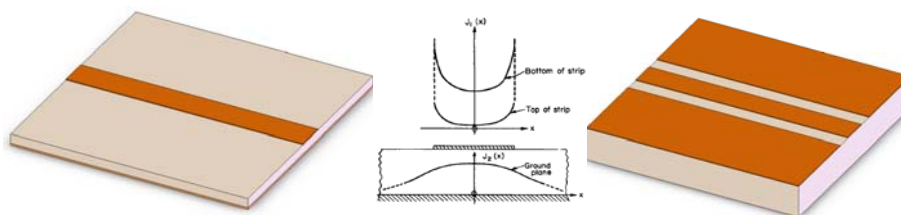
- Interconnectivity of 5G Systems (5B people & 50B things) -



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## "Good", "Bad" and "Ugly"

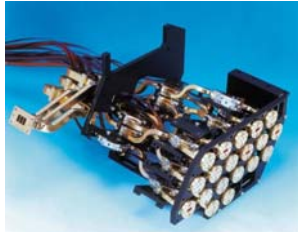
Mainstream planar techniques



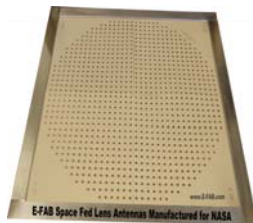
- Antenna design vs. array design (circuit effect)
- Integrated and easy-to-design radiating element
- Low-cost and small form factor
- Parasitic coupling and unwanted radiation
- Difficult-to-achieve large array efficiency
- Sensitive bandwidth and millimeter-wave hurdle

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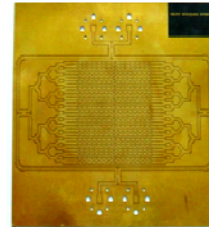
## Typical Examples and Evolution



- Heavy
- Bulky
- Need annual assembly



- Loss -> gain saturation\*
- Radiation loss -> SLL degradation and gain loss

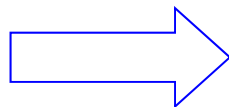
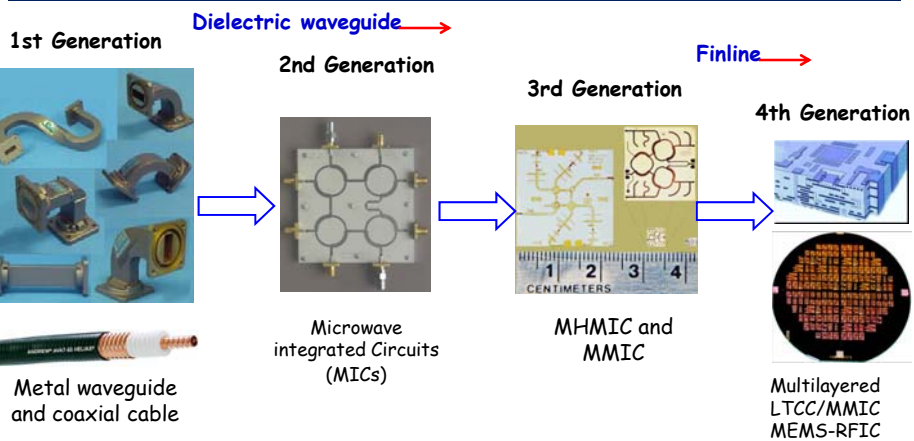


- SIW loss < microstrip
- PCB process
- Light weight/low-profile

\* P. S. Hall and C. M. Hall, "Coplanar corporate feed effects in microstrip patch array design," *Proc. Inst. Elect. Eng.*, vol. 135, pt. H, pp. 180–186, June 1988.

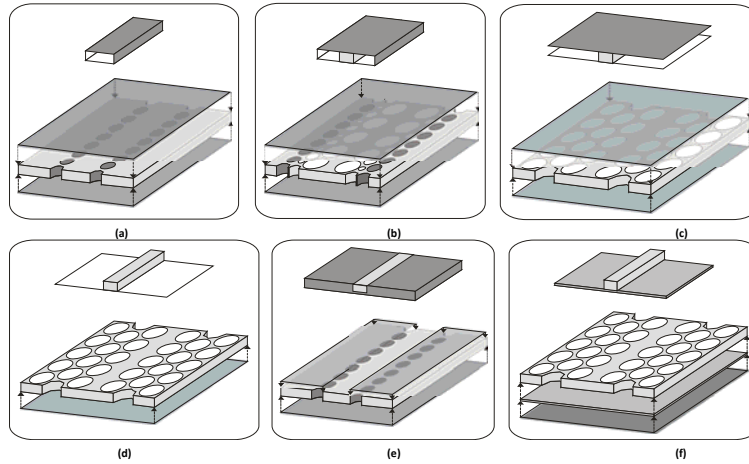
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## Evolution of GHz/THz Technologies



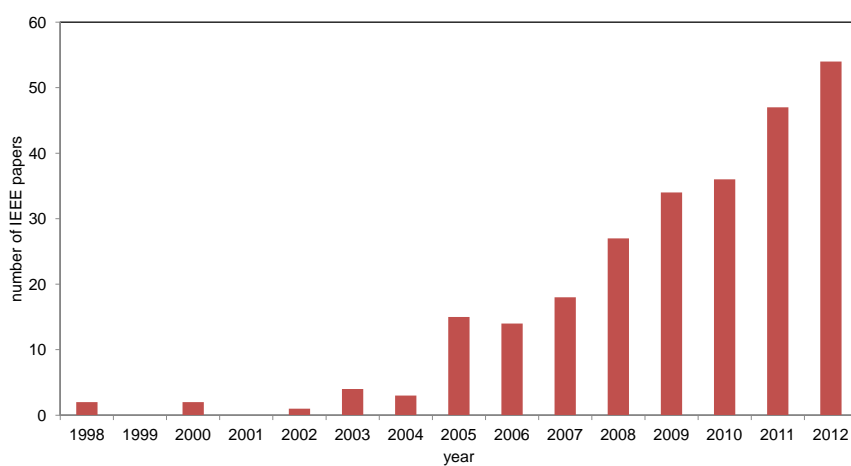
**What's next ? .....**  
**Substrate Integrated Circuits (SICs)!**

## Substrate Integrated Waveguide (SIW) Techniques



Synthesized Waveguides and Substrate Integrated Circuits (SICs)  
*non-planar structure in planar form*

## SICs-Related IEEE Publications



Courtesy of Maurizio Bozzi



## DIVINE INNOVATION: 10 TECHNOLOGIES CHANGING THE FUTURE OF PASSIVE AND CONTROL COMPONENTS

**In "The Innovator's Dilemma" (1997), Clayton Christensen, Professor of Business Administration at the Harvard Business School, coined the term "disruptive technology" to describe innovation that changes the fundamentals of an existing market and related value network through displacement of an entrenched technology. Although the phrase connotes an abrupt transition, the innovation itself often takes years to develop and be adopted.**

Christensen described a process by which a product or service initially took root in simple applications at the bottom of a market and then repeatedly moved "up market," eventually displacing established competitors. In contrast, he defined "sustaining innovation" as a continuous evolution of an existing technology by the established market leaders to remain competitive. This type of innovation does not necessitate creating new markets, but does have the ability to transform the market with better products and services. Yet it is the disruptive technology that drastically lowers prices, enables new functionality or alters product efficiency, desirability or competitive advantage to the extent that the market is changed forever.

Established companies in technology-driven markets recognize the need for continual technology development, yet many remain vulnerable to unforeseen market transitions. Unfortunately, in today's current business climate many companies are unwilling to redirect their

resources resources away from immediately profitable ventures for fear that they cannot afford to invest their R&D beyond sustaining innovations, such as those needed to compete against current competitors. And yet, market leaders need to be on the alert for innovations occurring elsewhere in their industry, lest a game-changing technology transforms the market and leaves them behind.

In "The HP Phenomenon" (2006), Charles House and Raymond Price tell the story of how Hewlett-Packard innovated and transformed itself six times. Continually prevailing over each challenge, the company came across along the way. Early on, Packard observed that "change and conflict are the only real constants." As a result, HP developed internal philosophies, practices and organizational principles that led to a sequence of innovations and transformations, made possible through the company's customer-oriented, contribution-driven, and growth-focused approach.

The "HP Way," with its emphasis on bottom-up innovation and the flexibility to see results brought to the marketplace, is a classic example of what is required to develop disruptive technologies. Perhaps HP's most drastic game

### GaN Hybrid Amplifiers

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Part Number	Frequency Range (MHz)	Power (dBm)	Efficiency (%)	Package
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HM1005-1A	20-50	40	40	50
HM11005-1A	2700-4000	21	50	45
TM1005-02-10	100-2000	12	35	20
TM1005-03	100-2000	35	35	9



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### COVER FEATURE



**Fig 1** Examples of SIW construction showing metal (apertures) and dielectric layers along with via hole walls.

**SUBSTRATE INTEGRATED WAVEGUIDES FOR GREATER POWER HANDLING AND LOWER LOSS**

Substrate integrated waveguide (SIW) structures also known as laminated waveguide or post-wall waveguide have received some attention over the past several years. The construction offers easy fabrication while showing comparable electrical and mechanical performance with conventional rectangular waveguide. This new family of transmission line and distributed planar waveguide component is formed by a dielectric substrate and densely arrayed metalized posts or vias that form side-walls connecting upper and lower metal plates, which sandwich the substrate material. The metal layers along with the array of metalized vias define the waveguide walls as shown in Figure 1.

Developments in SIW technology target both multi-layer PCB and CMOS substrates and can be easily fabricated with through-hole techniques for low cost and mass-production. The post-wall waveguide is known to have similar guided wave and mode characteristics to conventional rectangular waveguide with equivalent guided wavelength. The result-

ing power handling capability and low loss performance of the SIW are much better than conventional transmission planar lines.

In the February Microwave Journal cover story, R. Holzman of Eltra Electronic Systems (Israel) wrote that "one current area of research is substrate integrated waveguide (SIW) components. Using this technique, some of the alumina filters may be replaced by SIW filters." In a Microwave Journal article appearing last December, Y. Yun employed a periodically arrayed grounded-strip structure (PAGS) on silicon substrate to create an ultra-wideband multi-section transformer using a Chebyshev polynomial design technique. At 0.026 m<sup>2</sup> on a silicon substrate, the resulting transformer was more than 60 percent smaller than the one fabricated using conventional coplanar waveguide and showed good HF performance over an ultra broadband from 9 to 49.5 GHz.<sup>1</sup>

High precision PCB manufacturing techniques including LTCC should support passive component design using SIW structures to extend up to the 100 GHz range while advanced micro-fabrication techniques, such as photo-etching, micromachining, CMOS process, and others, have the potential to push design of substrate integrated structures up to the hundreds GHz and THz ranges.<sup>2</sup>



**2**

**METAMATERIALS: MATERIALS UNBOUNDED OR WERE SCIENCE**

Metamaterials are synthetic materials constructed from periodically

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November Issue, Microwave Journal, 2011

## Interfaces/Transitions of Dissimilar Structures



Microstrip ↔ SIW



Waveguide ↔ SIIG



CPW ↔ SIW

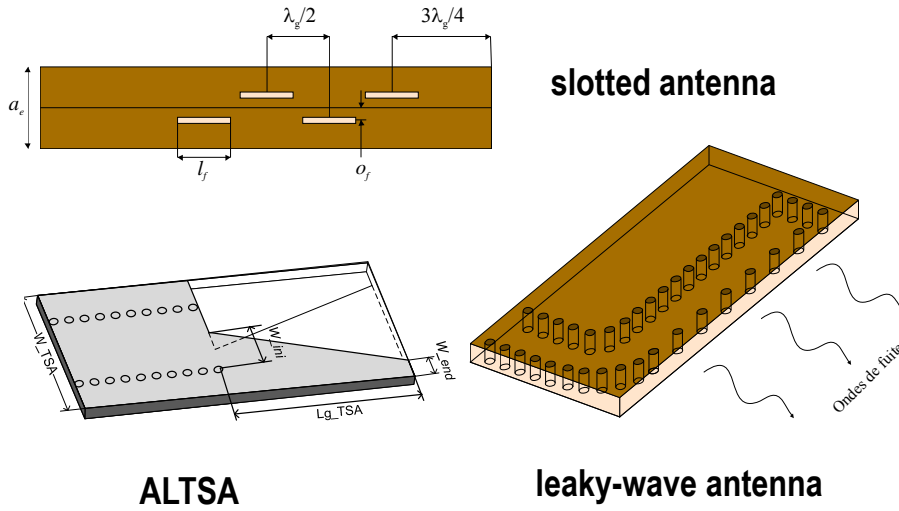


CPW ↔ SIIG

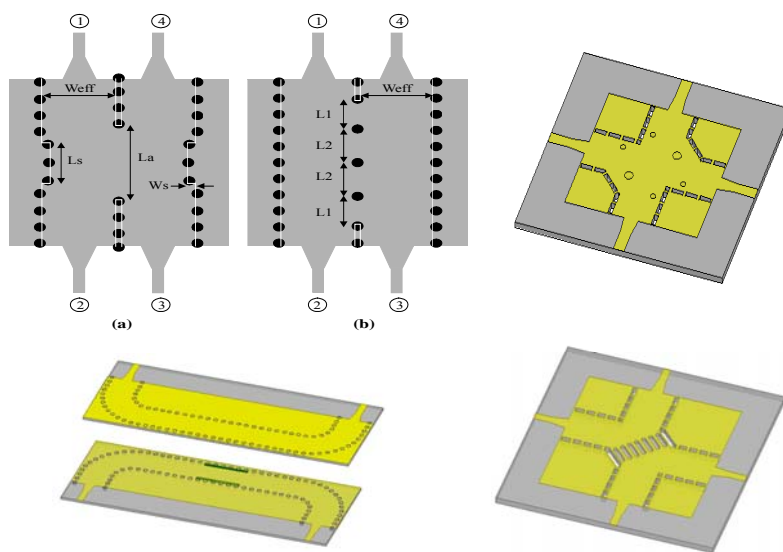
— Courant électrique  
- - - - - Champ magnétique

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## Basic SIW-based Antenna Elements

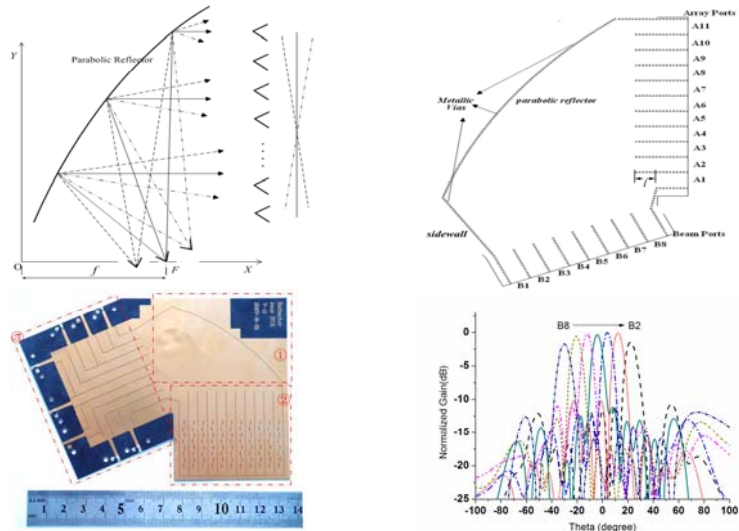


## Basic SIW-based BFN Building Blocks

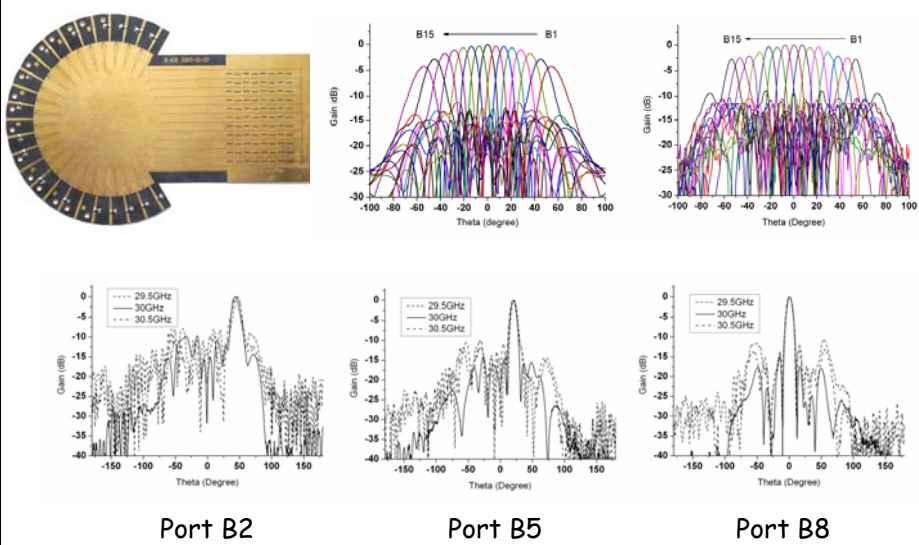


# Integrated SIW Antennas and Arrays

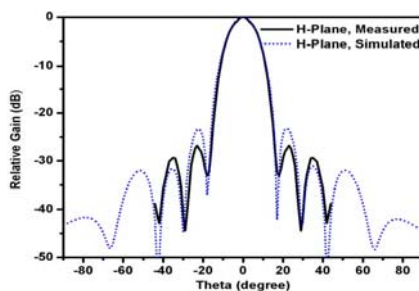
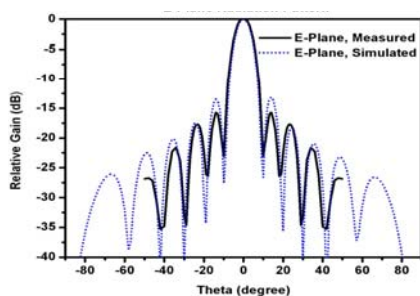
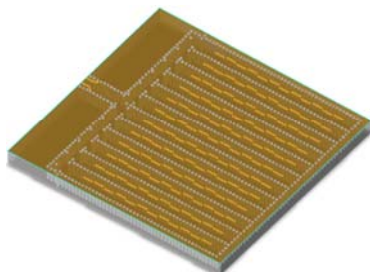
## Substrate Integrated Parabolic Reflector and Multibeam Antenna



## Substrate Integrated R-KR Lens

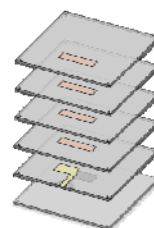


## 60-GHz High-Gain SIW Antenna Array System

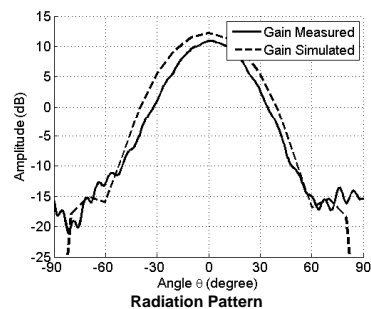


## First Vertically Stacked Yagi-like Antenna

- Designed at 5.8 GHz
- Measured gain: 11 dBi
- Bandwidth: 17%
- Elements can be: dipole, patch...
- Different polarisations can be used



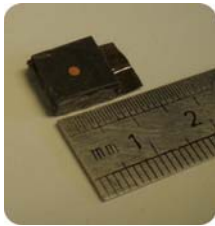
Photography of the prototype  
(80x80x29mm<sup>3</sup>)



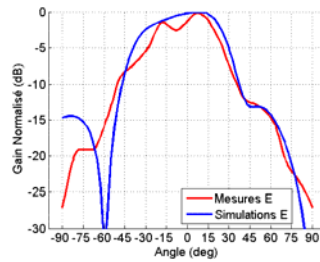


## 60 GHz Vertically Integrated Yagi-like Antenna

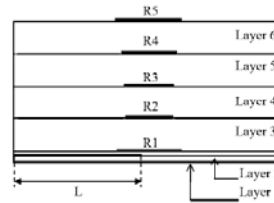
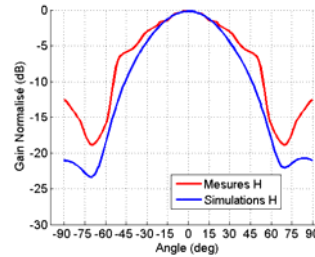
- Bandwidth: 4.2%
- Circular patch is used (driver & director)
- Measured gain: 11 dB



Prototype



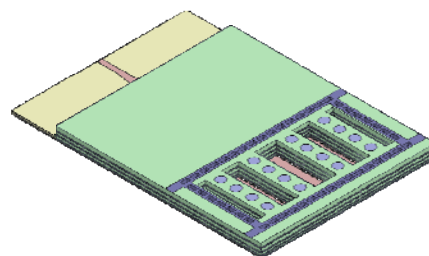
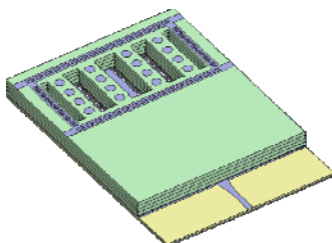
Radiation Pattern



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## Vertically Stacked Yagi-like Antenna Array

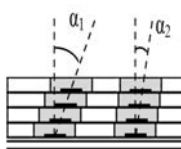
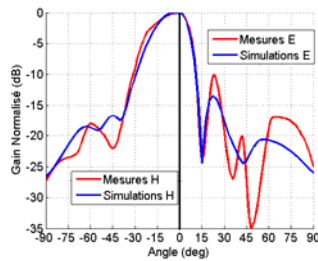
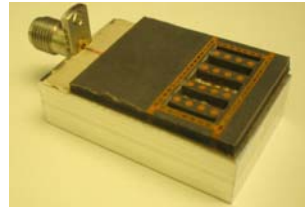
- SIW feeder
- 4x4 array of Yagi antenna at 60 GHz
- Array branch spacing  $\sim 0.9\lambda$
- Air slots used to reduce coupling
- Metalized slot around patch structure



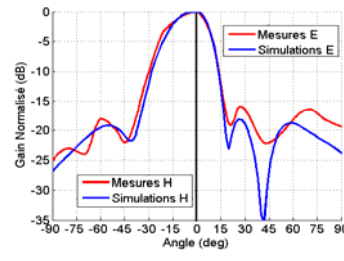
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## Prototypes and Results

- Bandwidth: 10% à 60 GHz
- Size: 28 x 24 x 2.4 mm
- Measured gain: 18 dBi (simulated: 19dBi)
- High SLL (can be reduced)



Angled elements



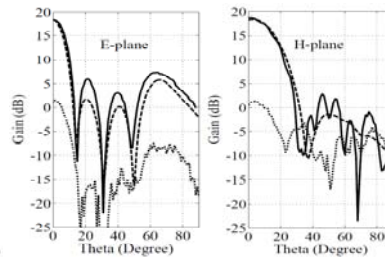
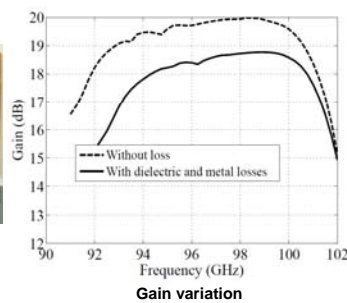
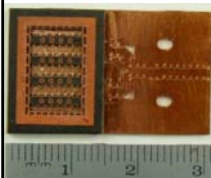
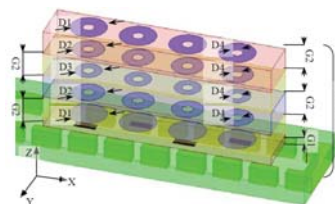
Radiation Pattern

Radiation Pattern

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## 98 GHz Vertically Stacked Yagi-like Array

- Wide bandwidth (7.5 GHz at 98 GHz)
- 19 dBi Gain
- Stable gain & radiation pattern
- Estimated 90% radiation efficiency



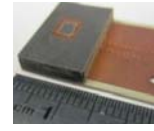
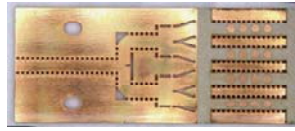
Radiation patterns at 98.75 GHz  
(sold: measured, dashed: simulated)

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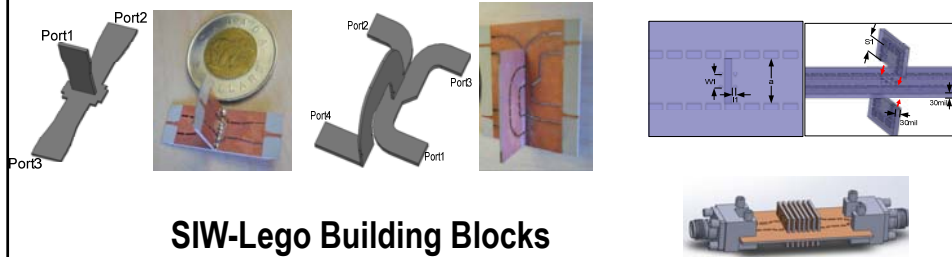
## Multi-Dimensional Lego-Style Design

Compelling advantages of multilayered and 3-D structures:

- ☞ Small footprint
- ☞ Higher array gain
- ☞ Different polarization
- ☞ Wide bandwidth
- ☞ Multi-beam
- ☞ Possible E-plane expansion with Lego-style design

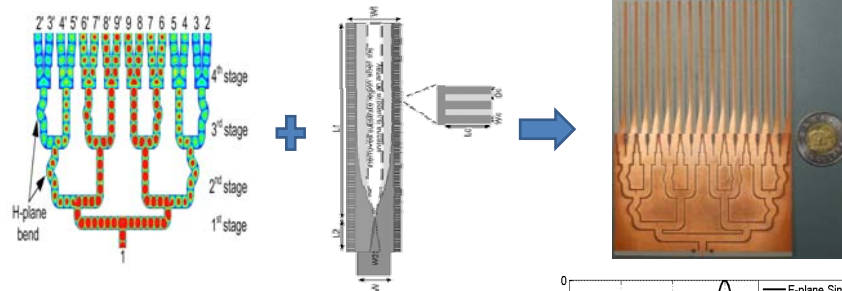


E-band array prototype    70-105 GHz integrated horn

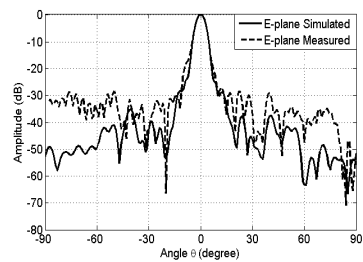


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## SIW Feeder for Fermi Tapered Slot Array

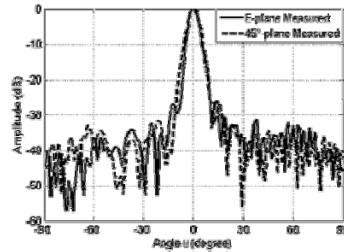
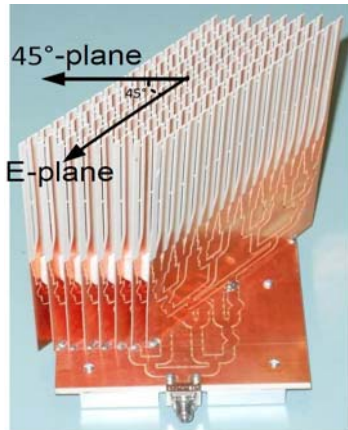


- Bandwidth of 21.1% at 35GHz
- Design spacing at  $0.68 \lambda$
- Measured gain of 23.4 dBi (simulated 24.5 dBi)
- SLL of 27 dB
- Bandwidth of  $5.3^\circ$  in E-plane



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## 3-D SIW Fermi Tapered Slot Array

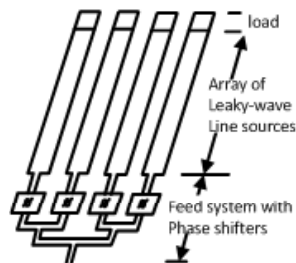


- Bandwidth: 21.1%
- Gain: 27 dBi.
- SLL of 26 dB in two planes.
- Beamwidth of 5.15° in E-plane and 6.20° in D-plane (45°).
- Network efficiency of 61%
- Weight: 175g

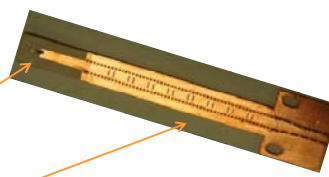
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## Two-Dimensional SIW Scan Array Antenna

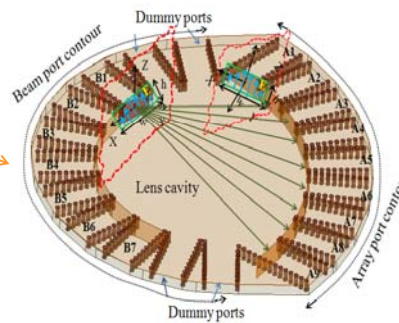
- Frequency scan in one plane
- Phase shift control in the orthogonal plane



Schematic for simple 2D scanning



Leak-wave antenna

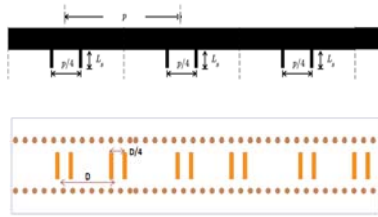


Simulated SIW Rotman lens diagram

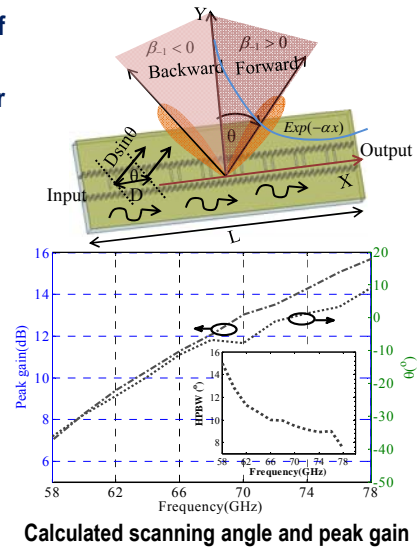
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## Leaky-Wave Antenna (LWA) Block

- Angle of the main beam is a function of the first radiating space harmonic
- Gain increases with  $f$  due to a larger electrical length of antenna at higher  $f$



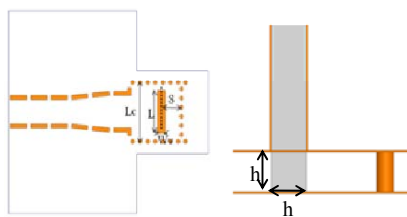
Reflection cancellation forward wave LWA



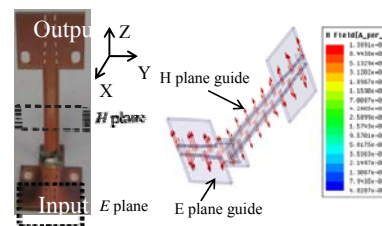
Calculated scanning angle and peak gain

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## 2-D Scan Array Antenna Element

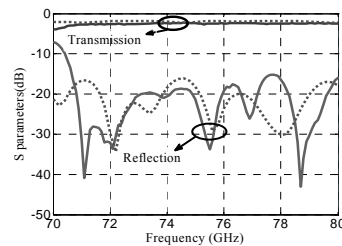


Proposed E2H corner



H fields coupling through corner for TE<sub>10</sub> mode

- Measured bandwidth (return loss  $\leq -15$  dB) of 11.9% covers frequency range from 71 GHz to 80 GHz
- Measured insertion loss is  $\leq -2.3$  dB over the entire bandwidth

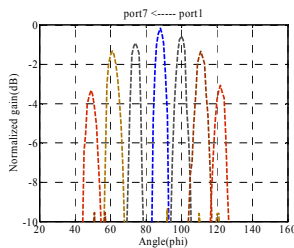
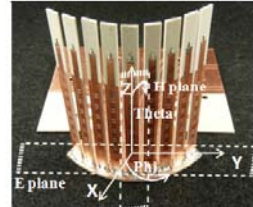
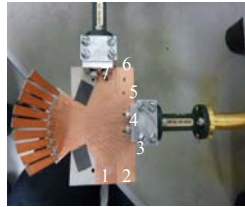


Simulated (dashed) & measured (solid)

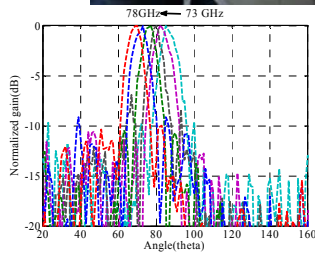
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## 2-D Scan Array Antenna Prototype

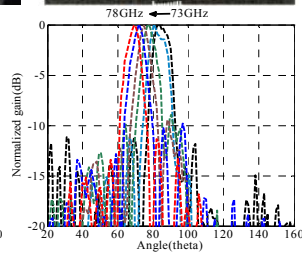
Multibeam antenna can efficiently cover a solid angle of  $(49^\circ, 84.5^\circ)$  to  $(120^\circ, 70^\circ)$  with multiple beams



Measured E-plane patterns excited from ports 1-7 at 75 GHz



Measured H-plane patterns excited Input port 1

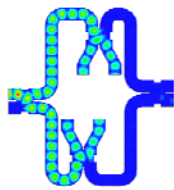


Input port 4

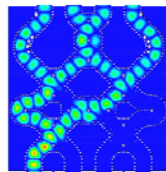
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## Different SIW-based Beamforming Networks

Butler Matrices

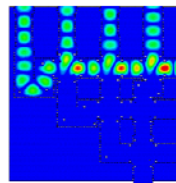


Without cross

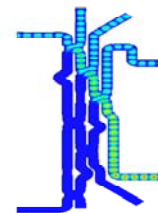


Ultra wideband (30%)

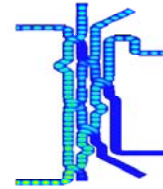
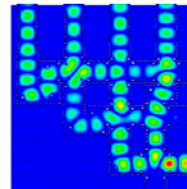
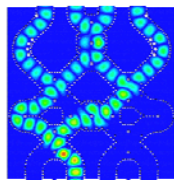
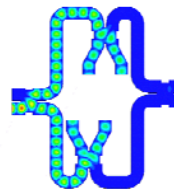
Nolen Matrices



Beam squint control



Delay compensation



K. Wu, et al., "Substrate integrated millimeter-wave and terahertz antenna technology," *Proceedings of the IEEE*, pp. 2219-2232, Vol. 100, No. 7, July 2012

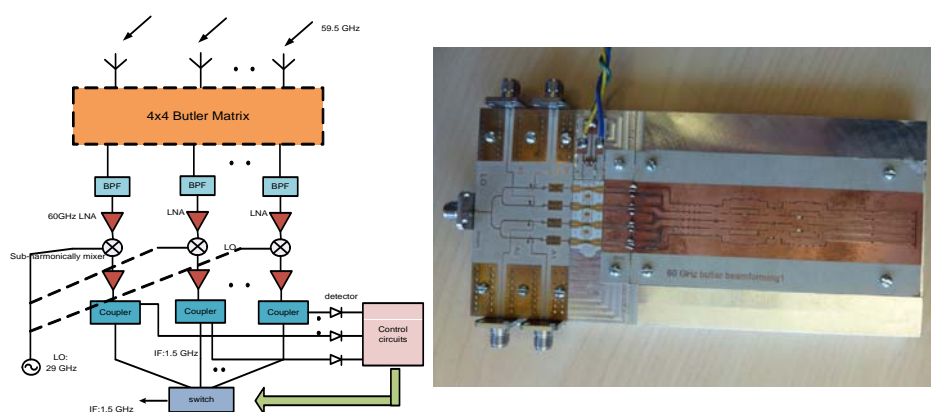
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## Multi-Functional & Multi-Format Schemes

- Dual-polarization systems
- Circular polarization techniques
- Millimeter-wave MIMO systems
- Active and smart antennas
- Tunable and reconfigurable antennas and arrays
- Multi-band and multi-beam systems
- Mixed waveguide design platforms
- Hybrid radio and radar antenna architectures

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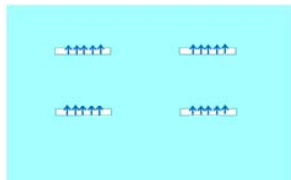
## Millimeter-Wave (60 GHz) Smart Array System



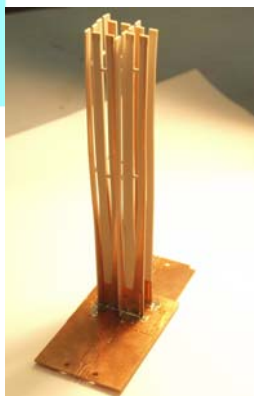
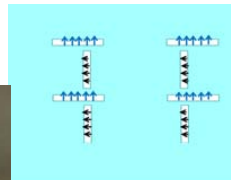
30

## Dual-Linearly Polarized Antenna Design

Single Linearly Polarized Array

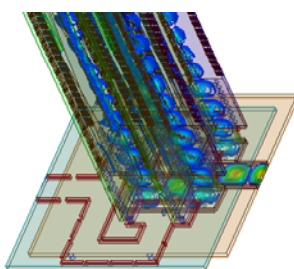


Dual Linearly Polarized Array

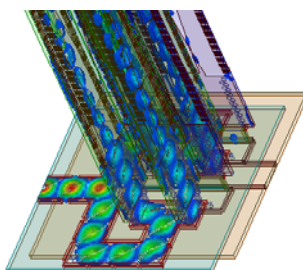


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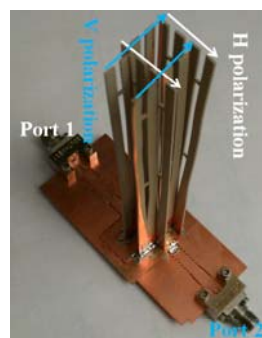
## V-pol and H-pol High-Gain Antennas



V-Polarization



H-Polarization

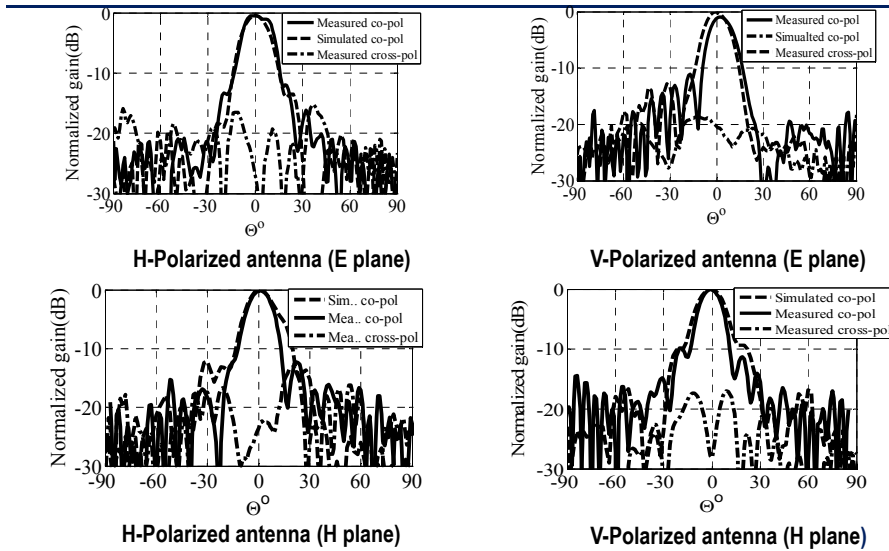


Experimental Prototype

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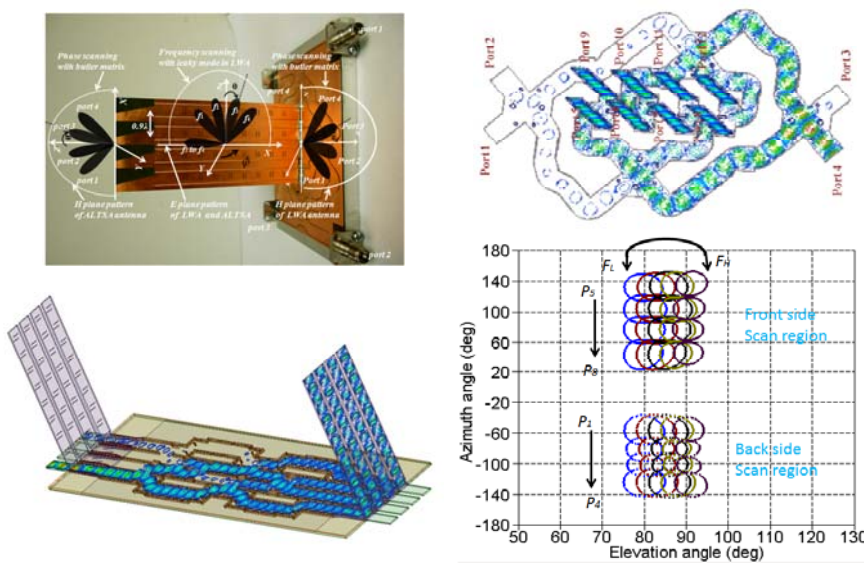


## Simulated and Measured Results



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## 30 GHz Multi-Dimensional Scan Phased Array System



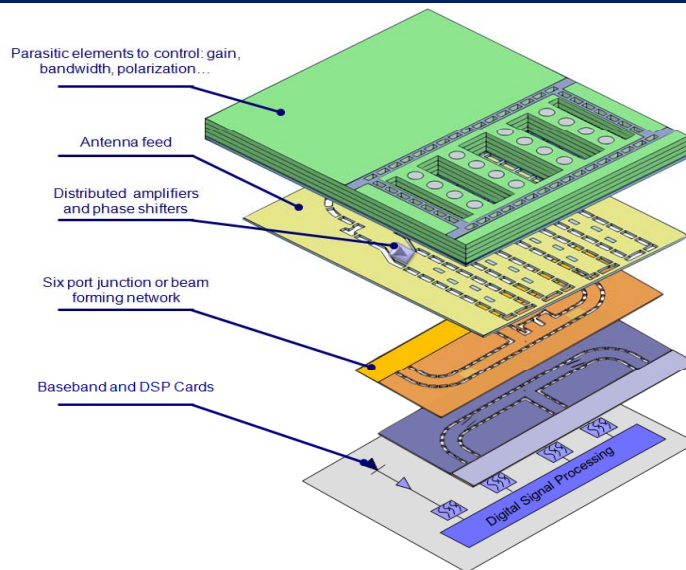
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## Conclusion and Future Outlook

- Recent achievements are presented in connection with the design and development of low-cost SIW antenna and array architectures.
- Multi-dimensional small-footprint and high-gain antenna arrays are shown for millimeter-wave applications.
- Vertically expanded LEGO building blocks and multi-format/multi-functional design techniques are demonstrated for various system developments.
- Future GHz and THz systems will benefit from this research with a further expansion of SICs-based mixed waveguide techniques in conjunction with emerging materials.

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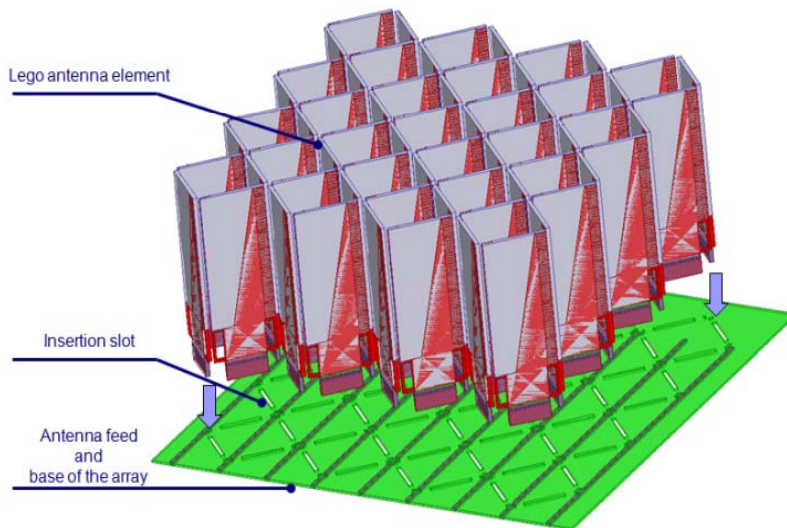
## Example of Stacked Multilayered SIW Integrated Antenna Arrays



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## Illustrative LEGO-style Design of an Antenna Array System

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## Acknowledgements

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- ☺ Many year contributions by the speaker's students and research fellows as well as technical support of technologists at the Poly-Grames Research Center have made this presentation possible
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- ☺ Research collaborators including Dr. Wei Hong and his team at Southeast University, Dr. Maurizio Bozzi and his colleagues at University of Pavia and others have made contributions to this presentation