Abstract/Keywords

Abstract: In this presentation, the recent research activities on "Small and Wideband Patch Antennas and Planar Microwave Circuits for Wireless and Biomedical Applications" conducted by the research group led by Associate Professor Yongxin Guo at the Department of Electrical and Computer Engineering, National University of Singapore will be reported.

The topics on "Antennas and Wireless Power for Biomedical Applications" has received a lot of attention. On-body antennas for wearable applications and In-body antennas for bio-implants will be presented first. Wireless power and energy harvesting have become more important to enable bio-telemetry. In addition to the traditional inductive near-field wireless power, capacitive wireless power and far-field wireless power will also be addressed. In the meantime, effort has been made to improve the dynamic range of the rectifier circuit for the energy harvesting, especially for low-power scenarios.

The topic on "Small and Wideband Patch Antennas" has been focused previously. The wideband L-probe feeding technique will be introduced here. In the meantime, wideband patch antennas with broadband feeding networks will be presented. The antenna performance can be improved significantly in a wide bandwidth with the proposed broadband feeding networks. Various wideband millimeter-wave antennas-in-package and on-chip antennas will also be reported for future system in package applications since antennas are small in size at higher frequencies.

"MMIC modeling and design" is another topic we are put effort on as it is crucial to develop high-density integrated transceivers for wireless and biomedical applications. It is believed that developing high-density integrated transceiver technologies for wireless and biomedical applications will attract more interests.

Keywords: Wideband patch antennas, small antennas, wearable antennas, implantable antennas, antennas in package, on-chip antennas, wideband feeding networks, wireless power, inductive wireless power, capacitive wireless power, far-field wireless power, RF energy harvesting, MMIC, LTCC.
Briefbio

Dr Yong Xin Guo joined the Department of Electrical and Computer Engineering, National University of Singapore (NUS), as an Assistant Professor in February 2009 and was promoted to an Associate Professor with tenure in Jan 2013. He received the B.Eng. and M.Eng. degrees from Nanjing University of Science and Technology, Nanjing, China, and the Ph.D. degree from City University of Hong Kong, all in electronic engineering, in 1992, 1995 and 2001, respectively. From September 2001 to January 2009, he was with the Institute for Infocomm Research, Singapore, as a Research Scientist.

He has authored or co-authored 171 international journal papers and 176 international conference papers. Thus far, his publications have been cited by others more than 2086 times and the H-index is 28 (source: Scopus). He holds one Chinese Patent, one U.S. patent and one filed PCT patent. His current research interests include small and wideband patch antennas, implantable/wearable antennas, on-chip antennas and antennas in package, RF energy harvesting and wireless power, MMIC modeling and design, etc.

Dr Guo was General Chairs and TPC Chair for a few IEEE conferences. He is serving as Associate Editors for the IEEE Antennas and Wireless Propagation Letters (AWPL), IET Microwaves, Antennas & Propagation and Electronics Letters. He was a recipient of the Young Investigator Award 2009, National University of Singapore. He received 2013 Raj Mittra Travel Grant Senior Researcher Award. He received the Best Poster Award in 2014 International Conference on Wearable & Implantable Body Sensor Networks (BSN 2014), Zurich, Switzerland. He is a co-recipient of of Design Contest Award of the 20th International Symposium on Low Power Electronics and design (ISLPED), Rome, Italy, July 2015. His PhD students received Best Student Paper Awards from IEEE MTT-S IMWS-Bio 2015 in Taiwan, IEEE iWEM 2013 in Hong Kong, 2011 National Microwave and Millimeter-Wave Conference at Qingdao, China and IEEE ICMMT 2010 in Chengdu, China.

Research Areas

High-Density Integrated Transceiver Technologies for Wireless and Biomedical Applications

- MIC / MMIC
- EM / Antenna
- RF Energy Harvesting

Microwave and millimetre-waves
- Microwave semiconductor device modelling and characterisation
- LTCC based System-in-package technology
- (1) Wideband antennas; (2) multiband antennas; (3) small antennas; (4) Tunable antennas; (5) New material antennas
- (1) LTCC on-package antennas; (2) CMOS on-chip antennas
- (1) Wearable and Implanted antennas; (2) Inductive power transmission for implants; (3) In-body and on-body channel modeling; (4) Heating and SAR for implanted devices.
# Outline

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| Secondary Area: Microwave circuits                |                                                     |       |
| MMIC modeling and design                          |                                                     | 141-155|
| Advanced passive devices                          |                                                     | 156-165|

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# Lab Facilities

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On-/In-Body Antennas for Bio-Medical and Healthcare

Demand for utilization of wireless telemetry systems in medicine has recently significantly increased due to needs for early diagnosis of diseases and continuous monitoring of physiological parameters.

Small Wideband On-body/In-Body Antennas

Wireless Medical Communications

• The ageing population poses many challenges to healthcare systems, especially on chronic illness management. **Early warning systems using body sensor networks are necessary** for human health.
• There is a need for cable clutter to be reduced in the hospital setting. **Wearable and wireless biosensors** can address this need.

**Philips wearable sensors (no wireless)**

**Self-powered wireless sensor plaster for ECG, respiratory rate, position**

**Self-powered wireless wristband for blood press, temperature, etc.**

**Health Cloud**

**Applications for doctors/ nurses**

Wireless Implantable Neuroprobe Microsystems

• A potential treatment for paralysis (e.g. tetraplegia) is to route control signals from the brain around the injury. Such signals could control electrical stimulation of muscles and restore movement of paralyzed limbs.

**Recording of Neural Signal Using Implanted Microelectrode Array**

**Pre-processing and Wireless Transmission of Recorded Signal**

**Actuation of Prosthesis to Achieve Desired Task**

**Off-site Real-Time Processing of Signal for Prosthesis Control**

**Visual and Tactile Feedback to Recording Site**

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Peripheral Nerve Prothesis

- The signal from the injured nerve can be detected and decoded, and then transmitted to stimulating electrodes implanted in multiple target muscles to restore dexterous hand function after nerve injury.

Capsule Endoscopy

- Capsule endoscopy is a way to record images of the digestive tract for use in medicine. The capsule is the size and shape of a pill and contains a tiny camera. After a patient swallows the capsule, it takes pictures of the inside of the gastrointestinal tract. The primary use of capsule endoscopy is to examine areas of the small intestine that cannot be seen by other types of endoscopy such as colonoscopy or esophagogastroduodenoscopy (EGD).
Implanted Antennas

Efficient implantable antennas are crucial to establish the reliable wireless link in the communications between the implants and the external devices or between wearable devices and external devices.


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Printing Technology for On-Body Antennas


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Dual Band Metamaterial antenna for body centric communications


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System block diagram and conceptual drawing of fully implantable wireless neural recording microsystem


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The FPGA board generates the data for transmission. The two frequencies of transmitter output are 433.92 MHz and 542.4 MHz. The transmitter is directly connected with the differential dual-band implantable antenna embedded in minced pork, eliminating the usage of baluns and matching circuits. The external half-wavelength dual-band dipole, which is spaced 20 mm apart from the implanted antenna, is connected with the signal analyzer.

The transmitter output power is around -23 dBm, the received power by the external dipole is around -56 dBm. Therefore the path loss is around 33 dB, and the theoretic result from HFSS simulation of the coupling strength is around -29 dB at a coupling distance of 20 mm.
In-Vivo Tests of A CP Antenna


Dual-band Capsule Antenna

Wireless Power and RF energy harvesting

• Introduction:
  - Need for Wireless Power and Data Telemetry
• Wireless Power Delivery Schemes
  - Near-field Inductive Power Transfer Links
  - Near-field Capacitive Power Transfer Links
  - Far-field Power Transfer Links
• RF Energy Harvesting

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Wireless Power and RF energy harvesting


Related Patent Applications:
Y.X. Guo, Z. Zhong, H.C. Sun, Rectenna circuit elements, circuits, and techniques for efficiency wireless power transmission or ambient RF energy harvesting, filed for PCT on Feb 27, 2014, PCT international publication number WO 2014/113461 A1; US application number 14/767,125; Chinese Patent Application No. 201480011007.1

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Need for Wireless Power Delivery

- Wireless power delivery is hassle-free and aesthetic
  - Power limitations exist
  - but sufficient for most implants
  - Extra implant-side coil and electronics
- Power Budget – Most permanent implants require

<table>
<thead>
<tr>
<th>Power Budget</th>
<th>Artificial Pacemaker</th>
<th>Cochlear Implant</th>
<th>Peripheral Nerve Implant</th>
<th>Cortical Implant</th>
<th>Functional Muscle stimulation (Ventricular, Gastric, Motor)</th>
<th>Total Artificial Heart</th>
</tr>
</thead>
<tbody>
<tr>
<td>1mW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10mW</td>
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<tr>
<td>60mW</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>200mW</td>
<td></td>
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</tbody>
</table>

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Wireless Power Link for muscle stimulation

<table>
<thead>
<tr>
<th>Implant type</th>
<th>Power Requirement</th>
<th>Data to Implant</th>
<th>Data from Implant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulation</td>
<td>100 mW</td>
<td>4.8 Kbps</td>
<td>4.8 Kbps</td>
</tr>
<tr>
<td>Recording</td>
<td>50 mW</td>
<td>NA</td>
<td>1.3 Mbps</td>
</tr>
</tbody>
</table>

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Inductive Wireless Power

- Inductive power transmission is one important power transfer method for implants.
- Efficient wireless power transfer methods have a significant reduction of power loss in the implants, thereby eliminating health hazards due to the heat produced.
- The challenges for inductive links in biomedical implants lie in varying coupling coefficients due to the presence of air, skin, tissues and variation in separation and misalignment between the coupled coils.

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Four Possible Topologies

- The type of resonance (Series/parallel) in the secondary side and the type of compensation (Series/Parallel) in the primary side gives raise to four possibilities: SS, SP, PS and PP topologies.
- It would be insightful to derive the efficiency expressions for the power transferred to the load and identify which topology is better for a specific wireless link.


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Efficiency Expressions

\[ \eta_{SS/PS} = \frac{1}{1 + \frac{R_s(\omega)}{R_l} + \frac{R_p(\omega)}{k^2 L_p R_l}} \left[ \frac{(R_l + R_s(\omega))^2}{L_s} + \frac{1}{\omega^2} \left( \frac{1}{L_s} \right) + \frac{1}{\omega^2} \right] \]

\[ \eta_{SP/PS} = \frac{1}{1 + \frac{R_s(\omega)}{R_l} + \frac{R_p(\omega)}{\omega^2 R_l} + \frac{R_p(\omega)}{k^2 L_p R_l}} \left[ \frac{(1 - \omega^2 L_s C_s) R_l + R_s(\omega)}{\omega^2} \right] + \left( \frac{1}{L_s} + \frac{R_l C_s R_s(\omega)}{\omega^2} \right)^2 \]

- It must be noted that the type of resonance at the secondary determines the efficiency of the wireless link, irrespective of the type of primary compensation used. Hence it would suffice if we compare the SS topology with the SP topology.

- The compensating capacitor in the primary side does not affect the efficiency of the wireless link, and hence serves as an independent parameter that can control the power transferred to the load without affecting the efficiency.

Maximizing Efficiency

- The efficiency expressions were maximized with respect to the secondary capacitance \( C_s \) in both the topologies and the maximum efficiency was found as

\[ \eta_{SS/PS}^{\text{max}} = \frac{1}{1 + \frac{R_s(\omega)}{R_l} + \frac{R_p(\omega)(R_l + R_s(\omega))^2}{k^2 L_p L_s \omega^2 R_l}} \]

\[ \eta_{SP/PS}^{\text{max}} = \frac{1}{1 + \frac{R_s(\omega)}{R_l} + \frac{R_p(\omega)}{\omega^2 R_l} + \frac{R_p(\omega)}{k^2 L_p L_s \omega^2 R_l}} \left[ \frac{R_s(\omega)}{\omega^2} \right] + \left( \frac{1}{L_s} + \frac{R_l C_s R_s(\omega)}{\omega^2} \right)^2 \]

- It is to be noted that in both the topologies the coupling coefficient enhances the efficiency and the series resistances degrades the efficiency.

- However the effect of the load resistance, primary and secondary inductance on the efficiencies are different for both the topologies.
Cross Over Frequency (Fixed Load)

When the load is fixed and no matching networks are allowed, the topology that is more efficient needs to be selected based on the cross over frequency.

\[
f_c = \frac{R_T}{2\pi L_s \sqrt{1 + \frac{k^2 L_p R_p}{L_s R_T}}}
\]

Measured values @ 3MHz:
- \( L_p = 12.8 \, \text{uH}, \, L_s = 2.83 \, \text{uH} \)
- \( R_p = 4.47 \, \text{Ohm}, \, R_s = 2.67 \, \text{Ohm} \)
- \( k = 0.173 \)
Optimal Load

If load is allowed to be chosen or matching network is allowed, the link can be matched to an optimized load which maximizes the power transfer efficiency.

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Application to Neural Implant

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**Table 2.1** Single-, Three- and Six-layered Spherical Head Models with an Outer Radius of Ω cm

<table>
<thead>
<tr>
<th>Biological Tissue</th>
<th>Homogeneous Head (cm)</th>
<th>Three-layered Head (cm)</th>
<th>Six-layered Head (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>$x_1 = 9.00$</td>
<td>$x_2 = 8.10$</td>
<td>$x_3 = 8.30$</td>
</tr>
<tr>
<td>CSF</td>
<td>$x_1 = 9.30$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dura</td>
<td>$x_1 = 8.35$</td>
<td>$x_2 = 8.55$</td>
<td>$x_3 = 8.75$</td>
</tr>
<tr>
<td>Bone</td>
<td>$x_1 = 8.00$</td>
<td>$x_2 = 8.26$</td>
<td>$x_3 = 8.50$</td>
</tr>
<tr>
<td>Fat</td>
<td>$x_1 = 8.30$</td>
<td>$x_2 = 8.50$</td>
<td>$x_3 = 8.70$</td>
</tr>
<tr>
<td>Skin</td>
<td>$x_1 = 8.00$</td>
<td>$x_2 = 8.2$</td>
<td>$x_3 = 8.5$</td>
</tr>
</tbody>
</table>

Coil Separation = 10.2mm

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Coil Misalignment

Square planar inductors A and B of turns $N_A$ and $N_B$ respectively separated by a distance $D$ and have lateral ($m$) and angular ($\alpha$) misalignment.

3-Coil Case

- IX coil is introduced to boost flux linkage.
- The efficiency improvement is quantified using our method by computing mutual inductance between the coils at various positions of the IX coil.

R. Jegadeesan, Y.X. Guo, M. Je, Overcoming coil misalignment using magnetic fields of induced currents in wireless power transmission, IEEE MTT-S IMS 2012.
Overcome coil misalignment

- For a receiving coil inclined at 45 degrees to the transmitting coil and having a lateral misalignment of 10mm, the optimal location of the intermediate coil is evaluated using our computation method for mutual inductance between misaligned coils.
- The IX coil is optimally positioned when placed at a distance of 15mm from the TX coil and has 8mm lateral misalignment with no angular orientation.
- The optimal Efficiency for the shown set up is 34%. The Power Transfer efficiency without flux linkage boosting is 2%.

4-Coil Case - Retinal implant

Four coil topology for retinal implants improves the PTE and provides robustness to misalignment caused by rotation motion of eye ball.
**Cadaver Head Experiment**

- Optimized inductive power links
  - secondary coil (8mm X 8mm, 13 turns)
  - primary coil (40mm X 40mm, 20 turns)

Both anterior and lateral sub muscular method were tested.

- angular orientation of the coils (movement of the eyeballs)
- translation of the coils (possible motion artifacts)

**Observations:**
- 20-25% reduction in power delivered to the implant due to the introduction of bones.
- When the primary coil undergoes translation, there is a 10-15% reduction in power delivered to the implant.
- The power delivered to the implant reduces considerably as the inclination of the primary coil with respect to the secondary coil increases.
- The wireless power link was able to transfer a maximum power of 6mW with an input power of 37.5mW for a separation of 25mm.

**Capacitive Wireless Power**

- Wireless power transfer for biomedical implants using capacitive coupling (electric near field coupling) provides an attractive alternative to the traditional inductive coupling method with the benefits of simple topology, fewer components on the implant side, better EMI performance and robustness to surrounding metallic elements.

In-Vivo Capacitive Power Transfer

- Skin Thickness and Bending Effects

<table>
<thead>
<tr>
<th>Link Parameter</th>
<th>3mm skin</th>
<th>4mm skin</th>
<th>5mm skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation between patches ‘d’</td>
<td>4.6mm</td>
<td>5.6mm</td>
<td>6.6mm</td>
</tr>
<tr>
<td>Area of patches</td>
<td>380 mm²</td>
<td>380 mm²</td>
<td>380 mm²</td>
</tr>
<tr>
<td>Load</td>
<td>50 ohm</td>
<td>50 ohm</td>
<td>50 ohm</td>
</tr>
<tr>
<td>Power transfer efficiency at 402 MHz (Measured)</td>
<td>68.3%</td>
<td>67.2%</td>
<td>67.0%</td>
</tr>
<tr>
<td>Power transfer efficiency(^{(1-2)}) at 402 MHz (Computed)</td>
<td>72.85%</td>
<td>72.78%</td>
<td>72.63%</td>
</tr>
<tr>
<td>Average SAR (10mw at receiver)</td>
<td>7.9E-2 W/Kg</td>
<td>8.4E-2 W/Kg</td>
<td>1.2E-1 W/Kg</td>
</tr>
</tbody>
</table>

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Far-Field Wireless Power


Wireless Energy Harvesting

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A rectenna is a rectifying antenna, a special type of antenna that is used to directly convert microwave energy into DC electricity.

A simplest rectenna element consists of an antenna (or antenna array) with a Schottky diode placed across the antenna elements. The diode rectifies the RF current induced in the antenna by the microwaves, to produce DC power. Schottky diodes are used because they have the lowest voltage drop and highest speed and therefore waste the least amount of power due to conduction and switching. Good rectennas consist of impedance transformation, band pass filter and low pass filter to improve its RF-DC conversion efficiency.

Adaptive Rectifier Design

Fig. 1. Overview of the wireless power transmission system.

- Requirement for Rectifier Design
  - $P_t$ varies
  - $d$ changes
  - Receiving antenna is on mobile devices.

Requirement for rectifier: High efficiency over wide input power range.

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Adaptive Rectifier Design

- Diode Selection for Rectifier
  - Threshold Voltage (Vth) determines rectifier’s efficiency at low input power. Low Vth is preferred for low-input-power applications.
  - Breakdown Voltage (Vbr) determines rectifier’s efficiency at high input power. High Vbr is preferred for high-input-power applications.

- Limitation of Normal Rectifier
  - Low Vth and high Vbr cannot be obtained at the same time.
  - High efficiency can only be achieved in a narrow input power range.

Adaptive Rectifier Design

- Limitation Illustration
  - (a) Single shunt-mounted diode. Rectifier (a) is only suitable for low-input-power applications.
  - (b) Two shunt-mounted diodes. Rectifier (b) is only suitable for high-input-power applications.
Operation Mechanism of Proposed Rectifier

(c) Two diodes with one FET as a switch.

(d) Two diodes with two FETs as a switch.

- Rectifier (c): small Vth and large Vbr can be achieved for the combination of D1 and D2. High efficiency -18 dBm to 22 dBm.
- Rectifier (d): two FETs to enhance efficiency from 5 dBm to 20 dBm.

Adaptive Rectifier Design

Wideband Patch Antennas


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Wideband Annular Ring Patch Antenna


Wideband Dual-Polarization Patch Antenna

Wideband Patch Antenna with Conical Radiation Pattern


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Wideband Patch Antennas with Broadband Feeding Networks


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Feed Network Comparison

Conventional Narrowband Balun

- Narrowband 180° phase shifting capabilities

Proposed Broadband Balun

- Broadband 180° phase shifting capabilities

Feed Network Comparison: Amplitude/Return Loss

Conventional Narrowband Balun

- Balanced outputs ($S_{31} = S_{21} = -3$ dB) over a very wide band
- Wide impedance bandwidth ($S_{11} < -10$ dB) of 159%

Proposed Broadband Balun

- Balanced outputs ($S_{31} = S_{21} = -3$ dB) over a wide band of 60.5%
- Relatively narrower but still wide impedance bandwidth ($S_{11} < -10$ dB) of 70%
Feed Network Comparison:
Phase

Conventional Narrowband Balun
- $180^\circ \pm 5^\circ$ output ports phase difference only at frequency points near operating frequency

Proposed Broadband Balun
- $180^\circ \pm 5^\circ$ output ports phase difference across a wide band of 38.4% from 1.6 to 2.4 GHz

Proposed Wideband Feed Network

- $180^\circ \pm 5^\circ$ output ports phase difference across a wide band of 38.4% from 1.6 to 2.4 GHz

Broadband Low X-Pol Antennas


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Wideband Patch Antenna: Dual-Polarization


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Prior-Art Wideband CP Antennas

- Wide impedance (SWR < 2) and 3-dB axial ratio bandwidths of 42% and 27.23%, respectively

- Wide impedance (SWR < 2) and 3-dB axial-ratio bandwidths of 45% and 45%, respectively

Prior-Art Wideband CP Antennas

Provides impedance matching, balanced power splitting and 90° (± 5°) phase shifting across a narrow bandwidth of 14%


90° Wideband Feed Network

Provides impedance matching, balanced power splitting and 90° (± 3°) phase shifting across a wide bandwidth of 75%

Wideband CP Patch Antenna:

- Impedance bandwidth (SWR < 2) of 79.4%
- 3-dB axial-ratio bandwidth of 82%
- Gain bandwidth (Gain > 3 dBi) of 59.3%

Wideband 90° Schiffman Phase shifter

- Rectangular slot on the ground plane layer allows for even-mode capacitance to decrease faster than odd-mode capacitance
- Patterned ground plane approach incurs minimal insertion losses

Wideband CP Patch Antenna:

- Measured impedance bandwidth of 61.03%
- Measured 3-dB axial ratio bandwidth of 37.66%


Small Wideband and Multiband Antennas

1. Small Dual-Band Antennas using Shorted Unequal-Arm U-Slot


2. Quad-Band Internal Antennas


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3. Quad-Band Internal Antennas


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4. Quad-Band Internal Antennas


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Antennas in Package

On-Package Antenna solutions realize an antenna (or antennas) with highly-integrated radio die (or dies) into a standard surface mounted device symbolizing an innovative and important development in wireless frontier in recent years.

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**Millimeter-wave and Sub-THz Radios**

![Graph showing frequency bands and attenuation](image)


---

**Why is Operation at 60 GHz Interesting**

- License-free deployment
- Multi-gigabit operation
- Oxygen attenuates 60 GHz signals by 12-16 dB/km
- Immunity to interference
- Security from signal interception
- Wireless replacement of cables
- **Wireless Personal Area Networks**
- High definition video streaming
- **Wireless High-Definition Multimedia Interface (HDMI)**

*The intended range: 10 meters or less*

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Applications of 60-GHz Radios

Consumer Electronics: HDTV, video streaming

Mobile Phones: Video download, bulk file transfer

PC & Peripherals: WUSB, Gaming

Movie and Game Kiosk

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Wire-bonding Study at 60 GHz

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Why CP Antennas

- The commonly used linearly-polarized (LP) antenna necessitates rotating the transmitting and receiving antenna properly for polarization matching, particularly in the case of the line-of-sight (LOS) radio links.
- Using the CP antenna this problem can be mitigated while also allowing for reduction in interference from multi-path reflections.

Single CP Elements

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Single CP Elements

16-Element Array

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60-GHz SiP Radios

Transmitted and recovered data using the OOK modulator and 4x4 antenna array with a data rate of 2Gb/s


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The proposed antenna element is composed of open loops at various layers connected by via holes to form an axial-mode helical structure to generate traveling wave radiation.
Tolerance Study

Shows the effect of the trace width variation. With a variation of ±0.01mm of \( r_1, r_2 \) and \( r_3 \), the antenna performance can be kept almost unchanged in the bandwidth.

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As for the misalignment of via holes, catch pads have been used to enhance the electrical connection. With a change of ±0.01mm of radius of via holes, the antenna impedance bandwidth is also kept almost unchanged.

16-Element Antenna Array

Composed of 16 antenna elements, T-junction feeding network and GCPW to stripline transition. Distance between neighboring elements is 2.5 mm and the size of this array is 12×10×2 mm³.

Measured \(|S_{11}|\) is less than -10 dB in the frequency range from 52.5 GHz to 65.5 GHz.

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16-Element Antenna Array

Measured AR is less than 3 dB in the frequency range from 54 GHz to 66 GHz.

16-Element Antenna

60-GHz Vertical Off-center Dipole Antenna


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60-GHz Vertical Off-center Dipole Antenna

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60-GHz Vertical Off-center Dipole Antenna

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60-GHz Vertical Off-center Dipole Antenna

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60-GHz Vertical Off-center Dipole Antenna

Simulated radiation pattern

Measured radiation pattern

LTCC L-Probe Antenna

<table>
<thead>
<tr>
<th>Para.</th>
<th>Dimensions (mm)</th>
<th>Para.</th>
<th>Dimensions (mm)</th>
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<tbody>
<tr>
<td>w</td>
<td>0.7</td>
<td>l</td>
<td>0.7</td>
</tr>
<tr>
<td>w₁</td>
<td>0.15</td>
<td>l₁</td>
<td>0.25</td>
</tr>
<tr>
<td>w₂</td>
<td>0.1</td>
<td>l₂</td>
<td>0.4</td>
</tr>
<tr>
<td>h</td>
<td>1</td>
<td>h₁</td>
<td>0.5</td>
</tr>
<tr>
<td>h₂</td>
<td>0.3</td>
<td>h₃</td>
<td>0.3</td>
</tr>
</tbody>
</table>

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LTCC L-Probe Antenna with Soft-Surface

Three LTCC L-Probe Antennas
Simulated Results for LTCC L-Probe Antennas

LTCC L-Probe Antennas with 3 Different Soft-Surface
LTCC L-Probe Antenna with Soft-Surface - Electrical Field Distributions

(a) with the parasitic structure

(b) without the parasitic structure


60-Ghz Test Setup

(a)

(b)

(c)

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LTCC L-Probe Antennas with Soft-Surface
- Simulated and Measured Results

Without Soft-Surface

With Soft-Surface

LTCC L-Probe Antenna with Soft-Surface
- Comparison with Published Results

<table>
<thead>
<tr>
<th>Type</th>
<th>Size &amp; elements number</th>
<th>Impedance bandwidth</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid array [20]</td>
<td>13.5×8×1.265 mm³</td>
<td>14.8%</td>
<td>14.5 dBi</td>
</tr>
<tr>
<td>SIW fed Cavity array [20]</td>
<td>47×31×2 mm³, 8×8 elements</td>
<td>17.1%</td>
<td>22.1 dBi</td>
</tr>
<tr>
<td>Patch array with UC-EBG [21]</td>
<td>18.5×18.5 mm², 4×4 elements</td>
<td>5.4%</td>
<td>18 dBi</td>
</tr>
<tr>
<td>Patch array with embedded-cavity [22]</td>
<td>18.6×18.6×0.6 mm³, 4×4 elements</td>
<td>5.8%</td>
<td>15.7 dBi</td>
</tr>
<tr>
<td>Patch array with open air cavities [26]</td>
<td>4×4 elements</td>
<td>14%</td>
<td>16.6 dBi</td>
</tr>
<tr>
<td>Our work</td>
<td>14.4×14.4×1 mm³, 4×4 elements</td>
<td>29%</td>
<td>17.5 dBi</td>
</tr>
</tbody>
</table>
LTCC L-Probe Antennas with Soft-Surface - Simulated and Measured Results

LTCC U-Slot Antenna

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LTCC U-Slot Antenna Array

LTCC U-Slot CP Antenna


Copyright © Dr. Yongxin Guo
LTCC U-Slot CP Antenna Array

60-GHz Chip-Level Antennas

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Typical CMOS Integrated Circuits

Illustration of IC modelling including silicon dioxide layer for a typical CMOS integrated circuit. Not to scale.

State of Arts
- Inverted-F Antenna

In the measurement, a gain of -19 dBi was obtained at 61 GHz for the inverted-F antenna; the simulated efficiency is 3.5%.

State of Arts
- Quasi-Yagi Antenna

In the measurement, a gain of -12.5 dBi was obtained at 65 GHz for the quasi-Yagi antenna; the simulated efficiency is 5.6%.


State of Arts
- Using Standard CMOS Process

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (mm²)</th>
<th>Simulated gain (dBi)</th>
<th>Measured gain (dBi)</th>
<th>BW</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yagi</td>
<td>1.1*0.95</td>
<td>-8</td>
<td>-10.6db</td>
<td>&gt;10GHz</td>
<td>10%</td>
</tr>
<tr>
<td>Invert F</td>
<td>0.815*0.706</td>
<td>-13.82</td>
<td>-15.7db</td>
<td>&gt;10GHz</td>
<td>10.2%</td>
</tr>
<tr>
<td>Monopole</td>
<td>1*0.81</td>
<td>-7.2</td>
<td>-9.4db</td>
<td>&gt;10GHz</td>
<td>12%</td>
</tr>
</tbody>
</table>

60-GHz On-Chip Linearly Polarized Antennas

On-Chip Antennas using AMC

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On-Chip Antennas using AMC - Current Distribution

(a) Patch

(b) AMC cells

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60-GHz Silicon On-Chip Antenna - Measured and simulated |S11|


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60-GHz Silicon On-Chip Antenna
- Measured and simulated gain

![Graph showing radiation gain vs frequency for simulated and measured results.]

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60-GHz Silicon On-Chip Antenna
- Radiation pattern at 60 GHz

![Graphs showing radiation patterns in XZ and YZ planes for simulated and measured results.]

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60-GHz On-Chip Circularly Polarized Antennas


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60GHz On-Chip CP Antenna without AMC
- Single and double loops comparison

![Diagram of Single and Double Loops]

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Axial Ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>-14</td>
</tr>
<tr>
<td>55</td>
<td>-12</td>
</tr>
<tr>
<td>60</td>
<td>-10</td>
</tr>
<tr>
<td>65</td>
<td>-8</td>
</tr>
<tr>
<td>70</td>
<td>-6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>55</td>
<td>6</td>
</tr>
<tr>
<td>60</td>
<td>7</td>
</tr>
<tr>
<td>65</td>
<td>8</td>
</tr>
<tr>
<td>70</td>
<td>9</td>
</tr>
</tbody>
</table>

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60-GHz On-Chip CP Antenna
- AMC parametric study

![Diagram of AMC Parametric Study]

Lb

d is the distance between elements
60-GHz On-Chip CP Antenna
- |S11|, AR and gain

Simulated
Measured

Frequency (GHz)
Return Loss (dB)

50 55 60 65 70 75 80 85 90 95 100 105

-12 -9 -6 -3 0

Simulated
Measured

Gain (dBi)

50 55 60 65 70 75 80

0 3 6 9 12

Simulated
Measured

Axial Ratio (dB)

0 dB -20 dB -10 dB -30 dB -40 dB

Simulated
Measured

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60-GHz On-Chip CP Antennas
- Gain and Radiation pattern

<table>
<thead>
<tr>
<th>Technology</th>
<th>Simulated Results in the Article</th>
<th>Measured Power Gain</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>Poor back-end-of-line</td>
<td>NA</td>
<td>-12.5 dB@67 GHz</td>
</tr>
<tr>
<td>[1]</td>
<td>Poor back-end-of-line</td>
<td>NA</td>
<td>-19 dB@67 GHz</td>
</tr>
<tr>
<td>[2]</td>
<td>0.18-μm CMOS</td>
<td>-8.5 dB</td>
<td>-15 dB</td>
</tr>
<tr>
<td>[3]</td>
<td>0.18-μm CMOS</td>
<td>-8 dB</td>
<td>-15 dB</td>
</tr>
<tr>
<td>[5]</td>
<td>0.18-μm CMOS</td>
<td>-13.82 dB</td>
<td>-15.7 dB</td>
</tr>
<tr>
<td>Our work</td>
<td>0.18-μm CMOS</td>
<td>-4.6 dB@60 GHz</td>
<td>Circularly Polarized</td>
</tr>
</tbody>
</table>

Simulated
Measured

XOZ

Simulated
Measured

YOZ

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60-GHz Indoor Communications - Link Budget Analysis

The transmission distance and the overall Tx and Rx antenna gain for a QPSK communication link with a data rate of 2 Gbps:

\[ G_T + G_R = 2 + C/N + 20 \log d \]

- \( G_T \) and \( G_R \) are the Tx and Rx antenna gain;
- The carrier-to-noise ratio \( C/N \) required for QPSK modulation is 10.7 dB.
- \( d \) is the distance between Tx and Rx in meter.

Findings:
1. Overall Tx and Rx gain \( (G_T + G_R) \) of 12.7 dB can deliver 1-meter distance.
2. If the distance is 10 meter (indoor communications), the required overall Tx and Rx gain \( (G_T + G_R) \) is of 32.7 dBi.
3. It is not very difficult to have antenna gain of 15 dBi for a Tx antenna array.
4. For our on-chip antenna case, if the Tx/Rx antenna gain are 15 dBi and -4.4 dBi, respectively, then the achieved distance for the QPSK is

\[ d = 10^{(G_T + G_R - 2 - C/N)/20} = 0.785 \text{ meter} \]

Innovative CMOS process: Wafer Transfer Technology

Wafer Transfer Technology (WTT): The microwave device pattern was first fabricated on the Si substrate using the microelectronic technology, and then the pattern was transferred to the low-loss microwave substrate.

Micromachined Sub-THz On-Chip Antennas

135-GHz On-Chip Antenna - Monopole

135-GHz On-Chip Antenna
- Fabrication process

3 main steps:
1) cavity fabrication,
2) polymer cavity filling
3) pattern formation through back-end-of-line (BEOL) process; 2 redistribution layers (RDLs) are required.

135-GHz On-Chip monopole antenna
- |S11|, gain and radiation pattern

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135-GHz On-Chip Antenna
- 2*1 patch array

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1. Small Signal and large signal modeling
2. High-power Ku-/Ka-band Power amplifier on GaAs/GaN
3. 60/94 GHz power amplifier/LNA

- L. Wang, Y.X. Guo, Y. Lian, C.H. Heng, 3-5GHz 4-Channel UWB Beamforming Transmitter with 1° Phase Resolution through Calibrated Vernier Delay Line in 0.13um CMOS, IEEE International Solid-State Circuits Conference 2012 (ISSCC2012), USA
0.18 um GaAs MESFETs Wafer Device
Small-signal Modelling

8*150 um GaAs MESFET wafer device
$V_{gs} = -0.3V$, $V_{ds} = 7V$, 1 – 40GHz

16*150 um GaAs MESFET wafer device
$V_{gs} = -0.3V$, $V_{ds} = 7V$, 1 – 40GHz

0.18 um GaAs MESFETs Wafer Device
Large-signal Modelling

6×125 um GaAs MESFET wafer device
$V_{gs} = -3.1 – 0.5V$, $V_{ds} = 0 – 10V$

16×125 um GaAs MESFET wafer device
$V_{gs} = -3.1 – 0.5V$, $V_{ds} = 0 – 10V$


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ADS Design Kit for 0.18 um GaAs MESFETs Wafer Device

First open "Advanced Design System", choose "DesignKit" → "Install design kits",

Locate the path to the directory of our ADS design kit "NUS_GaAs_MESFET", press "OK" till installation finished.

All the GaAs MESFETs can be found as available design components in palette area of ADS.

Load-Pull Measurement Setup

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Load-Pull Measurement Setup

(A): Focus programmable tuner
   model 1808 (0.8GHz – 18GHz)
   model 4006 (6GHz – 40GHz)

(B) HP 11612 bias network
   (400MHz – 50GHz)

Load-Pull Measurement Verification

(1)

<table>
<thead>
<tr>
<th>Source Impedance</th>
<th>Load Impedance</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS Simulation</td>
<td>9 - j*1.8 Ohm</td>
<td>12.247 + j*12.06</td>
</tr>
</tbody>
</table>

Simulated Load Reflection Coefficients

Set Load and Source impedances at harmonic frequencies

- Z₁₁ = Z₀ + j*0
- Z₂₂ = Z₀ + j*0
- Z₃₃ = Z₀ + j*0
- Z₄₄ = 9-j*1.8
- Z₅₅ = 9-j*1.8
- Z₆₆ = 9-j*1.8
- Z₇₇ = 9-j*1.8
- Z₈₈ = 9-j*1.8
- Z₉₉ = 9-j*1.8

PAE, %

Power Delivered (dBm)

Move Marker m3 to select impedance value and corresponding PAE and delivered power values.
Load-Pull Measurement Verification (2)

8x75um  33GHz  \( V_{gs} = -0.6V, V_{ds} = 5.0V \)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Load Impedance</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Impedance</td>
<td>Load Impedance</td>
<td>Gain</td>
</tr>
<tr>
<td>9.07 – j*1.8 Ohm</td>
<td>13.3745+j*22.9913</td>
<td>7.45</td>
</tr>
<tr>
<td>ADS Simulation</td>
<td>9 - j*1.8 Ohm</td>
<td>12.418 + j*23.750</td>
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</table>

Set Load and Source impedances at harmonic frequencies

<table>
<thead>
<tr>
<th>Value</th>
<th>Symbol</th>
<th>Unit</th>
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<tr>
<td>1</td>
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<td>MHz</td>
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<tr>
<td>11,500</td>
<td>---</td>
<td>15,000</td>
</tr>
<tr>
<td>1</td>
<td>Gain</td>
<td>dB</td>
</tr>
<tr>
<td>35</td>
<td>---</td>
<td>36</td>
</tr>
<tr>
<td>3.3</td>
<td>Power, Flatness</td>
<td>dB</td>
</tr>
<tr>
<td>---</td>
<td>x1</td>
<td>---</td>
</tr>
<tr>
<td>2.4</td>
<td>Small signal gain</td>
<td>dB</td>
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<tr>
<td>24.8</td>
<td>25</td>
<td>26.3</td>
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<tr>
<td>5.4</td>
<td>Power, Variation over Vcc</td>
<td>dB</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>0.3</td>
</tr>
<tr>
<td>5.5</td>
<td>Output Power</td>
<td>dBw</td>
</tr>
<tr>
<td>15</td>
<td>---</td>
<td>---</td>
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<tr>
<td>6</td>
<td>Output Return Loss</td>
<td>dB</td>
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<tr>
<td>12</td>
<td>---</td>
<td>6</td>
</tr>
<tr>
<td>3-1</td>
<td>Gain</td>
<td>dB</td>
</tr>
<tr>
<td>5.5</td>
<td>---</td>
<td>5.5</td>
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<tr>
<td>5-1</td>
<td>Gain</td>
<td>dB</td>
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<tr>
<td>15</td>
<td>---</td>
<td>15</td>
</tr>
<tr>
<td>5-1</td>
<td>Power</td>
<td>dB</td>
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<tr>
<td>4.2</td>
<td>---</td>
<td>4.2</td>
</tr>
<tr>
<td>10.5</td>
<td>Envelope output Power</td>
<td>dBw</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
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<tr>
<td>11.1</td>
<td>Frequency range</td>
<td>MHz</td>
</tr>
<tr>
<td>6</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>10.1</td>
<td>DC drain current</td>
<td>mA</td>
</tr>
<tr>
<td>4,200</td>
<td>---</td>
<td>4,900</td>
</tr>
<tr>
<td>10.1</td>
<td>DC current</td>
<td>mA</td>
</tr>
<tr>
<td>40</td>
<td>---</td>
<td>40</td>
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</tbody>
</table>

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11.5 – 15.0 GHz Power Amplifier

Measured Data


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60 GHz Power Amplifier

Measured Data

This work received the “Best Student Paper Award” in International Conference on Microwave and Millimeter-Wave Technology 2010 (ICMMT2010) at Chengdu, China, May 8-11, 2010.

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**60 GHz Band-Tunable Power Amplifier**

Measured data

- **Peak gain Freq.:** 59 GHz
- **Peak gain:** 17.1 dB
- **DC power:** 63 mW
- **P_{sat}** 12.3 dBm
- **Peak PAE:** 20.4%
- **Stages:** 2
- **V_{DD}:** 1 V
- **Technology:** 65 nm CMOS


---

**94-GHz Low Noise Amplifier**

Measured data


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94-GHz Low Noise Amplifier

Measured data

New passive devices: Ka-Band SIW BPF (PCB); X-Band Balun BPF (PCB); 60-GHz LTCC BPF (LTCC); 40/50-GHz LTCC diplexer (LTCC); Use of Space Mapping to optimize two SIW BPFs (PCB); Ka-Band Triplexer (LTCC)

Ka-Band SIW Quasi-Elliptic Filter


X-Band SIW Balun Filter (1/2)

Coupling schemes of a fifth-order bandpass filter

Coupling schemes of a sixth-order balun filter extended from the previous filter.

Synthesized frequency responses of the fifth-order bandpass filter and the sixth-order balun filter extended from it

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X-Band SIW Balun Filter (2/2)


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60-GHz LTCC SIW filter (1/2)


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60-GHz LTCC SIW filter (2/2)

(d) Multi-coupling diagram  
(e) Coupling matrix

(f) Ideal circuit, simulated and measured responses

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40/50-GHz LTCC SIW Diplexer (1/2)

(a) Configuration and dimensions  
(b) Electric field patterns of TE modes in single SIW cavity resonator

(c) Photograph

40/50-GHz LTCC SIW Diplexer (2/2)

(d) Simulated S-parameter results

(e) Measured S-parameter results

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LTCC UWB Filter

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Should you have any queries, please contact:

Dr. Yongxin Guo, Associate Professor
Department of Electrical and Computer Engineering
National University of Singapore
Email: eleguoyx@nus.edu.sg