Antenna-in-Package (AiP) Technology

by

Y. P. Zhang, FIEEE
Micro Radio Group
Integrated System Research Lab
School of Electrical and Electronic Engineering
Nanyang Technological University (NTU)
Singapore
Abstract

The antenna-in-package (AiP) technology combines an antenna (or antennas) with a single-chip radio die into a standard surface mounted device symbolizing an innovative and important development in the miniaturization of wireless communications systems in recent years. The AiP technology is now the mainstream antenna technology and has been widely adopted by chip makers for 60 GHz radios. The slides focus on the development of the AiP technology in low-temperature cofired ceramic (LTCC) process for 60 GHz radios by Y. P. Zhang and his students and collaborators.

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Key Words

Antenna: Discrete antenna, integrated antenna, and AiP; Package: Wire-bond package, flip-chip package; Circuit: Discrete circuit, integrated circuit; Chip: Packaged die, bare die; Process: LTCC, PCB, and CMOS.
What is AiP Technology?

AiP technology is an antenna solution technology that implements an antenna or antennas on (or in) an IC package that can carry a highly-integrated radio or radar transceiver die (or dies).
Why AiP Technology?

As compared with current chip antenna solution, AiP has better system performance, smaller system PCB area, lower system and assembly cost, and shorter time to market. Obviously, AiP offers an elegant antenna solution to single-chip radio or radar transceivers.
How AiP Technology Evolved?

Inspired from the similarity between ceramic patch antenna\(^1\) and hermetic ceramic package\(^2\), AiP\(^5-7\) evolved from used ceramic package\(^3\) through PCB mockup\(^4\).
Who Have Created Knowledge about AiP?

**On-chip antennas for 60-GHz radios in silicon technology**
Abstract—The recent advances in 60-GHz radios have called for the parallel development of compact and efficient millimeter-wave antennas. This brief addresses for the first time the design, fabrication, and characterization of on-chip inverted-F and quasi-Yagi antennas ...
Cited by 210  Related articles  All 14 versions  Web of Science: 123  Cite  Save

**Antenna-in-package design for wirebond interconnection to highly integrated 60-GHz radios**
YP Zhang, M Sun, KM Chua, LL Wai... - ... and Propagation, IEEE ..., 2009 - ieeexplore.ieee.org
... evaluated the AoC solution for 60-GHz radio on a silicon substrate and found that both inverted-F and quasi-Yagi on-chip antennas have very poor radiation efficiency about 5% due to the low resistivity and high permittivity of the silicon substrate [8]. Micromachining techniques ...
Cited by 97  Related articles  All 10 versions  Web of Science: 53  Cite  Save

**Antenna-on-chip and antenna-in-package solutions to highly integrated millimeter-wave devices for wireless communications**
YP Zhang, D Liu - Antennas and Propagation, IEEE ..., 2009 - ieeexplore.ieee.org
... We will therefore concentrate on antenna technology and address newly-proposed AoC and AiP solutions to highly-integrated 60-GHz radios in this paper. ... Nevertheless, we believe that high-directivity AoC is not practical at 60 GHz with the expected die size. ...
Cited by 175  Related articles  All 10 versions  Web of Science: 93  Cite  Save
Who Have Created Knowledge about AiP?

A chip-scale packaging technology for 60-GHz wireless chipsets
UR Pfeiffer, J Grzyb, D Liu, B Gaucher... - Microwave Theory ..., 2006 - ieeexplore.ieee.org
This paper demonstrates the first fully package-integrated 60-GHz chipset including receive and transmit antennas in a cost-effective plastic package. The authors are with the IBM TJ Watson Research Center, Yorktown Heights, NY 10598 USA (e-mail: ullrich@us.ibm.com).
Cited by 131
Related articles
All 8 versions
Web of Science: 87
Cite
Save

LTCC packages with embedded phased-array antennas for 60 GHz communications
DG Kam, D Liu, A Natarajan, S Reynolds... - Microwave and ..., 2011 - ieeexplore.ieee.org
Cited by 39
Related articles
All 7 versions
Web of Science: 22
Cite
Save

24-element antenna-in-package for stationary 60-GHz communication scenarios
WHong, AGoudelev, KBaek... - Antennas and ..., 2011 - ieeexplore.ieee.org
The proposed AiP consists of a 4x6 array of 24 stacked circular patch antennas and corresponding LTCC AIP FOR 60 GHZ PHASED ARRAY Low-Temperature Co-fired Ceramics (LTCC) multilayer technology have been actively studied for 60 GHz antenna and package ...
Cited by 13
Related articles
All 3 versions
Web of Science: 6
Cite
Save

Multilayer antenna package for IEEE 802.11 ad employing ultralow-cost FR4
WHong, KHBaek, AGoudelev - Antennas and Propagation, ..., 2012 - ieeexplore.ieee.org
IV. CONCLUSION A new multilayer AiP devised based on a high-volume FR4 process is proposed A. Goudelev, K. Baek, V. Arkhipenkov, and J. Lee, "24-el-ement antenna-in-package for stationary 60-GHz communication sce- narios," IEEE Antennas Wireless Propag ...
Cited by 7
Related articles
All 5 versions
Web of Science: 3
Cite
Save
Who Have Been Recognized for AiP Technology?

IEEE Antennas and Propagation Society

2012 Sergei A. Schelkunoff Transactions Prize Paper Award

is presented to

Y. P. Zhang


IEEE, Antennas and Propagation Society

iWAT07 BEST PAPER PRIZE

The Technical Committee has awarded

Yue Ping Zhang, Mei Sun, Kai Meng Chua, Lai Lai Wai, Duixian Liu, Brian Gaucher

with the iWAT 07 Best Paper Prize for their outstanding quality paper

Antenna-in-Package in LTCC for 60 GHz Radio

Cambridge, March 23rd, 2007
Who Else Contributed to AiP Technology?

Incomplete list of early AiP contributors

- PRC
- IMEC
- CUHK
- YONSEI
- IMST
- Insight SiP
- ITRI
- AMKOR
- FRACTUS
Who Else Contributed to AiP Technology?

Incomplete list of early AiP contributors

NEC
IBM
Panasonic
Who Developing AiP Technology Right Now?

Incomplete list of current AiP developers

IBM

SAMSUNG

STM

Infineon
Who Developing AiP Technology Right Now?

Incomplete list of current AiP developers

- Hittite
- Panasonic
- NTT
- Qualcomm
- Tensorcom
- Intel
- IMEC
AiP Technology

It is now the mainstream antenna technology for 60 GHz.
AiP Design

Codesign of antenna and package will maximize the AiP performance. Of course, it would be much better if chip could be also included in the design flow.

Fig. 4. Design methodology.
AiP Fabrication

Low temperature cofired ceramic (LTCC) material and process are suitable for AiP mass production.

Fig. 5. LTCC Fabrication Facilities (SIMTech).
AiP Measurement

Probe-based measurement setup is needed to measure an AiP and a balun for a differential signal operation.

\[
Z_d = 2Z_o \frac{(1 - S_{11}^2 + S_{21}^2 - 2S_{21})}{(1 - S_{11})^2 - S_{21}^2} \quad (1)
\]

\[
RL = 20\log_{10}\left|\frac{Z_d - Z_c}{Z_d + Z_c}\right| \quad (2)
\]

where \(Z_o = 50 \, \Omega\) and \(Z_c = 100 \, \Omega\).

Fig. 6. Measurement setup (IBM).
Regulations for 60-GHz Radio

Realized in 1995 that unlicensed use could be an appropriate regime for using such spectrum since most of the justifications for radio licensing were not applicable in these frequencies. Japan first issued 60-GHz regulation for unlicensed utilization in the 60-GHz band in the year of 2000.
WirelessHD
ECMA
IEEE 802.15.3c
WiGig
IEEE 802.11ad
CWPAN

Supports data transmission rates up to 7 Gbps.

To encompass available but inconsistent unlicensed frequencies, the IEEE 802.15.3c standard divides nearly 9 GHz of spectrum from 57.24-65.88 GHz into four 2.16-GHz channels.
# Package Technology Choices for 60-GHz Radio

<table>
<thead>
<tr>
<th>Technology</th>
<th>Density</th>
<th>Interconnect</th>
<th>Stability</th>
<th>Mechanical Stability</th>
<th>Thermal Conductivity</th>
<th>RF Loss</th>
<th>Antenna</th>
<th>Cost</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-interposer /Through-Si-Via</td>
<td>😊</td>
<td>😞</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😞</td>
<td>😞</td>
<td>😞</td>
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</tr>
<tr>
<td>LTCC</td>
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<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
</tr>
<tr>
<td>Laminate</td>
<td>😞</td>
<td>😞</td>
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</tr>
</tbody>
</table>

Si-interposers/ TSV – Current efforts for 3D-integration don’t address the needs of 60GHz.

Low temperature co-fired ceramic (LTCC) technology is established for mm-wave applications.

Laminate requires compromise / material development to provide better capability.

Wire bonding possible and flip-chip bonding suitable for 60-GHz die attach.
### Antenna Type Choices for 60-GHz Radio

<table>
<thead>
<tr>
<th>Year</th>
<th>Patch</th>
<th>Pole</th>
<th>Yagi</th>
<th>Slot</th>
<th>Grid</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1980</td>
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<td>1985</td>
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<tr>
<td>1990</td>
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<td>1995</td>
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<td>2000</td>
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<td>2005</td>
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<tr>
<td>2010</td>
<td></td>
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</tr>
</tbody>
</table>

**Others:** Silica, glass, quartz, ceramic, foam, polymer, resin and MEMS.

**Others:** Lens, PIFA, IFA, cavity, horn, and waveguide antennas.

- **Silicon**
- **LTCC**
- **III-V**
- **LCP**
- **PCB**
- **Others**
### LTCC Material Properties

<table>
<thead>
<tr>
<th>LTCC</th>
<th>Electrical</th>
<th>Mechanical</th>
<th>Thermal</th>
<th>Conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_r$</td>
<td>$\tan \delta$</td>
<td>MPa</td>
<td>GPa</td>
</tr>
<tr>
<td>A6 M</td>
<td>5.7</td>
<td>0.0023</td>
<td>170</td>
<td>92</td>
</tr>
<tr>
<td>ACX</td>
<td>7.5</td>
<td>0.01</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>943</td>
<td>7.4</td>
<td>0.002</td>
<td>230</td>
<td>150</td>
</tr>
<tr>
<td>GL 940</td>
<td>18.7</td>
<td>0.00025</td>
<td>220</td>
<td>188</td>
</tr>
<tr>
<td>GL 950</td>
<td>9.4</td>
<td>0.0014</td>
<td>400</td>
<td>173</td>
</tr>
<tr>
<td>GL 330</td>
<td>7.5</td>
<td>0.0015</td>
<td>400</td>
<td>178</td>
</tr>
<tr>
<td>GL 570</td>
<td>5.6</td>
<td>0.0019</td>
<td>200</td>
<td>128</td>
</tr>
<tr>
<td>GL 771</td>
<td>5.2</td>
<td>0.0036</td>
<td>170</td>
<td>74</td>
</tr>
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</table>
LTCC Design Rules

<table>
<thead>
<tr>
<th>Items</th>
<th>Symbol</th>
<th>Specification (Min in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/B pad width</td>
<td>A</td>
<td>0.125</td>
</tr>
<tr>
<td>W/B pad width</td>
<td>B</td>
<td>0.200</td>
</tr>
<tr>
<td>Gap between W/B pads</td>
<td>C</td>
<td>0.100</td>
</tr>
<tr>
<td>Line width</td>
<td>D</td>
<td>0.100</td>
</tr>
<tr>
<td>Line to part pad spacing</td>
<td>E</td>
<td>0.150</td>
</tr>
<tr>
<td>Cavity to part pad spacing</td>
<td>F</td>
<td>0.200</td>
</tr>
<tr>
<td>Cavity to W/B pad spacing</td>
<td>G</td>
<td>0.200</td>
</tr>
<tr>
<td>Cavity to cavity spacing</td>
<td>H</td>
<td>1.000</td>
</tr>
<tr>
<td>Cavity to substrate edge</td>
<td>J</td>
<td>1.000</td>
</tr>
<tr>
<td>Line to line spacing</td>
<td>K</td>
<td>0.100</td>
</tr>
<tr>
<td>Cavity to line (surface)</td>
<td>L₁</td>
<td>0.200</td>
</tr>
<tr>
<td>Cavity to line (inner)</td>
<td>L₂</td>
<td>0.200</td>
</tr>
<tr>
<td>Via (d) pitch or to part edge</td>
<td>M</td>
<td>2d</td>
</tr>
<tr>
<td>W/B pad to line</td>
<td>N</td>
<td>0.100</td>
</tr>
<tr>
<td>Conner of cavity</td>
<td>O</td>
<td>0.150</td>
</tr>
<tr>
<td>W/B pad to via edge</td>
<td>P</td>
<td>0.200</td>
</tr>
<tr>
<td>Via edge to cavity edge</td>
<td>Q</td>
<td>0.250</td>
</tr>
</tbody>
</table>
LTCC Design Rules

- Au catch pad diameter 0.25 mm
- Au extension = 0.15 mm × 0.35 mm
- Au W/B pad = 0.25 mm × 0.25 mm
- W/B pad offset = 0.25 mm
LTCC Tolerances

- Finished part dimensional tolerance is generally $\pm 0.7 \%$ of part size but not less than $\pm 100\mu\text{m}$ for green cut parts.
- The shrinkage tolerance of circuit features in x and y direction is typically less than $\pm 0.1 \%$ (production $\pm 0.2\%$ typically).
- The minimum recommended substrate thickness is 500 $\mu\text{m}$. Layer thickness tolerance is $\pm 7 \%$ (typically $< \pm 2\%$ within manufacturing lot).
- The via hole punching to the tape sheet can be made typically to 10 $\mu\text{m}$ accuracy in production.
- The layer-to-layer alignment accuracy for via and conductor is typically 10~20 $\mu\text{m}$. The screen printed conductor alignment error is typically 5~10 $\mu\text{m}$.
- The line width tolerance is typically 5%.
- Dielectric constant of $5.9 \pm 0.2$, loss tangent of $0.002 \pm 0.02\%$, and conductivity of $2.5 \times 10^7 \text{ S/m}$ for A6M at 60 GHz.

www.ltcc.de
LTCC Roughness

- **Conductor roughness**
  - Increase in conductor loss more than 2 times (experimentally demonstrated).
  - Affects effective permittivity.
  - Affects phase constant especially in thinner substrates

- **Ceramic roughness**
  - Affects thickness (so impedance).
  - Affects effective permittivity.

www.ltcc.de
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

Microstrip Patch Array Antenna

**Major advantages:** Low profile, conformable to planar and non-planar surfaces, easy to design, simple to manufacture, compatible with both single-ended and differential silicon radio.

**Major disadvantages:** Low efficiency, high Q, poor polarization purity, spurious feed radiation and very narrow impedance bandwidth.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Patch Array Antenna
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Patch Array Antenna
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

Microstrip Grid Array Antenna

It was invented by Kraus in 1964, revived by Conti, et al in 1981, and studied by Nakano, et al at lower microwave frequencies.

**Major structural advantages:** Low profile, conformable to planar and non-planar surfaces, easy to design, simple to manufacture, simple feeding network, compatible with both single-ended and differential silicon radio.

**Major operational advantages:** High efficiency, high gain, good polarization purity, wide impedance and gain bandwidth, can be travelling-wave and able to beam steering by frequency shift, can be resonant with boresight beam radiation.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

Microstrip Grid Array Antenna Design Guidelines and Examples

**Choice of substrate:** A thick substrate means using a low dielectric constant to limit the generation of surface waves.

**Number of loops:** Given the specified gain $G$, the number of loops can be estimated by $2 \times 10^{(G - G_d)/10}$ where $G_d$ is the gain of microstrip half-wave dipole.

**Loop short side design:** A short side is a radiating element. The length is required to be $\lambda_g/2$ for resonance. The width sets the radiation resistance, which is governed by the desired amplitude taper on the array.

**Loop long side design:** A long side is a transmission line. The length is required to be $\lambda_g$ for resonance. The width sets the characteristic impedance, which should match the short side impedance.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 1

<table>
<thead>
<tr>
<th>Specifications @ 60 GHz in Ferro LTCC A6M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth = 7 GHz, efficiency &gt; 80%, and maximum gain = 15 dBi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single Feed Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of meshes 14</td>
</tr>
<tr>
<td>Mesh dimensions $l = 2.5 \text{ mm} \approx \lambda g$, $w = 1.365 \text{ mm} \approx \lambda g/2$</td>
</tr>
<tr>
<td>Substrate dimensions $13.5 \text{ mm} \times 8 \text{ mm} \times 0.375 \text{ mm}$</td>
</tr>
<tr>
<td>Line width and thickness $0.15 \text{ mm}$ and $0.01 \text{ mm}$</td>
</tr>
<tr>
<td>Excitation location $x_v = 7.3 \text{ mm}$, $y_v = 3.98 \text{ mm}$</td>
</tr>
<tr>
<td>Feeding dimensions $d_v = 0.1 \text{ mm}$, $d_a = 0.3 \text{ mm}$</td>
</tr>
</tbody>
</table>
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 1

Simulations show that large impedance bandwidth of 13 GHz (21.4% @ 61.5 GHz), maximum gain of 15 dBi, and 3-dB gain bandwidth of 10 GHz are achieved.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 1

Simulations show that desirable patterns with low side lobe and week cross-polarization radiation are achieved.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio
LTCC Microstrip Grid Array Antenna Design Example 1
An excellent matching to a 50-Ω source achieved from 56.3-65 GHz. The measured and calculated peak gain values are both 14.5 dBi with estimated efficiency better than 95% at 60-GHz. **No de-embedding was made between the post-layout simulation and measurement.**
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 1

60 GHz
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 2

<table>
<thead>
<tr>
<th>Specifications @ 60 GHz in Ferro LTCC A6M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth = 7 GHz, efficiency &gt; 80%, and maximum gain = 15 dBi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dual Feed Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of meshes 14</td>
</tr>
<tr>
<td>Mesh dimensions ( l = 2.5 , \text{mm} \approx \lambda g, , w = 1.365 , \text{mm} \approx \lambda g/2 )</td>
</tr>
<tr>
<td>Substrate dimensions 13.5mm ( \times ) 8mm ( \times ) 0.375 mm</td>
</tr>
<tr>
<td>Line width and thickness 0.15mm and 0.01 mm</td>
</tr>
<tr>
<td>Excitation location ( x_{v1} = 4.57 , \text{mm}, , x_{v2} = 3.5 , \text{mm}, , y_v = 3.98 , \text{mm} )</td>
</tr>
<tr>
<td>Feeding dimensions ( d_v = 0.1 , \text{mm}, , d_a = 0.3 , \text{mm} )</td>
</tr>
</tbody>
</table>
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 2

Simulations show that large impedance bandwidth of 10 GHz (16.3% @ 61.5 GHz) and maximum gain of 14 dBi for single-ended excitation and of 8 GHz (13% @ 61.5 GHz) maximum gain of 16 dBi for differential excitation are achieved, respectively.
Simulations show that differential excitation has narrower beamwidth in the E plane and similar beamwidth in the H plane than those of single-ended excitation.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 2

Solder balls

PCB board

60-GHz radio die

PCB cavity

M1

M2

M3

M4

V_d+

V_d-

V_s
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 2

An excellent matching to a 50-Ω source achieved from 56.3-63.2 GHz. The measured and calculated peak realized gain values agree well with estimated efficiency better than 95% at 60-GHz. No de-embedding was made between the post-layout simulation and measurement.
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 2

60 GHz
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio
LTCC Microstrip Grid Array Antenna Design Example 3

Specifications @ 60 GHz in Ferro LTCC A6M

- Bandwidth = 7 GHz, efficiency > 80%, and gain ≥ 15 dBi over 7-GHz
- Number of meshes 32
- Substrate dimensions 15mm × 15mm × 0.5 mm
- Linearly polarized
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio
LTCC Microstrip Grid Array Antenna Design Example 3
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 3

[Graphs showing the comparison of $|S11|$ (dB) and Peak realized gain (dBi) across different frequency bands.]
Array-Antenna-in-Package Design for Highly-Integrated 60-GHz Radio

LTCC Microstrip Grid Array Antenna Design Example 3

60 GHz
Concluding Remarks

The AiP technology originated from Zhang’s work has emerged as the most elegant antenna solution to modern radio systems.

The AiP technology has been demonstrated for WLAN, UWB, and millimeter-wave (60 GHz) radios, respectively.

The AiP technology combines an antenna (or antennas) with a single-chip radio die into a standard surface mounted device symbolizing an innovative and important development in the miniaturization of wireless communications systems in recent years.
Acknowledgement

Zhang would like to acknowledge the contribution from his former students: Mr. Xue Yang, Mr. Lin Wei, Dr. Wang Junjun, Dr. Sun Mei, Dr. Zhang Bing and from his collaborators: Mr. Chua Kai Meng, Ms. Wai Lai Lai, and Dr. Albert Lu Chee Wai from Singapore Institute of Manufacturing Technology, Dr. Liu Duixian and Mr. Brain P. Gaucher from IBM T. J. Watson Research Center, USA, and Prof. C. Luxey, Dr. D. Titz, and Dr. F. Ferrero from Université Nice Sophia-Antipolis, France in the development of AiP technology.
References


References


Y. P. ZHANG is a Professor of Electronic Engineering with the School of Electrical and Electronic Engineering at Nanyang Technological University, Singapore. He serves as an Associate Editor of the IEEE Transactions on Antennas and Propagation. He received the S. A. Schelkunoff Transactions Prize Paper Award of the IEEE Antennas and Propagation Society (2012). He was the Chair, leading the Singapore Chapter to win the Best Chapter Award of the IEEE Antennas and Propagation Society (2013). He was the Advisor, guiding the Singapore Chapter to win the Outstanding Chapter Award of the IEEE Microwave Theory and Technique Society (2014). He was elevated as a Fellow of IEEE in 2009 for his contributions in subsurface radio and integrated antenna.
Antenna Boy

Questions and Comments to eypzhang@ntu.edu.sg