Finite-difference time-domain analysis of integrated ceramic ball grid array package antenna for highly integrated wireless transceivers

Zhang, Yue Ping

2004

Zhang, Y. P. (2004). Finite-difference time-domain analysis of integrated ceramic ball grid array package antenna for highly integrated wireless transceivers. IEEE Transactions on Antennas and Propagation, 52(2), 435-442.

<https://hdl.handle.net/10356/91331>

<https://doi.org/10.1109/TAP.2004.823889>

IEEE Transactions on Antennas and Propagation © 2004 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE. This material is presented to ensure timely dissemination of scholarly and technical work. Copyright and all rights therein are retained by authors or by other copyright holders. All persons copying this information are expected to adhere to the terms and constraints invoked by each author's copyright. In most cases, these works may not be reposted without the explicit permission of the copyright holder.
<http://www.ieee.org/portal/site>.

Finite-Difference Time-Domain Analysis of Integrated Ceramic Ball Grid Array Package Antenna for Highly Integrated Wireless Transceivers

Y. P. Zhang

Abstract—This paper presents a study of the integration of an antenna in a ceramic ball grid array package for highly integrated wireless transceivers. The study has been carried out on an $11 \times 11.66 \text{ mm}^2$ small microstrip antenna in a thin 48-ball ceramic ball grid array package with the finite-difference time-domain (FDTD) method in *C* band. The impedance and radiation characteristics of the antenna are examined. More importantly, the loading effects of the complementary metal–oxide–semiconductor (CMOS) chip and bond wires on the performance of the antenna are investigated. It is found that the loading generally increases the impedance bandwidth but decreases the radiation efficiency of the antenna. To minimize detrimental loading, the shield of the antenna from the CMOS chip is considered. A new design has been realized. The new antenna achieves impedance bandwidth of 4.65%, radiation efficiency of 63%, and gain of 5.6 dBi at 5.52 GHz.

Index Terms—Ceramic ball grid array package technology, highly integrated wireless transceivers, microstrip antennas, the finite-difference time-domain (FDTD) method.

I. INTRODUCTION

BASIC wireless transceiver components consist of an antenna, a radio, and a baseband controller/processor. The antenna is deliberately separated from the radio because it has independent properties that affect the wireless transceiver as a whole. Traditionally, antennas for portable wireless transceivers are based around either a retractable whip monopole or an encapsulated helix because of their simple structures and high radiation efficiencies. However, since neither the monopole nor the helical antenna can be neatly integrated with the rest of a wireless transceiver, as a result, the wireless transceiver appears bulky. Furthermore, being external to the wireless transceiver, damage to the antenna also explains a high proportion of wireless transceiver failures [1]. Currently, antennas for portable wireless transceivers are mainly derived from a planar inverted-F radiator. As the planar inverted-F antenna (PIFA) can be fully embedded into the body of the wireless transceiver, thus it can offer to the wireless transceiver with reduced maintenance and improved aesthetic appearance [2]. More recently, driven by growing pressure to further lower

cost and shrink physical volume, various chip antennas have been developed for portable wireless transceivers [3]–[7]. A one-wavelength loop chip antenna from the thick film process has the size of $17.5 \times 17.5 \times 8.3 \text{ mm}^3$. The chip antenna grounded on a big copper plate was measured. The results show that this chip antenna resonates at 1.765 GHz and has impedance bandwidth of 1.02% and gain of 4.79 dBi [4]. A multilayer chip antenna from the low temperature ceramic technology has the volume $9.5 \times 2 \times 2 \text{ mm}^3$. The chip antenna mounted on a laptop personal computer was tested. The results reveal that this chip antenna has impedance bandwidth of more than 4.1% and gain comparable to the conventional resonance mode dipole antenna at 2.45 GHz [6]. All these chip antennas employ the dielectric loading techniques to miniaturize their sizes. The dielectric materials are often ceramics with high permittivity [8].

The radio was largely discrete and now is usually implemented as a multichip module with gallium arsenide (GaAs) for the power amplifier and perhaps for the low-noise amplifier and bipolar or BiCMOS for the mixer and intermediate frequency (IF) functions. The baseband controller/processor was realized with general-purpose complementary metal–oxide–semiconductor (CMOS) integrated circuits and is now always implemented with special-purpose CMOS integrated circuits. Considering the overwhelming dominance of CMOS in the electronics industry and the steady improvement in the radio frequency (RF) performance of CMOS, there is much interest today in the integration of the radio with the baseband controller/processor into a single CMOS chip. For example, single-chip wireless transceivers have been fabricated in $0.25\text{-}\mu\text{m}$ at 1.8 GHz for DCS-1800 wireless communications and at 2.45 GHz for Bluetooth applications [9], [10]. Advances in deep submicron CMOS will also make single-chip CMOS wireless transceivers at 5–6 GHz band feasible [11], [12]. Single-chip solutions have employed the zero- or low-IF architectures for the wireless transceivers. As such, the difficulty of the integration of different high-Q analog bandpass filters for image frequency rejection and for channel selection has been circumvented. However, not all integration difficulties can be overcome or avoided by the proper selection of the transceiver architectures. There are the antenna filter for spurious emission suppression and the antenna itself for efficient radiation. They are independent of the architectures for wireless transceivers and appear currently impossible to be combined into a single silicon chip with the size of several square millimeters. Consequently, they are left external to the single silicon chip (or

Manuscript received September 20, 2001; revised January 29, 2003. This work was supported in part by the National Science Foundation of China under Grant 69972030.

The author is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, Singapore 639798 (e-mail: eypzhang@ntu.edu.sg).

Digital Object Identifier 10.1109/TAP.2004.823889

Fig. 1. Integrated ceramic ball grid array package antenna (ICPA): (a) 3-D view of laminated layers, (b) geometry of radiator layer, (c) geometry of bottom layer, and (d) bare chip attachment and bond wires.

chips) in virtually all solutions of highly integrated wireless systems.

Single-chip wireless transceivers in their bare forms are susceptible to the effects of mechanical stress, environmental change, and electrostatic discharge. Therefore, they are packaged with ceramic materials. A ceramic package that can carry a single-chip wireless transceiver has a typical volume around 200 mm³. The larger ceramic package offers an alternative solution and enough estate to integrate the antenna filter and the antenna. In fact, the integration of the antenna filter, balun, and switch into the ceramic package has been realized recently [13]–[15]. However, little work has been done to integrate an antenna into the ceramic package [16]. The integration of the antenna into the ceramic package is a radically different approach as compared with chip antenna solutions. It is indeed a rather novel topic and is worthwhile being investigated. For this purpose, we have carried out a study on an 11×11.66 mm²

small microstrip antenna in a thin 48-ball ceramic ball grid array package with the finite-difference time-domain (FDTD) method in *C* band. We call the antenna implemented in this manner the integrated circuit package antenna simply (ICPA). We describe the details of the ICPA in Section II and the FDTD analysis in Section III. The performance of the ICPA with and without the CMOS chip loading is presented in Section IV. Finally the conclusions are summarized in Section V.

II. ICPA

Surface mounted packages are suitable to carry single-chip wireless transceivers. For example, small-outline module ceramic land grid array (MCLGA), micro lead frame (MLF), and lead quad flat pack (LQFP) packages have been utilized to carry single-chip wireless transceivers [15], [17], [18]. Ceramic ball grid array (CBGA) packages have recently become the package

Fig. 2. Feed of ICPA for simulations.

Fig. 3. ICPA return loss versus frequency.

of choice to carry single-chip wireless transceivers because of their excellent RF performance [19], [20].

Fig. 1(a) shows a custom designed 48-ball thin CBGA package. The CBGA package consists of four cofired laminated ceramic layers, with a bare chip cavity formed by the third layer. There are two buried metallization layers in the construction. The lower buried layer provides the metallization for the chip cavity base and the signal traces, while the upper buried layer provides the metallization for the radiating element. The CBGA package has the dimensions of $17 \text{ mm} \times 17 \text{ mm} \times 2.68 \text{ mm}$. The package ceramic material is typical alumina with dielectric constant of 9.7 and loss tangent of 0.0002 at 5 GHz. The fabrication of this custom CBGA is compatible with the standard CBGA technology but with a slight increase in the cost due to the additional ceramic and metal layers. This cost increase can, in fact, be diluted by the added function and the save in the board space and the assembly cost in the next-level package.

Fig. 1(b) shows the geometry of the radiator layer. It is seen that the radiating element takes the basic form of a microstrip patch on a high permittivity substrate. The microstrip patch of size $11 \text{ mm} \times 11.66 \text{ mm}$ is fed through a microstrip line $4 \text{ mm} \times 0.67 \text{ mm}$. The microstrip line resides on the substrate of effective thickness 1.34 mm and dielectric constant 9.7. The microstrip line width was chosen to be 0.67 mm to have a line characteristic impedance close to 50Ω . Fig. 1(c) shows the details of the bottom layer. As shown, there are 48 signal traces. The outer ends of all 48 signal traces will be connected to 48

(a)

(b)

Fig. 4. ICPA input impedance versus frequency: (a) resistance and (b) reactance.

solder balls through 48 vias, while the inner ends of 45 signal traces will be connected to the bare chip through 45 bond wires. There are three signal traces directly linked to the grounded chip cavity base.

Fig. 1(d) shows the attachment of a bare CMOS chip to the cavity base and the linkage of the CMOS chip to the signal traces through the bond wires. Note that the CMOS chip is adhered to the cavity base. The signal traces and the bond wires are made of copper and gold materials, respectively, to minimize signal transmission loss. The focus on the single CMOS chip is in line with the single-chip solutions of wireless transceivers. However, we believe that the ICPA design would also be appropriate for multichip architectures within the CBGA package. Furthermore, the ICPA could also be used with other (or mixed) IC technologies.

III. FDTD ANALYSIS DETAILS

Performance analysis of the ICPA requires a versatile numerical tool that can simulate both metallic and dielectric structures. The FDTD method was chosen because of its applicability to such problems [21]–[23]. To model the ICPA, the spatial step sizes Δx , Δy , and Δz have to be properly chosen so that an

Fig. 5. ICPA radiation patterns in the E plane: (a) ICPA, (b) ICPA with a large CMOS chip, and (c) ICPA with the large CMOS chip and bond wires.

integral number of Yee cells can fit the ICPA. Furthermore, the spatial step sizes should be much less than the smallest guided wavelength λ_g , for accuracy. In our simulations the spatial step sizes were chosen to be $\Delta x = \Delta y = \Delta z = 0.333$ mm. Thus, the ICPA was fitted with $51 \times 51 \times 8$ cells and also the spatial step sizes were much smaller than the smallest guided wavelength $\lambda_g =$ from 16.1 to 19.3 mm, which corresponds to free space wavelength $\lambda_0 =$ from 50 to 60 mm in C band. A solder ball was approximately represented by $2 \times 2 \times 1$ cells. The CMOS chip was modeled by a piece of silicon with dielectric constant of 11.9 and loss tangent of 0.005 at 5 GHz. Two CMOS chip sizes were considered. One was $12 \times 12 \times 1$ cells and the other

was $24 \times 24 \times 1$ cells. The smaller one corresponds to the current CMOS chip size of $4 \text{ mm} \times 4 \text{ mm} \times 0.305 \text{ mm}$ and the larger one to the future CMOS chip size of $8 \text{ mm} \times 8 \text{ mm} \times 0.305 \text{ mm}$ [24], [25]. Both vias and bond wires were treated as thin perfect electric conductors with the same diameter 0.0333 mm. A via was 0.67 mm long (2 spatial step sizes), the shortest bond wire was 3.63 mm long (11 spatial step sizes), and the longest bond wire was 6.6 mm long (20 spatial step sizes). To calculate the far-field patterns, the additional free space mesh cells were added to all six sides of the ICPA. The total computational space was $85 \times 85 \times 45$ cells. The outer boundary was second order stabilized Liao [26].

Fig. 6. ICPA radiation patterns in the H plane: (a) ICPA, (b) ICPA with a large CMOS chip, and (c) ICPA with the large CMOS chip and bond wires.

Fig. 2 illustrates the feed of the ICPA in our simulations, where a gap of length Δz was realized along the via and a Gaussian pulse voltage source was inserted in the gap to energize the ICPA. The gap excitation is not practical in real implementations of the ICPA. However, it is able to facilitate simulations. In real implementations of the ICPA, the feed from the chip to the radiating element involves a bondwire, a signal path, and a via. The time step in our simulations was $\Delta t = 614.3$ fs, which satisfies the Courant stability criterion. The Gaussian pulse width was 32 time steps. The source resistance was set to 50Ω to reduce the time steps needed for FDTD calculations. It was found that 5000 time steps were sufficient for our simulations.

IV. RESULTS AND DISCUSSIONS

In this section, the ICPA performance in terms of the impedance and radiation characteristics is presented. The effects of the CMOS chip and bond wires on the ICPA performance are determined and discussed from the antenna viewpoint.

A. Impedance Characteristics

The resonant frequency of the ICPA is determined by the return loss dip. Fig. 3 shows the return losses against frequency for the ICPA with and without the loading of the CMOS chip and bond wires. As shown, the resonant frequency of the ICPA

without the loading of the CMOS chip and bond wires appears at 5.9 GHz. It drops to 5.84 and 5.7 GHz with the loading of the small and large CMOS chips, respectively. The resonant frequency of the ICPA further reduces to 5.14 GHz with the attachment of bond wires between the CMOS chip and the CBGA package. It is believed that the decrease in the resonant frequency from the loading of the CMOS chip is because the package cavity partially occupied with the CMOS chip increases the effective permittivity of the package or the substrate of the ICPA, as a result, the resonant frequency of the ICPA decreases. We conjecture that further reduction in the resonant frequency from the attachment of bond wires is due to the increase in the equivalent inductance of the ICPA by bond wires.

The impedance bandwidth of the ICPA is defined as the difference between the upper and lower frequencies for which the return loss is less than or equal to -10 dB. It is found that the impedance bandwidth of the ICPA without the loading of the CMOS chip and bond wires is 275 MHz (4.66%). The impedance bandwidth increases to 287 MHz (4.91%) and 325 MHz (5.7%) with the loading of the small and large CMOS chips, respectively. The increase in the impedance bandwidth of the ICPA from 4.66% to 5.7% due to the CMOS chip loading is expected as the inherent loss of the CMOS chip decreases the quality factor of the ICPA. The effect of bond wires on the impedance bandwidth of the ICPA is rather interesting. It is noted that the absolute impedance bandwidth reduces to 239.5 MHz but the relative impedance bandwidth returns to 4.66%, which happens to be the same as the ICPA without any loading.

The resistance and reactance of the input impedance versus frequency for the ICPA with and without the loading of the CMOS chip and bond wires are plotted in Fig. 4(a) and (b), respectively. It is interesting to see that the impedance has peaks in the resistance and swings in the reactance. The resistance is $68\ \Omega$ at 5.9 GHz for the ICPA without the CMOS chip, $40\ \Omega$ at 5.7 GHz with the large CMOS chip, and $27\ \Omega$ at 5.14 GHz with the attachment of bond wires, respectively. The reactance of the ICPA with the CMOS chip exhibit less capacitance as compared with that of the ICPA without the CMOS chip, and the reactance of the ICPA changes from capacitive to inductive with the attachment of bond wires over the frequency range from 5.14 to 5.9 GHz.

B. Radiation Characteristics

The radiation characteristics of the ICPA were evaluated at respective resonant frequencies. The far-field radiation patterns of the ICPA were calculated for the most important planes. Figs. 5 and 6 show the far-field radiation patterns of the ICPA for the copolarization and cross-polarization in the E and H planes, respectively. Note that there is little difference between the radiation patterns of the ICPA with and without the CMOS chip loading in the E and H planes. The radiation patterns of the ICPA in the E and H planes are, however, greatly changed with the attachment of bond wires. The ICPA with and without the CMOS chip loading are basically microstrip patch antennas of different substrates on the same ground plane. Therefore, they share the same radiation mechanism, that is, the fundamental electromagnetic mode E_{10} generates the copolarization radiation, while the higher mode E_{20} generates the cross-polarization

Fig. 7. New ICPA return loss versus frequency.

Fig. 8. New ICPA input impedance versus frequency.

radiation. The other modes contribute to either co or cross-polarization radiation with less significant effect. As a result, it is not surprising that the radiation patterns of the ICPA with and without the CMOS chip loading are similar to those of a conventional microstrip antenna on a small ground plane. The asymmetry in the copolarization patterns and the null shift in the cross-polarization patterns are caused by the signal traces that surround the ground plane of the ICPA. The ICPA with the attachment of bond wires can not be regarded as a microstrip patch antenna any longer because the fundamental and higher-order electromagnetic modes under the microstrip patch are greatly altered by the existence of bond wires, and so are the radiation patterns. The induced currents in those bond wires have different amplitudes, phases, and directions. They cause higher cross-polarization radiation and make it difficult to realize the desirable radiation patterns. The ICPA is linearly polarized. The E_ϕ component dominates in the E plane, whereas the E_θ —component dominates in the H plane. Besides, the radiation is stronger in the upper hemisphere, i.e., in the direction normal to the ICPA. This feature of the radiation patterns is desirable because it not only helps improve the efficiency of the ICPA but also reduces the human interaction with the single-chip wireless transceiver.

Fig. 9. New ICPA radiation patterns: (a) in the E plane and (b) in the H plane.

The gain of an antenna is a critical parameter in wireless network design. The high antenna gain is often required to extend the network coverage. It is found that the gain is 6.7 dBi for the ICPA without the loading of the CMOS chip and bond wires. The gain drops to 3.6 dBi for the ICPA with the CMOS chip loading and it further drops to -4.2 dBi for the ICPA with the attachment of bond wires. Thus, we can conclude that the loading of the CMOS chip and bond wires severely reduces the gain of the ICPA. The antenna efficiency is the parameter that takes into account the reflection, conduction, and dielectric losses of an antenna. The high antenna efficiency is desired particularly for personal wireless transceiver antennas because the higher the antenna efficiency is, the longer the battery life and the lower the noise figure are. The efficiency for the ICPA without the CMOS chip loading is 74%. The efficiency becomes as low as 35% for the ICPA with the CMOS chip loading. The lower efficiency is because the loading of the CMOS chip introduces the additional dielectric loss and enhances the surface wave excitation. The efficiency of the ICPA deteriorates to 9% with the attachment of bond wires. This deterioration is probably due to the larger reflection loss, the bond wire loss, and the electromagnetic mode conversion loss. The attachment of bond wires severely disturbs the electromagnetic mode distribution under the microstrip patch and makes the ICPA an ineffective radiator.

C. Another Design

From the above analysis, it is clear that the loading of the CMOS chip and bond wires affects the performance of the ICPA. On the other hand, this also implies that the ICPA has the potential to interfere with the functionality of the CMOS chip. To minimize these mutual effects, it is necessary to shield the CMOS chip from the ICPA. This can be easily done with an additional metallic layer, which is inserted between the radiating element of the ICPA and the CMOS chip. A new design

that has taken the shield into consideration is implemented as follows. The thickness of the CBGA package remains. However, the radiating element of the ICPA is brought to the top surface of the package and reduced to the smaller size of $11 \text{ mm} \times 8.33 \text{ mm}$, and the shield screen is inserted in the middle of the original radiator layer. The shield short-circuited to the chip cavity base functions as the ground plane of the ICPA. The original feeding via was extended to go through a cell-sized cut on the shield screen to excite the ICPA. Fig. 7 shows the return loss of the new ICPA as a function of frequency. As shown, the resonant frequency occurs at 5.52 GHz with the impedance bandwidth of 256.5 MHz (4.65%). Fig. 8 illustrates the input impedance versus frequency for the new ICPA. The far-field radiation patterns of the new ICPA in the E and H planes are illustrated in Fig. 9. Once again, they are similar to those of a conventional microstrip antenna on a small ground plane. The gain is 5.6 dBi and the radiation efficiency is 63% for the new ICPA. Nevertheless, the achieved efficiency of the new ICPA is indeed acceptable when we consider those efficiency reduction factors such as the high permittivity, the thick package, the lossy CMOS chip, and etc. Furthermore, the ICPA has a much shorter distance to the RF output of the wireless transceiver than a conventional antenna. This implies a smaller transmission loss, which can be translated as an improvement to the ICPA efficiency by a few percent.

V. CONCLUSION

The integration of an antenna in a ceramic ball grid array package for highly integrated wireless transceivers has been fully studied from the antenna viewpoint in C band. The study has focused on the single chip in CMOS technology but it can be easily extended to multichip architectures in mixed semiconductor technologies within the CBGA package.

It has been demonstrated that the performance of the ICPA is affected with the loading of the CMOS chip and bond wires. The CMOS chip loading generally increases the impedance bandwidth but decreases the efficiency of the ICPA. The prototype ICPA has achieved the impedance bandwidth of 4.66%, the radiation efficiency of 9%, and a gain of -4.2 dBi. It has also conjectured that the prototype ICPA has the potential interference to the functionality of the CMOS chip. A shield has been called for to protect the CMOS chip and to enhance the ICPA performance. This has resulted in a new ICPA, which has achieved the comparable impedance bandwidth of 4.65%, the improved radiation efficiency of 63%, and an enhanced gain of 5.6 dBi.

The novel concept of the ICPA has opened up many opportunities for further investigations. First and most importantly, the ICPA should also be studied from the circuit viewpoint to understand the effect of the ICPA on the signal integrity of the single-chip CMOS wireless transceiver. This is believed to be quite challenging work and has received our attention. Second, more efficient printed antenna candidates for the ICPA application should be developed. Third, various feeding techniques should be comparatively evaluated for optimal excitation of the ICPA. Finally, the codesign tool of the CMOS integrated circuits, the ceramic package, and the antenna should be made available for the successful realization of single-chip wireless transceivers.

ACKNOWLEDGMENT

The author would like to thank Mr. C. K. Sim, Mr. W. C. Sim, Ms. C. T. Sim, and Mr. S. K. Sin for their assistance in this work. The author would also like to thank the anonymous reviewers, whose comments enhanced the quality of this paper considerably.

REFERENCES

- [1] C. Hill and T. Kneisel, "Portable radio antenna performance in the 150, 450, 800, and 900 MHz bands outside and in vehicle," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 750–756, July 1991.
- [2] K. Fujimoto and J. R. James, *Mobile Antenna Systems Handbook*. Norwood, MA: Artech House, 2000.
- [3] H. Matsushima, E. Hirose, Y. Shinohara, H. Arai, and N. Goto, "Electromagnetically coupled dielectric chip antenna," in *Proc. IEEE Int. Symp. Antennas and Propagation*, vol. 4, 1998, pp. 1950–1953.
- [4] H. Tanidokoro, N. Konishi, E. Hirose, Y. Shinokara, H. Arai, and N. Goto, "1-wavelength loop type dielectric chip antenna," in *Proc. IEEE Int. Symp. Antennas and Propagation*, vol. 4, 1998, pp. 1954–1957.
- [5] Y. Dakeya, T. Suesada, K. Asakura, N. Nakajima, and H. Mandai, "Chip multilayer antenna for 2.45 GHz-band application using LTCC technology," in *Proc. IEEE MTT-S Int. Symp. Dig.*, vol. 3, 2000, pp. 1693–1696.
- [6] H. H. Kim, K. Y. Kim, J. H. Lee, and J. M. Woo, "Surface-mounted chip dielectric ceramic antenna for PCS phone," in *Proc. Int. Symp. Antennas, Propagation and EM Theory*, 2000, pp. 582–585.
- [7] W. Choi, S. Kwon, and B. Lee, "Ceramic chip antenna using meander conductor lines," *Electron. Lett.*, vol. 37, no. 15, pp. 933–934, 2001.
- [8] Y. P. Zhang, T. K. C. Lo, and Y. Hwang, "A dielectric loaded miniature antenna for microcellular and personal communications," in *Proc. IEEE Int. Symp. Antennas and Propagation*, vol. 3, 1995, pp. 1152–1155.
- [9] M. Steyancert, M. Borremans, J. Janssens, B. de Muer, I. Itoh, J. Craninx, J. Crols, E. Morifuji, S. Momose, and W. Sansen, "A single-chip CMOS transceiver for DCS-1800 wireless communications," in *Proc. Int. Solid-State Circuits Conf.*, 1998, pp. 48–49.
- [10] Cambridge Silicon Radio: *CSR's Single-Chip Bluetooth Radio System*, U.K., 2001.
- [11] K. Runge, D. Pehlke, and B. Schiffer, "On-chip matched 5.2 and 5.8 GHz differential LNA's fabricated using 0.35 mm CMOS technology," *Electron. Lett.*, vol. 35, no. 22, pp. 1899–1900, 1999.
- [12] C. C. Hsiao, C. W. Kuo, and Y. J. Chan, "6.8 GHz monolithic oscillator fabricated by 0.35 mm CMOS technologies," *Electron. Lett.*, vol. 36, no. 23, pp. 1927–1928, 2000.
- [13] P. Wambacq, S. Donnay, H. Ziad, M. Engels, H. D. Man, and I. Bolsens, "A single-package solution for wireless transceivers," in *Proc. Conf. Exhibition Design, Automation and Test*, Europe, 1999, pp. 425–429.
- [14] G. Arnold, "RF IC and MCM-D codesign for wireless communication systems," in *Proc. IEEE Int. Workshop Chip-Package Codesign*, 1998, pp. 53–58.
- [15] Lucent Technologies: *Complete RF Solution W7020 for Bluetooth Applications*, USA, 2000.
- [16] Y. P. Zhang and M. A. Do, "Integrated circuit pressed ceramic package antenna for the single-chip solution of a wireless transceiver," *Microw. Opt. Technol. Lett.*, vol. 30, no. 5, pp. 330–332, 2001.
- [17] Silicon Wave: SiW1502 Radio Modem IC, USA, 2000.
- [18] Mitel Semiconductor: WL 600C 2.4–2.5 GHz RF IC, USA, 1997.
- [19] Alcatel: MTC60110 Radio Transceiver, France, 2001.
- [20] Zeevo: *A One-Chip Design Solution for Bluetooth Wireless Applications*, USA, 2001.
- [21] C. R. Rowell and R. D. Murch, "A capacitively loaded PIFA for compact mobile telephone handsets," *IEEE Trans. Antennas Propag.*, vol. 45, no. 5, pp. 837–842, 1997.
- [22] D. Singh, C. Kalialakis, P. Gardner, and P. S. Hall, "Small H-shaped antennas for MMIC applications," *IEEE Trans. Antennas Propag.*, vol. 48, pp. 1134–1141, July 2000.
- [23] M. S. Tong, M. W. Yang, Y. C. Chen, and R. Mittra, "Finite-difference time-domain analysis of a stacked dual-frequency microstrip planar inverted-F antenna for mobile telephone handsets," *IEEE Trans. Antennas Propag.*, vol. 49, no. 3, pp. 367–376, 2001.
- [24] A. Ajikuttira, C. Leung, E. S. Khoo, M. Chokey, R. Singh, T. H. Teo, B. C. Cheong, J. H. See, H. S. Yap, P. B. Leong, C. T. Law, M. Itoh, A. Yoshida, Y. Yoshida, A. Tamura, and H. Nakamura, "A fully-integrated CMOS RFIC for bluetooth applications," in *Proc. IEEE Int. Solid-State Circuits Conf.*, 2001, pp. 198–199.
- [25] K. Kim and K. O. Kenneth, "Integrated dipole antennas on silicon substrates for intra-chip communication," in *Proc. IEEE Int. Symp. Antennas and Propagation*, vol. 2, 1999, pp. 908–911.
- [26] Z. P. Liao, H. L. Wong, B. P. Yang, and Y. F. Yuan, "A transmitting boundary for transient wave analysis," *Scientia Sinica*, ser. A, vol. 27, no. 10, pp. 1063–1076, 1984.

Y. P. Zhang received the B.E. degree from Taiyuan Polytechnic Institute, Taiyuan University of Technology, Shanxi, China, in 1982, the M.E. degree from Shanxi Mining Institute, Taiyuan University of Technology, in 1987, and the Ph.D. degree from the Chinese University of Hong Kong, Hong Kong, in 1995, all in electronic engineering.

He worked at Shanxi Electronic Industry Bureau from 1982 to 1984, taught at Shanxi Mining Institute from 1987 to 1990, worked at the University of Liverpool, U.K., from 1990 to 1992, City University of Hong Kong from 1996 to 1997, and taught at the University of Hong Kong from 1997 to 1998. He has been a full Professor at Taiyuan University of Technology, since 1996. He is now an Associate Professor at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He has worked in the areas of propagation of radio waves, characterization of radio channels, miniaturization of antennas, and implementation of wireless communications systems. He is currently working with his nine graduate students at the Integrated Systems Research Lab, Nanyang Technological University, to develop circuits and components required to implement highly integrated wireless transceivers operating above 2 GHz using advanced packaging and silicon IC technologies.

Prof. Zhang received the Sino-British Technical Collaboration Award in 1990 for his contribution to the advancement of subsurface radio science and technology, an Overseas Research Students Award in 1992 from the Committee of Vice-Chancellors and Principals of the Universities of the United Kingdom, and an Excellent Graduate Award in 1995 from the Chinese University of Hong Kong. He also received the Best Paper Award from the Second International Symposium on Communication Systems, Networks and Digital Signal Processing, 18–20th July 2000, Bournemouth, U.K. He is listed in *Marquis Who's Who in Science and Engineering*.