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<td>Author(s)</td>
<td>Yang, PH; Li, Y; Jiang, L; Chew, WC; Ye, TT</td>
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<tr>
<td>Citation</td>
<td>IEEE Transactions On Antennas And Propagation, 2011, v. 59 n. 12, p. 4454-4462</td>
</tr>
<tr>
<td>Issued Date</td>
<td>2011</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10722/155705">http://hdl.handle.net/10722/155705</a></td>
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Compact Metallic RFID Tag Antennas With a Loop-Fed Method

Peng H. Yang, Yan Li, Lijun Jiang, Member, IEEE, W. C. Chew, Fellow, IEEE, and Terry Tao Ye

Abstract—Several compact, low profile and metal-attachable RFID tag antennas with a loop-fed method are proposed for UHF RFID systems. The structure of the proposed antennas comprises of two parts: (1) The radiator part consists of two shorted patches, which can be treated as two quarter-wave patch antennas or a cavity. (2) A small loop printed on the paper serves as the feeding structure. The small loop provides the needed inductance for the tag and is connected to the RFID chip. The input impedance of the antenna can be easily adjusted by changing loop dimensions. The antenna has the compact size of 80 mm × 25 mm × 3.5 mm, and the realized gain about −3.6 dB. The measured results show that these antennas have good performance when attached onto metallic surfaces.

Index Terms—Compact antenna, feeding network, low profile, metallic surface, RFID tag antenna.

I. INTRODUCTION

RADIO FREQUENCY identification (RFID) tag has been widely used recently in supply chain and logistics applications to identify and track goods. Tag antenna is one of its key technologies. In order to reduce the cost, most existing RFID systems use modified dipole antennas as tags; these dipole-type antennas can be printed on paper or plastic materials and then pasted on products. They have the merits of small size and are easy to fabricate. However, dipole-type antennas are sensitive to the environment due to their omni-directional radiation characteristics [1], [2]. For example, dipole antennas often show high performance when pasted on paper or plastic boxes, but they do not work when pasted on metal surfaces or bottles with liquid in it.

Microstrip antenna is a good choice for metal-attachable RFID tags because of the ground plane in its structure. In [3], the author investigated the performance of microstrip-type tag antennas using the cheapest dielectric FR4 as substrate. These antennas are easy to fabricate but are large in size. Hence, it is unsuitable for RFID tag applications. In [4], a compact microstrip antenna with some slots loaded is proposed. Also, a simple feeding structure is used and the input impedance can be adjusted easily by changing the length of the feeding line alone. However, this structure requires a via-hole to connect the patch and the ground, which increases the fabrication cost. In [5], [6], patches are fed by a small loop. The merit of this inductively coupled feeding technique is that the imaginary part of the input impedance can be easily changed by tuning the loop size and the distance between the loop and the patches. In order to further reduce the size, the planar inverted-F antenna (PIFA) is also proposed for RFID tag antenna designs [7]. However, because PIFA antennas often need coaxial probe feedings, this type of structure requires embedding the RFID chip vertically between the ground plane and the radiation patch. Hence, it is difficult to fabricate. In [8], [9], the authors proposed to use a slot or aperture antenna as the radiator. A RFID chip is put on the center of the slot as the feeding source. In [10], the RFID chip is connected to a small dipole as a coupling source of the slot. The input impedance of this tag can be adjusted by changing the location of the small dipole. The shortcomings of these slot-type antennas are their size seem still large for RFID tags.

Recently, many people consider using artificial magnetic conductor (AMC) or electronic band gap (EBG) structures for tag antenna designs. Because these new artificial structures have the character of zero-reflection phase, the dipole-type tag antenna can be put very close to them. In [11], a dipole is put on a 5 × 3 AMC plate as the tag antenna. This antenna has the advantage of the high gain (about 4.5 dB) but the drawbacks of large size and high cost. It is suitable for reader antennas instead of tag antennas. There are some other compact and low-profile AMC structures [12], but the complicated structures and narrow bandwidth (just a few megahertz) limit its application.

Most RFID tags are disposable, which is acceptable for dipole-type antennas because of their low cost. However, for microstrip-type antennas, disposable designs will lead to a big waste. The microstrip-type antennas introduced above have relatively higher cost compared to dipole-type tags. Meanwhile their structures are unchangeable, implying that a fixed structure can only be used for one RFID chip. If we want to replace the chip, the entire antenna must be re-designed and re-fabricated. Therefore, a simple, reusable microstrip antenna is attractive for low-cost metal-attachable RFID systems.

In [13], we have proposed an idea for the reusable microstrip tag antenna design. This antenna shows good performance when
attached on metallic objects. But the physics of its feeding struc-
ture was not very clear and the size was relatively large. In this
paper, several compact structures are proposed, analyzed and
tested. In Section II, the motivation and principle of the design
are introduced. Then, in Section III, several key parameters of
the structure are analyzed and discussed. In Section IV, proto-
types are fabricated and tested. This kind of designs is summa-
rized in Section V.

II. ANTENNA DESIGN

Two issues motivated us to design a flexible feeding structure
for low cost metallic RFID tags: First, unlike conventional
50 Ohms antennas, RFID tag antenna has complex input
impedance because it should be a conjugate match to the RFID
chip. There is no unified standard for RFID chips. Different
chips have different impedance. It is impossible to design an
antenna that can match all kinds of chips. Second, most tag
antennas are disposable design because the information in the
chip is unique for a certain product. If the chip is integrated into
the antenna, the antenna can be used only once.

For the reasons mentioned above, we propose to design the
feeding network and the radiator separately. The radiator con-
ists of two symmetrical patches, which are mounted on a di-
electric substrate. One edge of the patch is shorted to the ground,
and there is a gap between the two patches. This gap is the ra-
diating slot. The radiator part can be seen as two quarter-wave
patch antennas sharing a common radiating slot, or a cavity with
a slot loaded. For traditional patch antennas, whose radiating
slots are on the side edges of the patch, the ground is usually
larger than the patch. The advantage of our design is to move
the radiating slots from the edge to the center, which can reduce
the total size of the antenna effectively.

The coaxial probe can be put at a proper location of one of the
two patches to feed this structure [14], [15]. Then this patch is
regarded as the primary patch. Another one is the parasitic patch.
This is the simplest feeding method. Unfortunately, it is not suit-
able for the RFID tag antenna. Another problem is that the para-
sitic patch has a phase delay compared to the primary patch due
to the asymmetric feeding. To feed two patches simultaneously,
we can connect the two patches directly by a RFID chip [8], [9],
[16], [17]. This is straightforward but has some drawbacks, such
as the inflexibility and difficulties of impedance matching.

A feeding method of putting a small dipole on the top of the
gap is proposed to feed the structure [10], [13]. The length of the
dipole is far less than the operating wavelength of the antenna.
To couple more energy into the cavity, the dipole should be put
very close to the slot \(d \ll \lambda_0\). This structure can be regarded
as a cavity-backed slot antenna. If the dimension of the cavity is
designed properly, TM_{10} mode will be excited and resonate in
the cavity. The dipole and the cavity have a strong coupling at
the resonant frequency, and then the energy can be transformed
from the dipole to the cavity through the slot.

Usually, the input impedance of a RFID chip has a small real
part and a large negative imaginary part (capacitive). Hence, for
conjugate matching, a loop (inductive) antenna is preferred than
the small dipole as the feeding network. The geometry of the
proposed loop-fed antenna is shown in Fig. 1(a).

\[
R = 20\pi^2 \left(\frac{P}{\lambda}\right)^4 (P < \lambda/3) \\
L = 0.4(L_L + W_L) \ln \left[\frac{2L_LW_L}{s(L_L + W_L)}\right] (\mu\text{H})
\]

where \(P\) is the perimeter of the loop and \(s\) is the width of the
loop strip.

Because the thickness \(h\) of the cavity is very thin, according
to the cavity model [18], [19], the two quarter-wave patch an-
tennas (or cavity) can be represented as two parallel circuits. The capacitance \( C_c \) of the patch can be estimated roughly by using the parallel plate wave guide model [2]

\[
\sqrt{\frac{I_c}{C_c}} = Z_{\text{parallel plate}} \approx \eta \frac{h}{W_p}
\]

(3)

where \( \eta = \sqrt{\mu/\varepsilon} \) is the intrinsic impedance of the medium between the parallel plates. Because the resonant frequency is \( \omega_r = 1/\sqrt{L_c C_c} \), we can obtain

\[
C_c = \frac{W_p}{\omega_r \eta h} = \frac{2\varepsilon W_p L_p}{\pi h}
\]

(4)

here we suppose that \( L_p = \lambda_g / 4 \) and \( \lambda_g \) is the guided wavelength in the cavity. Through (3) and (4), the equivalent capacitance \( C_e \) and inductance \( L_e \) of each patch are 7.7 pF and 4.0 nH, respectively. The radiation resistance \( R_c \) of single patch can also be estimated using cavity model. Since the energy is coupled from the gap into the cavity, the location of feeding point in cavity model should be chosen close to the gap (the radiation edge). The estimated resistance \( R_c \) is about 850 ohms.

The capacitance \( C_m \) can be estimated approximately by [20]

\[
C_m = \frac{\varepsilon W_p}{2\pi} \left\{ \ln \left[ 0.25 + \left( \frac{h}{g} \right)^2 \right] + \frac{g}{h} \tan^{-1} \left( \frac{2h}{g} \right) \right\}
\]

(5)

If the width of the gap \( g = 5 \) mm, then \( C_m = 0.14 \) pF. Note that these parameters are just approximate values. When the small loop is put close to the patches, these values would change due to the coupling between the loop and the patches. It is very hard to determine these values analytically if coupling effects are taken into consider. But they can be extracted by comparing the results of circuit model and full wave method (Volume Surface Integral Equation codes developed by our group). After a little bit tuning, the precise values of \( C \) and \( C_m \) as well as the coupling capacitance \( C_s \) can be determined and the results of circuit model can match well to the full wave results. The ultimate parameters of these lumped elements and the antenna are given in Fig. 1(b) and (c), respectively. The input impedance of full wave method and equivalent circuit models are shown in Fig. 2. Good agreement is achieved.

To evaluate the performance of the proposed antenna when mounted on metallic objects, we pasted this loop-fed tag antenna on a 200 mm × 200 mm metallic plate. The dielectric has a relative permittivity of 4.2 and loss tangent of 0.02. The medium between the small loop and the cavity was set as air to simplify the simulation. Fig. 3(a) is the gain pattern of the antenna. The simulated maximum realized gain is about −0.7 dB near 915 MHz, which is enough for most low-cost RFID tags. The current distribution on the loop and the patches are shown in Fig. 3(b). Note that the current at point “\( a \)” and point “\( b \)” are not symmetrical. Just as the current direction shown in Fig. 1(c), at point “\( a \)”, the \( x \) component of the current have the opposite direction. Hence they cancel each other. However, at point “\( b \)”, the current have the same direction then add together.

III. PARAMETERS STUDY

In this section, we focus on several key parameters of the structure to see their effects to the performances of the antenna. These parameters include: The loop size \( L_L \times W_L \), the distance \( w \) between the loop and the edge of the patches and the gap \( g \) between the two patches. In all simulations, the tags were supposed to be mounted on a 200 mm × 200 mm metallic plate.

A. Loop Size \( L_L \times W_L \)

Our goal is to design a separable feeding network which can match different RFID chips by changing the size or structure
Fig. 4. Input impedance and $S_{11}$ for different loop size. (a) Input impedance. (b) $S_{11}$. The blue line to match the RFID chip with impedance of $6 - j127$ at 915 MHz, the red line to $13 - j140$, the black line to $7 - j170$ and the pink line to $30 - j200$. Other parameters are: $L_p = 39$, $W_p = 25$, $g = 5$, $d = 0.5$ and $h = 3$. The strip width of the loop is 1 (all dimensions are in mm).

of the feeding network while keeping the radiator part unchanged. To simplify the problem, we fixed others parameters and adjusted the loop size $L_L \times W_L$ only. Four types of RFID chips were chosen to do the simulation. Around 915 MHz, their impedance are: $6 - j127$ [22], $13 - j140$ (Alien-H2), $7 - j170$ [23] and $30 - j200$ (Alien-H3). To make this tag work in the north American frequency range (from 900 MHz to 930 MHz) with these chips, we can change the loop size $L_L \times W_L$, the results are shown in Fig. 4.

Fig. 4(a) are the input impedance of the tag with different loop size. The blue line is to match the RFID chip with impedance of $6 - j127$ at 915 MHz, the red one is to $13 - j140$, the black one is to $7 - j170$ and the pink one is to $30 - j200$. It was found that with the perimeter of the loop becomes larger and larger, the resonance becomes stronger. Also, the resonant frequency tends to become lower because big loop will induce a large net current along the $x$ axis, which is equal to the increase of the coupling capacitance $C_x$. From circuit theory, it will decrease the resonant frequency. Fig. 4(b) shows the $S_{11}$. It can be seen that all of the four RFID chips can be matched well within the operating frequency range.

It is worth to say that in this example, to change the input impedance, we only adjusted the loop size. Hence, the freedom is very limited. To add more freedoms into the feeding network, more complex feeding network structures, such as the T-mach or Gamma-match [1] can be designed, and then more RFID chips might be matched.

B. The Distance $w$ Between the Loop and the Edge of the Patches

In all of the aforementioned examples, the loops were put at the center of the slot. In fact, the location of the loop is not sensitive to the input impedance. To approve this, we fixed the loop size $L_L \times W_L$ at 14 mm $\times$ 14 mm, other parameters were the same to last example except $w$. Then $w$ was changed from 0 mm to 10 mm. It is clear to see from Fig. 5 that the parameter $w$ will not affect the input impedance.

C. The Gap $g$ Between the Two Patches

In this example, we analyzed the effects of parameter $g$ to the input impedance. Similar, we fixed the loop size at 14 mm $\times$ 14 mm, other parameters are the same to last two examples except...
Fig. 7. The fabricated prototype of the loop-fed double patches antenna, the total dimension is 80 mm × 25 mm × 3.5 mm.

Fig. 8. The input impedance and $S_{11}$ of the loop-fed double patch antenna (Type A). The antenna was put on a 200 mm × 200 mm metallic plate.

It is found in Fig. 6 that with the value of $g$ decreases, the resonant frequency becomes lower. The reason can be explained as follow: The center of the antenna can be regarded as a virtual ground and the capacitance $C_m$ can be seen as the sum of two open ended capacitances (the capacitance between the radiating edge of the patch and the virtual ground). The length $L_p$ of the patch will be a little bit shorter than quarter-wave dielectric length because the open ended capacitance effects. When $g$ decreases, the two open ended capacitances will increase. It means for the same resonant frequency, the patch length $L_p$ looks more shorter, or, for the same length $L_p$, the resonant frequency looks more lower. Though small value of $g$ can reduce the total size of the antenna, it will also decrease the gain because of the strong mutual coupling between the two patches. Hence, $g$ cannot be set too small.

IV. FABRICATION AND MEASUREMENTS

The advantage of the proposed idea is that the feeding network and the radiator can be designed separately. From the discussion above, the working mode of the antenna is determined by the resonant mode of the cavity. If we choose the size of the cavity properly, the antenna can work well at the TM$_{10}$ mode. On the other hand, the feeding structures can be used as the excitation and impedance matching network. Different feeding structures will affect the input impedance significantly. This gives us an inspiration to design a disposable feeding network for tag antennas. This feeding structure should be simple, easy for fabrication and low cost.

In the aforementioned examples, in order to simplify the simulation, we use the air as the substrate between the feeding network and the patches. In practice, we should find a proper material as the substrate. Paper is a good choice because it is very cheap and easily available. The most important point is that it is easy to print feeding circuits on the paper by using the conductive ink or copper foil. In our designs, we use some common paper, such as those used for name cards, as the substrate. The estimated relative permittivity constant of the paper is around
of the loop-fed single patch antenna (Type B). The antenna is put on a 200 mm × 200 mm metallic plate.

3.2–3.5 [24], and the loss tangent is about 0.08. The drawback of paper is its high loss. But it is acceptable for tag antennas because the read range requirement of most passive RFID tag applications are just few meters.

A. Loop-Fed Double Patch Tag Antenna (Type A)

The loop-fed double patch antenna was fabricated and tested. The fabrication prototype is shown in Fig. 7. The antenna used the Alien’s RFID chip, whose impedance is about 30–200 j at 915 MHz. The dielectric in the cavity is FR4. Its measured permittivity is about 4.2 and loss tangent is about 0.02 [10], [17]. The parameters of the antenna are (all in mm): \( L_p = 35 \), \( W_p = 25 \), \( g = 10 \), \( L_L = 14 \), \( W_L = 12 \), \( w = 5 \), \( d = 0.5 \) and \( h = 3 \). The width of the loop is 1 mm. With the method proposed in [25], [26], the antenna was measured through the Agilent’s four ports vector network analyzer. Fig. 8 shows the input impedance and \( S_{11} \) of measured results. This tag antenna was mounted on a 200 mm × 200 mm metallic plate. It is clear to see that the antenna can match well around 920 MHz.

B. Loop-Fed Single Patch Tag Antenna (Type B)

The antenna proposed above has a symmetrical structure: The cross section (yz plane) at the center of the antenna can be seen as a perfect electric conductor (PEC), see Fig. 1. Hence, it is possible to split the antenna along yz plane to reduce the total dimension. Fig. 9(a) shows the geometry, where \( L_p = 45.5 \), \( W_p = 20 \), \( g = 7.5 \), \( L_L = 17 \), \( W_L = 11 \), \( d = 0.5 \) and \( h = 3 \) (all in mm). The width of the loop strip is 1 mm. Fig. 9(b) is the prototype. Fig. 10 is the measured input impedance and \( S_{11} \) of this antenna when mounted on a 200 mm × 200 mm metallic plate. Here the FR4 has a relative permittivity about 4.2 and loss tangent about 0.04. The paper is the same as Type A. It can match well around 925 MHz by adjusting the parameters carefully.

C. Loop-Fed Single Patch Tag Antenna With Slots Loaded (Type C)

In order to further reduce the size of the tag, two slots were added on the patch. These slots can bend the patch surface current paths to achieve a lower fundamental resonant frequency. The geometry and prototype of the compact tag antenna are shown in Fig. 11(a) and (b), respectively. The parameters in Fig. 11(a) are: \( L_p = 24 \), \( W_p = 20 \), \( g = 6 \), \( L_L = 16 \), \( L_1 = 15 \), \( W_1 = 9.25 \), \( W_2 = 5.5 \), \( W_L = 10 \), \( s = 1 \), \( d = 0.5 \) and \( h = 3 \) (all in mm). The width of the loop strip is 1 mm. The parameters of FR4 and paper are the same as Type B. The measured results of the compact antenna mount on a 200 mm × 200 mm metallic plate are shown in Fig. 12. From the results we can see that it can match well around 915 MHz.
Fig. 12. The input impedance and $S_{11}$ of the loop-fed single patch antenna with slots loaded (Type C). The antenna is put on a 200 mm x 200 mm metallic plate.

Fig. 13. The simulated realized gain of the three type tag antennas (The antennas are put on a 200 mm x 200 mm metallic plate).

D. Read Performance and Comparisons With Other Tags

The realized gains of these tags were also investigated and the results are shown in Fig. 13. The maximum gain within the operating frequency range are -3.6 dB, -6.9 dB and -11.8 dB for Type A, Type B and Type C, respectively. The main reason for the low gain is due to the high loss of the paper we used.

The read ranges of these prototypes were tested using Impinj reader IPJ-R1000. The operating frequency hods from 900 MHz to 930 MHz. We fixed the output power to 30 dBm and measured the read distances of these tags (summarized in Table I). These antennas have a good performance when mounted on metallic objects but poor performance in free space because the small ground will lead to a large back radiation. Also, the resonant frequency in free space would be lower than the case when they are mounted on a large metallic plate. Finally, we compared our tags with other designs. In [17], the structure is very similar to ours but with a direct feeding method. The gain of [17] is about -6.4 dB and the maximum read range is 3.1 meter when mounted on a $0.5\lambda \times 0.5\lambda \times 0.01\lambda$ metallic sheet. In [27], the maximum read range of the commercialize tag can reach 7 meter when mounted on a 300 mm x 300 mm metallic plate. The performance of [27] is very good but also with the drawback of large assembled size: 9.45 cm x 7.2 cm x 1 cm.

V. CONCLUSION

A type of loop-fed compact UHF band RFID tag antennas for metallic objects is presented in this paper. These antennas use the quarter-wave patch structure (or a cavity) as the radiator and a small loop as the feeding network. The cavity determines the resonant mode while the feeding part is adjustable to match the required input impedance. The feeding network and the radiator are designed separately. The feeding part is simple with the low cost. It can be printed on paper using some copper foil or conductive ink. Hence, it is a disposable design. Thanks to the separable idea, the radiator part (the quarter-wave structure) can be used many times for different RFID chips or feeding networks, which will lower the total cost of metallic tag antennas. Three designs are proposed. The smallest one has the size of 30 mm x 20 mm x 3.5 mm, which is just 1/10 wavelength in free space. The merits of their compact, low cost, and metal-attachable properties make the proposed antennas well suitable for packaging RFID applications with metallic objects.

ACKNOWLEDGMENT

The authors would like to thank Dr. H. L. Zhu, Dr. J. T. Xi, Mr. F. Lu and Mr. X. S. Chen for the antenna fabrication and testing.

REFERENCES


Peng H. Yang was born in Kunming, Yunnan, China. He received the B.S. degree and M.S. degree in electronic engineering from the University of Electronic Science and Technology of China (UESTC), in 2001 and 2008, respectively, where he is currently working toward the Ph.D. degree.

From January 2009 to November 2010, he was a Research Assistant with the Department of Electrical and Electronic Engineering, University of Hong Kong. His research interests include microstrip antenna theory and design, metamaterials, and smart microwave circuits design.

Yan Li was born in Shaanxi, China. He received the B.S. degree in electronic engineering and the M.S. degree in microwave engineering from the University of Electronic Science and Technology of China (UESTC), in 2007 and 2010, respectively, where he is currently working toward the Ph.D. degree.

From February 2010 to August 2011, he was a Research Assistant with the Department of Electrical and Electronic Engineering, University of Hong Kong. His research interests include antenna theory and design, antenna array optimization, and passive antenna systems.

Lijun Jiang (S’01-M’04) received the B.S. degree in electrical engineering from the Beijing University of Aeronautics and Astronautics, China, in 1993, the M.S. degree from Tsinghua University, China, in 1996, and the Ph.D. degree from the University of Illinois at Urbana-Champaign, in 2004.

From 1996 to 1999, he was an application Engineer with Hewlett-Packard. From 2004 to 2009, he was a Postdoctoral Researcher, research staff member, and Senior Engineer at the IBM T. J. Watson Research Center, New York. Since the end of 2009, he has been an Associate Professor with the Department of Electrical and Electronic Engineering, University of Hong Kong. His research interests focus on electromagnetics, IC signal/power integrity, antennas, multidisciplinary EDA solutions, RF and microwave technologies, and high performance computing (HPC), etc.

Prof. Jiang received the IEEE MTT Graduate Fellowship Award in 2003 and the Y.T. Lo Outstanding Research Award in 2004. He is an IEEE Antennas and Propagation Society (AP-S) Member, and a Sigma Xi Associate Member. He was the Semiconductor Research Cooperation (SRC) Industrial Liaison for several academic projects. Since 2009, he has been the SRC Packaging High Frequency Topic TT Chair. He also serves as a Reviewer of IEEE TRANSACTIONS and other primary electromagnetics and microwave related journals.

Weng Cho Chew (S’79–M’80–SM’86–F’93) received the B.S. degree in 1976, both the M.S. and Engineer’s degrees in 1978, and the Ph.D. degree in 1980, from the Massachusetts Institute of Technology, Cambridge, all in electrical engineering.

He is serving as the Dean of Engineering at The University of Hong Kong. Previously, he was a Professor and the Director of the Center for Computational Electromagnetics and the Electromagnetics Laboratory at the University of Illinois. He was a Founding Professor of the College of Engineering, and previously, the First Y.T. Lo Endowed Chair Professor in the Department of Electrical and Computer Engineering, University of Illinois. Before joining the University of Illinois, he was a Department Manager and a Program Leader at Schlumberger-Doll Research. His research interests are in the areas of waves in inhomogeneous media for various sensing applications, integrated circuits, microstrip antenna applications, and fast algorithms for solving wave scattering and radiation problems. He is the originator several fast algorithms for solving electromagnetics scattering and inverse problems. He has led a research group that has developed parallel codes that solve dense matrix systems with tens of...
Dr. Chew is a Fellow of the IEEE, OSA, IOP, Electromagnetics Academy, Hong Kong Institute of Engineers (HKIE), and was an NSF Presidential Young Investigator (USA). He received the Schelkunoff Best Paper Award from the IEEE Transactions on Antennas and Propagation, the IEEE Graduate Teaching Award, UIUC Campus Wide Teaching Award, and IBM Faculty Awards. In 2008, he was elected by the IEEE AP Society to receive the Chen-To Tai Distinguished Educator Award. He served on the IEEE Adcom for the Antennas and Propagation Society as well as the Geoscience and Remote Sensing Society. From 2005 to 2007, he served as an IEEE Distinguished Lecturer. He served as the Cheng Tsang Man Visiting Professor at Nanyang Technological University in Singapore in 2006. In 2002, ISI Citation elected him to the category of Most-Highly Cited Authors (top 0.5%). He is currently the Editor-in-Chief of JEMWA/PIER journals, and is on the board of directors of the Applied Science Technology Research Institute, Hong Kong.