The Effects of Substrate, Metal-line, and Surface Material on the Performance of RFID Tag Antenna

Chihyun Cho[1] · Hosung Choo[1] · Ikmo Park[2]

Abstract

We investigated the effects of substrate, metal-line, and surface material on the performance of radio frequency identification(RFID) tag antenna using a tag antenna with a meander line radiator and T-matching network. The results showed that readability of the tag antenna with a thin high-loss substrate could be increased so that it was similar to that of a low-loss substrate if the substrate was very thin. The readability of the tag antenna decreased significantly when the metal line was thinner than the skin depth. The readability of the tag also decreased drastically when the tag was attached to high-permittivity high-loss target objects.

Key words : RFID, Tag, Antenna.

Ⅰ. Introduction

Radio frequency identification(RFID) is used widely in stores, factories, security systems, and transportation cards. RFID in the ultrahigh frequency(UHF) band is more attractive than at other bands since it has a long readable range and large information storage capability. Recently, several studies have reported on the development of tag antennas[1]~[5], but the effects of the substrate and metal lines on the performance of a tag antenna have not been examined in detail. In addition, few studies have analyzed the performance degradation of a tag depending on the surface material of the target to which the tag antenna is attached. Thus, we studied the performance of tag antennas on various substrates, metal lines, and attached materials. The meander structure was adopted for the antenna radiator of a small antenna, and the T-matching network[6] was used for conjugate matching with a commercial tag chip (ALL-9238, 9250[7]). The detailed design parameters were optimized using a Pareto genetic algorithm(PGA)[8],[9] to guarantee the maximum performance in the readable range under a variety of conditions.

First, we examined how the permittivity and thickness of the substrate affected the performance of the tag with three substrates: Duroid, PET, and FR-4. Then, the performance of a tag antenna made using the conventional etching method was compared to the printing method using conducting ink[10]. Finally, we observed the effects of various target surface materials on the performance degradation, such as the readable range, radiation efficiency, and shift in the resonant frequency due to the material properties of the target.

Ⅱ. Antenna Structure and Optimized Method

A tag antenna consists of the conducting metal line and the dielectric substrate. We examined the performance of a tag antenna considering the differences in these materials using a simple meander tag structure, as shown in Fig. 1. The operating center frequency of the tag antenna is 912 MHz. The meander structure was used to examine how the size of the antenna affects the readability of the tag. A meander structure with line width e was constructed by bending an antenna with lengths c and d. In the UHF band, most tag chips obtain power from the electromagnetic waves radiated by the reader system, so the tag chip has an inner rectifying circuit and the input impedance was very capacitive [11],[12]. Therefore, the tag antenna had to be designed to match the conjugate impedance of the tag chip. The tag chip used in the paper has the input impedance of about $13-j130$ at 912 MHz. The T-matching network was

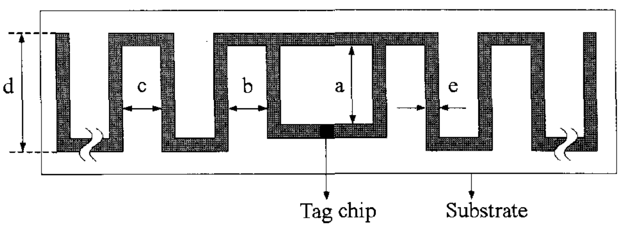

Fig. 1. Geometry of the meander tag antenna.

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[1]School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea.
[2]Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea.

adopted for conjugate matching with a commercial tag chip and was located at the center of an antenna with dimensions *a* and *b*. To search for optimal tag antenna performance for a given condition, we used a PGA in conjunction with IE3D of the Zealand EM simulator[13]. All the input and output of the IE3D software including CAD of the antenna structure can be provided as a text format. The output file from IE3D is linked with FRORTAN based PGA and, based on the output file, the PGA generates the input CAD file for the next GA iteration[8],[9].

Ⅲ. Analysis of Performance Changes

To examine the effect of the substrates, the meander tag antenna was optimized using PGA with various substrates. In the PGA, the cost functions were defined as

$$Cost1 = Antenna\ size \quad (1)$$

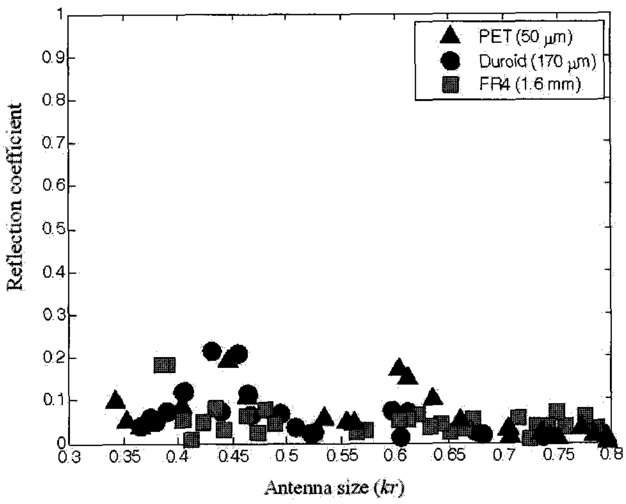
$$Cost2 = 1 - R_{norm.} \quad (2)$$

where $R_{norm.}$ is the normalized readable range of the tags and the readable range is calculated using (3)[14].

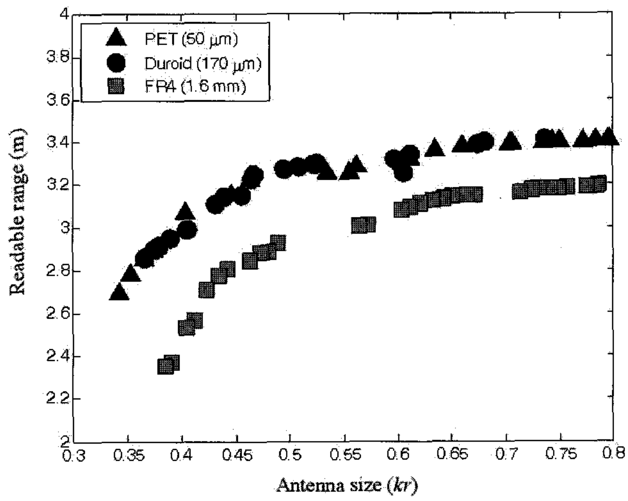
$$R = \sqrt[4]{\frac{P_T G_{Tag}^2 G_{Reader}^2}{P_{R,}\min}\left(\frac{\lambda}{4\pi}\right)^4} \quad (3)$$

In (3), P_T is the radiated power by the reader system, G_{Tag} and G_{reader} are the gains of the reader and the tag antenna, respectively, and $P_{R,min}$ is the required minimum power for detecting the tags by the reader systems. G_{reader}, $P_{R,min}$ and P_T were chosen as 3 dBi, −45 dBm and 1 W, respectively.

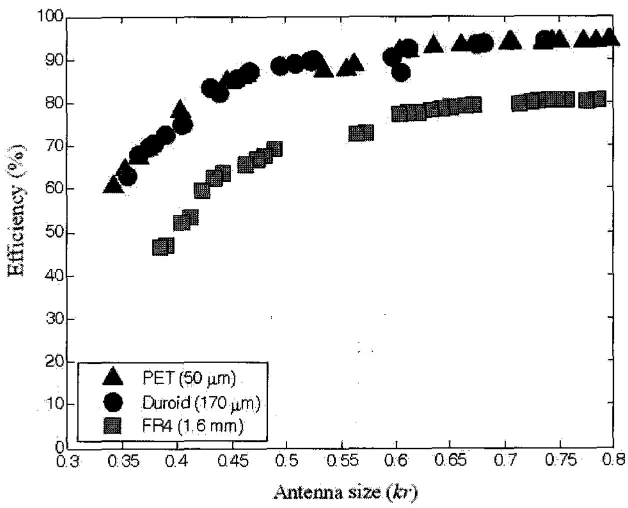
The optimized results are shown in Fig. 2. Three different substrates were used to examine the effect of the substrate on the performance: PET(ε_r: 3.9, $\tan\delta$: 0.003, thickness: 50 μm), Duroid(ε_r: 2.2, $\tan\delta$: 0.0009, thickness: 127 μm), and FR-4(ε_r: 4.25, $\tan\delta$: 0.02, thickness: 1.6 mm). They are shown with the triangles, circles, and rectangles in the figure, respectively. Fig. 2(a) shows the reflection coefficient of the optimized tag antennas when they are fully matched with the tag chip. Fig. 2(b) shows the readable range of the tag antenna as a function of antenna size. As the antenna size is reduced, the readable range decreases, since the radiation efficiency of the antenna also decreases, as shown in Fig. 2(c). The radiation efficiency of the FR-4 substrate is about 20 % lower than that of Duroid because a high-loss substrate such as FR-4 reduces the antenna efficiency even more. The efficiency of the PET substrate is very similar to that of Duroid, since the PET is very thin compared with the FR-4 substrate. This shows that if a thin substrate such as PET is used, the readable range of the tag can be



(a) Reflection coefficient



(b) Readable range



(c) Radiation efficiency

Fig. 2. Effect of substrate type on the performance of the tag antenna.

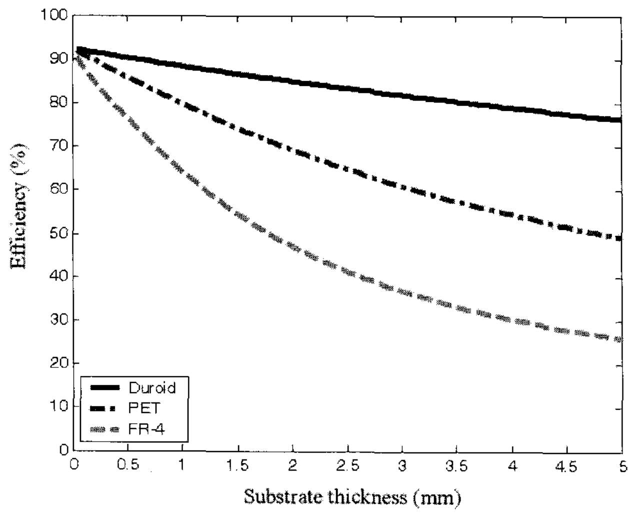
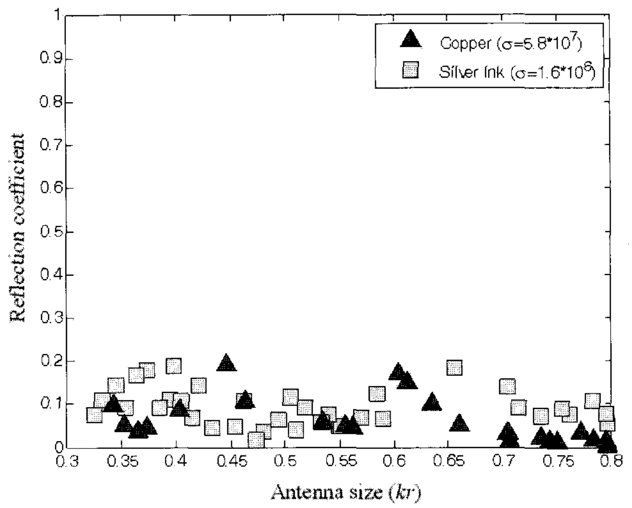


Fig. 3. Efficiency of the tag antenna as a function of substrate thickness.

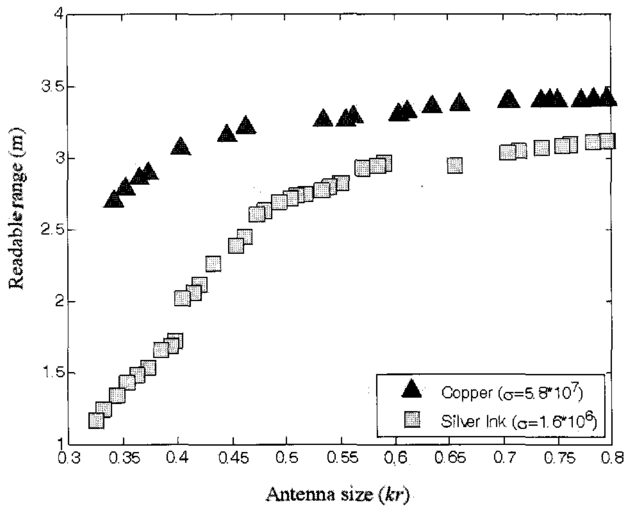
increased greatly and approaches the value of a low-loss, high-cost substrate such as Duroid despite the fact that the loss tangent (tan δ) of PET is about the same as that of FR-4. Fig. 3 plots the radiation efficiency as a function of the substrate thickness for a given antenna size (kr=0.6). As expected, the efficiency decreases as the substrate thickness increases.

Currently, printing methods using conducting ink instead of etching technology are being used for low-cost fabrication[10]. However, the low-cost printing methods reduce the conductivity of the metal line on the tag antenna. The performance of silver ink printing (rectangles) and copper etching (triangles) is compared in Fig. 4 using 50 μm PET as the substrate for both. The optimized results show that the readable range of the silver ink printing method is shorter than that of the copper etching method, although both optimized antennas are fully matched with the tag chip. In a small size (kr<0.55), the performance degradation of silver ink becomes more significant since the low conductivity of the metal line drastically increases the conducting loss, which results in a drop in the radiation efficiency.

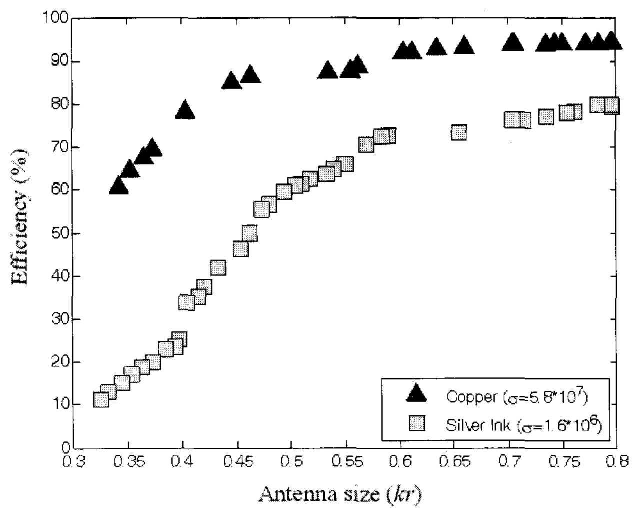
Next, we examined the performance change due to variation in the metal line thickness, as shown in Fig. 5. The antennas were printed on PET substrate with a copper metal line that varied in thickness between 0.1 and 5 μm. The resulting readable range again decreased rapidly when the copper line was less than 0.7 μm thick. This occurs because when the thickness of metal line is less than skin depth (about 0.7 μm at 900 MHz for copper), the antenna efficiency is greatly reduced due to the significant conducting loss in the metal line. Based on these result, we can see that the metal line should be thicker than the skin depth for adequate readability.



(a) Reflection coefficient



(b) Readable range



(c) Radiation efficiency

Fig. 4. Effect of the type of metal line on the performance of the tag antenna.

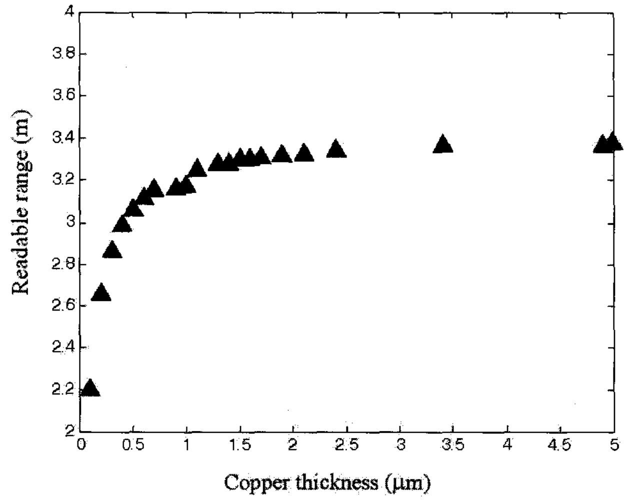
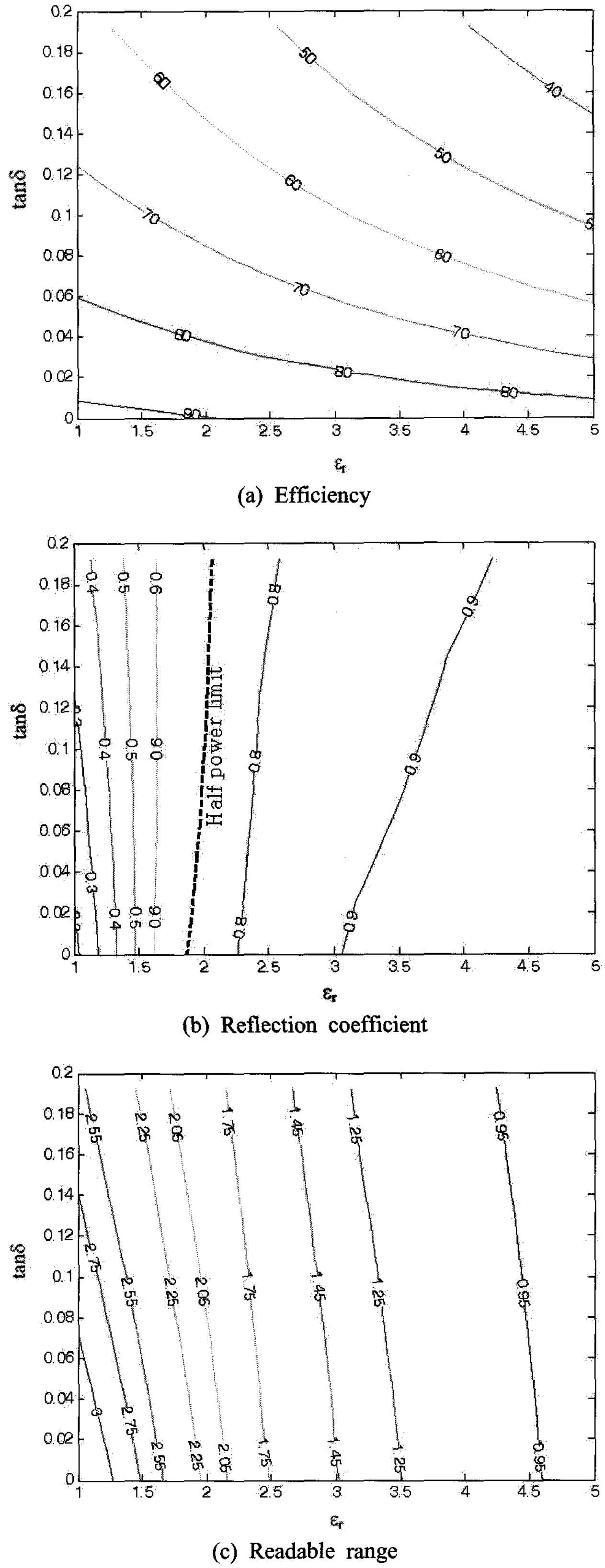


Fig. 5. Readable range according to the thickness of the metal line.

Finally, the degradation in the antenna efficiency and readable range was analyzed when the tag was attached to targets made of several different dielectric materials (all 0.5 mm-thick). The size of tag antenna used was *kr* =0.6 and it was printed on 50 μm thick PET substrate with cooper line. The resulting degradation in tag performance is plotted for various target materials with different permittivities and dielectric losses in Figs. 6. Fig. 6(a) shows the radiation efficiencies of antenna with various target materials. As the loss tangent of the attached materials is increased, the efficiency of the tag antenna is decreased rapidly, which results in a shorter readable range due to the reduction of the received power in the reader system. The small meander tag antenna (*kr*=0.6) can achieve the maximum of 50 % efficiency when the loss tangent of the target material has less than about 0.1. The reflection coefficients between the tag chip and the antenna are represented in Fig. 6(b). As the permittivity of the target object is increased, the mismatch between the antenna and tag chip also increases (the reflection coefficient increases). The dashed line plots the 3 dB reflection (half-power limit). The resulting readable ranges are plotted in Fig. 6(c). The readable range is affected by the antenna efficiency, as well as the mismatch between the antenna and the tag chip. Clearly, the readable range decreases as the permittivity and losses of the target objects increase. These results show that the electrical property of the target object should be considered when designing tag antennas for a given application.



(a) Efficiency

(b) Reflection coefficient

(c) Readable range

Fig. 6. Effect of attached target objects on the performance of the tag antenna.

Ⅳ. Conclusion

We studied the effect of the substrate, metal line and surface material on the performance of RFID tag antennas. To examine the performance of tag antennas, we used PGA optimization with a simple meander type tag structure. We showed that the readability of the tag antenna with the thin high-loss substrate could be increased similar to that of a low-loss substrate material if the thickness was less than 0.4 mm. The readability of the tag antenna decreased significantly with silver ink, especially when the antenna size was less than kr=0.55 and it also decreased when the thickness of the metal line was less than the skin depth. Finally, the readability of the tag decreased drastically when the tag was attached to high-permittivity and high-loss target objects.

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References

[1] M. Hirvonen, P. Pursula, K. Jaakkola, and K. Laukkanen, "Planar inverted-F antenna for radio frequency identification", *Elect. Lett.*, vol. 40, pp. 848-850, Jul. 2004.

[2] C. Cho, H. Choo, and I. Park, "Broadband RFID tag antenna with quasi-isotropic radiation pattern", *Elect. Lett.*, vol. 41, pp. 1091-1092, Sep. 2005.

[3] H. Kwon, B. Lee, "Compact slotted planar inverted-F RFID tag mountable on metallic objects", *Elect. Lett.*, vol. 41, pp. 1308-1310, Nov. 2005.

[4] K. V. S. Rao, P. V. Nikitin, and S. F. Lam, "Antenna design for UHF RFID tags: A review and a practical application", *IEEE Trans. Antennas Propagt.*, vol. 53, pp. 3870-3876, Dec. 2005.

[5] K. Penttila, M. Keskilammi, L. Sydanheimo, and M. Kivikoski, "Radar cross-section analysis for passive RFID systems", *IEE Proc. Microw. Antennas Propagt.*, vol. 153, pp. 103-109, Feb. 2006.

[6] C. A. Balanis, *Antenna theory: analysis and design*, New York: John Wiley & Sons, 1997.

[7] http://www.alientechnology.com, "RFID systems"

[8] N. Srinivas, K. Deb, "Multiobjective optimization using nondominated sorting in genetic algorithm", *J. Evol. Comput.*, vol. 2, pp. 221-248, 1995.

[9] Y. Rahmat-samii, E. Michielssen, *Electromagnetic Optimization by Genetic Algorithms*, New York: John Wiley & Sons, 1999.

[10] P. V. Nikitin, S. Lam, and K. V. S Rao, "Low cost silver ink RFID tag antennas", in *IEEE Antennas Propagat. Soc. Int. Symp.*, vol. 2B, pp. 353-356, Jul. 2005.

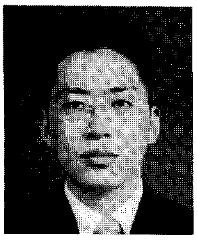
[11] U. Karthaus, M. Fischer, "Fully integrated passive UHF RFID transponder IC with 16.7 μW minimum RF input power", *IEEE J. Solid-State Circ.*, vol. 38, pp. 1602-1608, Oct. 2003.

[12] P. V. Nikitin, K. V. S. Rao, S. F. Lam, V. Pillai, R. Martinez, and H. Heinrich, "Power reflection coefficient analysis for complex impedances in RFID tag design", *IEEE Trans. Microw. Theory Tech.*, vol. 53, pp. 2721-2725, Sep. 2005.

[13] http://www.zeland.com/ie3d.html, Zeland Software, "IE3D MoM-based EM simulator"

[14] C. Cho, H. Choo, and I. Park, "Design of UHF small passive tag antennas", in *IEEE Antennas Propagat. Soc. Int. Symp.*, vol. 2B, pp. 349-352, Jul. 2005.

Chihyun Cho



received his B.S. and M.S. degrees in radio science and communication engineering from Hongik University, Seoul, Korea, in 2004 and 2006, respectively, and is currently working toward the Ph. D. degree at Hongik University. His current research interests include small antenna, RFID system, and optimization using genetic algorithm.

Hosung Choo

was born in Seoul, Korea. He received the B.S. degree in radio science and engineering from Hanyang University in Seoul in 1998, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Texas at Austin, in 2000 and 2003, respectively. From 1999 to 2003, he was a Research Assistant with the Department of Electrical and Computer Engineering, University of Texas at Austin. In September 2003, he joined the School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea, where he is currently an assistant professor. His principal area of research is the use of the genetic algorithm in developing microstrip and wire antennas and microwave absorbers. His studies include broadband and multiband antennas for wireless communications and miniaturized antennas for RFID applications.

Ikmo Park

received the B.E. degree in electrical engineering from the State University of New York at Stony Brook in 1984, and M.S. and Ph.D. degrees in Electrical Engineering from the University of Illinois at Urbana-Champaign in 1989 and 1994, respectively. From September 1994 to February 1996, he has been with the Device & Materials Laboratory of LG Corporate Institute of Technology, Seoul, Korea, where he had been engaged in research and development of various antennas for Personal Communication System, Wireless Local Area Network, and Direct Broadcasting System. He joined the department of electrical and computer engineering at Ajou University, Suwon, Korea, in March 1996 as an Assistant Professor, and promoted to a Professor in March 2004. His current research interests include the design and analysis of microwave, millimeter-wave, and Terahertz passive structures, and electromagnetic modeling of electronic packaging for high-speed digital interconnections.