JOURNAL OF THE KOREA ELECTROMAGNETIC ENGINEERING SOCIETY, VOL. 6, NO. 3, SEP. 2006 JKEES 2006-6-3-04

Application of Magneto-Dielectric Materials in Antenna Design

Kyeong-Sik Min · Viet-Hong Tran

Abstract

In this paper, magneto-dielectric material is proposed to use for minimizing antenna size. One examle of very small antenna is presented to prove this with antenna's area of 0.078 $\lambda_0 \times 0.016 \lambda_0$, and just moderate values of permittivity and permeability while the return loss can reach -38 dB at the resonant frequency. The parameters of dielectric material for that best performance are $\varepsilon_r = 1.71 - j0.004$, and $\mu_r = 2.39 - j2.58$. Besides, this material also has ability to control the trade-off between the gain and bandwidth while keeping the antenna size unchanged.

Key words : Magneto-Dielectric Material, Small Antenna Design, Relation Between Gain And Bandwidth.

Ⅰ. Introduction

Regularly, consumers expect that the electronic devices are provided with impressive improvement in size reduction for simplicity and mobility. Hence the small size is often paid attention in antenna design. There are many kinds of small antenna such as planar inverted-F antenna(PIFA), chip antenna, patch antenna, and etc. For those electrically small antennas, especially in low frequency range, some problems are arisen such as:

- decrease of radiation resistance, in other words, decrease of efficiency.
- increase of input impedance due to increasing reactance, and input resistance is often very low, causing impedance mismatch problem. In addition, bandwidth is limited by impedance mismatch.
- increase of effect from surrounding environment.
- the efficiency is reduced also because power is trapped in a limited space with high density.

The fundamental limits on antenna size have been studied since 1940s when Wheeler[1] and Chu[2] presented a mathematical relationship between antenna size and Q. Because this limit cannot be changed, the solutions for this problem can be: sharing the resource with radiated part (such as use PCB for ground plane in embedded antenna, fully utilize the volume for antenna, etc.), using new material, or system solutions. (such as smart antenna, etc.)

In this paper, it is suggested of using magneto-dielectric material in antenna design for minimized size approach. Magneto-dielectric material is one kind of dielectric material whose value of permeability can be varied easily. It is different from conventional dielectric materials in which the permeability is unit.

Most microstrip patch antenna designs until now are based on the dielectric which is just changed the permittivity. This makes the antenna design procedure simpler because only one parameter of dielectric coefficients affects to antenna performance. On the other hand, this limits the ability of easily improving the performance of antenna. Thus, magneto-dielectric material offers more number of parameters of dielectric in order to improve the performance of the antenna, so that some characteristics of antenna can be improved to satisfy the requirement of application.

Moreover, with the presence of permeability, the bandwidth and gain of the antenna can be adjusted. By controlling the ratio between permeability and permittivity, the gain-bandwidth product, as one factor to evaluate the quality of antenna, can be changed to meet the requirement.

In this paper, one example of patch antenna is presented to prove the ability of miniaturization from using magneto-dielectric material. In addition, its resonance frequency is 433.92 MHz and has omni-directional radiation pattern. The example antenna type is meander line, but the usage of magneto material as dielectric can be used for any kind of antenna. However, the manufacture process for this kind magneto-dielectric material requires a long time and a high cost. Hence, unfortunately, we do not have the measurement results until now. This manuscript shows the idea of using magneto-dielectric material in antenna design and the advantages when using this material.

Ⅱ. Magneto-Dielectric Materials

There are many methods have been reported to reduce

Manuscript received May 11, 2006 ; revised August 9, 2006. (ID No. 20060511-015J)

Department of Radio Sciences & Engineering, College of Engineering, Korea Maritime University, Busan, Korea.

the size of antenna[3],[9],[10]. They can be divided into 2 sets based on changing the geometry of radiating elements, or changing the parameters of electromagnetic materials. In this paper, the second method is presented. In the past, dielectric with high permittivity is often used. However, this causes some disadvantages such as narrow bandwidth and low efficiency. Hence, magneto-dielectric material is suggested to use instead of high permittivity dielectric.

In magneto-dielectric material, both ε_r and μ_r are complex number described as:

$$\varepsilon_r = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta) \tag{1}$$

$$\mu_r = \mu' - j\mu'' = \mu'(1 - j\tan\delta') \tag{2}$$

where tan δ and tand δ ' are dielectric loss tangent and magnetic loss tangent, respectively.

The magneto-dielectric composite consists of some metallic components and/or ferrite material, so that the permeability of dielectric can be changed easily. Unfortunately, magnetic losses of the material are rather high, due to the presence of those metal and ferrite components.

In general, resonant frequency of microstrip antennas relates directly to wavelength in dielectric λ_g instead of wavelength in free space λ where:

$$\lambda_g \cong \frac{\lambda}{\sqrt{\mu_r \varepsilon_r}} \tag{3}$$

In Eq. (3), $n = \sqrt{\mu_r \varepsilon_r}$ is called miniaturization factor, or refractive index. The higher value of this factor, the smaller size of antenna.

In order to achieve small size, conventional dielectric (μ_r=1) is required a very high value of ε_r to increase the refractive index. In case of magneto-dielectric material substrate, both ε_r and μ_r can be changed simultaneously to get the same value of n (the same size of antenna), so their values are moderate. Moreover, the permeability value different from unit in magneto-dielectric also leads to other advantages. Fig. 1 shows the comparison between ordinary dielectric and magneto-dielectric material.

η is intrinsic impedance of dielectric and η_0 is intrinsic impedance of free space, where

$$\eta = \eta_0 \sqrt{\mu_r / \varepsilon_r} \tag{4}$$

So, if the ratio between ε_r and μ_r becomes to 1, the matching between two intrinsic impedances is reached; the surface wave is disappeared and the efficiency of antenna is increase, as a consequence. The interaction of environment is eliminated. Hence, using magneto-dielectric material, many advantages can be achieved just by adjusting the permeability and permittivity.

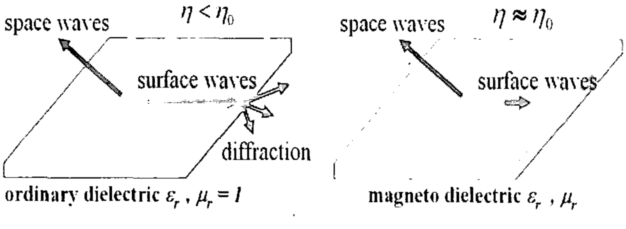

Fig. 1. Comparison between two kinds of dielectric.

III. Antenna Design

Magneto-dielectric materials can miniaturize the antenna by the same factor with ordinary dielectric material, but values of permittivity and permeability are more reasonable[4]. Thus, the field confinement is minimized and the medium is far less capacitive. Furthermore, since the characteristic impedance of magneto-dielectric material medium is close to that of the surrounding medium, it allows for ease of impedance matching over a wider bandwidth and suppression of the surface wave[5].

One antenna design is proposed as an example for applying magneto-dielectric material. The resonant frequency is 433.92 MHz. This frequency is used in active RFID system. The antenna size is required as small as possible, especially in mobile RFID system or Ubiquitous Sensor Network(USN). In addition to using of new material, meander line technique is also used to one more time reduce the size and utilize whole volume of the antenna.

Fig. 2 shows the structure of antenna, using probe feeding method.

The upper metal plate contains a conventional meander line structure, with the length of one meandered section is 11 mm. The line width is chosen at 1 mm and the gap between two adjacent meandered sections is chosen at 0.5 mm in order to reduce the antenna size. Firstly, thinking as using the popular FR4 dieletric, the permittivity is 4.4. The total length of the meander line is required about one wave length[6], so from equation (3), the number of turns is estimated:

$$N \approx \frac{\lambda_g}{2l} = \frac{\lambda}{2l\sqrt{4.4}} = 15.1 \tag{5}$$

where l is the length of one meandered section. However, actually the total length of meander line is required a little greater than one wavelength because of the mutual coupling between adjacent segments. Hence, the number of turns for this antenna is chosen at 16.

In order to analyse the effect of parameters of magneto-dielectric material, the permittivity and permeability is intentionally chosen at different values as using

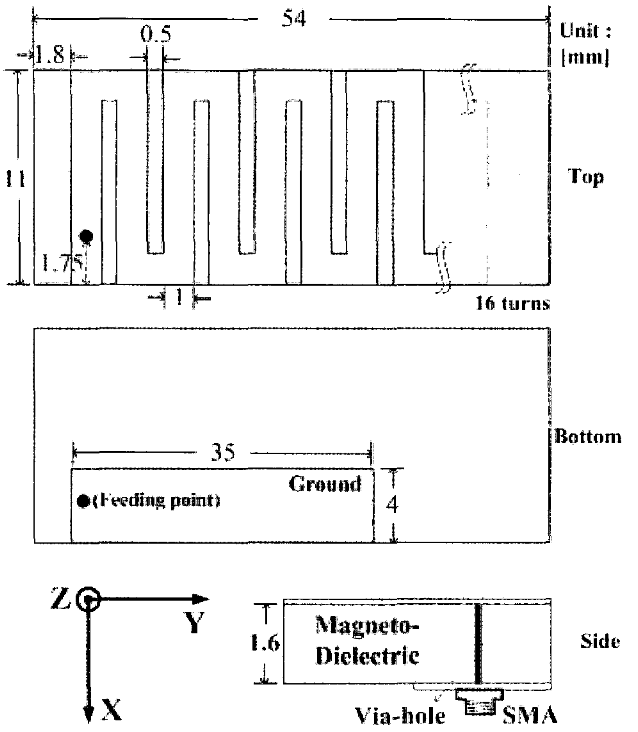

Fig. 2. Structure of miniaturization antenna resonated at 433.92 MHz.

for estimated above, 5.21$-j$0.012 and 2.39$-j$2.58, respectively. These values are based on properties of one commercial Ni-Zn material. In the bottom metal plate, the ground size is also kept reduce to expect an omnidirectional pattern. From simulation, the feeding point is found so that the input impedance is nearest to 50 Ω. The return loss of this initial model is shown in Fig. 3 (circular-marked line). The resonant frequency is lower than target frequency due to the higher values of permittivity and permeability compare with values using for calculation.

Because the interest in this paper is parameters of the substrate, so the structure of antenna is maintained as in Fig. 2, the dielectric's parameter study is conducted in the next step. The properties of magneto-dielectric material are changed to find the optimized values of ε_r and μ_r so that the antenna resonates at 433.92 MHz with best performance. The results of return loss when varying the permittivity of magneto-dielectric is shown in Fig. 3.

It can be seen that when dielectric constant increases, the resonant frequency shifted to low frequency area. At ε'=1.71 (rectangular-marked line), good resonant characteristic is calculated with return loss of meander line antenna of −30 dB at 433.92 MHz.

Second, in the permittivity component, only ε'' is changed. Value of ε' is fixed at 1.71 and permeability is not changed. The effect of ε'' applies only to return loss level without frequency shifting as shown in Fig. 4.

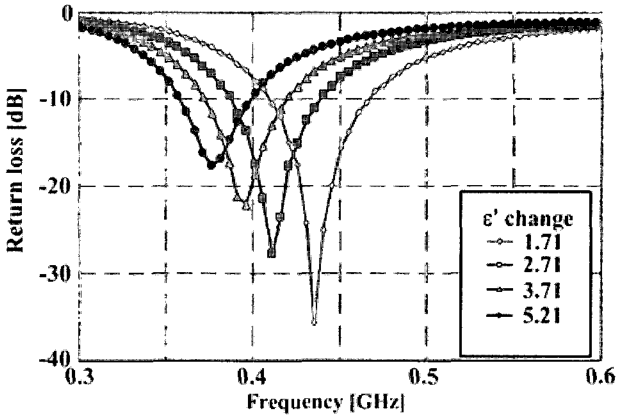

Fig. 3. Return loss against permittivity change.

The resonant frequency is almost same. It means that this loss property just affects to the efficiency of the antenna. To get the best return loss, 0.004 is chosen for ε'' value.

Fig. 5 and Fig. 6 show the return loss results of the permeability components of magneto-dielectric, when ε_r =1.71$-j$0.004.

From Fig. 5, when the permeability increases, the resonant frequency of antenna is lowered. This effect is well-known, similar with the change of permittivity. A good performance at 433.92 MHz is observed in the case of rectangular line.

In Fig. 6, μ'' participates in changing resonance frequency. It is because of mutual coupling between adjacent sections, the magnetic tangent loss makes change to equivalent inductance of the meander line (L_M), and so to resonant frequency of the antenna as shown in Fig. 7[7].

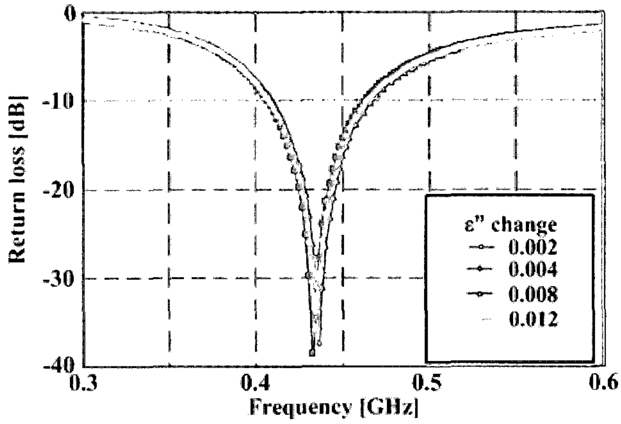

Fig. 4. Return loss with respect to dielectric tangent loss change.

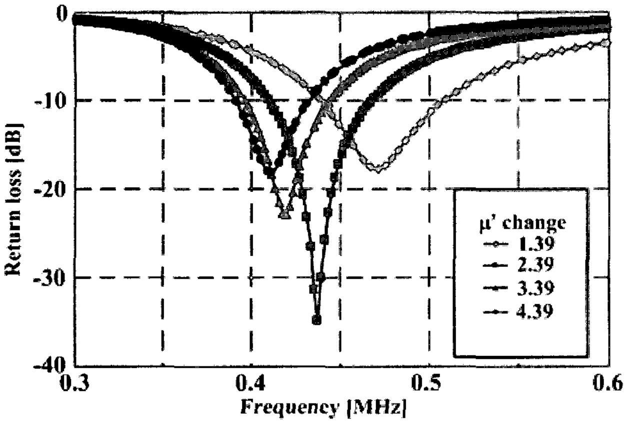

Fig. 5. Return loss with respect to permeability change.

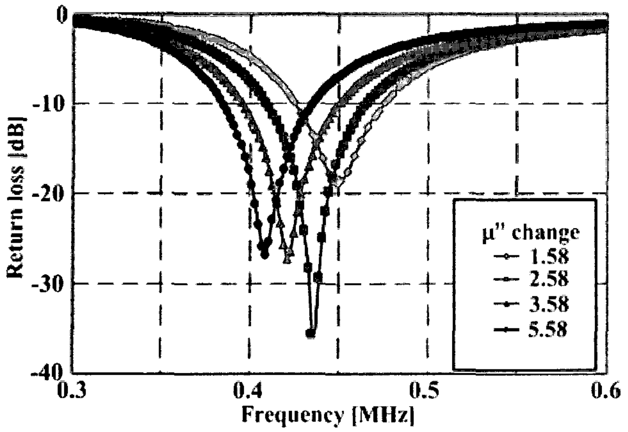

Fig. 6. Return loss with respect to magnetic tangent loss change.

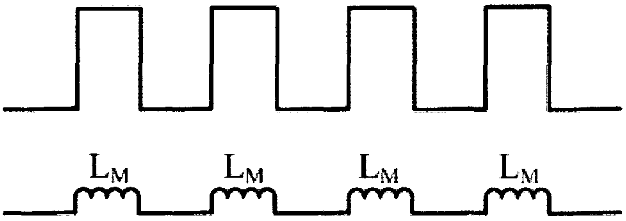

Fig. 7. Equivalent inductance of meander line.

The values of μ'' are chosen from database of popular magneto-dielectric material properties. These values are rather high. It is a disadvantage of magneto-dielectric material. The high loss affects to efficiency, and gain of antenna as shown in Fig. 8.

The gain limitation for small antenna has been expressed by Harrington in Ref. [8]. In this case, the maximum attainable gain of this antenna is 0.55 dBi. From Fig. 8, the maximum gain of the antenna is -4.3 dBi. However, compared with other designs in the same resonant frequency in Ref. [9], the gain reduction is not

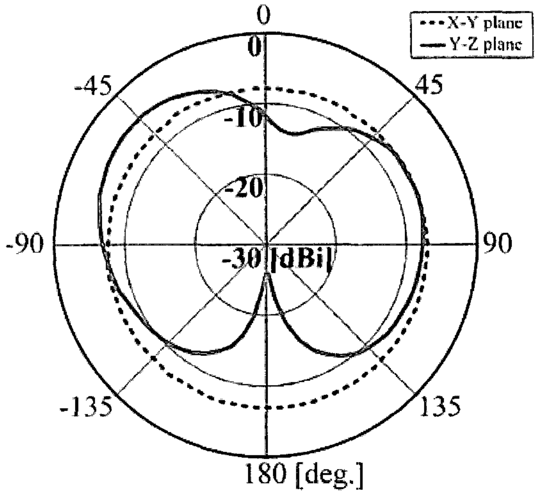

Fig. 8. Gain pattern of miniaturization antenna at 433.92 MHz.

much as miniaturization of antenna size.

The optimized parameters of magneto-dielectric substrate is achieved with the value of permittivity is $\varepsilon_r = 1.71 - j0.004$, and the value of permeability is $\mu_r = 2.39 - j2.58$. The small antennas techniques are generally used dielectric with high permittivity. However, proposed meander antenna has low permittivity constant of 1.71, but the results show good performance while the size reduction ratio is still high.

This antenna design has omni-directional characteristic. As seen from Fig. 8, it is omni-directional in XY-plane. In ZX-plane, because of the existence of the ground, there is a null point. However, the half power beam-width is also very large.

Ⅳ. Trade-off between Gain and Bandwidth

It is well-known that gain and bandwidth becomes trade-off. Hence, this phenomenon can be investigated to find the way to improve the gain of antenna. This trade-off is expressed by gain-bandwidth product(GBP), one of factors usually used to describe the relative quality of an antenna, defined as[5]:

$$\mathrm{GBP} = \mathrm{Gain} \times \mathrm{Bandwidth} \tag{6}$$

where gain is dimensionless and unit of bandwidth is Hz. It is noticed that the gain calculated in dB (or dBi, dBd) cannot be used in this equation, because of wrong comparison due to the sign of gain in the dB scale. Some designs concentrate on improving the bandwidth, even though the gain decreases as a consequence. Other designs aim to increase the gain of antenna and pay a price for narrow bandwidth. Hence, any design with the goal of enhancing the antenna quality must have actual improvement of GBP.

From Ref. [10], the zero-order bandwidth for an antenna over a magneto-dielectric material substrate can be approximated by:

$$BW \approx \frac{96\sqrt{\mu_r/\varepsilon_r}\,\frac{t}{\lambda_0}}{\sqrt{2}[4+17\sqrt{\mu_r \varepsilon_r}]} \qquad (7)$$

where t: thickness of the substrate

λ_0: wavelength at resonant frequency

It is easily seen that when the permittivity-permeability product is kept, i.e. the size of antenna is unchanged because of refraction index n, the bandwidth of antenna can be broader by increasing the ratio between permeability and permittivity.

It is quite an interesting matter. The size of antenna is still small, and the quality can increase just by changing the parameters of substrate. Therefore, in the following, the effect of μ_r/ε_r to GBP is analyzed because it affects not only to bandwidth but also the gain of antenna. The product $\varepsilon_r \mu_r$ is kept constant at 4.087. The values of ε_r and μ_r are changed. Each pair of (ε_r, μ_r) value forms one material. There are 7 different cases are calculated. The resonant frequency at each case is checked that they are nearly the same. Variance of GBP against μ_r/ε_r is shown in Fig. 9, and detailed values are presented in Table 1.

From Fig. 9, it is obviously seen that GBP always increases when μ_r/ε_r increases. The slope degree of the graph is high when μ_r/ε_r is in the range from 0 to 1.5. After that, the graph has saturation trend.

The gain of antenna always increases when the permeability increases, because it makes the efficiency of the antenna increases, as shown in Fig. 10. The efficiency is in the range from 18 % to 44 %. That is why the gain of antenna is so low compare with the maximum attainable gain 0.55 dBi, calculated from Ref. [8]. In small size antenna, the efficiency is reduced much due to the trapped power in a limited space with high density. Hence, the radiation resistance is small. When the permeability increases, and the permittivity decreases, the ability of storing energy inside the substrate is lower, and so the value of radiation resitance is higher. As a consequence, the efficiency increases.

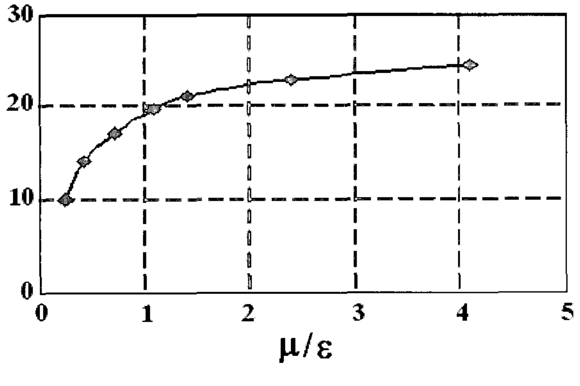

Fig. 9. GBP as a function of permeability-permittivity ratio.

Table 1. Gain-bandwidth product analysis.

Material	μ_r/ε_r	Gain (dB)	Gain	BW (MHz)	GBP
①	4.087	−2.70	0.537	46	24.702
②	2.382	−3.45	0.452	51	23.052
③	1.398	−4.34	0.368	58	21.351
④	1.089	−4.71	0.338	59	19.942
⑤	0.715	−5.39	0.289	60	17.344
⑥	0.420	−6.10	0.245	58	14.210
⑦	0.245	−6.52	0.223	45	10.035

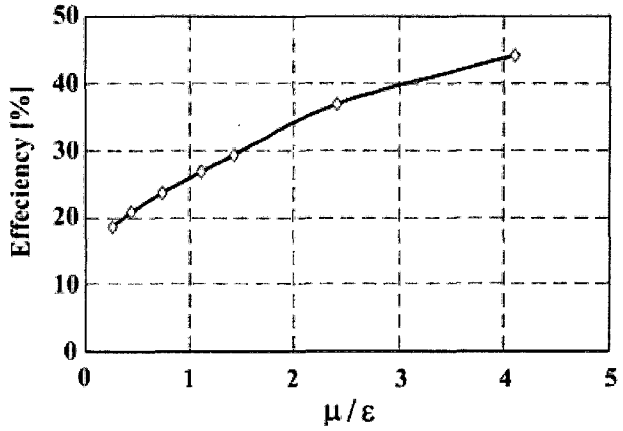

Fig. 10. Efficiency as a function of permeability-permittivity ratio.

However, the bandwidth has a peak value. When μ_r/ε_r is around 1, the bandwidth is nearly unchanged, while the gain still increases. It is because the bandwidth does not depend on efficiency like the gain. It depends on the impedance mismatching. When μ_r/ε_r converges to 1, the impedance contrast between dielectric and surrounding free space is much reduced, so the bandwidth reaches the maximum value. Although bandwidth does not increase continuously like gain, the quality of antenna is still improved because GBP always increases. That is the advantage of magneto-dielectric material.

V. Conclusion

This paper presents the usage of magneto-dielectric material to miniaturize antenna size. The proposed antenna, whose size is very small with overall dimension of $0.078\lambda_0 \times 0.016\lambda_0 \times 0.0023\lambda_0$, has return loss, and bandwidth of −38 dB, and 58 MHz at 433.92 MHz, respectively. This size is achieved by choosing the optimized values of 4 substrate's parameters, such as ε', ε'', μ', and μ''. The antenna structure is meander line type, but this method can be applied for any other antenna structures.

The maximum gain of the proposed antenna is −4.3 dBi, rather low. This is mainly because of the high concentration of electric and/or magnetic fields within a small volume of antenna structure due to small size, in addition to a lossy material as magneto-dielectric material.

However, magneto-dielectric material offers another advantage by controlling the ratio between permeability and permittivity (μ_r/ε_r). The trade-off between gain and bandwidth can be adjusted by this ratio. We can choose the value so that the antenna achieves the highest gain, or the best trade-off between gain and bandwidth based on GBP curve.

This research was supported by the Program for the Training of Graduate Student Regional Innovation which was conducted by the Ministry of Commerce, Industry and Energy of the Korean.

References

[1] H. A. Wheeler, "Fundamental limitations of small antennas", *Proceedings of the IRE*, vol. 35, pp. 1479-1484, Dec. 1947.

[2] L. J. Chu, "Physical limitation on omni-directional antennas", *Journal of Applied Physics*, vol. 19, pp. 1163-1175, Dec. 1948.

[3] Kin-Lu Wong, *Compact and Broadband Microstrip Antennas*, John Wiley & Sons, Inc., 2002.

[4] Hossein Mosallaei, Kamal Sarabandi, "Magneto-dielectric materials in electromagnetics: Concept and applications", *IEEE Transactions on Antenna and Propagation*, vol. 52, no. 6, pp. 1558-1567, Jun. 2004.

[5] J. T. Aberle, "A figure-of-merit for evaluating the gain-bandwidth product of microstrip patch antennas", *IEEE Africon Conference Digest(Invited Paper)*, pp. 1001-1004, Sep. 1999.

[6] Gyey-Taek Jeong *et al.*, "Design of a meander type microstrip antenna in the 5 GHz Band", *Journal of The Korea Communication Society*, vol. 29, no. 9A, pp. 1083-1090, Sep. 2004.

[7] Ho-Yong Kim *et al.*, "Triple-band compact chip antenna using stacked meander line structure for GPS/PCS/Satellite DMB services", *Journal of The Korea Electromagnetic Engineering Society*, vol. 16, no. 2, pp. 211-216, Feb. 2005.

[8] R. F. Harrington, "Effect of antenna size on gain, bandwidth, and efficiency", *Journal of Research of the National Bureau of Standards-D, Radio Propagation*, vol. 64D, no. 1, pp. 1-12, Jan.-Feb. 1960.

[9] Kent Smith, "Antennas for low power applications", *RFM App. Notes*.

[10] R. Hansen, M. Burke, "Antennas with magneto-dielectric materials", *Micro. Opt. Tech. Letter*, vol. 26, no. 2, pp. 75-78, Jul. 2000.

Kyeong-Sik Min

received the B.E. and M.E. degrees in the dept. of electronic communications engineering from the Korea Maritime University, in 1989 and 1991, respectively. He received the Ph.D. degree in dept. of electromagnetic wave and electronics engineering from the Tokyo Institute of Technology in 1996. Currently, he is professor of the dept. of radio sciences & engineering at the Korea Maritime University. His research interests include the design of plannar antenna, MIMO antenna, smart antenna for SDR, RFID and the design of microwave circuit.

Viet-Hong Tran

received the B.E. degree in the faculty of electrical and electronic engineering from the Hochiminh city National University of Technology, in 2002. He has just received the Master degree in dept. of radio sciences & engineering at the Korea Maritime University. He is currently pursuing the Ph. D. degree under the supervision of Prof. Kyeong-Sik Min at the Korea Maritime University. His research interests include the design of antenna, and RFID communication system.