11-1-2007

Wireless Power Transmission to a Buried Sensor in Concrete

Khan M.Z. Shams
University of South Carolina - Columbia, shams@engr.sc.edu

Mohammod Ali
University of South Carolina - Columbia, alimo@engr.sc.edu

Publication Info

Published in *IEEE Sensors Journal*, Volume 7, 2007, pages 1573-1577.
http://ewh.ieee.org/tc/sensors/SJ/Sensors_journal.htm

Wireless Power Transmission to a Buried Sensor in Concrete

Khan M. Z. Shams, *Student Member, IEEE*, and Mohammod Ali, *Senior Member, IEEE*

***Abstract*—The feasibility of sending wireless power to a buried sensor antenna within concrete was studied. A receive patch rectenna with 75.8% conversion efficiency was designed for operation at 5.7 GHz. The received DC power at the rectenna was measured within dry and wet concrete samples with various cover thicknesses and air-gaps. For the rectenna buried within 30 mm of the concrete, the received DC power was 10.37 mW, which was about 70% of the received DC power in free-space.**

***Index Terms*—Concrete, power transmission, rectenna, wireless sensor.**

I. INTRODUCTION

ROUTINE EVALUATION and prediction of the health of civil infrastructures, such as bridges, overpasses, and buildings is crucial to ensure public safety. Currently, the health monitoring of infrastructures is done by expensive and labor-intensive procedures such as spot checking [1] and ground penetrating radar (GPR) [2]. An alternative is to use distributed wireless sensors to perform structural health monitoring [3]–[5]. Researchers have also proposed the use of wireless embeddable sensors for infrastructure health monitoring [6], [7]. Such sensors must be installed within the structure itself during the construction phase of the infrastructure. Wireless embedded sensors are low cost and are more reliable than conventional wired sensors since the presence of wires within an infrastructure creates the possibility of loss of connection due to crack and corrosion. Power to the sensor may be supplied using inductive near-field technique [8] or radiated far-field technique [9]. For low data rate, RFID tag type sensors energizing the sensor using inductive coupling is a cheap and attractive option [10], [11]. A reader or interrogator is generally used to energize and interrogate the sensor. A passive tag type sensor does not collect or transmit any data unless energized and queried by an interrogator.

Unlike the above, there are sensors that collect data routinely whether queried by an interrogator or not require onboard batteries which must be replenished periodically. However, once the sensors are embedded within an infrastructure, they may not be easily accessible physically without damaging the structure. Thus, to recharge the embedded sensor batteries from outside the concept of radiated far-field power transmission to a rectenna (an antenna and integrated rectifier) is important. In that case, a rectenna can be integrated with the embedded wireless sensor which will receive radiated rf power, and then convert it to DC to recharge the batteries of the sensor.

Lately, there are reports on sending power to wireless sensors using rectennas [9], [12]–[14]. However, although there has been considerable research work on antennas that are embedded within the human body [15]–[17] or within soil or other objects [18], there has been no report of research activity on wireless power reception by rectennas that are buried within an infrastructure. In this paper, we report our observations and findings on the feasibility of sending wireless power to a buried rectenna in concrete.

This paper is organized as follows. First, a stacked microstrip patch antenna was designed for operation in free-space from a frequency of 5–6 GHz. To investigate the input return loss and radiation properties of the antenna it was placed within a sample of concrete. Antenna return loss properties were measured. The radiation patterns of the stacked patch antenna were computed using Ansoft HFSS. To study the feasibility of sending wireless power to a buried rectenna, a 4 × 4 transmit patch antenna array was designed and fabricated for operation at 5.7 GHz. The rectenna consisted of a stacked microstrip patch antenna, which was integrated with an HSMS-2862 rectifying Schottky diode, a smoothing capacitor, and a load resistor.

II. RECEIVE STACKED PATCH ANTENNA

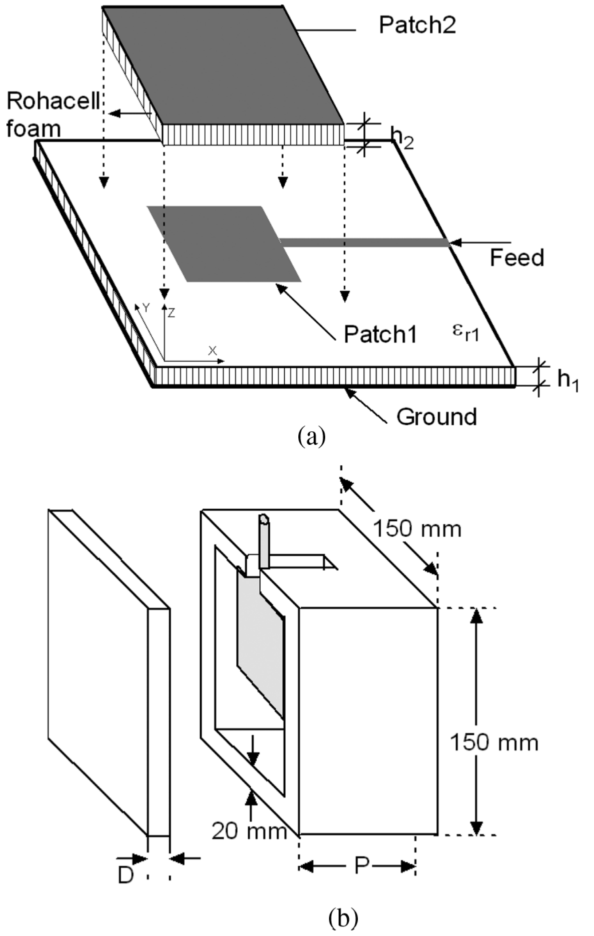
A. Measured Return Loss Characteristics

The stacked patch antenna introduced in this paper was designed in air following the same basic procedure that was used to design our earlier stacked patch antenna operating from 1.6–2.0 GHz [19]. The reason for choosing air as the design environment is because there is considerable variation in the value of the permittivity of concrete [20]–[23]. Depending on the moisture content and the porosity the dielectric constant of concrete can vary from 4.5 [20] to 9 [21]. Another reference [23] presents permittivity values of concrete as function of slab depth or thickness which are also in the above range. Thus, because of the variability of material characteristics of concrete, we decided to design the antenna in free-space. To ensure that concrete loading does not alter the antenna characteristics significantly, we later on determine an optimum air-gap between the antenna and the concrete cover. As an advantage, unlike an antenna which has no air-gap and, hence, has a much smaller physical aperture the proposed antenna should have increased directivity due to its larger aperture size. The geometry of the proposed 5–6 GHz stacked patch antenna is shown in Fig. 1(a). Patch1 (13 mm × 13 mm) was printed on a 1.5-mm-thick

Manuscript received May 15, 2007; revised July 19, 2007; accepted July 19, 2007. This work was supported in part by the National Science Foundation under Grant ECCS 0619253 and in part by the South Carolina State University under the University Transportation Center Grant. The associate editor coordinating the review of this paper and approving it for publication was Prof. Evgeny Katz.

The authors are with the Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208 USA (e-mail: shams@engr.sc.edu; alimo@engr.sc.edu).

Digital Object Identifier 10.1109/JSEN.2007.908230



(a)

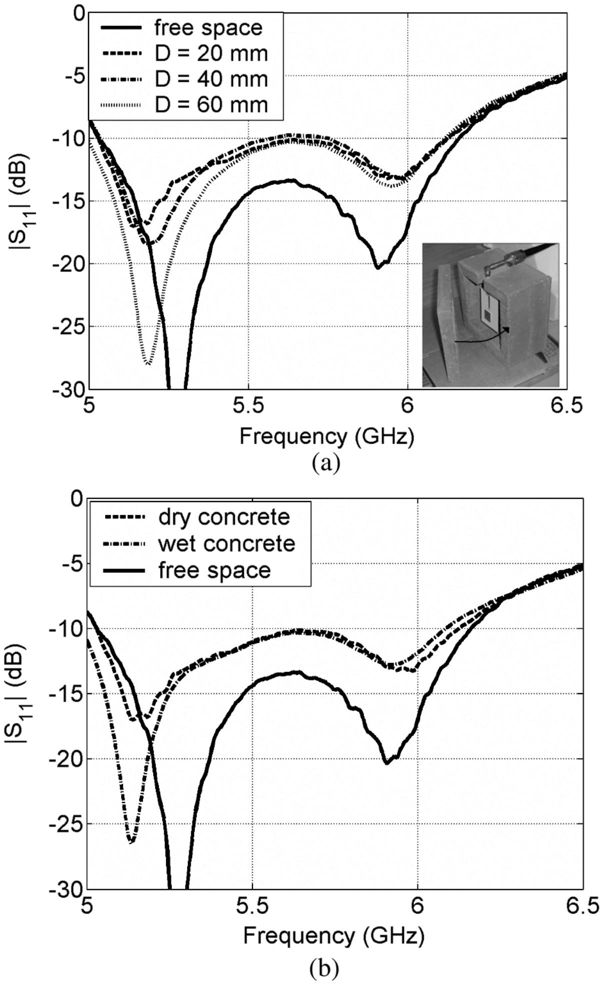
(b)

Fig. 1. (a) Geometry of the stacked patch antenna. (b) Antenna buried in concrete.

RO4003 substrate ($\varepsilon_r = 3.38$). Patch2 (19 mm × 19 mm) was placed on a 4.5-mm-thick Rohacel foam substrate. The ground plane size was 70 mm × 50 mm.

The geometry of the concrete sample fabricated to test the antenna is shown in Fig. 1(b). The sample contained a slit through which the coaxial cable connecting the antenna could be easily inserted. For all experimental samples, the distance $P = 70$ mm [see Fig. 1(b)]. Concrete covers with various thicknesses ($D =$ 20, 40, and 60 mm) were built. The air-gap d between the front surface of the antenna and the back surface of the concrete cover was optimized through experimentation. It was found that $d = 15$ mm resulted in optimum return loss performance.

Measured return loss data of the stacked patch antenna buried in dry concrete are shown in Fig. 2(a). Free space data are also included for comparison. The antenna operates from 5 to 6.2 GHz within 10 dB return loss in free-space. Once the antenna is buried in concrete, the return loss degrades slightly but the operating bandwidth remains unchanged. The effect of the concrete cover thickness is minimal on the return loss characteristics. The return loss of the stacked patch antenna buried in wet concrete was also measured. The antenna was taken out and the complete embedding concrete medium was placed in a bucket of water for 24 hours. After which the wet concrete was removed from the bucket and the antenna was placed within the wet concrete and remeasured. The return loss data of the antenna inside wet concrete are shown in Fig. 2(b). There is very little observable difference in between the data for the dry and wet concrete.



(a)

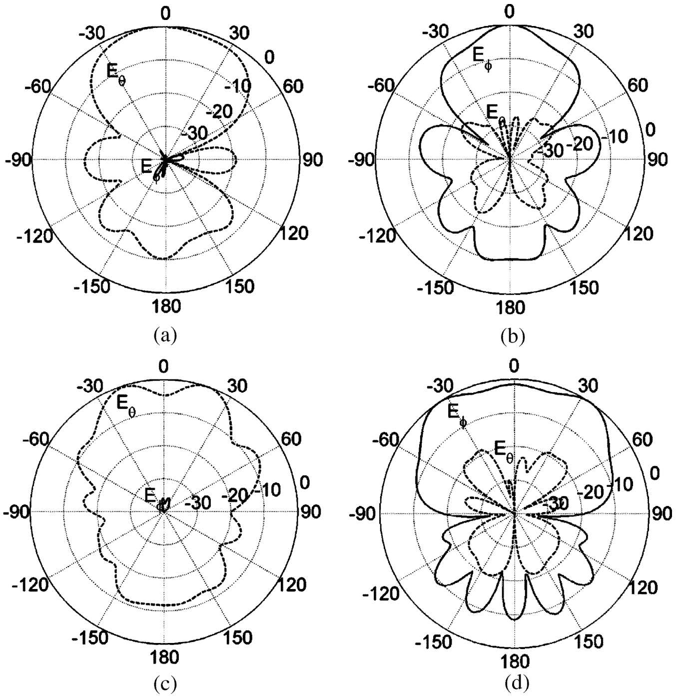
(b)

Fig. 2. (a) Measured return loss data of the stacked patch antenna (b) in free-space and within dry concrete and (b) in free-space and within wet concrete ($D = 20$ mm).

B. Computed Receive Patch Radiation Patterns

To compute the radiation patterns of the stacked patch antenna, a simulation model of the antenna and the embedding concrete medium ($\varepsilon_r = 4.5$ and $\tan\delta = 0.0111$) was developed in HFSS. Since the overall size of the concrete block described in Fig. 1(b) was too large to run successful simulations, a simplified model with $P = 21$ mm was used. The concrete back wall facing the antenna ground plane was removed. This should have negligible effect on antenna performance.

The effect of the concrete cover thickness D on the antenna radiation pattern is shown in Fig. 3. In both the E and H planes, the beam splits and the beam peak shifts from the $\theta = 0°$ direction when D increases from 20 to 40 mm. Even though increasing D increases the cross polarization slightly, the cross polarization is generally below 20 dB. The peak gain is 10.1 dBi for $D = 20$ mm and 9.2 dBi for $D = 40$ mm. Since the dielectric constant and the loss tangent of the embedding concrete medium was not measured and the assumed values used in our



(a) (b) (c) (d)

Fig. 3. Normalized antenna radiation patterns at 5.7 GHz. (a) E-plane; $D = 20$ mm. (b) H-plane; $D = 20$ mm. (c) E-plane; $D = 40$ mm. (d) H-plane; $D = 40$ mm.

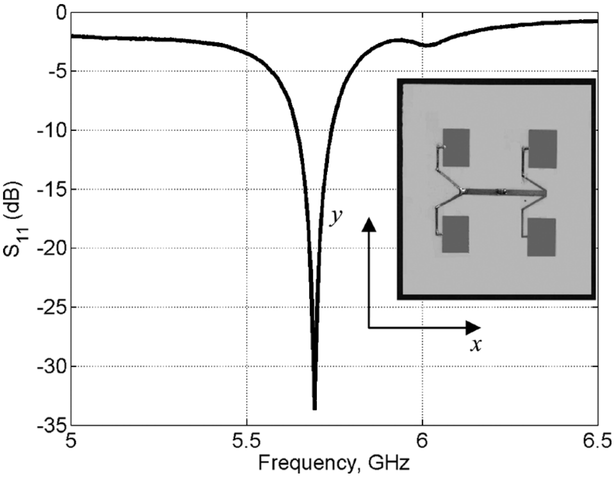


Fig. 4. Measured return loss of the transmit patch array.

Fig. 5. Photograph of the rectenna measurement setup and the rectenna.

HFSS simulation could not be confirmed, we will not use these gain numbers for any future calculation. Instead, we will focus on experimentally determining the effect of the embedding concrete medium in wireless power reception.

III. TRANSMIT PATCH ANTENNA ARRAY

A 4 × 4 microstrip patch array (90 mm × 100 mm total area) was designed for the transmitter section. The array was printed on a 1.5-mm × thick RO4003 substrate ($\varepsilon_r = 3.38$). Each patch measured 12.7 mm × 17.5 mm. The distance between any two patch elements was 28.7 mm in the x direction and 23.9 mm in the y direction. Measured return loss data of the transmitter array are shown in Fig. 4 along with a photograph of the array. The array bandwidth extends from 5.6–5.8 GHz. Antenna radiation pattern and gain were computed using HFSS. Patterns are directional as expected and the computed peak gain of the array is 13.6 dBi.

IV. MEASURED RECEIVED POWER BY THE BURIED RECTENNA

A photograph of the wireless power measurement setup is shown in Fig. 5. In the transmitter side, the 5.7 GHz input signal from the signal generator was fed to a 7 W power amplifier (from Microwave Power, Model: L0505-38) which was then radiated by the transmit microstrip patch array. In the receiver side, wireless microwave power was received and then converted to DC by the rectenna buried in concrete. The rectenna consisted of the stacked patch antenna and a rectifier circuit. The rectifier consisted of a microwave Si Schottky detector diode (HSMS-2862), a 68 pF capacitor and a load resistor R_L. The photograph of the rectenna is also shown in Fig. 5. The distance r between the transmitter and the receiver was kept fixed at a far-field distance of 600 mm.

The rectenna conversion efficiency can be defined as $\eta = P_{\mathrm{DC}}/P_{\mathrm{RF}}$, where P_{RF} is the received RF power by the antenna without the rectifier and P_{DC} is the received and converted DC power by the rectenna. To measure η first, we measured the received RF power by a stacked patch antenna without the rectifier in free-space. Thus, at the receiver side, we placed a stacked patch antenna without the rectifier which was directly connected to an RF power meter (Agilent E4417A power meter and E9326A power sensor). At 5.7 GHz and at a distance of 600 mm, we measured that the received RF power was 18.62 mW for a transmit power of 7 W.

Next, we replaced the stacked patch antenna with the rectenna and measured the received DC voltage at the rectenna in free-space by varying its load resistance. The objective was to determine an optimum load resistance value that can provide optimum conversion efficiency. These results are shown in Table I. Clearly, increasing R_L increases the DC voltage as expected. The received DC power is about 9 mW for $R_L = 51\ \Omega$, which increases to 14.1 mW for $R_L = 200\ \Omega$. The received DC power decreases monotonically as R_L increases. Since $R_L = 200\ \Omega$ resulted in the highest DC power, we decided to use that resistance value for all subsequent measurements. Considering $R_L = 200\ \Omega$, the rectenna conversion efficiency is 75.8%.

The rectenna with $R_L = 200\ \Omega$ was placed within the concrete, as shown in Fig. 5 for further measurements. For the rectenna buried in dry concrete, measurements were conducted

TABLE I
MEASURED DC VOLTAGE ACROSS R_L IN FREE SPACE AS FUNCTION OF THE LOAD RESISTANCE, R_L ($r = 600$ mm)

Load Resistance, R_L (Ω)	Received dc voltage, (volts)	Received DC Power (mW)
51	0.69	9.3
100	1.09	11.9
200	1.68	14.1
300	2.04	13.9
470	2.55	13.8
560	2.75	13.5
750	3.1	12.9
820	3.2	12.5

TABLE II
MEASURED DC VOLTAGE ACROSS R_L AS FUNCTION OF THE AIR GAP d. OTHER PARAMETERS: $r = 600$ mm, $D = 20$ mm, AND $R_L = 200\ \Omega$

Air gap, d (mm)	Load voltage, V_{DC} (volts)
0	0.43
10	1.44
15	1.06
20	0.9

TABLE III
MEASURED DC VOLTAGE ACROSS R_L AS FUNCTION OF D AND CONCRETE CONDITION. OTHER PARAMETERS: $r = 600$ mm, $d = 10$ mm, AND $R_L = 200\ \Omega$

Cover thickness, D (mm)	Dry concrete		Wet concrete	
	Load Voltage, V_{DC} (volts)	Load Power, P_{DC} (mW)	Load Voltage, V_{DC} (volts)	Load Power, P_{DC} (mW)
20	1.44	10.37	0.65	2.11
40	1.13	6.38	0.31	0.48
60	0.61	1.86	0.12	0.07

to determine an optimum air gap d in order to ensure maximum received DC voltage and, hence, also power. These results are shown in Table II. Clearly, increasing d from 0 to 10 mm increases the load voltage significantly. The small DC voltage received for $d = 0$ indicates that the antenna is largely mismatched due to dielectric loading. As d increases beyond 10 mm, the load voltage decreases gradually perhaps because the antenna being further inside the concrete suffers from attenuation from the nearby walls. Since $d = 10$ mm resulted in the highest DC voltage, we considered that to be the optimum air-gap for this particular frequency and measurement scenario.

Further measurements were performed by varying the concrete cover thickness D, while d was fixed (see Table III). Note that for all measurements the distance r between the transmit and receive antennas is 600 mm. Measurement results for the rectenna buried in dry concrete indicate that the power received is 10.37, 6.38, and 1.86 mW for $D = 20$, 40, and 60 mm, respectively. The received DC power decreases significantly with increasing concrete cover thickness as expected. Interestingly, for the rectenna buried within 30 mm of the concrete $(D + d)$, the received DC power is 10.37 mW, which is about 70% of the received DC power in free-space (14.1 mW). As an example, an ML 2430 series Sanyo lithium coin cell battery requires a charging voltage of 3.1 V and a charging current of 0.5 mA, respectively [24]. Such batteries are cheap and should be generally suitable for sensor applications. The power received by the embedded rectenna proposed here is 10.37 mW for $D = 20$ mm, which is adequate to recharge such batteries.

For the rectenna buried in wet concrete, the received DC power is 2.11, 0.48, and 0.07 mW for $D = 20$, 40, and 60 mm, respectively. These numbers are significantly smaller than the ones for dry concrete due to severe attenuation in wet concrete. For the rectenna buried within 30 mm of the wet concrete $(D + d)$, the received DC power is 2.11 mW, which is only about 15% of the received DC power in free-space (14.11 mW). Clearly, sending wireless power to a buried sensor when the embedding concrete medium is completely wet will be more inefficient than when the concrete is dry.

V. CONCLUSION

The feasibility of beaming wireless power to a buried rectenna in concrete was explored. The return loss characteristics of a stacked microstrip patch antenna were measured in free-space and within dry and wet concrete. In all cases, the antenna demonstrated an operation bandwidth extending from about 5 to 6.2 GHz within 10 dB return loss. Simulations performed on a simplified concrete and antenna model showed the evidence of beam splitting when the concrete cover thickness increased from 20 to 40 mm. The rectifier designed and integrated with the antenna tested to achieve optimum performance by varying its load resistance. An optimum resistance value of 200 Ω was identified which resulted in the highest received DC power. Interestingly, it was found that while the received DC power by the rectenna was 14.11 mW in free-space, it was 10.37 mW when buried inside concrete with the concrete cover thickness being 20 mm. For both cases, the distance between the transmitter and receiver was the same. The amount of power received (10.37 mW for $D = 20$ mm) is sufficient to energize the battery of a miniature wireless sensor. The major contributor of the loss is the RF path loss from the transmitter to the rectifier which can be reduced by using high gain antennas and by reducing the operating frequency. However, not all of these will go together since higher antenna gain at low frequencies, such as 900 MHz or 2.45 GHz will require relatively larger antennas. This investigation was limited to simple concrete as the embedding medium. Further investigation may be needed which uses more realistic concrete structure consisting of steel rebars etc.

REFERENCES

[1] [Online]. Available: http://www.efl.fhwa.dot.gov/about/page12.jpg

[2] C. Maierhofer, "Nondestructive evaluation of concrete infrastructure with ground penetrating radar," *J. Mater. Civil Eng.*, vol. 15, no. 3, pp. 287–297, May/Jun. 2003.

[3] S. Yuan, X. Lai, X. Zhao, X. Xu, and L. Zhang, "Distributed structural health monitoring system based on smart wireless sensor and multi-agent technology," *J. Smart Mater. Struct.*, vol. 15, pp. 1–8, 2006.

[4] J. P. Lynch, "Overview of wireless sensors for real-time health monitoring of civil structures," in *Proc. 4th Int. Workshop Struct. Control Monitoring*, New York, Jun. 10–11, 2004.

[5] S. W. Arms, J. H. Galbreath, A. T. Newhard, and C. P. Townsend, "Remotely programmable sensors for structural health monitoring," Structural Materials Technology (SMT): NDE/NDT for Highways and Bridges. Buffalo, NY, Sep. 16, 2004.

[6] J. T. Bernhard, K. Hietpas, E. George, D. Kuchma, and H. Reiss, "An interdisciplinary effort to develop a wireless embedded sensor system to monitor and assess the corrosion in the tendons of prestressed concrete girders," in *Proc. 2003 IEEE Topical Conf. Wireless Commun. Technol.*, Honolulu, HI, Oct. 2003, pp. 241–243.

[7] K. M. Z. Shams, M. Ali, and A. M. Miah, "Characteristics of an embedded microstrip patch antenna for wireless infrastructure health monitoring," in *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, Albuquerque, NM, Jul. 2006, pp. 3643–3646.

[8] C. Bartolettiy, R. Buonanniy, L. G. Fantasiay, R. Frullaz, W. Gaggioliy, and G. Sacerdotiy, "The design of a proximity inductive sensor," *Meas. Sci. Technol.*, vol. 9, pp. 1180–1190, 1998.

[9] B. Strassner and K. Chang, "Passive 5.8 GHz radio-frequency identification tag for monitoring oil drill pipe," *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 2, pp. 356–363, Feb. 2003.

[10] K. Finkenzeller, *RFID Handbook*, 2nd ed. New York: Wiley, 2003.

[11] N. M. Neihart and R. R. Harrison, "Micropower circuits for bidirectional wireless telemetry in neural recording applications," *IEEE Trans. Biomed. Eng.*, vol. 52, pp. 1950–1959, Nov. 2005.

[12] J. Heikkinen and M. Kivikoski, "Low-profile circularly polarized rectifying antenna for wireless power transmission at 5.8 GHz," *IEEE Microwave Wireless Component Lett.*, vol. 14, no. 4, pp. 162–164, Apr. 2004.

[13] M. Ali, G. Yang, and R. Dougal, "A new circularly polarized rectenna for wireless power transmission and data communication," *IEEE Antennas and Wireless Propagat. Lett.*, vol. 4, pp. 205–208, Jul. 2005.

[14] M. Ali, G. Yang, and R. Dougal, "Miniature circularly polarized rectenna with reduced out of band harmonics," *IEEE Antennas and Wireless Propagat. Lett.*, vol. 5, no. 1, pp. 107–110, 2006.

[15] K. Gosalia, G. Lazzi, and M. Humayun, "Investigation of a microwave data telemetry link for a retinal prosthesis," *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 8, pp. 1925–1933, Aug. 2004.

[16] P. Soontornpipit, C. M. Furse, and Y. Chung, "Design of implantable microstrip antenna for communication with medical implants," *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 8, pp. 1944–1951, Aug. 2004.

[17] J. Kim and Y. Rahmat-Samii, "Implanted antennas inside a human body: Simulations, designs, and characterizations," *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 8, pp. 1934–1943, Aug. 2004.

[18] P. Soontornpipit, C. M. Furse, Y. C. Chung, and B. M. Lin, "Optimization of a buried microstrip antenna for simultaneous communication and sensing of soil moisture," *IEEE Trans. Antennas Propagat.*, vol. 54, no. 3, pp. 797–800, Mar. 2006.

[19] M. Ali, A. T. M. Sayem, and V. K. Kunda, "A reconfigurable stacked microstrip patch antenna for satellite and terrestrial links," *IEEE Trans. Vehicular Technol.*, vol. 56, no. 2, pp. 426–435, Mar. 2007.

[20] D. K. Misra and K. Fenske, "Dielectric materials at microwave frequencies," *Appl. Microwaves Wireless* vol. 12, no. 12, pp. 92–100, Oct. 2000 [Online]. Available: http://www.microwaves101.com/encyclopedia/Miscdielectrics.cfm

[21] [Online]. Available: http://www.cflhd.gov/agm/engApplications/Pavements/411GroundPenetrationRadar.htm

[22] M. D. Comerchero, J. Polich, and A. Robert, "Dielectric permittivity of concrete between 50 MHz and 1 GHz and GPR measurements for building materials evaluation," *J. Appl. Geophys.*, vol. 40, no. 1, pp. 88–94, Oct. 1998.

[23] J. Davis and Y. Huang, "Determination of dielectric properties of insitu concrete at radar frequencies," *Non-Destructive Testing in Civil Engineering*, 2003. [Online]. Available: http://www.ndt.net/article/ndtce03/papers/v078/v078.htm, NDT-CE

[24] [Online]. Available: http://www.batterystore.com/Sanyo/SanyoLithiumML.htm

Khan M. Z. Shams (S'05–M'06) was born in Faridpur, Bangladesh, in 1973. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Bangladesh University of Engineering and Technology, Dhaka, in 1997 and 2001, respectively. He is currently working towards the Ph.D. degree in electrical engineering at the University of South Carolina, Columbia.

He was a faculty member with the Bangladesh University of Engineering and Technology, Dhaka, from 1998 to 2003. His current research interests include design of microwave circuits and antennas for wireless communications, left-handed materials, electromagnetic bandgap structures, and sensors.

Mohammod Ali (M'93–SM'03) received the B.Sc. degree in electrical and electronic engineering from the Bangladesh University of Engineering and Technology, Dhaka, in 1987, and the M.A.Sc. and Ph.D. degrees, both in electrical engineering, from the University of Victoria, Victoria, BC, Canada, in 1994 and 1997, respectively.

He was with the Bangladesh Institute of Technology, Chittagong, from 1988 to 1992. From January 1998 to August 2001, he was with Ericsson Inc., Research Triangle Park, NC, first as a Staff Engineer and then as a Senior Staff Engineer. Since August 2001, he has been with the Department of Electrical Engineering, University of South Carolina, Columbia, where he is currently an Associate Professor. He had also held appointments as a Visiting Research Scientist with the Motorola Corporate EME Research Laboratory, Plantation, FL, from June to August 2004. He is the author/coauthor of over 90 journal and conference publications and holds five U.S. patents. His research interests include miniaturized packaged (embedded) antennas, metamaterials and their antenna applications, distributed wireless sensors and rectennas, reconfigurable antennas, and portable/wearable antennas and their interactions with humans (SAR).

Dr. Ali is the recipient of the 2003 National Science Foundation Faculty Career Award. He is also the recipient of the College of Engineering and Information Technology Young Investigator Award from the University of South Carolina in 2006.