Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2008, Article ID 167980, 6 pages
doi:10.1155/2008/167980

Application Article

A 31.5 GHz Patch Antenna Design for Medical Implants

Yasir Ahmed,[1,2] Yang Hao,[1] and Clive Parini[1]

[1] *Antennas and Electromagnetics Group, Electrical Engineering Department, Queen Mary, University of London, London E14AH, UK*
[2] *Electrical Engineering Department, COMSATS Institute of Information Technology, Plot 30, Sector H8-1, Islamabad, Pakistan*

Correspondence should be addressed to Yasir Ahmed, yasirahmed@comsats.edu.pk

Received 7 November 2007; Revised 29 March 2008; Accepted 17 July 2008

Recommended by Tamer Ibrahim

We have proposed a 31.5 GHz patch antenna for medical implants. The design is based on the transmission line model and is simulated in CST. The patch antenna performs reasonably well in terms of return loss and radiation efficiency. However, the most attractive feature of this design is its form factor. Typical antennas designed for the microwave range are quite large in size, which makes them unsuitable for implants. The proposed design is much smaller in size but still retains the essential characteristics for reliable communication.

1. INTRODUCTION

The design of antennas for communication with implants inside the human body has received considerable attention from the research community. The design of these antennas is quite challenging, as there is a limit on the amount on power that can be transmitted and also on the size of these devices. The limitation on the transmit power is due to the amount of battery power available as well as due to concerns about the exposure of the human body to electromagnetic radiation. Typically these devices are allowed to have a peak transmit power of 25 uW (−16 dBm), which is quite insufficient at higher frequencies especially when embedded deep into the tissue. Today these implants are being used to monitor as well as facilitate the working of various human organs, for example, as cardiac pacemakers.

2. SURVEY OF ANTENNAS FOR IMPLANTS

A number of different antenna designs have been considered for medical implants. In [1], spiral and serpentine antenna designs have been considered and the authors have simulated the performance of these antennas using a single block of muscle and a realistic human shoulder. The results are also verified experimentally using a tissue simulant material composed of TX-151, sugar, salt, and water. The effect of shape and size of the dielectric as well as the location of the feed point on the performance of the antenna is studied. A similar analysis is performed in [2] for spiral and planar inverted-F (PIFA) antenna. However, the authors have primarily focused on the human brain using a six-layer model (brain, CSF, Dura, bone, fat, and skin). The results are again verified using a human tissue-simulating liquid made from deionized water, sugar, salt, and cellulose. In both these papers, the authors have considered a frequency of 402–405 MHz that has been recommended by the European Radiocommunications Committee (ERC) for ultra-low-power, active, medical implants. The simulations have been performed using finite difference time domain (FDTD) method. In addition, an analytic method using spherical dyadic Green's function (DGF) has also been considered [2].

In [3], the problem of antenna detuning and signal loss is studied for a subminiature loop antenna designed for the 900 MHz ISM and 402 MHz MICS radio bands. It is observed that with proper encapsulation of areas of high electric field strength antenna detuning can be considerably reduced. This is in contrast to a monopole that experiences considerable detuning (as high as 13%) and signal loss at the same frequencies.

The results of an actual implant operating in the 403 MHz MICS band are presented in [4]. The implant was placed inside a Perspex body (30 cm diameter cylinder), and the signal strength was measured as a function of the distance. The error rate of the link was also evaluated. It was observed that the communication link with the external device was maintained up to a distance of 3 m when the

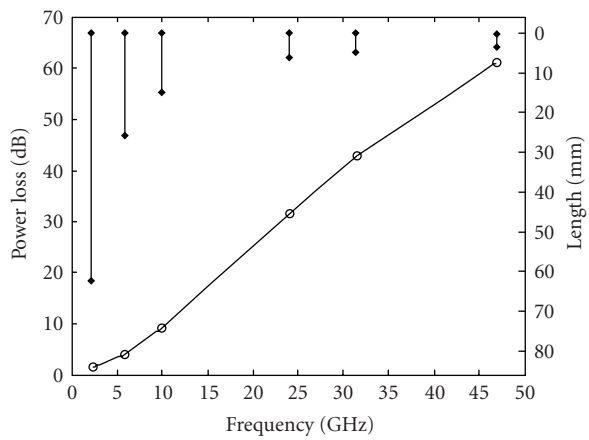


Figure 1: Power loss within 4 mm of skin. The corresponding half wavelengths are also shown.

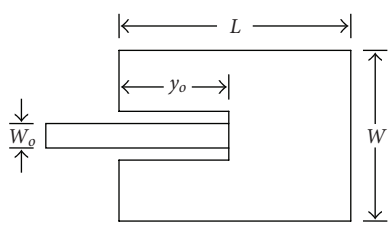


Figure 2: Patch antenna with a line feed.

Table 1: Dielectric properties of human tissues at 31.5 GHz.

Tissue	Permittivity	Conductivity (S/m)
Skin	14.7980	27.9710
Fat	3.5970	1.8636
Muscle	22.2700	36.8130

implant was placed at a depth of 10 cm. The implant used a sleep and wakeup sequence (2.4 GHz, 20 dBm wakeup signal) to prolong battery life.

3. LIMITATIONS IN THE DESIGN PROCESS

Microstrip antenna design is a fairly mature field, and several designs have been proposed over the years [5–7]. As with any other antenna design, the size of the microstrip is directly proportional to the wavelength at the operating frequency. At 402 MHz, the wavelength of an electromagnetic wave is approximately 0.75 m. It is obvious that any antenna with dimensions comparable to this wavelength cannot be used for an implant. The technique usually used to overcome this problem is to design a conducting surface that is spiraled along the surface of the substrate. The resonant frequency of the microstrip is then proportional to the total length of the spiral and not to the length of any individual element. Although this results in a size reduction, it is still not quite suitable for an implant (see Table 2). We have investigated the idea of using a rectangular patch antenna designed to operate at the millimeter wave frequencies. It is well known that at these frequencies the electromagnetic wave experiences very high attenuation, however, the implant does not need to be placed deep into the tissue and with proper transmit receive combination it is still possible to maintain reliable communication. The penetration depth of a medium is defined as

$$\delta = \frac{1}{\alpha}, \tag{1}$$

where α is the attenuation constant. It is the distance at which the amplitude of an electromagnetic wave is reduced to $e^{-1} = 0.3679$ of its original value.

It has been observed that at millimeter wave most of the loss occurs within the first layer, that is, skin. There is a relatively less loss within fat and at the dielectric boundaries. Figure 1 shows the power loss within the layer of skin as a function of frequency. Also shown are corresponding half wavelengths which should serve as a guideline to the antenna size. The actual antenna size would also be dependant on the substrate material; however, any size reduction would be proportionate across the frequency range.

4. DESIGN PROCEDURE

A microstrip antenna can be designed using either the transmission line model or the cavity model (more complex models also exist that suit a particular design). We have used the transmission line model since it is fairly simple to implement and results in antenna designs with reasonably good performance in terms of return loss and efficiency. It is also quite well suited to the rectangular designs that we have considered (other popular designs include circular, elliptical, and disc like). The design starts with selecting the operating frequency f_r, selecting a substrate with the required permittivity ε_r, and defining the width of the substrate h (Figure 2). Thick substrates with low permittivity result in antenna designs with high efficiency and large bandwidths. Thin substrates with high permittivity lead to a smaller antenna size but with a lower bandwidth and a high-radiation loss [5]. The tradeoffs between substrate thickness and permittivity and antenna bandwidth and efficiency have been discussed in [8–10]. We have used Rogers RT6002 in our design with a permittivity of 2.94 and a loss tangent of 0.0012.

According to the transmission line model, the length L and width W of the patch are calculated as

$$W = \frac{v_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}},$$
$$L = \frac{v_o}{2f_r\sqrt{\varepsilon_{\text{reff}}}} - 2\Delta L, \tag{2}$$

Table 2: Comparison of five different antennas designed for medical implants. The size of our antenna is governed by the dimensions of the ground plane.

Antenna type	True antenna size	Characteristics
Spiral [1] 402 MHz	 26.6 mm × 16.8 mm	Return loss >25 dB Frequency detuning ∼15% −21 dBW at 1 m (7 mm deep in 2/3 muscle, 1.6 W/kg)
Serpentine [1] 475 MHz	 26.6 mm × 16.8 mm	Return loss >10 dB Frequency detuning ∼20% −25 dBW at 1 m (7 mm deep in 2/3 muscle, 1.6 W/kg) Higher resonant frequency than a spiral with the same physical length
Spiral [2] 402 MHz	 40 mm × 32 mm	Return loss >18 dB Return loss >5 dB (measurement) Frequency detuning ∼5% (measurement) Front to back ratio ∼5 dB Radiation efficiency ∼0.16%
PIFA [2] 402 MHz	 32 mm × 24 mm	Return loss >16 dB Return loss >6 dB (measurement) Frequency detuning ∼10% (measurement) Front to back ratio ∼5 dB Radiation efficiency ∼0.25% Higher efficiency than the spiral
New design 31.5 GHz	 5.68 mm × 6 mm $W = 3.39$ mm $L = 2.66$ mm $h = 0.254$	Return loss >30 dB Frequency detuning ∼1% −57.49 dBW/m^2 at 1 m (8 mm deep in skin and fat) Front to back ratio ∼15 dB

where v_o is the speed of light in free space, $\varepsilon_{\text{reff}}$ is the effective permittivity, and $2\Delta L$ is the extension in length due to fringing effects:

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2},$$
$$\Delta L = 0.412h\frac{(\varepsilon_{\text{reff}} + 0.3)(W/h + 0.264)}{(\varepsilon_{\text{reff}} - 0.258)(W/h + 0.8)}. \quad (3)$$

Although the design of the patch is quite simple, the design of the feeding mechanism is not that straightforward. There are four possible methods that can be used:

(1) microstrip-line feed;

(2) probe feed;

(3) aperture-coupled feed;

(4) Proximity-coupled feed.

We have used a microstrip line feed since it is relatively easy to model, match, and fabricate. It results in low- antenna bandwidths (2–5%); however, this should be sufficient for our application. The calculation of the feed point is based on the principle that maximum power transfer would occur when the impedance of the line is matched to the patch. At the resonant frequency, the impedance of the patch is zero

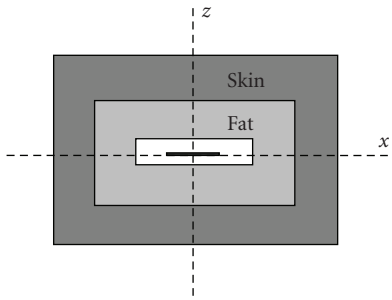


Figure 3: Patch implanted inside the model (4 mm Skin, 4 mm Fat, 1 mm cavity).

at the half point along its length. Therefore, the feed point is usually a little offset from the centre. We first calculate G_1 and G_{12} the self and mutual conductance of the patch terminals (also termed as the radiating slots), respectively:

$$G_1 = \int_0^{\pi} \left[\frac{\sin((k_o W/2)\cos\theta)}{\sqrt{120}\pi\cos\theta} \right]^2 \sin^3\theta \, d\theta,$$

$$G_{12} = \int_0^{\pi} \left[\frac{\sin((k_o W/2)\cos\theta)}{\sqrt{120}\pi\cos\theta} \right]^2 J_o(k_o L \sin\theta)\sin^3\theta \, d\theta, \tag{4}$$

where

$$k_o = \frac{2\pi\sqrt{\varepsilon_{\text{reff}}}}{\lambda}, \tag{5}$$

and J_o is the modified Bessel function of the first kind and order zero. The length of the inset y_o can then be calculated based upon the following relationship:

$$R_{\text{in}}(y = y_o) = \frac{1}{2(G_1 \pm G_{12})}\cos\left(\frac{\pi y_o}{L}\right). \tag{6}$$

Here, R_{in} is the impedance value required for perfect matching. Since the inset creates a physical notch in the patch, it also changes its resonant frequency (due to junction capacitance); however, this shift is usually a small percentage of the actual frequency and can be ignored. Alternatively, the length or width of the patch would have to be modified, and the feed location would have to be recalculated. The width of the inset is somewhat arbitrary.

5. SIMULATION RESULTS

The designed patch antenna is then simulated in CST at a frequency of 31.5 GHz. The antenna is placed within a three-layer body consisting of skin, fat, and air (Figure 3) and energized by a waveguide port with a normalized power of 1 W^{Φ} (Φ denotes the 10 gm tissue that we have used. The transmit power should be less than 16 mW (1.6 W/kg × 0.010 kg). This would reduce our link budget by approximately 18 dB). We used air as the cavity around the antenna; however, in practice, some other low permittivity medium might be used to provide a match between the antenna and the body. The dielectric data used in the simulation is given in Table 1.

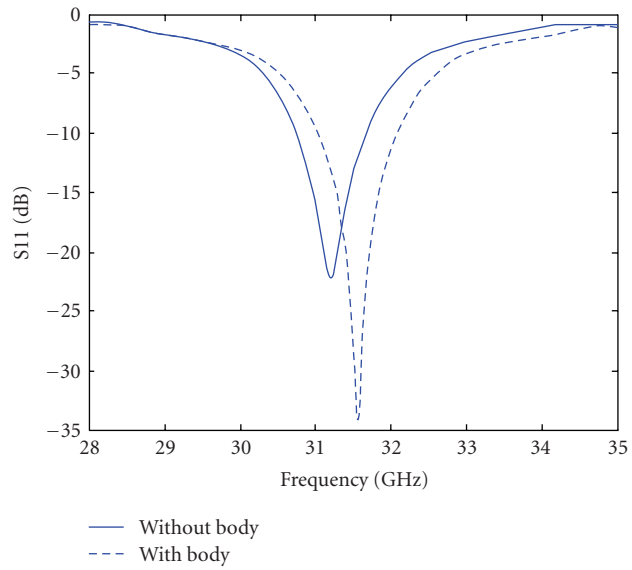


Figure 4: Return loss of the antenna with and without the body.

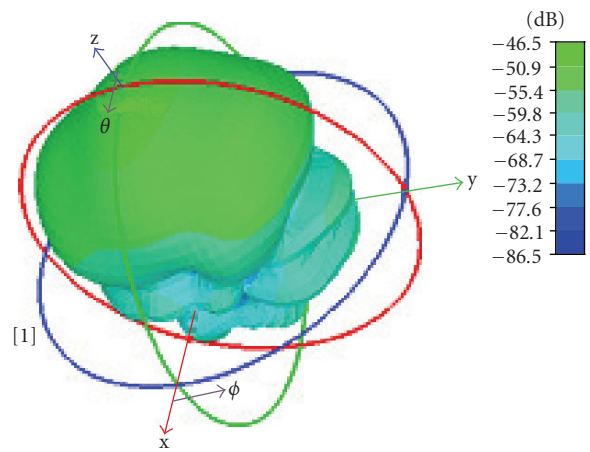


Figure 5: Gain of the antenna placed inside the cavity.

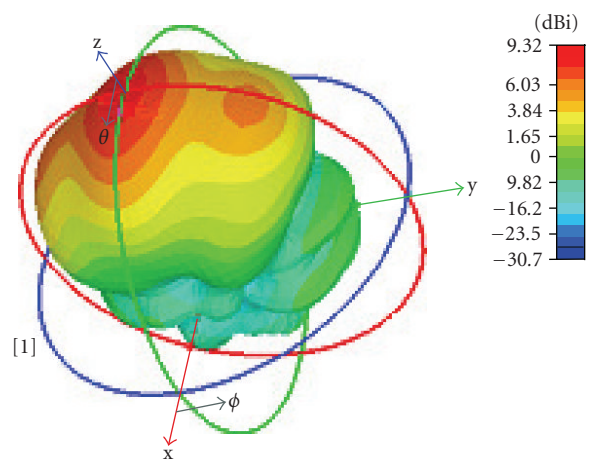
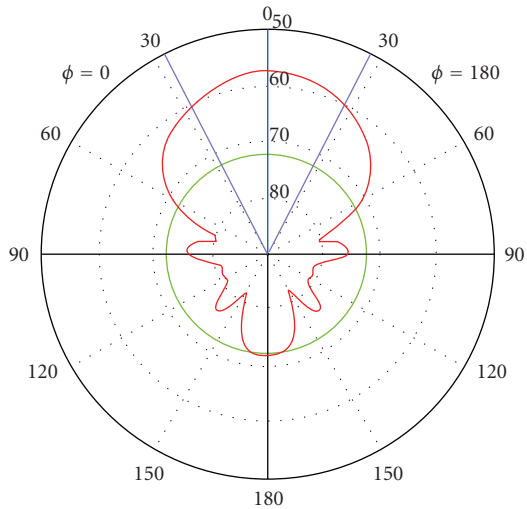
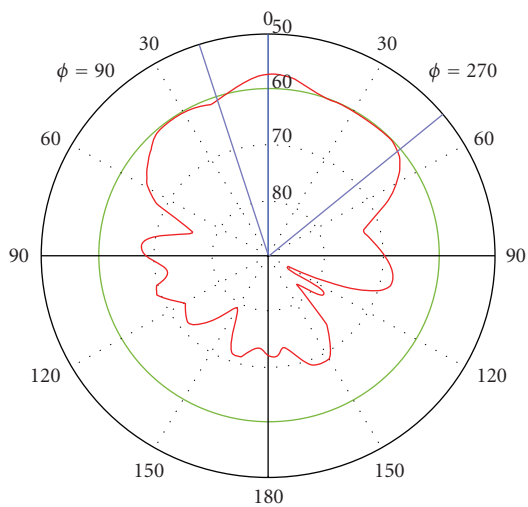


Figure 6: Directivity of the antenna placed inside the cavity.



Angular width (3 dB) = 54.8 deg
Side lobe level = −14.4 dB

(a)



Angular width (3 dB) = 68.2 deg
Side lobe level = −2.4 dB

(b)

Figure 7: P-field along (a) H-plane (b) E-plane.

The resulting S-parameters and 3D radiation patterns are shown below (Figures 4–6). The antenna has a return loss of more than 30 dB and max broadside directivity of 9.32 dBi. The antenna exhibits some detuning within the body which is removed by adjusting its dimensions. The P-field patterns in the E-plane and H-plane are shown in Figure 7. It is observed that the antenna has a very low efficiency due to the high loss within the body; however, it has a good front to back ratio. The embedded antenna has a peak broadside power density of −57.5 dBW/m^2 at a distance of 1 m.

For an isotropic radiator with a transmit power of 1 W, the power density at a distance of 1 m is

$$S = P_t/4\pi d^2 = 1/4\pi = -10.99\,\text{dBW/m}^2, \tag{7}$$

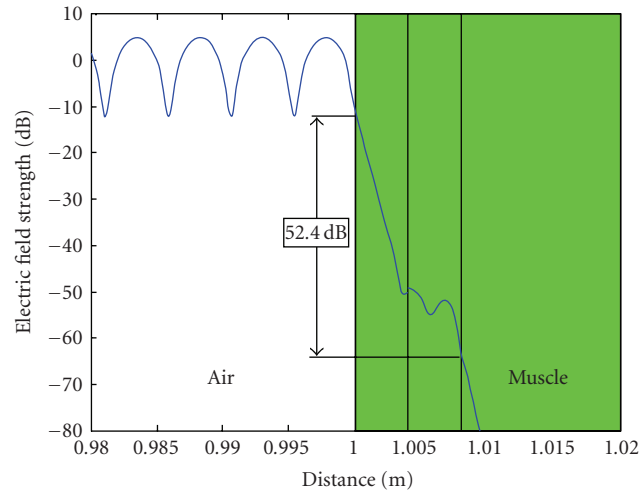


Figure 8: Relative electric field strength $20\log_{10}(|E_t|/|E_o|)$. External device to implant communication.

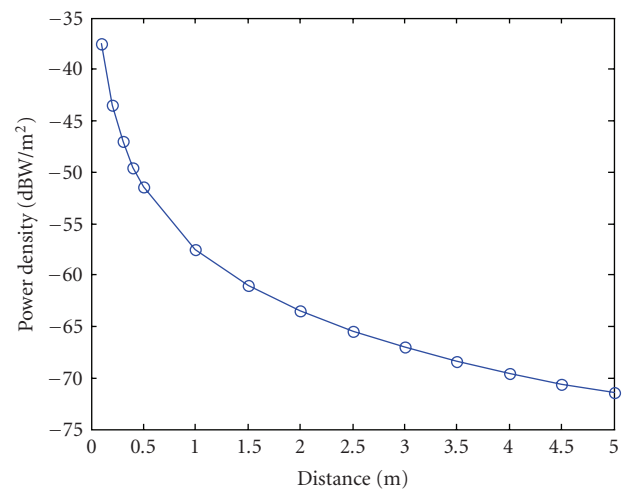


Figure 9: P-field from an implant as a function of distance.

and for the embedded patch with a gain of −46.5 dB† the power density would be

$$S = -10.99 - 46.50 = -57.49\,\text{dBW/m}^2, \tag{8}$$

which is equal to the result obtained through p-field simulation († denotes the computer simulation technology (CST) that considers the antenna and the body as the radiator. Therefore, the gain is the gain of the complete structure and not just the designed antenna).

Now, if the effective area A_e of the antenna is known then the received power P_r at a particular distance can be easily calculated. The effective area [11] of a half wave dipole is given as

$$A_e = \frac{G_r\lambda^2}{4\pi} = \frac{\lambda^2}{8} = -49.46\,\text{dBs}, \tag{9}$$

where G_r^Υ is the receive antenna gain. This gives a received power of −106.95 dBW or −76.95 dBm (Υ denotes the

formula given in the text that uses directivity instead of gain; however, this is only valid if there is no loss in radiation).

In the absence of the body, the antenna has a power density of $-3.63\,\mathrm{dBW/m^2}$ at a distance of 1 m. Therefore, there is a power loss of 53.87 dB within the body. Similar results are obtained for the reverse link using ray-tracing where a 52.40 dB loss is observed within the layers of skin and fat (Figure 8). It must be noted that the wireless communication channel between an implant and an external device is not symmetric and the link budget in one direction might be quite different from that in the other direction.

Finally, we have shown the p-field behaviour outside the body as a function of the distance (Figure 9). As expected, in the absence of any external body, the P-field follows the $1/d^2$ rule.

6. CONCLUSION

Although a signal level -76.95 dBm might be sufficient in theory, it would not be adequate in a realistic scenario where the signal would experience multipath fading and interference from other wireless equipment. However, it must be noted that we have considered a simple dipole antenna at the receiver with a nominal directional gain. Since there is no limitation on the size of the external equipment, we can make use of a large antenna with a very high gain along the direction of transmission. In some scenarios, it might also be possible to place the antenna close to the body (closer than 1 m) further improving the quality of the received signal.

Finally, it must be noted that the return loss of the antenna increases inside the body (+11.81 dB) and there is also some frequency detuning (1.14%). Higher return loss is a desirable characteristic but frequency detuning is not and can be removed by adjusting the dimensions of the antenna such that the null occurs at the desired frequency.

REFERENCES

[1] P. Soontornpipit, C. M. Furse, and Y. C. Chung, "Design of implantable microstrip antenna for communication with medical implants," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 8, part 2, pp. 1944–1951, 2004.

[2] J. Kim and Y. Rahmat-Samii, "Implanted antennas inside a human body: simulations, designs, and characterizations," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 8, part 2, pp. 1934–1943, 2004.

[3] M. Norris and J.-D. Richard, "Sub-miniature antenna design for wireless implants," in *Proceedings of the IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications*, pp. 57–62, London, UK, April 2007.

[4] H. Higgins, "Body implant communications—is it a reality?" in *Proceedings of the IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications*, pp. 33–36, London, UK, April 2007.

[5] C. A. Balanis, *Antenna Theory: Analysis and Design*, John Wiley & Sons, New York, NY, USA, 2nd edition, 1997.

[6] D. M. Pozar, "Microstrip antennas," *Proceedings of the IEEE*, vol. 80, no. 1, pp. 79–91, 1992.

[7] K. Carver and J. Mink, "Microstrip antenna technology," *IEEE Transactions on Antennas and Propagation*, vol. 29, no. 1, pp. 2–24, 1981.

[8] B. Pan, Y.-K. Yoon, G. E. Ponchak, M. G. Allen, J. Papapolymerou, and M. M. Tentzeris, "Analysis and characterization of a high-performance Ka-band surface micromachined elevated patch antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 5, no. 1, pp. 511–514, 2006.

[9] A. Derneryd, "A theoretical investigation of the rectangular microstrip antenna element," *IEEE Transactions on Antennas and Propagation*, vol. 26, no. 4, pp. 532–535, 1978.

[10] D. H. Schaubert, D. M. Pozar, and A. Adrian, "Effect of microstrip antenna substrate thickness and permittivity: comparison of theories with experiment," *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 6, pp. 677–682, 1989.

[11] J. D. Kraus, *Electromagnetics*, McGraw-Hill, New York, NY, USA, 3rd edition, 1984.