Micromachined On-Chip Dielectric Resonator Antenna Operating at 60 GHz

Mai O. Sallam, *Student Member, IEEE*, Mohamed Serry, *Member, IEEE*,
Sherif Sedky, *Member, IEEE*, Atif Shamim, *Senior Member, IEEE*, Walter De Raedt,
Guy A. E. Vandenbosch, *Fellow, IEEE*, and Ezzeldin A. Soliman, *Senior Member, IEEE*

Abstract— This paper presents a novel cylindrical Dielectric Resonator Antenna (DRA) suitable for millimeter-wave on-chip systems. The antenna was fabricated from a single high resistivity silicon wafer via micromachining technology. The new antenna was characterized using HFSS and experimentally with good agreement been found between the simulations and experiment. The proposed DRA has good radiation characteristics, where its gain and radiation efficiency are 7 dBi and 79.35%, respectively. These properties are reasonably constant over the working frequency bandwidth of the antenna. The return loss bandwidth was 2.23 GHz, which corresponds to 3.78% around 60 GHz. The antenna was primarily a broadside radiator with -15 dB cross polarization level.

Index Terms—On-chip antennas, dielectric resonator antennas, micromachining technology, mm-wave applications.

I. INTRODUCTION

THE ever increasing demand for high performance communication systems has motivated the shift of wireless systems towards the millimeter-wave (mm-wave) range. At these relatively high frequencies, microstrip antennas suffer from high conductor and substrate losses resulting in the deterioration of the antenna radiation efficiency. The replacement of the lossy planar metallic antennas with high permittivity Dielectric Resonator Antennas (DRAs) is considered a good solution to this problem. The idea of using Dielectric Resonators (DRs) as radiating

antennas was first introduced in 1983 [1]. Since that time, DRAs received great attention due to their appealing characteristics like small footprint, light weight, absence of surface wave and metallic losses. In addition, DRAs can have various geometrical topologies. DRAs can be excited using a variety of feeding structures like co-axial lines [2], microstrip lines [3], coplanar waveguides [4], aperture excitation [5], and even conformal strip excitation [6]. However, the fabrication of DRAs in the millimeter-wave range is challenging [7], owing to the relatively small features required. The thickness of the substrate carrying the feeding microwave circuit must be electrically thin in order to avoid surface wave modes excitation. Besides, any misalignment between the DRA and the feeding structure results in significant impedance mismatch [7].

Research carried out in the area of DRAs can be classified into two categories. The first category is concerned with improving the antenna electrical characteristics. The substrates carrying the driving circuit are made from non-semiconductor materials (neither silicon nor GaAs). Therefore, antennas in this category are not suitable for on-chip integration. In [8], the substrate used has relative permittivity, ϵ_r , of 10.2, whereas in [9-14], the substrates used were teflon with $\epsilon_r = 2.2$. In [8], stacked DRAs were designed to achieve good radiation characteristics where a gain of 6 dBi and bandwidth of 24% were realized. Another technique for improving the gain was introduced in [9]. The gain of the DRA was enhanced by using a superstrate located at a certain distance from the DRA. A gain higher than 11 dBi and a bandwidth of 18.4% were obtained. Further enhancement for the gain has been made in [10], where the superstrate was stacked with multiple metallic strips. The gain of that antenna was higher than 15.4 dBi over its working bandwidth. Excitation of higher order modes of the DRA is also considered a method for improving the gain [11-14]. The higher order modes of the TE_{118} mode (TE_{115} , and TE_{119}) were excited in [11]; whereas the modes HE_{158} and HE_{128} were excited in [12], and [13-14], respectively.

The second category of DRAs uses either silicon [15-18] or GaAs [7] substrate that can carry the driving electronics. In [15, 16], a DRA was fed by a coplanar waveguide (CPW) to excite the HE_{118} mode. The proposed antenna in that work has a gain of 3.2 dBi. However, it suffered from low radiation efficiency (51%). In [17], the DRA was fed by a H -slot which excited the TE_{118} mode. This antenna has an improved radiation efficiency of 59% while its measured gain was 0.5

M. O. Sallam is with Physics Department, School of Sciences and Engineering, The American University in Cairo (AUC), New Cairo 11835, Egypt. She is also with ESAT/TELEMIC, KU Leuven, 3001 Leuven, Belgium (e-mail: mai.sallam@aucegypt.edu; mai.sallam@esat.kuleuven.be).

M. Serry is with Mechanical Engineering Department, School of Sciences and Engineering, The American University in Cairo (AUC), New Cairo 11835, Egypt (e-mail: mserry@aucegypt.edu).

S. Sedky is with Physics Department, School of Sciences and Engineering, The American University in Cairo (AUC), New Cairo 11835, Egypt (e-mail: sedky@aucegypt.edu).

A. Shamim is with Department of Electrical Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia (e-mail: atif.shamim@kaust.edu.sa).

W. De Raedt is with IMEC, 3001 Leuven, Belgium (e-mail: deraedt@imec.be).

G. A. E. Vandenbosch is with ESAT/TELEMIC, KU Leuven, 3001 Leuven, Belgium (e-mail: guy.vandenbosch@esat.kuleuven.be).

E. A. Soliman is with Physics Department, School of Sciences and Engineering, The American University in Cairo (AUC), New Cairo, Egypt (e-mail: esoliman@aucegypt.edu).

dBi. In [7], a Dielectric Resonator Antenna above Patch (DRAP) was introduced. The substrate of the antenna was GaAs. This antenna has a good impedance bandwidth (29.2%), whereas it has a gain of 3.6 dBi. For all these designs, the DRA itself was constructed from a material different from the silicon or GaAs substrate material, which requires hybrid integration. In [18], a high resistivity ($\rho_{\text{si}} = 300 \Omega \cdot \text{cm}$) silicon was used as a material for both the substrate and the four DRAs arranged as 2×2 array. A number of BenzoCycloButene (BCB) films were deposited on top of the slotted ground plane at the back-side of the substrate to realize the feeding microstrip network. The gain of this DRA array was about 11 dBi and its simulated radiation efficiency was 62%. Such antenna represents a complete on-chip solution in which the DRA is micromachined from the same wafer carrying the driving circuit.

In this paper, a novel cylindrical DRA suitable for on-chip applications is introduced. The proposed DRA is micromachined in silicon. A Coplanar Waveguide (CPW) structure is used to feed the proposed DRA, instead of the microstrip network used in [18]. Therefore, no BCB layers are required, which leads to a simpler and less expensive design. Unlike the CPW-fed DRAs presented in [8, 15-17], the CPW feeding line of the proposed design is placed at the underside of the substrate. This facilitates the construction of the DRA and its feeding network using a single wafer.

The paper is organized as follows: the structure of the new antenna together with its radiation mechanism is introduced in Section II. A parametric study that leads to the optimum antenna dimensions is presented in Section III. The fabrication technology used to realize the proposed antenna is outlined in Section IV. The optimum design is characterized both theoretically and experimentally in Section V. The important conclusions are stated in Section VI.

II. ANTENNA STRUCTURE AND RADIATION MECHANISM

The structure of the proposed DRA is shown in Fig. 1. The cylindrical DRA, with radius R is defined in a high resistivity silicon wafer by etching the silicon around the cylinder as shown schematically in Fig. 1(b). The resistivity of the silicon wafer is $2,000 \Omega \cdot \text{cm}$, its dielectric loss tangent ($\tan \delta$) = 0.003 [19], and its relative permittivity $\epsilon_r = 11.9$. The wafers used were $675 \mu\text{m}$ thick. The height of the DRA is $400 \mu\text{m}$, whereas the remaining thickness for the substrate is $275 \mu\text{m}$. Such relatively thin substrate prevents the excitation of all surface wave modes except for the fundamental TM_0 mode [20]. The DRA is excited by a magnetic dipole with length L and width W . This dipole terminates the feeding CPW line, whose slot width and slots separation are 40 and $68 \mu\text{m}$, respectively. The line's dimensions correspond to a characteristic impedance of 50Ω . The feeding structure is located at the back side of the silicon wafer, as shown in Fig. 1. The lateral spacing between the center of the feeding line and that of the DRA is denoted by S .

The CPW feeding line is excited with its odd mode where the magnetic currents flow in the two slots of the CPW in opposite directions. This forces the magnetic currents to flow

through the arms of the magnetic dipole in the same direction. The magnetic and electric field distributions of the DRA designed at 60 GHz is shown in Fig. 2, as calculated by HFSS using finite element method. The magnetic field distribution matches that of the $HE_{11\delta}$ mode of the DRA [21]. It is clear from Fig. 2 that the magnetic field along the DRA has the same direction as the magnetic current flowing through the feeding magnetic dipole, and the maximum magnetic field occurs at the interface between the DRA and the substrate. This ensures maximum coupling from the feeding dipole to the desired DRA mode. On the other hand, the electric field at the top of the DRA is along the x -axis, normal to the magnetic field. It is worth noting that the coupling magnetic dipole is not located at the center of the DRA in order to achieve best matching with the feeding CPW line.

Fig. 1. Structure of the proposed DRA: (a) 3D view, (b) side view, and (c) projected top view.

Fig. 2. Field distribution of the DRA at 60 GHz: (a) Magnetic field along the top face of the DRA, (b) Magnetic field along the central plane perpendicular to the substrate and parallel to the magnetic dipole, and (c) Electric field along the top face of the DRA.

III. PARAMETRIC STUDY AND OPTIMUM DESIGN

This section shows the effect of varying the geometrical design parameters of the DRA: R , L , W , and S , shown in Fig. 1, on its frequency response. The DRA dimensions determine the resonant frequency. Table I shows the sensitivity of the resonance frequency and return loss of the DRA to 10% perturbation (increase) of its design parameters around their optimum values. The optimum values are listed in Table II. It is worth mentioning that in this study, the height of the DRA was kept constant. Since, we are bounded by the wafer thickness (675 μm), increasing the height of the DRA implies decreasing the substrate thickness which affects the mechanical stability of the antenna. On the other hand, decreasing the height of the DRA adversely affects the antenna's radiation characteristics. The choice of $H = 400 \mu\text{m}$ is considered a compromise between both factors. From Table I, it can be observed that the most effective parameter to tune the resonance frequency is the radius of the DRA, R . This is expected as the DRA is the radiating element whose size must control most the value of the resonance frequency. Fig. 3 shows the HFSS simulated return loss of the DRA versus frequency for different values of the DRA radius, R . As R increases the value of the resonance frequency decreases, while good matching is maintained.

According to Table I, the length, L , and location, S , of the feeding dipole play the major role in achieving good matching between the DRA radiating mode and the feeding line. In other words, the input impedance of the DRA is mostly controlled via the two parameters L and S .

Fig. 4 shows the variation of the input impedance of the DRA simulated using HFSS at 60 GHz versus L and S . According to Fig. 4(a), as S increases, the input resistance slightly increases due to the decrease and the increase of the DRA modal current and voltage, respectively, which are proportional to the modal magnetic and electric field, respectively. The modal magnetic field is shown in Fig. 2. This behavior is similar to the effect of varying the location of the probe feeding a microstrip patch antenna. In a similar manner to a microstrip patch electromagnetically excited by an inductively coupled slot terminated by a short-circuit [22], the input resistance of the proposed antenna is strongly dependent on the length, L , of the feeding magnetic dipole. As L increases, the real part of the input impedance decreases significantly, as shown in Fig. 4(a).

TABLE I
SENSITIVITY OF THE RESONANCE FREQUENCY AND RETURN LOSS TO THE PERTURBATION OF THE DRA DESIGN PARAMETERS

Antenna Parameter	Resonance Frequency Sensitivity (GHz/10% Perturbation)	Return Loss Sensitivity (dB/10% Perturbation)
R	-3.29	6.95
L	-0.59	12.29
W	-0.18	3.49
S	0.56	14.49

TABLE II
OPTIMUM DIMENSIONS OF THE DRA

Antenna Parameter	OPTIMUM VALUE	Antenna Parameter	Optimum Value
L	1.068 mm	W	265 μm
R	1.18 mm	S	1.2 mm

Unlike the resistive part of the input impedance, which is affected mainly by L , its imaginary part is affected by both L and S , as shown in Fig. 4(b). As L increases, the antenna input impedance becomes more inductive due to the increased spacing between the short-circuit termination of the magnetic dipole and the feeding point. On the other hand, as S increases the DRA becomes more capacitive due to the increase in the modal voltage as one move away from the center of the DRA. It is worth mentioning that the region of maximum current, i.e. magnetic field, corresponds to minimum voltage, i.e. electric field, and vice versa. All geometrical parameters of the proposed structure are simultaneously optimized using HFSS so as to obtain maximum gain and minimum return loss at 60 GHz.

Fig. 3: Return loss of the DRA versus frequency for different values of the radius, R . The rest of the parameters are kept constant at $L = 1.068 \text{ mm}$, $S = 1.2 \text{ mm}$, and $W = 265 \mu\text{m}$.

Fig. 4: Input impedance of the DRA at 60 GHz versus the feeding dipole length (L) and spacing (S): (a) real part, and (b) imaginary part. The other two parameters are kept constant at $R = 1.18$ mm, and $W = 265$ μ m.

IV. FABRICATION

The structure of the proposed DRA is relatively simple and can be fabricated using micromachining technology in three steps. Six inch double sided polished high-resistivity silicon wafers ($\rho_{si} \geq 2,000$ Ω .cm and thickness = 675 μ m) were used for fabrication. One side of this wafer was etched through a depth of 400 μ m using a Deep Reactive Ion Etching (DRIE) process in order to remove the silicon around the DRA [23–25] while maintaining vertical cylindrical sidewall. It is worth mentioning that a number of DRA prototypes were fabricated within the same wafer. Ideally, the silicon has to be removed totally in between adjacent DRAs. However, this process requires etching of huge amount of silicon. For fabrication simplicity, sufficient amount of silicon was etched away around the DRA, such that a minimum distance of 4 mm is kept clear in all directions. This leaves silicon walls surrounding the DRAs. The presence of these walls has a

minor effect on the antenna's characteristics, as discussed later in section V. The unetched bottom side of the wafer acts as the substrate for the antenna's feeding network. The backside was coated with a copper film having a thickness ≥ 5 μ m using an electroplating process. Then, the backside Cu was patterned using dry etching to define the feeding network. The schematic diagram in Fig. 5 gives an overview of the fabrication process.

The main advantage of the proposed process is that the DRA is fabricated using a two-mask process on a single wafer. This enhances the accuracy of the fabricated antenna since the misalignment between the DRA and the feeding network is minimized. In addition, this simple structure implies more mechanical stability and less fabrication costs compared to alternative mm-wave DRAs that require hybrid integration. It is clear from the SEM images displayed in Fig. 6 that the fabricated DRA prototype has sharp vertical walls.

Fig. 5: Process flow for fabricating the proposed DRA: (a) start-up silicon wafer, (b) DRIE from top-side, (c) copper electroplating at back-side, (d) copper patterning.

Fig. 6: SEM photos of the fabricated DRA: (a) top side showing the DRA, and (b) bottom side showing the feeding CPW line terminated by the magnetic dipole.

V. THEORETICAL AND EXPERIMENTAL CHARACTERIZATION

In this section, the measured electrical characteristics of the fabricated DRA are presented and compared with the simulated results. For accurate comparison, the silicon walls surrounding the DRA were taken into consideration in the simulation. Fig. 7 shows the measured and simulated return loss of the optimized DRA versus frequency. The simulations of the optimized DRA were carried out using HFSS. The return loss curves show good agreement between simulations and measurements. The measured resonance frequency was 59 GHz very close to the value determined by HFSS, which is 59.5 GHz. Measurements showed better matching and slightly wider bandwidth than simulations. This is mainly due to extra losses that are not considered by the simulators. The measured -10 dB impedance bandwidth was 2.23 GHz, which corresponds to 3.78% at 59 GHz. Such bandwidth is considered sufficient for a number of mm-wave wireless systems. For WPAN applications where the bandwidth extends from 57 GHz to 64 GHz, a few more proposed DRAs with different dimensions are required to cover the entire passband.

The 3D radiation pattern of the proposed DRA is shown in Fig. 8, as simulated using HFSS at 59.5 GHz. As shown, the antenna is radiating mainly towards the boresight. The simulated gain, directivity, and radiation efficiency are 8.27 dBi, 8.11 dBi, and 92.04%, respectively. The -15 dB back-side radiation is attributed mainly to radiation from the magnetic dipole etched within the ground plane.

Fig. 9 shows the measured and simulated co- and cross-polar components of the far field at the corresponding resonance frequency along the E - and H -planes. The detailed measurement setup is presented in [26]. The H -plane is the plane parallel to the magnetic dipole, while the plane perpendicular to it is the E -plane. There is reasonable agreement between simulations and measurements. The reason for the observed discrepancy is the fact that during measurements, the DRA structure is mounted within a large ground plate which is part of the measurement equipment. This alters the radiation patterns, mainly above 60° . It is also observed that around -10° , there is a noticeable difference between simulations and measurements since there is no complete isolation between the probe positioner side and the radiating side. Thus, reflection from the positioner gives rise to this dip as it appears in one plane at one side only. Comparing the co- and cross-polarization components in the E - and H -planes, it is clear that the proposed DRA enjoys a high degree of polarization purity especially in the broadside direction. The simulated and measured cross-polar levels in the broadside direction are -42.25 dB and -15.00 dB, respectively. The relatively higher measured cross-polarization level is mainly due to unwanted reflections within the measurement setup. The measured 3-dB beamwidth of the proposed DRA is 45° and 114° in the E - and H -planes, respectively.

Fig. 10 shows the simulated and measured gain versus frequency. From the figure, it is clear that antenna has an average gain of around 6.5 dBi along its working bandwidth. A maximum gain of 7 dBi was measured at the resonance

frequency (59 GHz). The radiation efficiency of the fabricated antenna can be calculated from the measured gain, and the estimated directivity of the antenna. In our calculations, we used the approximated formula of the directivity, D , which is given by [27]:

$$D = \frac{32400}{\theta_E \theta_H} \quad (1)$$

where θ_E and θ_H are the measured 3-dB beamwidths along the E - and H -planes, respectively. At 60 GHz, the calculated radiation efficiency is 79.35% compared to the simulated efficiency of 92.04%. It is clear that the approximated directivity is a source of error. The alternative is to measure the whole radiation pattern in all directions and calculate the directivity according to its definition. However, this is rather impractical and would take a much longer measurement time. Looking at Fig. 9(b), it can be seen that the radiation pattern widens once more outside the 3-dB beamwidth which implies that the real directivity is less than the approximated one.

Fig. 7: Measured and simulated return loss versus frequency for the optimized DRA.

Fig. 8: 3D radiation pattern of the DRA at its resonance frequency as simulated with HFSS.

Fig. 9: Measured and simulated radiation pattern of the DRA at its resonance frequency (—HFSS, - - - Measured): (a) co- and cross-polar components in E -

plane, (b) co- and cross-polar component in H -plane.

Fig. 10: Simulated and measured gain versus frequency for the proposed DRA.

VI. CONCLUSION

In this paper, a micromachined on-chip DRA with single silicon wafer is designed, fabricated, and measured for the first time. A complete parametric study for the proposed antenna has been presented. The new antenna has a number of appealing characteristics, such as: fabrication simplicity, high radiation efficiency, high gain, and low cross-polarization level. In addition, the proposed antenna is suitable for monolithic integration with the driving electronics. Such feature has a high value in the millimeter-wave range because the added parasitics due to hybrid integration may deteriorate the performance of such high-frequency systems.

ACKNOWLEDGMENT

This publication is based on work supported by award number: UK-C0015 OUK made by King Abdullah University of Science and Technology (KAUST) and was co-funded by the Fund for Scientific Research Flanders (FWO-V) of the Flemish government through the FWO project G.0897.10N.

REFERENCES

- [1] S. A. Long, M. McAllister, and L. Shen, "The resonant cylindrical dielectric cavity antenna," *IEEE Trans. Antennas Propag.*, vol.31, no.3, pp.406-412, May 1983.
- [2] K. W. Leung, K. M. Luk, K. Y. A. Lai, and D. Lin, "Theory and experiment of a coaxial probe fed hemispherical dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, vol.41, no.10, pp.1390-1398, Oct. 1993.
- [3] R. A. Kranenburg and S. A. Long, "Microstrip transmission line excitation of dielectric resonator antennas," *Electronics Lett.*, vol.24, no.18, pp.1156-1157, Sept. 1988.
- [4] R. A. Kranenburg, S. A. Long, and J. T. Williams, "Coplanar waveguide excitation of dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, vol.39, no.1, pp.119-122, Jan. 1991.
- [5] J. T. H. St. Martin, Y. M. M. Antar, A. A. Kishk, A. Ittipiboon, and M. Cuhaci, "Dielectric resonator antenna using aperture coupling," *Electronics Lett.*, vol.26, no.24, pp.2015-2016, Nov. 1990.
- [6] K.-W. Leung, "Conformal strip excitation of dielectric resonator antenna," *IEEE Trans. Antennas Propag.*, vol.48, no.6, pp.961-967, June 2000.
- [7] J. Oh, T. Baek, D. Shin, J. Rhee, and S. Nam, "60-GHz CPW-fed dielectric resonator-above-patch (DRAP) antenna for broadband WLAN applications using micromachining technology," *Microw. Optical Technol. Lett.*, vol.49, no.8, pp.1859-1861, Aug. 2007.

- [8] Y. Coulibaly, M. Nedil, L. Talbi, and T. A. Denidni, "Design of a mm-wave broadband CPW-fed stacked dielectric resonator antenna for underground mining communication," *IEEE Int. Symp. Antennas Propag. Soc. (APSURSI)*, pp.1-4, Toronto, Ontario, Canada, July 2010.
- [9] Y. Coulibaly, M. Nedil, L. Talbi, and T. A. Denidni, "High gain cylindrical dielectric resonator with superstrate for broadband millimeter-wave underground mining communications," *14th Int. Symp. Antenna Technol. Appl. Electromagnetics and the American Electromagnetics Conf. (ANTEM-AMEREM)*, pp.1-4, July 2010.
- [10] A. Agouzoul, M. Nedil, Y. Coulibaly, T. A. Denidni, I. Ben Mabrouk, and L. Talbi, "Design of a high gain hybrid dielectric resonator antenna for millimeter-waves underground application," *IEEE Antennas Propag. Soc.*, pp.1688-1691, July 2011.
- [11] Y.-M. Pan, K. W. Leung, and K.-M. Luk, "Design of the millimeter-wave rectangular dielectric resonator antenna using a higher-order mode," *IEEE Trans. Antennas Propag.*, vol.59, no.8, pp.2780-2788, Aug. 2011.
- [12] A. Perron, T. A. Denidni, and A.-R. Sebak, "High-gain hybrid dielectric resonator antenna for millimeter-wave applications: design and implementation," *IEEE Trans. Antennas Propag.*, vol.57, no.10, pp.2882-2892, Oct. 2009.
- [13] D. Guha, A. Banerjee, and Y. M. M. Antar, "New radiating mode in a cylindrical DRA to produce broadside high gain radiation," *IEEE Int. Symp. Antennas Propag. Soc. (APSURSI)*, pp.1-4, July 2010.
- [14] D. Guha, A. Banerjee, C. Kumar, and Y. M. M. Antar, "Higher order mode excitation for high-gain broadside radiation from cylindrical dielectric resonator antennas," *IEEE Trans. Antennas Propag.*, vol.60, no.1, pp.71-77, Jan. 2012.
- [15] P. V. Bijumon, A. P. Freundorfer, M. Sayer, and Y. M. M. Antar, "On-chip silicon integrated cylindrical dielectric resonator antenna for millimeter wave applications," *Int. Symp. Signals, Syst. and Electronics (ISSSE)*, pp.489-492, July 2007.
- [16] P. V. Bijumon, Y. M. M. Antar, A. P. Freundorfer, and M. Sayer, "Dielectric resonator antenna on silicon substrate for system on-chip applications," *IEEE Trans. Antennas Propag.*, vol.56, no.11, pp.3404-3410, Nov. 2008.
- [17] M.-R. Nezhad-Ahmadi, M. Fakharzadeh, B. Biglarbegian, and S. Safavi-Naeini, "High-efficiency on-chip dielectric resonator antenna for mm-wave transceivers," *IEEE Trans. Antennas Propag.*, vol.58, no.10, pp.3388-3392, Oct. 2010.
- [18] J. Svedin, L.-G. Huss, D. Karlen, P. Enoksson, and C. Rusu, "A micromachined 94 GHz dielectric resonator antenna for focal plane array applications," *IEEE/MTT-S Int. Microw. Symp. (IMS)*, pp.1375-1378, June 2007.
- [19] M. N. Afsar, H. Chi, X. Li, "Millimeter wave complex refractive index, complex dielectric permittivity and loss tangent of high purity and compensated silicon," *Conf. Precision electromagnetic Measurements*, pp. 238-239, June 1990.
- [20] M. Riazat, R. Majidi-Ahy, and I.-J. Feng, "Propagation modes and dispersion characteristics of coplanar waveguides," *IEEE Trans. Antennas Propag.*, vol.38, no.3, pp.245-251, 1990.
- [21] D. Kajfez and A. W. Glisson, and J. James, "Computed modal field distributions for isolated dielectric resonators," *IEEE Trans. Microw. Theory*, vol.32, no.12, pp.1609-1616, Dec. 1984.
- [22] L. Giauffret, J.-M. Laheurte, and A. Papiernik, "Study of various shapes of the coupling slot in CPW-fed microstrip antennas," *IEEE Trans. Antennas Propag.*, vol.45, no.4, pp.642-647, April 1997.
- [23] E. A. Soliman, S. Sedky, M. O. Sallam, S. Hassan, O. El Kattab, A. K. S. Abdel Aziz, and M. Refaat, "Novel MEMS dipole/monopole antenna for wireless system operating at 77 GHz," *Progress in Electromagnetics Research Symp. Online*, vol.6, no.6, pp.547-550, July 2010.
- [24] E. A. Soliman, S. Hassan, O. El Kattab, M. O. Sallam, M. Serry, and S. Sedky, "77-GHz MEMS brick-wall antenna fed by coupled microstrip lines," *IEEE Int. Symp. Antennas Propag. Soc. (APSURSI)*, pp.1-4, Toronto, Ontario, Canada, July 2010.
- [25] M. O. Sallam, E. A. Soliman, and S. Sedky, "Novel linearly and circularly polarized 60 GHz MEMS antennas on low- and high-resistivity silicon," *5th European Conf. Antennas Propag. (EuCAP)*, pp.1194-1198, Rome, Italy, April 2011.
- [26] K. Mohammadpour-Aghdam, S. Brebels, A. Enayati, R. Faraji-Dana, G. A. M. Vandenbosch, and W. De Raedt, "RF probe influence study in millimeter-wave antenna pattern measurements," *Int. J. of RF Microw. Comput.-Aided Eng.*, vol. 21, no. 4, pp.413-420, July 2011.

[27] C. A. Balanis, *Antenna Theory and Design*, John Wiley & Sons, Inc., 1997.

Mai O. Sallam(S'13) was born in Cairo, Egypt, in October 1986. She received her B.Sc. degree (with honors) in Electronics and Communications Engineering from Ain-Shams University, Cairo, Egypt in 2008 and the M.Sc. degree in Physics in 2012 from the American University in Cairo, Egypt. She is currently working towards her Ph.D. degree at both the American University in Cairo and the Katholieke Universiteit Leuven, Belgium.

Since December 2008, she joined the Youssef Jameel Science and Technology Research Center (YJ-STRC) at the American University in Cairo as a research assistant. Her research interests include RFID tag antennas, micromachined on-chip antennas for millimeter wave applications, and plasmonics.

Mohamed Serry was born in Cairo in 1975. He received a B.Sc. in Mechanical Engineering from Ain Shams University (Egypt) in 1999; a M.Sc. in Mechanical Engineering from the University of Alberta (Canada) in 2003; and a Ph.D. from the University of Toronto (Canada) in 2007. In 2008, Serry joined the Professor Osamu Tabata's Group in the Department of Micro engineering, Kyoto University (Japan), as a JSPS Scholar, and in 2009 he joined Professor Sherif Sedky's

Group at the Youssef Jameel Science and Technology Research Center at the American University in Cairo as a postdoctoral fellow. Presently, Serry is an Assistant Professor in the Department of Mechanical Engineering at the American University in Cairo. He currently holds two patents, and has authored and coauthored over thirty-five international publications.

Sherif Sedky(M'99) was born in Cairo (Egypt) in 1969. He received the B.Sc. degree, with honors, in electronics engineering in 1992, and the M.Sc. degree in engineering physics in 1995 both from Faculty of Engineering, Cairo University, and the Ph.D. degree in microelectronics in 1998 from the Katholieke Universiteit Leuven, Belgium. In 1995 he joined the MEMS group of the Interuniversity Microelectronics Center (IMEC) in Leuven (Belgium). During the academic year 1999-2000, he was a postdoctoral

fellow at the Katholieke Universiteit Leuven, and a visiting professor at the same university during Summer 2001, 2003, 2004, 2005, 2006, 2007 and 2008. In 2002 he was a visiting researcher at the University of California, Berkeley. In February 2004 he has been promoted to associate professor and to full professor in 2008. He served as the director of Youssef Jameel Science and Technology Research Center, and associate dean for graduate studies and research at The American University in Cairo. In 2012 has was appointed as the founding provost of Zewail University of Science and Technology and the Director of the Nanotechnology Center at Zewail City. Currently he is the Provost of The American University in Cairo. He holds thirteen patents and authored and coauthored over one hundred international publications and a book chapter. He is the author of the book titled: "Post-processing techniques for integrated MEMS". He established a MEMS fabrication facility at The Science and Technology Research Center at The American University in Cairo. He is a recipient of the 2007 Excellence in research and creative endeavors award. He is also a recipient of the Egyptian prestigious national award in advanced technological sciences in 2002, and the graduate studies award from Cairo University in 1996. He served on the scientific committees of several international conferences.

Atif Shamim(S'03-M'09-SM'13) received his M.A.Sc. and Ph.D. degrees in electrical engineering at Carleton University, Canada in 2004 and 2009 respectively. He was an NSERC Alexander Graham Bell Graduate scholar at Carleton University from 2007 till 2009 and an NSERC postdoctoral Fellow from 2009-2010 at Royal Military College Canada and King Abdullah University of Science and Technology (KAUST), KSA. In August 2010, he joined the

Electrical Engineering Program at KAUST, where he is currently an Assistant

Professor and principal investigator of IMPACT Lab. He was an invited researcher at the VTT Micro-modules Research Center (Oulu, Finland) in 2006. Dr. Shamim was the recipient of the best paper prize at the European Wireless Technology Conference in 2008. He was given the Ottawa Centre of Research Innovation (OCRI) Researcher of the Year Award in 2008. His work on Wireless Dosimeter won the ITAC SMC Award at Canadian Microelectronics Corporation TEXPO in 2007. He received the best student paper finalist prize at IEEE APS conference in 2005. He also won numerous business related awards, including 1st prize in Canada's national business plan competition and was selected for OCRI Entrepreneur of the year award in 2010. He has authored/co-authored over 65 international publications and is an inventor on 8 patents. His research interests are in integrated on-chip antennas, low power CMOS RFICs for system-on-chip (SoC) applications and advanced system-on-package (SoP) designs in multilayer LTCC, LCP, and paper substrates through screen and inkjet printing techniques. Dr. Shamim serves on the editorial board of IEEE Transactions on Antennas and Propagation.

Walter De Raedt received the M.Sc. degree in electrical engineering from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1981. He subsequently joined the Electronics, Systems, Automation and Technology (ESAT) Laboratory, where he was a Research Assistant involved directly with electron beam technology. Since 1984, he has been with the Interuniversity Microelectronics Centre (IMEC),

Leuven, where he has been involved with research on MICs and sub micrometer technologies for advanced high electron mobility transistor (HEMT) devices. From 1997, he joined the MCM group at IMEC in charge of the design, modeling and characterization activities for packaging. As a head of the RFCDM group at IMEC he was involved in many EU research projects (3DµTune, e-cubes, e-brains). In 2003 he received the IEEE microwave prize with his team. He authored and co-authored more than 200 papers, several patents and book chapters in the field of microwave/mm wave modeling, design and packaging. His current interests are centered around SiP (System in package) integration of sensors for body area network applications.

Guy A. E. Vandenbosch(M'92-SM'08-F'13) received the M.S. and Ph.D. degrees in Electrical Engineering from the Katholieke Universiteit Leuven, Belgium, in 1985 and 1991, respectively. From 1991 to 1993, he held a postdoctoral research position at the KU Leuven. Since 1993, he has been a Lecturer, and since 2005, a Full Professor at this university. His research interests are in the area of electromagnetic theory, computational electromagnetics, antennas and radiation, electromagnetic compatibility, nano-electromagnetics, and bio-electromagnetics. Guy Vandenbosch has been a member of the "Management Committees" of the consecutive European COST actions on antennas since 1993, where he is leading the working group on modeling and software for antennas. Within the ACE Network of Excellence of the EU (2004-2007), he was a member of the Executive Board and coordinated the activity on the creation of a European antenna software platform. In the period 1999-2004, he was vice-chairman, and in the period 2005-2009 secretary of the IEEE Benelux Chapter on Antennas en Propagation. Currently he holds the position of chairman of this Chapter.

Ezzeldin A. Soliman(S'97-M'99-SM'12) was born in Cairo, Egypt, in May 1970. He received his B.Sc. degree (distinction with honors) in Electronics and Communications Engineering and his M.Sc. degree in Engineering Physics both from Cairo University, Egypt, in June 1992 and Nov. 1995, respectively. He received his Ph.D. degree (summa cum laude) in Electrical Engineering from the Katholieke Universiteit Leuven (KU Leuven) jointly with the Interuniversity MicroElectronics Center (IMEC), Belgium, in Feb. 2000. Dr. Soliman held the following positions: Assistant Professor at Cairo University (2000-2005), Visiting Scholar at McMaster University, Canada (2002-2003), Associate Professor at King AbdulAziz University, KSA (2005-2007). From 2007 to 2012, he has been an Associate Professor at the American University in Cairo (AUC), Egypt. Since 2013, he is a Full Professor at the AUC. He has been a

Visiting Professor at both IMEC and KU Leuven during Spring 2002, Summer 2006, Winter 2008, Summer 2008-2013. Dr. Soliman was invited as Visiting Professor at McMaster University, Canada, in Fall 2014. His research interests include integrated antennas, computational electromagnetics, and plasmonics. He holds four patents, published over 60 international journal papers, in addition to more than 40 international conference publications. Dr. Soliman is the founder of the Microwave and Millimeter-Wave Laboratory at Yousef Jameel Science and Technology Research Center of the AUC. He is the recipient of the “Outstanding Scholarly Research” offered by School of Sciences and Engineering at the AUC on 2010, and the “Excellence in Research and Creative Endeavors Award” offered by the AUC on 2011.