Special Issue on Artificial Magnetic Conductors, Soft/Hard Surfaces, and Other Complex Surfaces

I. Introduction

ATTENTION has increased in the design of periodic structures that control the propagation characteristics or the boundary conditions of electromagnetic (EM) fields in a desirable way. Such structures have been referred to as photonic bandgap structures (PBG), but are now preferably called electromagnetic bandgap structures (EBG), or electromagnetic crystals. Under certain conditions, their surfaces act as artificial magnetic conductors (AMC). Soft and hard surfaces are also related to the EBG structures. Ideal soft and hard surfaces can be represented by a grid of parallel perfectly electric conducting (PEC) and perfectly magnetic conducting (PMC) strips, for which the strip width and spacing is incrementally small. The intention of this Special Issue is to present recent research advances on theory, numerical modeling, and realizations of such complex artificial surfaces, as well as their application to antenna design.

The corrugated surface may be considered as an archetypical artificial surface, which has been used since the sixties, mainly to design horn antennas with low cross polarizationw and rotationally symmetric beams. The first articles on this subject were presented by Simmons and Kay, Rumsey, and Minnett and Thomas in 1966 following earlier work by Cutler. Later investigations were due to many researchers among whom we mention Clarricoats, Thomas, Jeuken, and Bryant in the 1970s, and James, Kühn, and Olver in the 1980s. The corrugations were used to create a zero boundary condition of the vertical field component at the surface, and, consequently, to stop vertically polarized waves from propagating along the surface. The horizontally polarized field at the surface is also zero, being enforced by the metallic ridges between the grooves. Therefore, the same zero boundary condition could be created in both E and H planes of the horn antenna aperture, resulting in a rotationally symmetric radiation pattern with low cross polarization. The corrugations had also been used before this, as chokes to reduce coupling (stop waves) in both electromagnetic compatibility and antenna applications. Thus, the stopband characteristics of the transversely corrugated surface were well understood, as well as the surface waves appearing at the boundaries of the stopband. Peters, Elliot, and Oliner among others presented theoretical contributions on this subject.

Several early researchers investigated the use of the surface impedances in guiding and radiating structures, particularly Barlow, Cullen and Wait. One of us (Kildal) started in 1986 to generalize the stop characteristics of the transversely corrugated surface, by investigating other types of antenna applications. While applying diffraction theory to the edges of transversely corrugated surfaces, he found that modifying the dyadic edge diffraction coefficients into a unique scalar "soft" diffraction coefficient for both polarizations was sufficient to predict the field in both the E and H planes. Thus, the transversely corrugated surface behaved in the stopband in the same way as a soft surface in acoustics. This led further to the question whether or not there also existed an electromagnetic equivalent to the hard surface in acoustics that would facilitate wave propagation along the surface. By simple physical reasoning he determined that this could be obtained with corrugations as well, when they were oriented longitudinally in the propagation direction of the waves along the surface, and filled with dielectric material. The latter was a major difference compared to the transversely corrugated soft surface, which could be air filled. Lier worked during the same period with alternative realizations of the soft surface in terms of metal strips on a grounded dielectric substrate. There were also previous studies of longitudinally corrugated hard horns but these either did not include dielectric material or did not detect the frequency at which transverse electromagnetic (TEM) wave appeared.

During the early 1990s, Kildal worked further on the soft and hard surface concept, and as a distinguished lecturer for IEEE Antennas and Propagation Society he had the opportunity to present it for other research groups. This led to cooperation with the two other Guest Editors of this Special Issue. There were also several other contributors to the work on soft and hard surfaces during and after this period, including Aas, Ando, Carlsson, Freni, Lindell, Manara, Pelosi, Sipus, Skobelev, Tiberio, and Ying.

In 1999, Sievenpiper and his coauthors at UCLA published an important paper on high impedance EM surfaces. This was based on Sievenpiper's supervisor Yablonovitch's long experience with photonic bandgap materials, and thereby brought this significant optical activity into the microwave and antenna domain. Sievenpiper's mushroom-type surface represented a way of realizing an AMC ground plane, as well as a way to stop the propagation of both vertically and horizontally polarized waves in any direction along the surface. The latter characteristic was the EM surface equivalent of a PBG. This also made the surface behave similarly to the soft surface. The difference is that the high impedance mushroom-surface is realized by two-dimensional (2-D) periodicity (originally patches with vias, i.e., mushrooms) that leads to an average isotropic effect, whereas the soft surface is intrinsically anisotropic because it is realized by one-dimensional (1-D) periodic structure (originally corrugations or strips). In parallel with the Sievenpiper's article, Itoh and coworkers used artificial magnetic surfaces to create what they referred to as quasi-TEM waveguides. The latter are essentially the same as a linearly polarized version of the hard waveguides introduced by Kildal in 1988.

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TABLE I

CHARACTERISTICS OF DIFFERENT TYPES OF CANONICAL SURFACES WITH RESPECT TO PROPAGATION OF WAVES ALONG THE SURFACE FOR DIFFERENT EFIELD POLARIZATIONS. VER MEANS VERTICAL POLARIZATION (I.E., TM-CASE), HOR MEANS HORIZONTAL (I.E., TE-CASE). THE BACKGROUND COLOR AND PATTERN SYMBOLIZE THE PEC (YELLOW), PMC (BLUE) AND PEC/PMC STRIPS (PARALLEL YELLOW AND BLUE STRIPS). THE DIFFERENT ORIENTATIONS OF THE COLORED STRIPS FOR THE SOFT AND HARD CASES SYMBOLIZE STOP (CURRENT FENCES) AND GO (CURRENT LANES) CHARACTERISTICS FOR WAVES PROPAGATING FROM LEFT TO RIGHT (AS SHOWN BY THE ARROWS) IN THE PAPER PLANE. THE COLORED BACKGROUND IN THE BOX OF THE PMC-TYPE EBG SYMBOLIZES THE TEXTURE OF THE SIEVENPIPER'S SURFACE

Canonical Surface		E-field Polarization	
		VER (TM)	HOR (TE)
PEC		GO	STOP
PMC		STOP	GO
PEC/PMC Strip grid	SOFT	STOP	STOP
	HARD	GO	GO
PMC-type EBG	grazing	STOP	STOP
	close to normal	PMC	

The last five years has seen an explosion of research on new applications of periodic structures referred to as metamaterials, which has involved both the microwave and antenna communities. This has grown from corresponding research within the optics community. The Special Issue on metamaterials in the present TRANSACTIONS in October 2003, edited by Ziolkowski and Engheta, represented the first systematic effort to collect and categorize such research within the Antennas and Propagation community. Following their categorization, metamaterials can be divided in two groups: EBG materials and double negative (DNG) materials, both being realized by periodic locations of structural elements in three dimensions. The EBG materials provide frequency bands (so-called bandgaps or stopbands) inside which waves cannot propagate in the materials, and the DNG materials possess effectively both a negative real permittivity and negative real permeability within a frequency band of interest. Both these types of metamaterials can be used either to obtain desired volume or surface characteristics. The EBG surface does not allow surface waves to propagate, making it similar to a soft surface as described above, whereas for normal and close to normal incidence it performs as an AMC. The same surface can normally be used also as an AMC for grazing incidence for frequencies above the bandgap, but only for TE-case (E field parallel with the surface). The DNG materials can also be used to realize AMCs.

We also mention here that the artificial surfaces described above are closely related to traditional frequency selective surfaces (FSS), the difference being that the FSS is transparent at some frequency bands whereas the modern 2-D periodic surface always exhibits either total reflection or trapped surface waves. The periodic structure is normally backed by a ground plane, and the resonances of the surface structure characterize the possible presence of bandgaps.

We complete this brief retrospective introduction by mentioning that in September 2001, Felsen and Maci gathered some specialists on metamaterials, periodic surfaces and diffraction in a Workshop on "Wave dispersion in complex environment" in Siena, Italy. A result of this event was that the similarities between the ideas of different researchers became clearer, and this stimulated the organization of joint activities. These activities have since 2002 included special EBG surface sessions at the IEEE AP-S Symposia (together with Engheta), short courses (together with Sievenpiper), and the present Special Issue.

It should be clear from the above that the concepts have emerged from different backgrounds and, as a result, the terminology is nonuniform and sometimes confusing, making it difficult to understand how the different surfaces work and how they can be applied. Therefore, in order to help clarify the situation, we will in the next section define some simplified canonical surfaces with idealized boundary conditions, which can be used in the description of desired performances of some complex surfaces, as well as for numerical analysis.

II. DEFINITION OF CANONICAL SURFACES

Table I illustrates the relation between some 2-D periodic surfaces and soft/hard surfaces. This introduces four types of canonical surfaces. The first three surfaces are as follows.

1) *The Perfect Electric Conductor (PEC)*: This surface is well known in the EM community. It is used in most EM modeling and computations as it describes metal conductors very well when analyzing guiding or radiating properties.
2) *The Perfect Magnetic Conductor (PMC)*: The EM field theory is easily extended to allow a PMC. This surface does not exist naturally, but it can be realized artificially within frequency bands and is then referred to as an artificial magnetic conductor (AMC).
3) *The PEC/PMC strip grid*: This is the physical equivalent of an ideal soft/hard surface. The surface has locally infinite and unidirectional electric and magnetic conductivity, i.e., both the electric and magnetic currents can only flow in one and the same direction. The PEC/PMC strip grid can have any shape. This means that the direction of current flow (i.e., the direction of the PEC/PMC strips) can

change along the surface (e.g., circular PEC/PMC strip rings around an antenna element), and that the surface itself can have arbitrary shape (singly or doubly curved, finite and so on).

The characteristics of the three different surfaces with respect to polarization of the grazing waves are illustrated in Table I. The PEC supports vertically polarized waves that can propagate with strong amplitude; it is a "GO" surface for vertical polarization. These propagating waves are not really surface waves in the mathematical sense; a branch point rather than a pole represents them in the spectral domain. However, when the surface has a thin dielectric coating the propagating space wave becomes a TM (with respect to normal) surface wave (i.e., a pole). The PEC stops effectively horizontally polarized waves, because the horizontal field component is zero. The PMC performs naturally in the opposite way; it is a "GO" surface for horizontal polarization and a "STOP" surface for vertical polarization (see table). The classical soft/hard surfaces can be represented physically by a PEC/PMC strip grid as explained above and illustrated in the table as well. This will stop waves propagating with both horizontal and vertical polarizations when the strips are oriented transverse to the direction of propagation (soft case), and it will allow the waves to pass (i.e., go) when they are oriented longitudinally in the same direction as the waves propagate (hard case).

The soft/hard surfaces were originally realized by metal corrugations or metal strips loading a grounded substrate. The soft/hard characteristics appear when they are oriented transversely/longitudinally with respect to the direction of wave propagation. For the soft case, they form so-called electric and magnetic current fences that stop the waves, and for the hard case they form electric and magnetic current lanes that enhance wave propagation.

The 2-D periodic EBG surface behaves normally like a PMC within some frequency band (or bands) and for wave incidence close to normal. However, for wave incidence close to grazing and within the lower part of the same frequency band, the EBG surface behaves more like a transverse PEC/PMC strip surface, i.e., like a soft surface stopping waves. This is advantageous in some applications, enabling electric current antennas to be located close to the ground plane at the same time as the mutual coupling to neighboring antennas is reduced. The original anisotropic 1-D periodic soft surface has STOP characteristics over an infinite bandwidth for the TE case (i.e., horizontal polarization). Still, the 2-D bandgap surface may be preferable in some applications because it is isotropic, stopping waves from any direction. For grazing incidence the 2-D periodic surface normally transforms from STOP to AMC-type surface at the upper edge of the stop band. These rather complex characteristics of the 2-D bandgap surface make it difficult to categorize them completely in terms of the canonical surfaces defined above. We have, therefore, extended the table with a fourth category:

4) *PMC-type bandgap surfaces*: This is a surface that stops waves at grazing angles for both horizontal and vertical polarizations, whereas it works essentially as a PMC close to normal incidence. This canonical surface cannot be represented with simple general boundary conditions as for the three previous canonical surfaces, and at present it can only be analyzed for practical cases.

The above definition of canonical surfaces leads us to speculate on the existence of other types of bandgap surfaces, such as PEC-type bandgap surfaces, i.e., surfaces that behave essentially like a PEC for incidence close to the normal and at the same time STOP both horizontally and vertically polarized waves propagating close to and at grazing incidence. Such surfaces could definitely be of interest.

There have already been important developments resulting from the mutual interactions between researchers on 2-D bandgap surfaces and soft/hard surfaces. For example, there have been proposed new realizations of soft/hard surfaces using metal strips on dielectric material, where the strips are provided with vias such as the mushroom bandgap surfaces.

Finally, we mention that there is also recent work on periodic surfaces that do not fall into any of the categories given by Table I. For example, leaky wave antennas that can be realized by the same periodic surfaces but in a frequency band normally above the bandgap. There is also research on active complex surfaces in which the surface impedance is changed by using active elements to obtain some kind of controlled function.

III. About the Articles in the Present Issue

Most of the articles in this Special Issue describe or utilize surfaces that fit into the classification described in Table I. A summary of these articles is given below in the order they appear in the issue.

The first nine papers are on EM modeling and methodologies to characterize the surfaces themselves. Aspects related to reflection, dispersion, diffraction and Green's function are treated in this first group of papers. Kern *et al.* describe how to design FSS based artificial magnetic surfaces to provide specific phases of the reflection coefficient in several frequency bands. Their procedure is based on a periodic method of moment (MoM) analysis with genetic algorithm optimization. Aminian *et al.* use finite-difference time-domain (FDTD) to characterize a corrugated soft/hard surface and a mushroom-type EBG surface. They use an analytical continuation of the reflection coefficient for complex incidence angles to generalize the soft and hard concept beyond the light line in a dispersion diagram. The paper by Bozzi *et al.* presents a method to analyze the dispersion properties of FSS-type EBG surfaces based on a tracking of the MoM matrix eigenvectors. Baccarelli *et al.* analyze the dispersion properties for arbitrary wave direction of a grounded strip grating, with emphasis on leaky wave diagrams. Chen *et al.* treat a strip-realization of soft/hard surfaces with periodic perturbations, where the latter is used to remove undesirable microstrip modes. The full-wave numerical analysis of complex artificial surfaces is presently complicated. Therefore, it is of interest to represent a complex periodic surface by a simpler smooth surface, via a homogenization process. The paper by Silveirinha shows how plane wave reflection from a mesh of crossed wires can be homogenized and characterized by an analytical formula. The network model presented by Maci *et al.*, based on Foster's reactance theorem, allows a network synthesis of FSS-type EBG surfaces by matching a few spectral points of the FSS poles and zeros in the frequency-wavenumber diagrams.

This also allows prediction of bandgaps and surface waves. Two papers about diffraction and Green's function analysis conclude this first group of papers. Diffraction at the edge of metal strip gratings play an important role in connection with truncated soft and hard surfaces. Nepa *et al.* show how uniform high-frequency diffraction theory can be extended to treat edges in such surfaces by the use of approximate boundary conditions. On the basis of the array scanning method used in connection with the periodic method of moments, Capolino *et al.* illustrate some general properties of the 2-D Green's function of 2-D EBG and soft surfaces.

A second group of seven articles deals with artificial surfaces used to modify modal propagation and radiation characteristics in waveguide and horn antennas. An important application of hard surfaces and AMCs is to realize waveguides that can support a plane TEM wave at a specific frequency, referred to as quasi-TEM waveguides, or hard waveguides. These can give waveguide cross-section dimensions smaller than a half wavelength and this is advantageous in interlaced multi-frequency arrays. This application is studied in the paper by Ng *et al.* by using a dielectric loaded waveguide as an example. Miniaturized waveguides for such application can also be realized by periodic loading of the interior of the waveguide, as studied in both the experimental paper by Hrabar *et al.* and the theoretical paper by Kshetrimayum *et al.*. Hard surfaces have since their invention been considered for use in horn antennas. Lier *et al.* show that dielectric horns can be made either soft or hard without a periodic loading of the wall, by making use of the different reflection coefficients of a multilayer dielectric surface for TE and TM case. The paper by Skobelev *et al.* analyzes a hard horn realized by loading the walls with strips short circuited to the ground plane with vias. The analysis is performed by mode matching, and the paper shows that the horn behaves in the same way as a longitudinally corrugated horn except for distances between the vias causing resonances. Hard horns also find application in spatial power combiners, as demonstrated in the paper by Ozkar *et al.* Xin *et al.* load a hard metal-strip surfaces with voltage controlled varactor diodes, thus realizing waveguide phase shifter for use in a waveguide lens antenna.

The last group of nine papers covers different types of single element antennas radiating in the presence of artificial surfaces. In the first four papers, the objective is to reduce, by means of EBG, AMC, or soft ground plane, sidelobes induced by the finite size of the ground plane. These papers describe: volumetric AMC realizations of low-profile dipole antennas (Erentok *et al.*), EBG surfaces for curl antennas (Baracco *et al.*), and slot-ring antennas (Elek *et al.*), comparing corrugated soft surfaces and EBG surfaces for helical and spiral antennas (Nakano *et al.*), and soft strip-surfaces for patch antennas (DeJean *et al.*). A second subgroup of papers uses the artificial surfaces as 'lenses' above the radiating element to increase the gain. Very high improvement of gain is obtained for a patch placed on an AMC when superimposing an FSS (Feresis *et al.*), as well as for a single element (a patch or a slot pair) placed under a woodpile-type EBG (Weily *et al.*) or a crossing-rods type EBG (Lee *et al.*). This set of papers concludes with a contribution from Sievenpiper on a leaky wave antenna with electronic control of the beam direction, which is constituted by large bandwidth elements placed over an electronically tunable mushroom surface.

IV. The Future

Although the papers describe many applications of special surfaces, more are expected to be discovered in the future. The categorization in Table I should help to envisage new technical solutions. The investigation of new applications is somewhat restricted by the computational effort required in both modeling the details of the surface and its large structure in a system that may be curved or truncated. Therefore, it would be useful to have available commercial computer codes with the ability to analyze the ideal canonical surfaces defined in Table I when they occur in large and arbitrary shaped geometries. Then the computational effort would not be larger than analyzing a PEC of the same size. Such an analysis could result in documented new applications of the ideal canonical surfaces, and these could become goals for working with different realizations of the surfaces. Most computer codes today can handle PMCs as infinite planes, but we need also to analyze finite and curved PMCs as well as the other canonical surfaces. We hope this will be possible in the near future, so that it can open up more research in this area.

Finally, homogenization techniques should be developed further and also implemented in computer codes, to speed up accurate surface analysis in real applications with arbitrary shaped surfaces.

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We are grateful to the IEEE Transactions on Antennas and Propagation Editorial Board for accepting our proposal for this Special Issue, and we are glad for the many received contributions. We thank the reviewers for their important help, particularly during some hectic weeks in August and September 2004 when manuscripts were re-revised, reviewed, and selected. Most of all, we thank the authors of the papers who have done a magnificent job in completing the necessary research, writing the papers and revising them in a short time scale. Finally, we are grateful to the Editor-in-Chief, Dr. T. S. Bird, for his help with this Guest Editorial.

We hope that you, the reader, enjoy this Special Issue and find it helps with your future research.

Per-Simon Kildal (M'82–SM'84–F'95) was born in Molde, Norway, on July 4, 1951. He received the M.S.E.E., Ph.D., and Doctor Technicae degrees from the Norwegian Institute of Technology (NTH), Trondheim, Norway, in 1976, 1982, and 1990, respectively.

From 1979 to 1989, he was with the Electronics Research Laboratory (ELAB), NTH, and The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF). Since 1989, he has been a Professor at Chalmers University of Technology, Gothenburg, Sweden, where he has educated 11 antenna doctors. He has done the electrical design and analysis of two very large antennas. The first was the 120-m long and 40-m wide cylindrical parabolic reflector antenna of the European Incoherent Scatter Scientific Association (EISCAT), located in North Norway. The second was the Gregorian dual-reflector feed of the 300-m diameter radio telescope in Arecibo, on a contract for Cornell University. He is presently involved in the design of feeds for the U.S. proposal of the Square Kilometer Array (SKA). He holds many granted patents and patents pending, and based on these he has founded three companies: COMHAT AB which (since 2002 is COMHAT-Provexa AB) (www.comhat-provexa.com), Bluetest AB (www.bluetest.se) and Kildal Antenna Consulting AB (www.kildal.se). He has authored or coauthored more than 167 papers in IEEE or IEE journals and conferences, concerning antenna theory, analysis, design and measurement. He gives short courses and organizes special sessions at conferences, and he has given invited lectures in plenary sessions at four conferences. His textbook *Foundations of Antennas—A Unified Approach* (Lund, Sweden: Studentlitteratur, 2000) has been warmly received.

Prof. Kildal received an award from ELAB in connection with an industrial project where the results of his reflector antenna research were applied in 1984. He received the R.W.P. King Award for the Best Paper by a Young Author in the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 1984. He also received the S.A. Schelkunoff Transactions Prize Paper Award in 1990 from the same IEEE TRANSACTIONS. From 1995 to 1998, he served as an Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.

Ahmed A. Kishk (S'84–M'86–SM'90–F'98) received the B.S. degree in electrical engineering from Cairo University, Cairo, Egypt, in 1977, the B.S. degree in applied mathematics from Ain Shams University, Cairo, in 1980, and the M.Eng. and Ph.D. degrees from the Department of Electrical Engineering, University of Manitoba, Winnipeg, MB, Canada, in 1983 and 1986, respectively.

From 1977 to 1981, he was a Research Assistant and Instructor at the Faculty of Engineering, Cairo University. From 1981 to 1985, he was a Research Assistant at the Department of Electrical Engineering, University of Manitoba. From December 1985 to August 1986, he was a Research Associate Fellow at the same department. In 1986, he joined the Department of Electrical Engineering, University of Mississippi, University, as an Assistant Professor. He was on sabbatical leave at Chalmers University of Technology, Gothenburg, Sweden, during the 1994–1995 academic year. He has been a Professor at the University of Mississippi since 1995 and was Chair of the Physics and Engineering Division of the Mississippi Academy of Science from 2001 to 2002. He was a co-editor of the Special Issue on "Advances in the Application of the Method of Moments to Electromagnetic Scattering Problems" in *Applied and Computational Electromagnetics Society Journal*. He was Editor-in-Chief of the same journal from 1998 to 2001. He is a coauthor of *Microwave Horns and Feeds* (London, U.K., Institution of Electrical Engineering, 1994; New York: IEEE, 1994) and a coauthor of chapter 2 of *Handbook of Microstrip Antennas* (London, U.K.: Peter Peregrinus, 1989). He has published over 118 refereed journal articles and book chapters. His research interest includes the areas of design of millimeter frequency antennas, feeds for parabolic reflectors, dielectric resonator antennas, microstrip antennas, soft and hard surfaces, phased array antennas, and computer aided design for antennas.

Dr. Kishk is a Member of Sigma Xi, the Phi Kappa Phi Society, the U.S. National Committee of International Union of Radio Science (URSI) Commission B, the Applied Computational Electromagnetics Society, the Electromagnetic Academy, the IEEE Antennas and Propagation Society, and Microwave Theory and Techniques Society. He was an Associate Editor of the *IEEE Antennas and Propagation Magazine* from 1990 to 1993 and is now an Editor. He received the 1995 Outstanding Paper Award from the *Applied Computational Electromagnetic Society Journal*, the 1997 Outstanding Engineering Educator Award from the Memphis section of the IEEE, the Outstanding Engineering Faculty Member in 1998, the Award of Distinguished Technical Communication from IEEE ANTENNAS AND PROPAGATION MAGAZINE in 2001, the 2001 Faculty Research Award for outstanding performance in research, and the 2004 Microwave Prize.

Stefano Maci (M'92–SM'99–F'04) was born in Rome, Italy, in 1961. He received the Laurea degree (*cum laude*) in electronic engineering from the University of Florence, Florence, Italy, in 1987.

From 1990 to 1998, he was with the Department of Electronic Engineering, University of Florence, as an Assistant Professor. Since 1998, he has been an Associate Professor at the University of Siena, Siena, Italy. He was a co-author of an incremental theory of diffraction, for the description of a wide class of electromagnetic scattering phenomena at high frequency, and of a diffraction theory for the high-frequency and hybrid analysis of large truncated periodic structures. He has been and presently is responsible for several research contracts and projects supported by the European Union, by the European Space Agency (ESA-ESTEC, Noordwijk, The Netherlands), and by various industry and research centers. In the sixth EU framework program, he is responsible of the European School of Antennas in the Antenna Center of Excellence. He is principal author or co-author of about 40 papers in IEEE journals, 40 papers in other international journals, and more than 200 papers in proceedings of international conferences. His research interests include electromagnetic engineering, mainly concerned with high-frequency and numerical methods for antennas and scattering problems.

Prof. Maci is a Member of the Technical Advisory Board of the International Scientific Radio Union (URSI) Commission B, and the Advisory Board of the Italian Ph.D. school of Electromagnetism. In 2004, he won the national competition for Full Professor. He was an Associate Editor of IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY. He organized and/or served as a Chairman for several special sessions at international conferences and has been Chairman of two international workshops.