EM MODELING OF SURFACES WITH STOP OR GO CHARACTERISTICS – ARTIFICIAL MAGNETIC CONDUCTORS AND SOFT AND HARD SURFACES

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Abstract:
We discuss and demonstrate by measurements and computations the relation between electromagnetic bandgap surfaces (EBG) used to realize artificial magnetic conductors and the so-called soft and hard surfaces in electromagnetics, with respect to their STOP and GO characteristics for surface waves. We show how the main characteristics of such surfaces can be modeled by using ideal surfaces representing perfect magnetic conductors (PMC) and PEC/PMC strip grids. Unfortunately, commercial codes do not allow such modeling for general shapes of the surfaces.

1. Introduction to EBGs, AMCs and soft and hard surfaces

In the last few years, there has been much research on using periodic structures to make new materials for application in the design of antennas and microwave components. Such materials are most often referred to as photonic bandgap structures (PBG), electromagnetic bandgap structures (EBG), or electromagnetic crystals. In some of this work, the main concern is the surface characteristics of the periodic structures, in the sense that the goal is to obtain a high surface impedance [1], or to remove surface waves from a dielectric substrate. This latter characteristic is herein referred to as a STOP-characteristic. A high impedance surface represents an artificial magnetic conductor (AMC). AMCs have the characteristic that electric current sources such as dipoles can be located at the surface and still radiate well. Thereby very low profile antennas can be realized [2]. Other applications of AMCs are to realize waveguides that can support TEM waves [3], which in this paper is referred to as a GO-characteristic. Actually, the waves should be regarded as quasi-TEM waves, as they only appear at the frequency where the surface impedance is infinite.

A classical relative to the above-mentioned surfaces is the transversely corrugated surface. These types of surfaces were originally been used as chokes to reduce coupling, see e.g. the recent papers [4] and [5], and in corrugated horn antennas that have found so many applications in large reflector antennas. In 1987 the relation between the corrugated surfaces and the so-called soft and hard surface described in diffraction theory and acoustics was discovered (in acoustics the soft and hard surfaces are actually soft and hard to touch). In terms of the boundary conditions of the fields, an edge in a transversely corrugated surface should be analyzed as an edge in a soft surface by using the soft diffraction coefficient, both in E-plane and H-plane (STOP-characteristics in both planes). In comparison, for a normal smooth conductor the edge is soft in H-plane and hard in E-plane. This fact was used to define soft and hard surfaces in electromagnetics [6]-[7] in terms of surface impedances and the boundary conditions in E- and H- planes. In short, the soft and hard surfaces are anisotropic. The soft surface behaves like a perfect electric conductor (PEC) in H-plane and as a perfect magnetic conductor (PMC) in E-plane, and visa versa for the hard surface, see Figure 1. The preferred illustration of an ideal soft-hard surface today is a PEC/PMC strip grid with zero strip period, or in other words, a surface with electric and magnetic conductivity in one (and the same) direction only, see Figure 2a. Note that the surfaces in the figure are color-coded with blue meaning PEC and gold meaning PMC. The PEC/PMC strip grid represents a hard surface when the strips are oriented in the same direction as the wave propagates (longitudinal strips), and a soft surface when they are oriented orthogonal to this direction (transverse strips). The concept of soft and hard surfaces has later been generalized to arbitrary orthogonal PEC/PMC anisotropy [8]-[9], but this will not be treated here.

Surface Name		Polarization	
new	classical	VER	HOR
	PEC	GO	STOP
AMC PBG EBG EMXtal	PMC	STOP	GO
	Soft	STOP	STOP
	Hard	GO	GO

GO surfaces: Enhances propagation of waves along.
STOP surface: Stops propagation of waves along.
PEC = Perfect Electric Conductor
PMC = Perfect Magnetic Conductor
AMC = Artificial Magnetic Conductor
PBG = Photonic Bandgap Material
EBG = Electromagnetic Bandgap Material
EMXtals = Electromagnetic Crystals.

Figure 1. Characteristics of different types of surfaces with respect to propagation of surface waves for different polarizations (top), and explanation of abbreviations (bottom). Note that we here use the term surface waves in an extended sense, so that they even include grazing waves along a PEC surface (behaving like guided surface waves at cut-off).

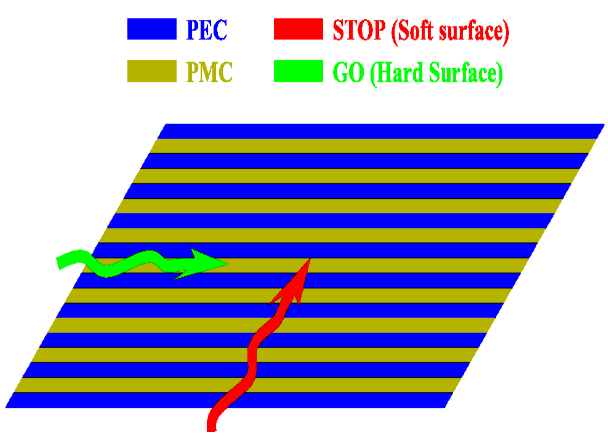

Figure 2a. PEC/PMC strip representations of ideal soft and hard surfaces. The red and green wave-shaped arrows represent the direction of propagation of the waves that makes the PEC/PMC strip surface soft and hard, respectively.

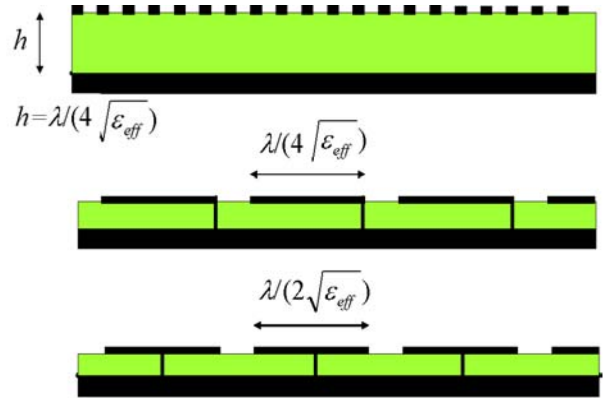

Figure 2b. Three modern realizations in terms of metal strips on grounded dielectric substrates. The upper case consists of close and narrow metal strips, in which case the thickness of the dielectric layer determines the frequency at which the surface is soft or hard. The lower case consists of wide metal strips, in which case the strip width determines the soft/hard frequency. The performance is considerably improved if the strip is grounded with metal posts or vias, as shown. In the middle case the metal posts or vias are located along one edge of the strips, in order to reduce the width to half. The effective permittivity in the formula is for the transverse strips (soft case) given by $\varepsilon_{eff} = \varepsilon_r$ for the lower two geometries. For the hard case and the upper soft case they are given by $\varepsilon_{eff} = \varepsilon_r - 1$.

2. EBG realizations of soft and hard surfaces

The original realizations of the soft and hard surfaces, which were initially proposed and studied, were transverse corrugations (soft), dielectric-filled longitudinal corrugations (hard), and dielectric substrates with transverse (soft) or longitudinal (hard) metal strips. These realizations give a thick surface compared to common EBGs, because the thickness $h = \lambda / 4\sqrt{\varepsilon_{eff}}$, where ε_{eff} is defined in the caption of Figure 2b. However, new and much thinner EBG-inspired realizations are readily available as shown in Figure 3, even if the detailed performance has not yet been investigated. The AMCs work also without metal posts , but the performance is reduced. In the same way the strip-loaded soft and hard surfaces work without metal posts or vias, but the performance is much better with them. The strip-loaded soft and hard surfaces suffer from severe problems with strip modes that are effectively killed with close metal connections to the ground such as posts or vias.

3. Applications of STOP Surfaces

An important application of EBGs and AMCs today is to reduce the sidelobes in E-plane (STOP-characteristic) for aperture [12] and microstrip antennas [11]. The principle of operation is readily explained in terms of the table in Figure 1. From this table it is also clear that a soft surface will provide sidelobe reduction (STOP-characteristic) of antennas in any plane and for any polarization, such as the cases treated in [13]. Different realizations of soft surfaces for sidelobe reduction are studied in [14]. Recent papers also propose metal strips in combination with an AMC (making it a soft surface) to reduce coupling [15].

4. Application of GO surfaces (quasi-TEM waveguide and hard horn)

Another application of AMCs and EBGs is, as already mentioned, TEM waveguides [3]. By using a PMC on the E-plane walls, a rectangular waveguide can support a TEM wave. Actually, if all the waveguide walls are made of a hard surface the TEM performance is better, because a TEM wave of any polarization can propagate in such a hard waveguide of arbitrary cross section. This was described already in the original papers on soft and hard surfaces. The first simulation of the field solution in a hard quasi-TEM waveguide was done by a FDTD code in [16]. The simulations were done both for realizations in terms of corrugations and strips, and the latter case included also a study of an homogenized asymptotic model for the strip grid [17]. Two simulated cases are shown in Figure 2. We see the uniform field distribution over the cross section and evanescent fringe fields around the strips (Figure 2a). In practice, the TEM waves of these ideal guides can only be present at the center frequency where the surfaces have close to ideal performance. Still, their bandwidth is sufficient to be attractive for use in cluster-fed multi-beam antennas for Ka band multimedia satellites. They are also studied at several places for use in quasi-optical grid amplifiers in the millimeter wave region (see e.g. [21]). Some attempts to realize hard horns with uniform aperture distribution were made more than 10 years ago, but at that time the numerical techniques were not developed sufficiently to control of the performance. Today, it is possible to analyze hard horns very accurately with commercial software based on FEM or FDTD approaches. The horns can be analyzed more time-efficiently by the special mode matching technique used in [22]-[23]. This makes use of asymptotic strip and corrugation boundary conditions [17] to simplify the analytical modal expansion in each cylindrical section (see Figure 4).

Hard surfaces can also be used to let waves GO past or through obstructions without generating blockage [24], and to let them GO along a metal cylinder [25].

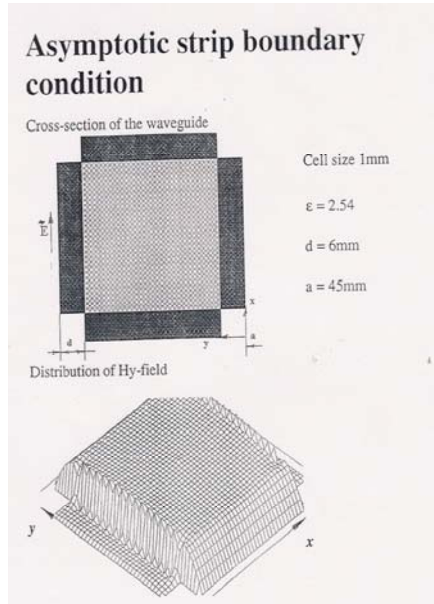

Figure 3a. Geometry (upper) and computed H-field distribution (lower) in dual-polarized quasi-TEM hard waveguide realized by strip-loaded dielectric substrate. This case has been computed by using the asymptotic strip boundary condition [17].

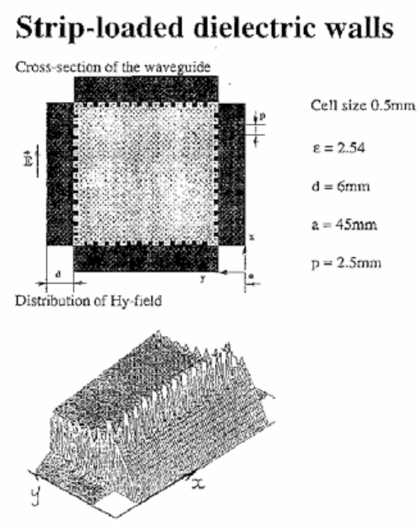

Figure 3b. Geometry (upper) and computed H-field distribution (lower) in dual-polarized quasi-TEM hard waveguide realized by modeling each metal strip of finite thickness. The computations have been done by FDTD as explained in [16].

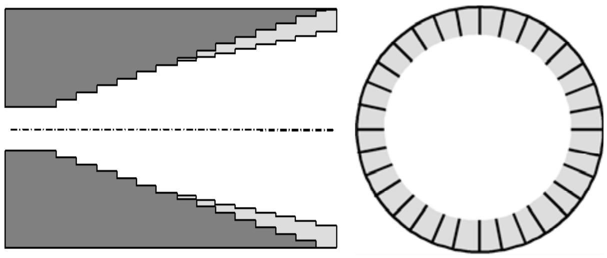

Figure 4. Hard horn geometry approximated as cascaded sections of cylindrical corrugated sections, for analysis by mode matching and generalized scattering matrices [23]. The fields in each corrugated cylindrical section is expanded in modes by making use of the asymptotic corrugation boundary condition [17]. A similar mode matching approach has been developed for strip-loaded hard horns.

5. About EM modelling of complex surfaces

The needs for future research on EM modelling in connection with AMCs and soft and hard surfaces can be divided in four categories:

A. Studies based on ideal surface models.
Existing literature does not contain any theoretical studies of characteristics of ideal PMCs or soft and hard surfaces, such as e.g. waveguide solutions and Green's functions. This would be desirable in order to foresee possible applications. Some Green's functions are available in [26] focusing mainly on studies of surface waves. Commercial codes can often model infinite plane PMCs, but finite PMCs and PEC/PMC strip models are not included. Sometimes the latter can be modelled approximately by locating PEC strips on an infinite AMC surface.

B. Studies based on homogenized boundary cond.
The major performance of a surface in different applications can most effectively be found if the periodicity of the surface can be removed by homogenization of the boundary condition. The asymptotic strip and corrugation boundary conditions in [17] are examples of homogenized boundary conditions. They have already been used in [16], [18]-[20], [23] and [26]. The homogenized strip and corrugation boundary conditions can also be used to derive analytical solutions of realized soft and hard waveguides, such as the circular strip-loaded guide in [27]. They have been used in FEM software [28], and they have been implemented in algorithms and software based on plane wave, cylindrical mode and spherical mode analysis of, respectively, planar, circular cylindrical and spherical multilayer structures [29]. They have also been implemented in software based on the moment method for cylindrical structures of arbitrary cross section, such as e.g. [30]. Commercial codes can normally not make use of homogenized boundary conditions. The impedance boundary condition is also a homogenized boundary condition that is applied to such surfaces [31]. However, it is not very convenient when modelling soft and hard surfaces because it will vary with angle of incidence. The asymptotic boundary conditions are much more accurate.

C. Studies based on exact modeling.
The exact modeling of the surfaces in all details is always desirable, but it can rarely be done due to the computational effort involved. The segment size often becomes too small to accurately model periodicity and thereby the computation time and memory becomes larger than for smooth surfaces.

D. Ray techniques.
The computational effort with FEM, FDTD and moment method for large structures can be reduced by using ray techniques. These will not be mentioned here, except referring to one of the papers in this area [32].

6. Experimental illustration of relation between AMC-type EBGs and soft and hard surfaces

In this section, we will illustrate the relation between AMCs and soft and hard surfaces by taking an AMC and transforming it to a soft/hard surface by using metal tape in the form of narrow strips, see Figure 5. The EBG surface was obtained from Ericsson AB. Some previous work on it was presented in [33]. It consists of two patch layers of Sievenpiper mushroom type [1] for 900 MHz applications. All the patches on both layers are connected to the metal ground plane by metal posts. We choose to measure coupling for both horizontal (HOR) and vertical (VER) polarizations between two quarterwave vertical monopoles and two horizontal parallel halfwave dipoles, respectively. The results in Figures 5c and 5d show the coupling after we have corrected for the mismatch of the two antennas by using the following formula:

$$C_{net} = 10\log\left\{\frac{|S_{21}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2)}\right\} \qquad (1)$$

The formula represents the coupling that would be measured if we match both antennas and neglect multiple interactions between them (i.e. coupling to the

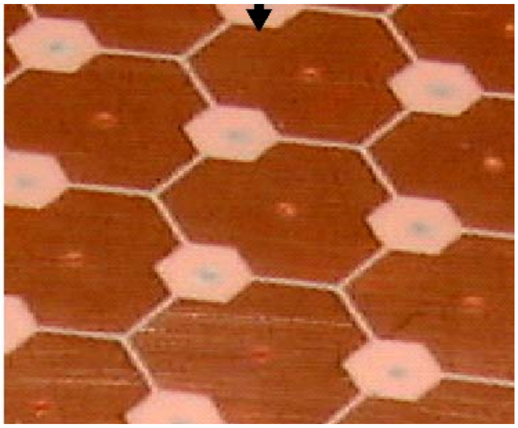

Figure 5a. Photo of the dual-layer mushroom-type AMC of Sievenpiper type.

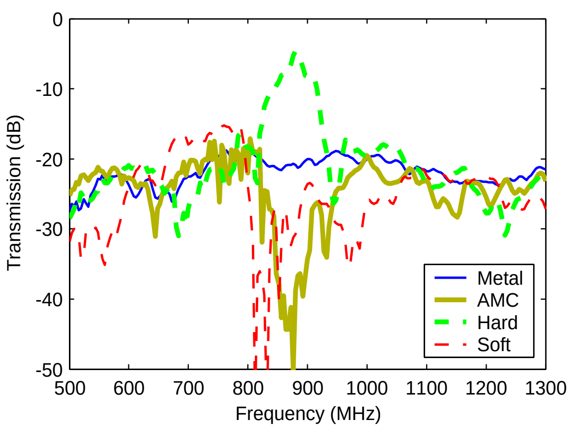

Figure 5c. Measured net transmissions between two vertical quarterwave monopoles on 4 different surfaces: The metal plate, the original AMC, the strip-loaded hard AMC (shown in Figure 5b), and the strip-loaded soft AMC.

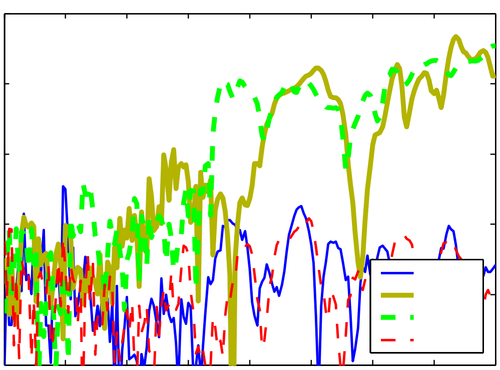

Figure 5d. Measured net transmission between two horizontal halfwave dipoles located 9mm above the 4 different surfaces.

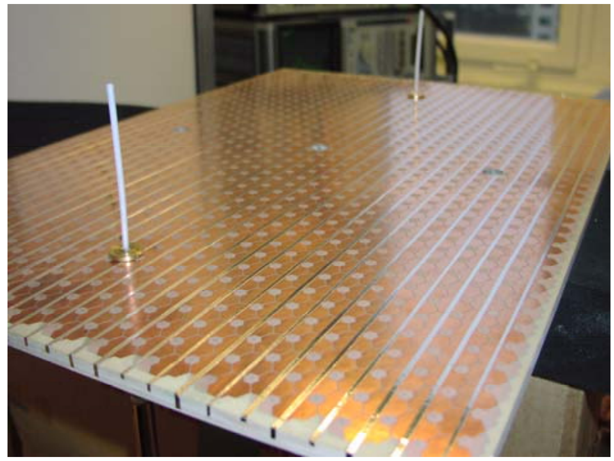

Figure 5b. Two monopoles on the dual-layer mushroom-type AMC in Figure 5a that has been transformed to a hard surface by providing it with longitudinal metal strips made from Aluminum tape. If the strips are taped to the surface in the opposite transverse direction, the surface becomes soft.

neighboring dipole and back again). This is satisfied if the distance between them is sufficiently large. We refer to (1) as the net coupling. The two antennas were mounted at a fixed distance, and four different cases were measured: metal ground plane of same size as the EBG (corresponding to a PEC), the original EBG surface working as an AMC, the EBG with longitudinal metal strips on it (corresponding to a hard surface, see Figure 5b), and the EBG with transverse metal strips on it (corresponding to a soft surface). The measured results show that both the AMC and the soft surface have a clear bandgap (i.e. STOP band) for VER polarization. For HOR polarization, there is a STOP band below 900 MHz, but a GO band above. Thus, the EBG surface acts as an AMC around 900 MHz for VER polarization, and it transforms gradually into STOP one at that frequency for HOR polarization. The PEC STOPs the waves for HOR polarization and lets them GO for VER polarization. The soft surface effectively stops the waves for both VER and HOR polarization, whereas the hard surface lets them GO. The STOP characteristics of the soft surface are not as good for VER polarization as for the AMC case, but this may be better if actual anisotropic soft EBGs of the kind shown in Figure 2b are realized. It seems to be possible to use the original EBG as a STOP surface for both HOR and VER polarization slightly below 900 MHz, due to some frequency shift between the AMC performances for the two polarizations. The GO characteristics of the hard surface are very clearly present for both polarizations.

7. Numerical results for ideal surfaces (PEC, PMC, soft and hard surfaces)

We have also computed the net coupling between VER monopoles and HOR dipoles located on the different corresponding ideal surfaces. For this we have used three different moment method codes, one commercial code WIPL-D [34] and two in-house codes. The latter are WireMoM [35] and G2DMULT [30].

1. The commercial code models the actual finite metal surfaces as an ideal PEC, and the currents on both the ground plane and the wires are solved for using the entire domain basis functions. The PMC modeling assumes an infinite ground plane. Soft and hard surfaces were modeled by locating metal strips on the PMC.

2. The WireMoM program calculates the current distribution on any wire antenna by using subsectional basis functions. The PEC and PMC ground planes are included by imaging.

3. G2DMULT uses a spectrum of two-dimensional solutions solved by the moment method to determine the coupling between antennas with a given cosine-shaped current distribution. It can handle all kind of ground planes: PEC, PMC, soft and hard. The finite widths of the different ground planes are included, which are assumed infinitely long.

The measured and computed results are shown in the Tables 1 and 2. Some values are missing in the tables because the codes could not be used, or the results were unreasonable. In particular, it was difficult to calculate horizontal dipoles located close to a PEC and a soft surface, and vertical monopoles on a PMC. The reasons are that the PEC and soft surface short-circuits HOR electric currents and make their impedances close to zero, and the impedances approach infinity for vertical monopoles on a PMC. The presented computed values correspond well to the measurements although we cannot of course predict the frequency variations due to the actual surfaces with such ideal models, but the major STOP and GO characteristics are well predicted.

8. Conclusion

We have demonstrated the relation between PBG surfaces of AMC-type and the soft and hard surfaces regarding their STOP and GO characteristics with respect to surface waves. We have also shown that there is a large need for being able to model finite and arbitrarily shaped ideal PMCs and soft and hard surfaces by commercial codes, but first the numerical techniques must be further developed to enable such code extensions.

Table 1. Measured net coupling levels in dB between wire antennas on different surfaces (ground planes) for an antenna spacing of 1.26λ in a frequency band of about 50 MHz around 900 MHz. VER means vertical, HOR means horizontal, h is height over ground. The STOP cases with low coupling are marked with bold. (Soft and hard are made by strips on AMC).

	VER monopoles	HOR dipoles	HOR dipoles
	E-plane	H-plane, h=0	H-plane, h=λ/4
Metal	-21	**-28 to -40**	**-22 to -35**
AMC	**-43 to -26**	-30 to -10	-20 to -11
Soft	**-32 to -23**	**-32 to -45**	**-22 to -35**
Hard	-5 to -14	-10 to -17	-11 to -15

Table 2. Computed net coupling levels in dB between wire antennas on different infinite ideal surfaces for an antenna spacing of 1.26λ at 900 MHz. The different results are obtained by using different codes based on the moment method. VER means vertical, HOR means horizontal, h is the height over ground and x represents missing data. The STOP cases with low coupling are marked with bold. (Soft and hard are made by PEC/PMC strips).

	VER monopoles	HOR dipoles	HOR dipoles
	E-plane	H-plane, h=0	H-plane, h=λ/4
PEC	-22, -20	**X, -30,X**	**-26, -26, -26**
PMC	**X, -30**	-20, -20, -21	-14, -13, -14
Soft	**-29, X**	**X, -30, X**	**-26, -23, X**
Hard	-10,**X**	-10,**X, X**	-13, **X**, **X**
Codes Used	G2DMULT, Wire Mom	G2DMULT, WIPL-D, Wire Mom	G2DMULT, WIPL-D, Wire Mom

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He was with ELAB (the Electronics Research laboratory) at NTH from 1979 to 1989, as a principal research scientist from 1986. He is now a Professor at the Department of Microwave Technology at Chalmers University of Technology, Gothenburg, Sweden. He was since 1984 a consultant for Cornell University, Ithaca, NY, in connection with the upgrading of the radiotelescope in Arecibo, Puerto Rico. He is also consulting for others via his own company Kildal Antenna Consulting AB. This company also develops and markets commercial software for synthesis and analysis of reflector antennas.

Kildal is the principal author of more than 40 scientific articles in international journals, and he has in addition coauthored more than 30. All papers are within the area of antenna theory and design. His speciality is reflector antennas. He has also authored the textbook "Foundations of Antennas – A Unified Approach", Studentlitteratur, April 2000 (www.studentlitteratur.se/antennas).

ELAB awarded his work in 1984, in connection with an industrial project where the results of his reflector antenna research were applied. He received the R.W.P. King Award for the best paper by a young author in IEEE Transaction on Antennas and Propagation in 1984 (about the EISCAT cylindrical reflector antenna). Later he received the S.A. Schelkunoff Transactions Prize Paper Award for the best paper in 1990 in the same IEEE Transactions (about the synthesis of the dual-reflector feed for the Arecibo radio telescope). He has given invited lectures in plenary sessions at four conferences (Antem 92 in Winnepeg, 23rd EuMC 93 in Madrid, MIKON 94 in Polen, JINA 94 in Nice, and AP2000 in Davos).

Kildal has been largely involved in the electrical design of some large antennas. The first was the cylindrical parabolic reflector antenna of the EISCAT Scientific Association. This antenna is located in North Norway and has an aperture that is l20m long and 40m wide. The second is the new Gregorian dual-reflector feed of the Arecibo radio telescope. This telescope has a spherical main reflector of 300m diameter. He has also designed feed horns for a radio telescope with 30m diameter.

Kildal is the inventor of three granted patents, and he has in addition applications that are not yet granted. Two of these designs relate to feeds for paraboloids, which are in production in Scandinavian companies. These are the dipole disk feed with beam-forming ring and the hat feed. The hat feed is also the basis of the new Swedish company COMHAT (www.comhat.se) for manufacturing of reflector antennas for millimeter wave link applications. Kildal has also started the company Bluetest AB (www.bluetest.se) for commercialization of a small reverberation chamber for testing of small antennas and mobile phones.

Kildal served 1991-94 as a Distinguished Lecturer of the IEEE Antennas and Propagation Society. He offered two lectures, on the concept of artificially soft and hard surfaces for electromagnetic waves, and on the techniques for synthesis and analysis of reflector antennas that was developed in connection with the design of the dual-reflector feed for the radiotelescope in Arecibo.

Ahmed A. Kishk was born in Egypt. He received the BS degree in Electronic and Communication Engineering from Cairo University, Cairo, Egypt, in 1977, and in Applied Mathematics from Ain_Shams University, Cairo, Egypt, in 1980. In 1981 he joined the Department of Electrical Engineering, University of Manitoba, Winnipeg, Canada, where he obtained his M.Eng and PhD degrees in 1983 and 1986, respectively.

From 1977 to 1981, he was a research assistant and an 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 University of Manitoba. In 1986, he joined the Department of Electrical Engineering, University of Mississippi. He is now a Professor at The University of Mississippi (since 1995). He was on sabbatical leave at Chalmers University of Technology during the 1994-1995 academic year. He was an Associate Editor of *Antennas & Propagation Magazine* from 1990 to 1993. He is now an Editor of *Antennas & Propagation Magazine*. He was a Co-editor of the special issue on Advances in the Application of the Method of Moments to Electromagnetic Scattering Problems in the *Applied and Computational Electromagentics Society* Journal. He was an Editor-in-Chief of the same *Journal* from 1998 to 2001.

Dr. Kishk research interest includes the areas: 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. He has published over 110 refereed Journal articles and book chapters. He is a coauthor of the ***Microwave Horns and Feeds*** book (London, UK, IEE, 1994; New York: IEEE, 1994) and a coauthor of chapter 2 on ***Handbook of Microstrip Antennas*** (Peter Peregrinus Limited, United Kingdom, Ed. J. R. James and P. S. Hall, Ch. 2, 1989). Dr. Kishk received the 1995 outstanding paper award for a paper published in the *Applied Computational Electromagnetic Society Journal*. He received the 1997 outstanding engineering educator award from Memphis section of the IEEE. He received the Outstanding Engineering Faculty Member of the 1998. He received the Award of Distinguished Technical Communication for the entry of IEEE Antennas and Propagation Magazine, 2001. He also received the 2001 Faculty Rsearch Award for Outstanding Performance in Research. Dr. Kishk is a ***Fellow*** member of IEEE (Antennas and Propagation Society and Microwave Theory and Techniques), a member of Sigma Xi society, a member of the U.S. National Committee of International Union of Radio Science (URSI) Commission B, a member of the Applied Computational Electromagnetics Society, a member of the Electromagnetic Academy, Chair of Physics and Engineering division of the Mississippi Academy of Science (2001-2002), and a member of Phi Kappa Phi Society.