



## **Metasurfing since 1987 - A personal story involving soft and hard surfaces, EBG surfaces, cloaking, gap waveguides and mass production**

Downloaded from: <https://research.chalmers.se>, 2020-09-29 21:52 UTC

Citation for the original published paper (version of record):

Kildal, P. (2014)

Metasurfing since 1987 - A personal story involving soft and hard surfaces, EBG surfaces, cloaking, gap waveguides and mass production

IEEE Antennas and Propagation Society, AP-S International Symposium (Digest): 529-530

<http://dx.doi.org/10.1109/APS.2014.6904596>

N.B. When citing this work, cite the original published paper.

# Metasurfing Since 1987 – A Personal Story Involving Soft and Hard Surfaces, EBG Surfaces, Cloaking, Gap Waveguides and Mass Production

Per-Simon Kildal

Department of Signals and Systems, Chalmers University of Technology (Chalmers)  
41296 Gothenburg, SWEDEN. per-simon.kildal@chalmers.se

**Abstract—** This paper will describe my personal experiences with what today is referred to as metamaterials, and in particular in my case metasurfaces. My journey starts with the introduction of a concept of soft and hard surfaces in 1988, being a generalization of the corrugated surface, and today most conveniently represented by canonical PEC/PMC strip grids. The first industrial application of the soft surface was the patent-protected hat feed in 1987. This has until now been manufactured in more than 940 000 copies mainly for Ericsson’s successful MINILINK product. The anisotropic soft surface is a forerunner of the isotropic EBG surface appearing around year 2000, and the hard surface was used for cloaking 10 years before cloaking became a popular research topic in 2007. The concept of soft and hard surfaces has since 2009 developed into a novel gap waveguide technology. The gap waveguide technology is used to package microstrip and CPW circuits, but also to replace them. The gap waveguides can have similar low-loss performance as solid rectangular waveguides, but they can be realized in a much simpler way in particular at millimeter- and submillimeterwave frequencies. Good performance has been demonstrated for filters, transitions, MMIC packaging, corporate distribution networks, and slot and horn array antennas. The first commercial applications can come soon, probably at 60 GHz.

## I. INTRODUCTION

We call them metamaterials today; these natural materials that are just periodic on microscopic level, whereas they on macroscopic level have electromagnetic material characteristics that cannot be found in nature. We knew them 30 years ago also, mainly in the form of artificial dielectrics, and they were used in practical antenna designs to achieve permittivity that was not available by natural dielectrics, or to realize materials with smaller weight than natural materials and having similar permittivity. Today metamaterials are also used to realize fascinating characteristics that cannot be found for in nature, and they are proposed for a lot of different applications. Unfortunately many claims are unrealistic because the artificial characteristics in most case are extremely narrowband, and the losses are high, or they are simply not documented in a reliable way. The present paper deals with the metasurface concept known as soft and hard surfaces that has been used to design practically useful since 1987, and that also has resulted in mass-produced antennas. The concept itself has first of all been useful as a simplification, to improve creativity; to see solutions that otherwise could not so easily be seen. This paper will summarize this story including the main references.

## II. CONCEPT OF SOFT AND HARD SURFACES

The soft and hard surfaces were defined in 1987 [1] and described more thoroughly in 1990. The soft and hard surfaces terms are taken from acoustics, and were already used in electromagnetics (EM) as names for the two boundary conditions (BC) appearing in H-plane (soft case) and E-plane (hard case) in diffraction theory. The soft surface has accordingly a polarization-independent soft boundary condition. This was initially only associated with transversely corrugates as used in corrugated horn antennas, which were very popular in the 1980s. The hard surface was new and was foreseen as longitudinal corrugations, but these had to be filled with dielectrics in contrast to the soft surface that could be realized with air-filled corrugations. The soft surface texture was used to stop waves from propagating along the surface, similar to EBG surfaces. The hard surface texture was used to enhance propagation of EM waves along the surface, and two applications were foreseen: hard horn antennas, and to make masts and struts invisible to EM waves. The latter is today more commonly known as cloaking.

### A. PEC/PMC strip model, asymptotic BC and EBG surfaces

The EBG surface appeared in the literature around 2000, and this was isotropic, with similar characteristics in all directions along the surface as the soft surface has in one direction. The relation between the soft surface and the EBG surface was sorted out in [2], where also the PEC/PMC strip model of the soft and hard surfaces was introduced. This simplifies the physical understanding, and the general usage of the surfaces in EM computations. The isotropic EBG surface does not have a similar simple model, but some simplifications have been constructed [3]. The PEC/PMC model of the ideal soft and hard surfaces is useful in initial works, but it cannot be used to predict bandwidth. The asymptotic boundary conditions introduced in [4] can predict bandwidth very accurate, in particular for small periods of the surface texture. The published EBG research after year 2000 stimulated the further development of the strip-loaded realization of the soft surface. Erik Lier actually already studied this during the first “soft and hard” years in the late 1980s. It is important to point out that the soft surface generally is much more wideband than the EBG in most applications [5], and also that the anisotropy of the soft surface normally is no problem. This is because in antennas the location of the source is known, and thereby normally also the direction of propagation of the waves.

## B. Hard surface and cloaking

The possibility of making invisible struts was mentioned already in a conference paper in 1988, and the invisibility concept was referred to as superstealth in a paper at a Swedish conference in 1994. The full paper on invisible struts appeared in 1996, but we were not allowed by the editors of the transactions to use the superstealth term in the paper, so the invisible struts were published in 1996 under the more scientific title “reduction of forward scattering by using hard surface” [6]. Thus, this was a paper on cloaking 10 years before the famous paper by Schurig, Pendry et. al. was published. We also demonstrated the invisibility experimentally and even for dual polarization, which has not been done by later approaches. This inspired us to write a paper pointing out this fact [7].

## III. THE MASS-PRODUCED HAT FEED, AND HARD HORNS

The hat feed is a result of the concept of soft and hard surfaces. It is based on a simple theoretical model of slots radiating around soft and hard cylinders and involve also a reflector (or soft-brimmed hat) at the radiating end [8], but the hard cylinder was abandoned for mechanical simplicity in the first paper [9], and also in the later prototype in [10]. The bandwidth was later improved to 30% [11] by genetic algorithms. The hat feed has till now been mass produced in more than 940 000 copies for use by Ericsson AB in their popular MINI-LINK for microwave backhaul.

The hard horns are left out of this paper due to the space limitations. Erik Lier has published a comprehensive overview [12]. I have also myself co-authored several papers with Sergej Skobelev and others that are available on IEEE Xplore.

## IV. THE VERSATILE PEC/PMC GAP WAVEGUIDES FOR PACKAGED MILLIMETERWAVE ANTENNA SYSTEMS

The gap waveguides were published first time in 2009 [13]. They appear in gaps between metal surfaces, and in three main forms depending on how the waves are guided in the gap [14]: ridge gap waveguide [15], groove gap waveguides [16] and microstrip gap waveguides [17]. The latter appears also in a version with via holes in the strip [18], now referred to as a microstrip-ridge gap waveguide. The waves are prohibited from propagating in other directions inside the gap by means of periodic structures, working ideally as PMC. However, the stopband of the parallel-plate waves in the gap is very different from and much larger than the bandwidth of the PMC itself. Therefore, the dispersion diagrams of the gapwaves are determined by this stopband [19]. The gap waveguide technology is in particular applicable for solving the problem of electronic packaging at millimeterwaves: of passive devices [20], filters [22], RF front-ends and MMICs [23]. Presently, several array antennas with gap waveguide-based distribution networks are being designed for the commercial 60 GHz band. We foresee commercial applications in a few years.

## V. CONCLUSION AND ACKNOWLEDGEMENTS

I am thankful to all who have worked with me to develop these technologies during the years. Unfortunately, it was not possible to include all their papers in this short overview.

## REFERENCES

- [1] P.-S. Kildal, “Definition of artificially soft and hard surfaces for electromagnetic waves”, *Electronic Letters*, Vol. 24, No. 3, pp. 168-170, 4th Feb. 1988.
- [2] P.-S. Kildal, A. A. Kishk, S. Maci, “Special issue on artificial magnetic conductors, soft/hard surfaces, and other complex surfaces”, *IEEE Trans. Antennas Propagat.*, vol. 53, no. 1, pp. 2-7, Jan. 2005.
- [3] P.-S. Kildal, A. Kishk, M. Bosiljevac, Z. Sipus, “The PMC-amended DB boundary - A canonical EBG surface”, *ACES Journal*, Feb. 2011.
- [4] P.-S. Kildal, A. Kishk and Z. Sipus, “Asymptotic Boundary Conditions for strip-loaded and corrugated surfaces”, *Microwave and Optical Technology Letters*, Vol. 14, No. 2, pp. 99-101, Febr., 1997.
- [5] E. Rajo Iglesias, M. Caiazzo, L. Inclan-Sanchez, and P.-S. Kildal, “Comparison of bandgaps of mushroom-type EBG surface and corrugated and strip-type soft surfaces”, *IEEE Microwaves, Antennas and Propagation*, Vol. 1, No. 1, pp. 184-189, Feb. 2007.
- [6] P. S. Kildal, A. A. Kishk, A. Tengs, “Reduction of forward scattering from cylindrical objects using hard surfaces”, *IEEE Trans. Antennas Propagat.*, Vol. AP-44, Issue 11, Nov. 1996, pp. 1509 – 1520.
- [7] P.-S. Kildal, A. Kishk, Z. Sipus, “RF invisibility using metamaterials: Harry Potter's cloak or the Emperor's new clothes?”, *IEEE AP-S 2007 Symposium in Hawaii*, 10-15 June 2007
- [8] T. Ulversoy and P. S. Kildal, “Radiation from slots in artificially soft and hard cylinders,” *IEEE TAP*, vol. 37, pp. 1628-32, 1989.
- [9] P. S. Kildal, “The hat feed: a dual-mode rear-radiating waveguide antenna having low cross polarization,” *IEEE TAP*, vol. AP-35, pp. 1010-16, 1987.
- [10] J. Hansen, A. A. Kishk, P. S. Kildal, and O. Dahlsjo, “High performance reflector hat antenna with very low sidelobes for radio-link applications,” in *IEEE APS 1995*, New York, 1995, pp. 893-6.
- [11] M. Denstedt, T. Ostling, J. Yang, and P. S. Kildal, “Tripling bandwidth of hat feed by genetic algorithm optimization,” in *2007 IEEE APS*, Piscataway, NJ, USA, 2008, pp. 2197-200.
- [12] E. Lier, “Review of Soft and Hard Horn Antennas, Including Metamaterial-Based Hybrid-Mode Horns”, *IEEE Antennas and Propagation Magazine*, Vol. 52, No. 2, pp. 31-39, 2010.
- [13] P. S. Kildal, E. Alfonso, A. Valero-Nogueira, and E. Rajo-Iglesias, “Local metamaterial-based waveguides in gaps between parallel metal plates,” *IEEE AWPL*, vol. 8, pp. 84–87, 2009.
- [14] P. S. Kildal, “Three metamaterial-based gap waveguides between parallel metal plates for mm/submm waves,” in *3rd European Conference on Antennas and Propagation (EuCAP 2009)*, pp. 28–32.
- [15] P. S. Kildal, A. U. Zaman, E. Rajo-Iglesias, E. Alfonso, and A. Valero-Nogueira, “Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression,” *IET Microwaves, Antennas and Propagation*, vol. 5, no. 3, pp. 262–270, 2011.
- [16] A. U. Zaman, A. Kishk, and P.-S. Kildal, “Narrow-band microwave filter using high Q groove gap waveguide resonators without sidewalls”, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 2, No. 11, pp. 1882-1889, November 2012.
- [17] A. Valero-Nogueira, M. Baquero, J. I. Herranz, J. Domenech, E. Alfonso, and A. Vila, “Gap waveguides using a suspended strip on a bed of nails,” *IEEE AWPL*, vol. 10, pp. 1006–1009, 2011.
- [18] E. Pucci, E. Rajo-Iglesias, P.-S. Kildal, “New Microstrip Gap Waveguide on Mushroom-Type EBG for Packaging of Microwave Components”, *IEEE MWCL*, Vol. 22, No. 3, pp. 129-131, March 2012.
- [19] E. Rajo-Iglesias, P.-S. Kildal, “Numerical studies of bandwidth of parallel plate cut-off realized by bed of nails, corrugations and mushroom-type EBG for use in gap waveguides”, *IET Microwaves, Antennas & Propagation*, Vol. 5, No 3, pp. 282-289, March 2011.
- [20] E. Rajo-Iglesias, A. Uz Zaman, P.-S. Kildal, “Parallel plate cavity mode suppression in microstrip circuit packages using a lid of nails”, *IEEE MWCL*, Vol. 20, No. 1, pp. 31-33, Dec. 2009.
- [21] A. Kishk, A. Uz Zaman, P.-S. Kildal, “Numerical Prepackaging with PMC lid - Efficient and Simple Design Procedure for Microstrip Circuits including the Packaging”, *ACES journal*, Vol. 27, No. 5, May 2012.
- [22] A. Algaba Brazález, A. Uz Zaman, P.-S. Kildal, “Improved Microstrip Filters Using PMC Packaging by Lid of Nails”, *IEEE Trans. Components, Packaging and Manufact. Techn.*, Vol. 2, No. 7, July 2012.
- [23] A.U. Zaman, T. Vukusic, M. Alexanderson, P.-S. Kildal, “Gap Waveguide PMC Packaging for Improved Isolation... in High Frequency Microwave Modules”, accepted for *IEEE Trans. Comp., Packaging and Manufact. Techn*, July 2013.