Modal Propagation in Ideal Soft and Hard Waveguides

Giuseppe Ruvio (1), Per-Simon Kildal (2), Stefano Maci (1)

(1), **Dept. of Information Eng., Univ. of Siena, Via Roma 56, 53100, Siena, Italy**
ruviogius@inwind,it, macis@ing.unisi.it
(2), **Chalmers Univ. of Tech., Dept. of Electromagnetics, 41296 Gothenburg, Sweden** simon@kildal,se

1. INTRODUCTION

Recently, a lot of research efforts have been devoted to periodic planar surfaces used to model new equivalent boundary conditions and various engineering applications have accompanied the theoretical studies. In some applications, these surfaces constitute the modern version of transversely corrugated structures, often used to improve the performance of feed-horns. In the early nineties, the so-called “soft” and “hard” surfaces were introduced and their relation with the corrugated surfaces discussed [1] (the terminology is derived from acoustics). The soft surface behaves like a perfectly electric conductor (PEC) in H plane and as a perfectly magnetic conductor (PMC) in the E-plane, and vice versa for the hard surface.

This paper presents an investigation on the modal wave propagation in circular and rectangular waveguides with perfectly soft and hard boundary conditions on the walls [3]. For the case of soft rectangular waveguides, the solution cannot be derived in analytical form, thus requiring a numerical analysis. The knowledge of the field distribution associated to perfectly hard or soft waveguide modes, although a schematization of the reality, may help the design of corrugated horns or quasi-TEM waveguides, and to find new uses of soft and hard surfaces.

2. PEC/PMC STRIP MODEL FOR IDEAL HARD AND SOFT SURFACES

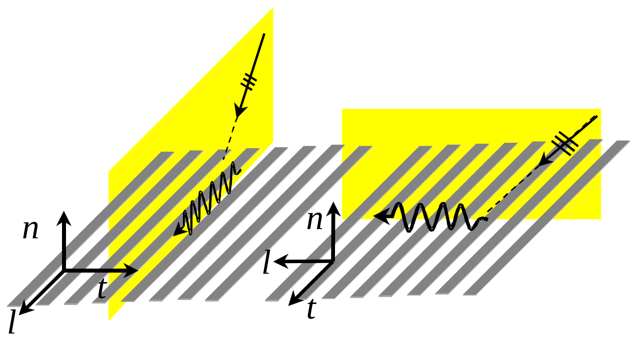


Fig. 1. *PEC/PMC strip-model for Hard (left) and Soft (right) surface*

Let us consider an anisotropic surface impedance defined by $E_t\hat{t} + E_l\hat{l} = Z_t H_l \hat{t} - Z_l H_t \hat{l}$, where Z_t and Z_l are the transverse and longitudinal impedances. Ideal soft (hard) surfaces are characterized by $|Z_l| = \infty$ ($Z_l = 0$) and $Z_t = 0$ ($|Z_t| = \infty$) [1]. The ideal hard surface may be represented by a strip-model constituted by alternation of PEC and PMC strips with vanishing widths, oriented in the longitudinal l-direction of propagation (*strip*-direction, see Fig. 1). The longitudinal PEC strips impose the annulment of E_l, thus satisfying the longitudinal impedance condition

0-7803-7846-6/03/$17.00 ©2003 IEEE

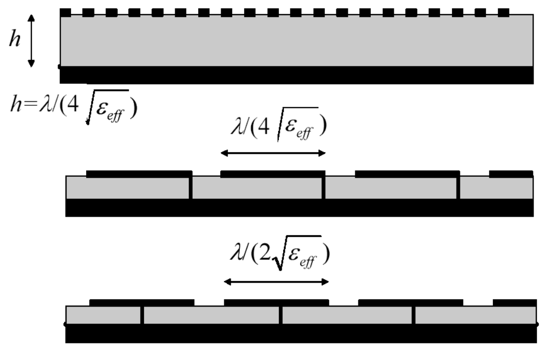


Fig. 2 *Different types of quasi-planar artificial soft or hard surfaces. ε_{eff} stands for ε_r for the soft case and ε_r -1 for the hard case.*

Z_l = 0. Simultaneously, the longitudinal PMC strip annuls H_l, thus fulfilling the transverse impedance condition $|Z_t|$ = ∞. Correspondingly, for modeling the soft surface the strips are oriented along the transverse direction ***t*** (see Fig. 1) thus implying vanishing of transverse components for both electric and magnetic fields. A modern realization of artificially soft and hard surfaces is presented in Fig. 2 [2], where the upper case consists of close and narrow metal strips on a grounded dielectric substrate; for this case the thickness of the slab determines the central operative frequency. The middle and lower cases consists of wide metal strips short-circuited on the ground plane at the edge. This allows to reduce the thickness of the slab, being the operative frequency dictated by the strip width.

Coming back to the ideal PEC/PMC strip model, it is evident that the equivalent currents induced on the surface are always oriented along the strips. This provides a very simple guideline to interpret the physical behavior of hard and soft waveguides. For instance, although the mode in hard and soft waveguides can be derived by the conventional longitudinal potential approach a complete set of modes can be alternatively obtained via radiation in free-space of longitudinally or transversely polarized currents [3].

2. HARD WAVEGUIDES

Consider first a waveguide with hard boundary conditions on the walls (*z* is the axis). Practical realization can be obtained by using the technological solutions shown in Fig. 2. The most important and quite curious feature of this "hard waveguide" is its compatibility with TEM mode propagation. Indeed, independently on the cross-section profile, the boundary conditions impose $E_z|_{\sup} = H_z|_{\sup} = 0$ which are automatically satisfied by a uniform plane wave. Additionally, this property is identically verified for any polarisation of the plane wave, thus leading to an invariance of the TEM mode polarisation when rotating the arbitrarily shaped cross-section. As mentioned before, the other modes can be obtained by using a current model where electric and magnetic currents are directed longitudinally. Examples relevant to rectangular and circular cross-section are shown in Fig. 4. From this

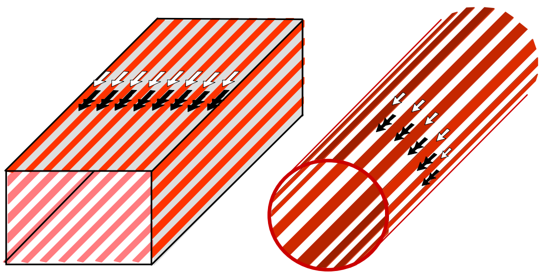


Fig. 3 *Strip line current distribution of hard circular and rectangular waveguides (single and double arrows denotes electric and magnetic currents)*

model, it is evident that we can select independently uncoupled TE and TM mode as associated to the radiation contributions from individual magnetic and electric currents, respectively. By imposing an unknown wave-number for the z-propagation, the various double-indexed TE or TM waveguide modes and the relevant transverse eigenvalues are found by enforcing the hard boundary

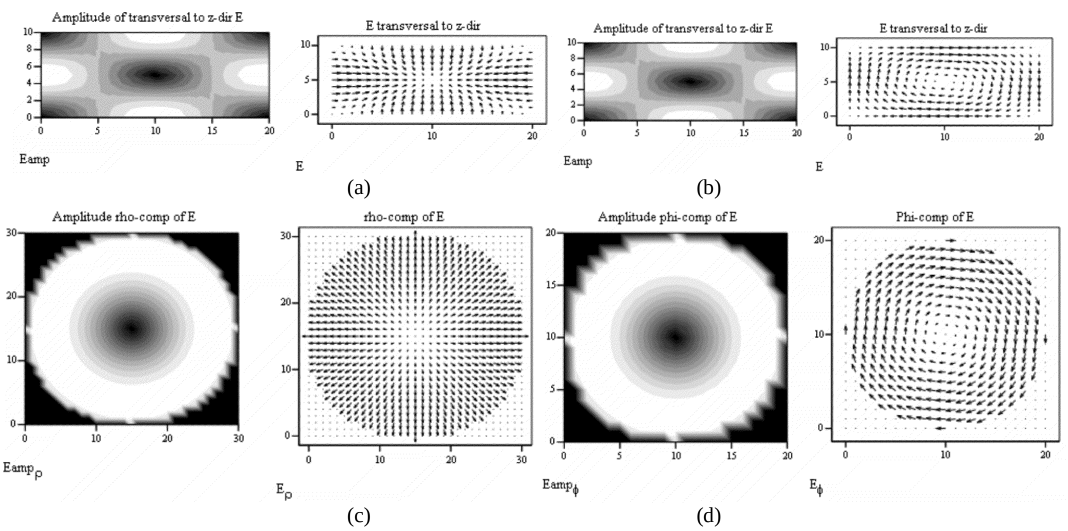
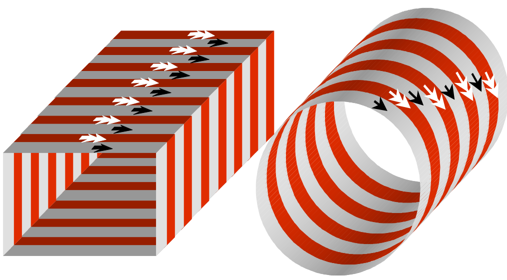


Fig. 4. *Hard rectangular waveguide: (a)* TM_{11} *mode. (b)* TE_{11} *mode. Hard circular waveguide :(c)* TM_{01} *mode. (d)* TE_{01} *mode. A strong distribution of the E- and H-field on the boundary can be observed.*

conditions. This procedure is very simple for rectangular and circular waveguides and leads to closed form expressions of the modes. However, it can be applied for general cross-section by numerically solving the relevant homogeneous integral equation.

3. SOFT WAVEGUIDES

For a rectangular or circular waveguide with perfectly soft condition at the walls, the "soft modes" can be derived by assuming transverse electric and magnetic currents (Fig. 5). The boundary conditions to be satisfied are $E_t|_C = H_t|_C = 0$, where C is the contour of the structure. It is clear from the current orientation that TE and TM modes cannot satisfy independently the boundary conditions, since both the *z*-components of the *E*- and *H*-field must co-exist. This also implies the general difficulties in finding analytical expression of the modes even for simple shapes. However, it can be shown surprisingly that for circular waveguides an analytical hybrid-mode expression does exist (the formulation not showed here is presented in [3] and also known from corrugated waveguides as a balanced hybrid mode). Examples of soft hybrid modes for circular waveguide are shown in Fig. 6.



(a) (b)

Fig. 5. *Strip line current distribution of a soft circular and rectangular waveguide.*

Oppositely, for a soft rectangular waveguide no exact analytical solution is found. The results presented in Fig. 7.a-b, have been obtained by a numerical approach (G2DMULT, [4-5]). Note in particular that the fundamental propagating mode in the soft rectangular waveguide can be approximated very well by the TE_{10}^{z} associated to a rectangular waveguide with vertical PEC walls and horizontal perfectly soft wall (the latter mode possesses an analytical expression). The

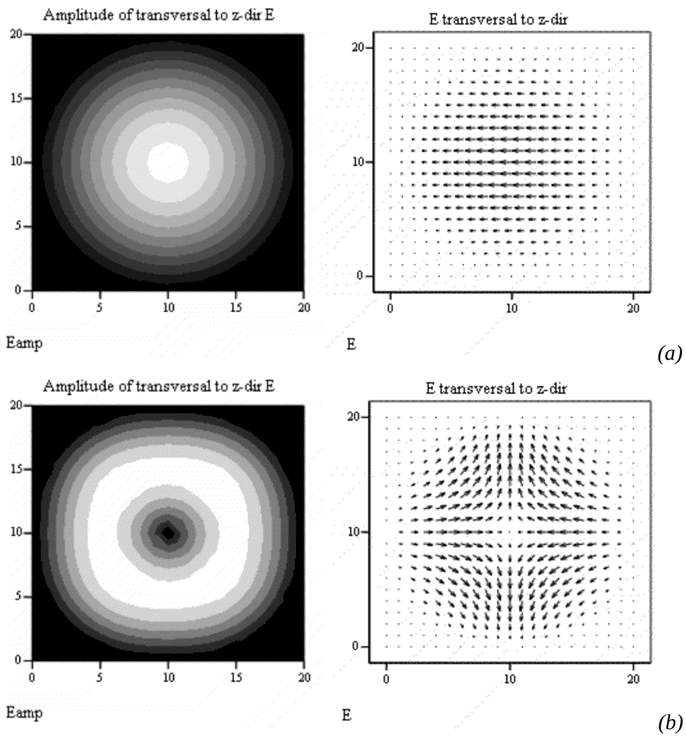


Fig. 6. *Soft circular waveguide: (a)* HEM_{11} *mode (b)* HEM_{21} *mode.*

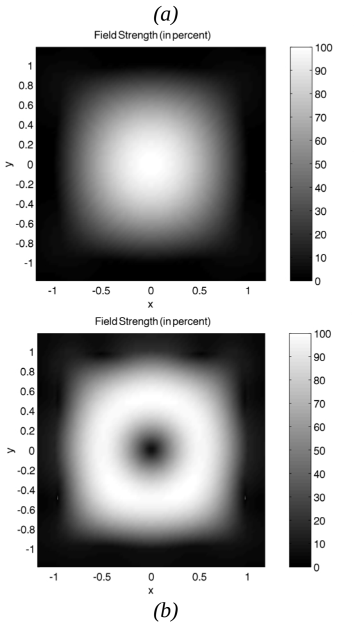


Fig. 7. *Numerical maps for hybrid modes in soft rectangular waveguide:(a) basic mode (b) first higher order mode.*

resemblance is not present for other modes. Then, the modes of the soft rectangular waveguide look more similar to that of the soft circular waveguide.

References

[1] P.-S. Kildal, "Artificially soft and hard surfaces in electromagnetics", IEEE Transactions on Antennas and Propagation, vol. 38, 10, pp. 1537-1544, Oct. 1990.

[2] P-S. Kildal and A. Kishk, “EM Modeling of Surfaces with STOP or GO Characteristics - Artificial Magnetic Conductors and Soft and Hard Surfaces”, invited paper at ACES conference, Monterey, CA, March 24-28, 2003.

[3] G. Ruvio, "Field solutions in soft and hard waveguides", Technical report, Dept. of Electromagnetics, Chalmers University of Technology, Gothenburg, Sweden, Sept. 2002.

[4] P.-S. Kildal, "Description of G2DMULT moment method algorithm for calculating Green’s functions of cylindrical multiconductor structures of arbitrary cross-section", IEEE AP-S Symposium, vol. No. 4, 1999.

[5] Ulf Carlberg, Jian Yang, and Per-Simon Kildal, “Moment method solutions of cylindrical waveguides by searching in a spectrum of two-dimensional solutions”, to be presented at the present IEEE AP-S Symposium, Columbus, June 2003.