Semi-transparent lossy surfaces for cutoff of the fields in microwave shadow domain

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Abstract. Semi-transparent surfaces for cutoff of the fields in the shadow domain of an antenna are considered. For relatively large screen sizes, the analytical synthesis procedure of the grid impedance is formulated in the approximation of geometric optics (GO), which provides a purely real impedance. For smaller sizes, a numerical procedure to synthesize realizable complex impedance has been implemented. A prototype of the compact antenna system with lossy semi-transparent impedance surface has been developed. No noticeable degradation of the antenna gain in the open space domain has been detected. Perspectives for further reduction in the screen size by employment of a dual-current layer are discussed; estimates of the serial impedance of the magnetic portion are provided.

1. Introduction
For antenna and microwave areas, radiation outside the angular domain of interest could be highly undesirable. Employing the optics analogy, we call the undesirable domain as a shadow domain. In some cases, it is desirable to achieve a sharp decay (cutoff) of the fields against a desirable light-shadow boundary. The problem is relevant to electromagnetic compatibility, noise immunity in communication systems and precision of satellite positioning. With the latter, antenna gain in shadow domain defines the minimal potentially achievable error to positioning [1].

For the case of diffraction over a solid half-plane, the decay of the far field in the shadow domain versus the angular distance from the light-shadow boundary is proportional to the Fresnel integral [2]. However, the speed of decay of the fields could be enhanced by considering a semi-transparent edge of the half-plane. In [3] an electrically thin plane semitransparent screen with smooth impedance profile has been discussed. The paper is a continuation of [3]. We consider a more practical geometry illustrated in Figure 1. A wide-angle source of radiation 1 is equipped with a concave screen 2 of radius \( \rho \) that circumscribes the source. The domain I is an open space with the radiation pattern of the source being not disturbed and the domain II is the desirable shadow. For \( |x| > \rho \), the \( x \)-axis is a desirable light-shadow boundary. We consider screen 2 as consisting of two portions: a perfectly conductive portion shown by a solid line and a semi-transparent portion shown by a dashed line. The semi-transparency is understood in terms of the averaged boundary conditions across the sheet [4] and is characterized by a grid impedance \( Z_g(\theta) \) distributed over the screen. We consider the synthesis of \( Z_g(\theta) \) for a given radiation pattern of the source such that a cutoff of the pattern within a transition domain III \( \pi/2 - \alpha \leq \theta \leq \pi/2 + \alpha \) is achieved. Here \( \alpha \) is a certain small angle. The case of Figure 1 is treated in 2-dimensional approximation. The impedance is assumed to be complex with \( \text{Re}[Z_g(\theta)] > 0 \). In Section 2 we discuss analytical and numerical synthesis procedure and relevant results. In Section 3 we show an
implementation example of a compact antenna for high precision positioning with the Global Navigation Satellite Systems (GNSS), finally, in Section 4 we discuss the opportunities for the screen size reduction.

Figure 1. Concave screen geometry.

Figure 2. The equivalent circuit.

2. Screen Impedance Synthesis: Geometrical Optics Approximation and Numerical Procedure

Let \( F(\theta) = \frac{1+\cos(\theta)}{2} \) be the radiation pattern of the source. We assume that the source forms a smooth suppression of the radiation in downwards direction \( \theta = \pm \pi \); the pattern is shown in Figure 3 by solid line. Let \( F^d(\theta) \) be the desired pattern. The pattern coincides with that of the source in the domain \( I \) while exhibiting a cutoff within the transition domain (Figure 3, dashed line).

In case \( \rho \gg \lambda \), the geometrical optics (GO) approximation holds. One writes:

\[
F^d(\theta) = T(\theta) F(\theta).
\]  

Here \( T \) serves as a pattern transformation coefficient, we assume \( T \) to be pure real, in the open space domain \( T(\theta) = 1 \); in the shadow domain \( T(\theta) = 0 \); in the transition domain \( T(\theta) \) smoothly changes from unity to zero \( 1 \geq T(\theta) \geq 0 \). At the same time, \( T \) is a transmission coefficient from terminals 1 to terminals 2 at the equivalent circuit of Figure 2. We assume the characteristic impedance of the line and the load equal to \( \eta_0 = 120 \pi \text{Ohm} \) – the impedance of free space. Hence:

\[
Z_g(\theta) = R_g(\theta) = \eta_0 \cdot T(\theta) / (2(1 - T(\theta))) \geq 0.
\]

For the case the impedance occurs to be pure real. The validity of (2) has been verified by solving the exact integral equation

\[
\int G(\theta - \theta') j^r(\theta')d\theta' + E_r(\theta) = Z_g(\theta) j^i(\theta).
\]

by method of moments similar to [5] except that for the fact that we are using cylindrical coordinate frame. In (3) \( Z_d(\theta) \) was taken from (2), \( G \) is the Green function, \( E_r \) is the field radiated by the source, \( j^r \) is the equivalent electric current of the screen.

Figure 3 illustrates the thus achievable far field pattern \( F^d(\theta) \) for \( \alpha = 10^\circ \), for various radii of the screen. Here we assume the H-polarization case with the magnetic field having the only projection perpendicular to the drawing of Figure 1; for the E-polarization the results are similar and are omitted for brevity. Symmetry with respect to the direction \( \theta = 0^\circ \) is assumed. As seen, for \( \rho \geq 30 \lambda \) the impedance defined by (2) allows to obtain the pattern that differs from \( F^d(\theta) \) by about -40dB in the transition and shadow domains. However, with \( \rho \) decreasing, the shadowing performance of the screen with the GO impedance as of (2) degrades.
3. Compact GNSS Antenna Implementation Example

For rover antennas for high precision positioning with the GNSS, the $DU(90^\circ) \approx -15$dB is shown to be practical [1]. However, compact integrated solutions with the antenna mounted atop the compartment with the receiver electronics the common antenna ground plane does not allow to achieve the numbers. Figure 6 shows the dual frequency patch antenna stack with artificial dielectric substrate [1] equipped with the semi-transparent frame designed as of above. Semi-transparency of the frame for L-band applications is realized by a means of a system of metal strips and gaps equipped by lumped components [5]. For the purpose, the inductances and resistances connected in parallel were used. The $DU(90^\circ)$ versus frequency is illustrated in Figure 7. By the employment of the frame the $DU(90^\circ) \approx -17$dB has been achieved.

![Figure 6. The antenna stack equipped with the semi-transparent frame.](image)

![Figure 7. $DU(90^\circ)$ versus frequency.](image)
It should be noted that the synthesis of above is relevant to lossy impedance with \( \text{Re}[Z_g(\theta)] > 0 \). However, with the synthesis procedure developed the energy absorption occurs in the shadow angular domain with the antenna gain being small. No noticeable degradation of the antenna gain in the open space domain has been detected.

4. Perspectives for the Screen Size Reduction
For further analysis the desired far field has been expanded in a set of cylindrical waves and transferred to the domain of the near fields of the screen. Calculations have shown that for \( DU(10\degree) \approx -20\text{dB} \) and for \( \rho \) being twice as less than that of Figure 4, the aperture \( Q \)-factor of the screen stays on the order of unity hence avoiding superdirectivity. It is both equivalent electric and magnetic currents that are to be distributed over the screen then; this results in double-current layer [6] with certain positive power loss factor. Taking the thus obtained the desired and the source fields as exact values, one estimates the serial impedance of the magnetic portion as having both real and imaginary terms that are on the order of \( \eta_0/2 \).

5. Conclusion
Concave semi-transparent surfaces are employed for cutoff of the fields in the antenna shadow domain. The main constraint factor that determines the realizable cutoff values is the radii of the screen. To achieve cutoff on the order of -20dB in the angular sector of +/-10 degrees with respect to the desired boundary of the shadow area, the diameter of the concave screen reaches about 4 wavelengths. In the prototype of a compact antenna system of satellite positioning with the size of a conventional ground plane of about 1/2 of the wavelength, the use of the semi-transparent frame with lossy complex impedance provides field suppression in the nadir direction on the order of -15...- 17dB. No noticeable degradation of the antenna gain in the open space domain has been detected. With further reduction of the size of the screen, aperture \( Q \)-factor stays on the order of unity up to dimensions that are twice as less than the presented. The required serial impedance of the magnetic portion of the double-current layer is estimated as being on the order of half-the characteristic impedance of open space.

References
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