Electromagnetic Energy Absorption within Extensive Impedance Structures

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The filamentary-source excitation problems are considered with regards to extensive cavities and plane structures with surface impedance specified. The solutions are based on rigorous approaches. Particular features of the electromagnetic field absorption in such structures are shown. The choice and optimal values of impedance are proposed to ensure the fastest field attenuation when going through a duct with impedance walls. The problem regarding top possible (hopefully, total) field suppression of a filamentary source placed above non-uniform impedance plane is discussed. New designs of the electromagnetic field absorbers and resonators are suggested which may be engineered with the use of metamaterials.

Introduction: Electromagnetic modeling a cavity lined with coating

Interest to the field propagation along the imperfect surface has about century-old history, the beginnings of which trace back to the Sommerfeld's solution of the classical problem for the dipole radiating above the plane with finite conductivity. Later, as the radio broadcasting evolved, a lot of publications appeared which dealt with electromagnetic field propagation in the presence of an absorbing half-space. At present, a large number of problems exist which require understanding of the electromagnetic processes peculiar to the multiple interactions ("re-reflections") of the wave traveling between imperfect surfaces. Corresponding phenomena are rather complicated even if the wave propagates between a pair of parallel plates. In any case, an effective investigation of the corresponding electromagnetic processes is possible only if the deep insight into the simpler problem of the point source excitation of an imperfect plane is reached.

Solutions of these problems form the basis of the modern hybrid algorithms to calculate electromagnetic fields within extensive cavities; an important example of such a cavity is the air duct of a jet aircraft intake [1].

Numerous particular features of the electromagnetic excitation of a cavity can be revealed by studying rather not complicated structures, see Fig. 1*a*, [2], [3].

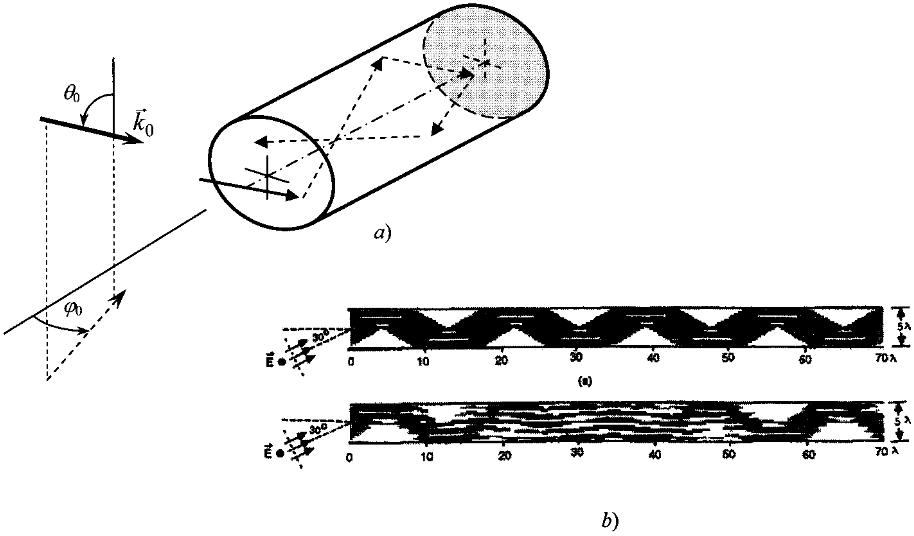


Fig. 1

More sophisticated models and algorithms which account for the complex shape and the presence of absorber coatings on the cavity walls give reliable results close to the measured data (see, for example, [4]-[6]). However, a very important "inverse" problem, namely, how to choose the absorber properties to secure a lowest possible level of the radar backscattering from the cavity, is solved by today mainly through selection of the coatings with proper angular dependencies of reflection coefficient, bearing in mind a ray picture of the field transport along the cavity. Note, the grazing wave incidence onto the walls is of prime interest because of the low efficiency of coatings in this case; that is why the backscattering patterns of intakes show significant peaks around the nose-on directions of the external illumination. At the same time, the geometrical optics considerations do not necessarily result in the optimal choice of coating because of complex diffraction phenomena in a realistic duct. Fig. 1*b*, reproduced from [7], shows an example of the strong discrepancies between the results of the field calculation by the ray (upper picture) and the rigorous (lower picture) techniques even in a simple case of a waveguide formed by a pair of parallel conducting plates.

This paper shows another possible way to get near to optimal absorber properties originating from energy considerations applied to a model problem for the point source excitation of an impedance plane. The surface impedance is chosen so as to provide for a maximum power flux density along the normal to the coating. The conclusion is made that the optimized coatings secure lowest backscattering at the typical dimensions and geometry of a duct. Usage of metamaterials for the same purposes is considered. It was found that with a point source radiating in a presence of an impedance plate one can attain even complete field suppression in an outer space provided several relationships are perfectly satisfied.

Choice of RAM to coat the walls of an extended cavity

Let's consider a possible definition of the model problem, Fig. 2.

For the sake of simplicity, we shall consider 2D monochromatic case with the field frequency ω. Let the point source be placed above the plane $y = 0$ with the constant surface impedance Z specified. The source is a filament of x-directed magnetic current, therefore vector $\vec{E}^i$ of the incident field has a component perpendicular to the impedance plane, and vector $\vec{H}^i$ is parallel to the plane. We should determine the value of impedance which provides for the highest possible power flux density transferred across the plane $y = 0$ in the given point z_0 or through the specified area of that plane.

Rigorous solution of the boundary problem results in the following expressions for the tangent component of the magnetic field H_x and the real part of the Poynting vector in the direction of $-\vec{i}_y$ normal at $y = 0$:

$$H_x = -\frac{i\omega\varepsilon_0}{2\pi} I_0 \int_0^\infty \frac{2\cos(\xi z)}{q + ikZ_W} \exp(-qy_0)\,d\xi; \qquad \mathrm{Re}(S) = \frac{1}{2}\mathrm{Re}(Z_W)|H_x|^2,$$

where $q = \sqrt{\xi^2 - k^2}$, $k = 2\pi/\lambda$, $Z_W = Z/W_0$, $W_0 = 120\pi$ (Ohms), λ is the wavelength.

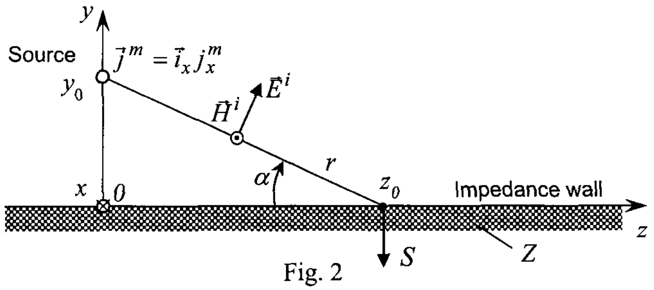


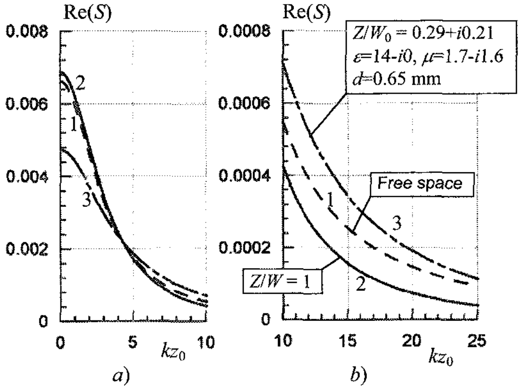
Fig. 2

Consider the illustrative example, when the filament is placed at the altitude of about half a wavelength, $ky_0 = 3$. Fig. 3 shows the results of calculation of the power flux density transferred across the plane $y = 0$ as the dependence upon the location of observation point z_0. Three options for the impedance *Z* are tested. Curve 1 refers to the case of the absence of impedance plane, when the filament is located in the unbounded space and the electromagnetic wave freely travels across boundary $y = 0$ without reflection. Curve 2 corresponds to the case when the impedance of the plane is equal to the intrinsic impedance of the free space $Z = W_0$. Note, this particular value of *Z* provides for the total transmission ("absorption") of the plane wave, normally incident onto the plane. When an observation point is located not so far from the filament (at small z_0 values and rather large angles *α*, see Fig. 2) the curves 1 and 2 are close to each other. However, at the larger z_0 (i.e., at low, "grazing" angles *α*) the power flux across the plane $y = 0$ with $Z = W_0$ appears to be much less as compared to the case of the free space (see Fig. 3*b*).

Nevertheless, one can create an electromagnetic wave absorbing coating to secure an increase in power flux transition across the media interface and, correspondingly, attenuation of the field energy at grazing incidence.

For example, let a conducting plane be coated with 0.65 mm layer of RAM, its permittivity and permeability be chosen as $\varepsilon = 14 - i0$, $\mu = 1.7 - i1.6$. At the wavelength of λ=3 cm the equivalent impedance of such a structure is almost independent from the angle of plane wave incidence, and its value is about $Z / W_0 = 0.29 + i0.21$. Curve 3 is drawn for this case. It shows that in a wide region of z_0 values (at the low angles *α*, Fig. 3*b*) a much greater portion of the field energy is transferred across the coating boundary as compared to the case of "matched against normal incidence" (curve 2) or even "perfectly non-reflective" coating (i.e., free space, curve 1). The coating with these properties is suitable to apply onto the air duct walls to achieve RCS reduction of the intake at the incidence directions close to the compressor axis.

Varying the of impedance at the given task options (for example, y_0 and z_0), one can define its optimum value, which assures the maximum power flux density (see example shown in Fig. 4). Numerous calculations indicate that when using homogeneous coatings, the best results are likely to be achieved at the inductive surface impedance, if $\mathrm{Re}(Z / W_0) \approx 0.2...0.5$ and $\mathrm{Im}(Z / W_0) \approx 0.1...0.3$. This conclusion agrees with the published data and physical assumptions that the better conditions for wave absorption are secured by an impedance with inductive component, particularly, due to surface waves excitation and higher field concentration nearby the duct walls. Finally, calculations carried out for the realistic designs of complex intakes demonstrated the superiority of the coatings chosen in the way described above.



a) *b*)

Fig. 3

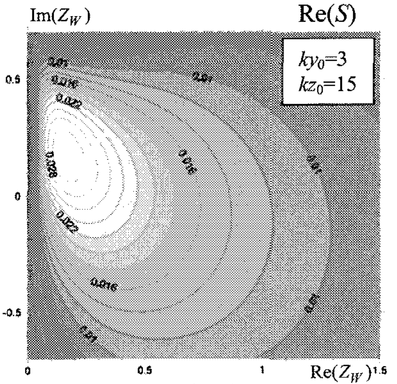


Fig. 4

Point source energy absorption by a half-space

Now it is natural to set few questions about what value of impedance of a plane should be chosen to absorb the maximum portion of energy radiated by a point source (say, filamentary current), how much the amount of the absorbed energy is and how to create such an impedance. Note, in view of the symmetry of the radiation pattern of the filament, at the absence of the plate (in the free space) equal power fluxes are radiated into upper and lower half-spaces, and exactly one half of the radiated energy penetrates through the plane $y = 0$, see Fig. 5.

Calculations showed that even at some "optimal" but constant value of Z (see, for example, Fig. 4) the integral of the real part of the Poynting vector taken over the surface $y = 0$ (that is, $z_0 = -\infty ... +\infty$) does not exceed a half of radiated power as well. However it is evident that the lower half-space can absorb more than one half of radiated power provided the impedance distribution is inhomogeneous. For example, one can define a function of impedance distribution over the plane to have $Z \approx W_0$ closer to the filament, at large angles α, and choose Z from considerations of maximum energy absorption (see, for example, Fig. 3 and Fig. 4) while moving away from the source, i.e., at lower values of α. Of course, impedance Z should vary rather smoothly along the plane to prevent from strong diffraction, which may cause degradation of the coating performance.

Another way may be suggested to create a system which would consume more than half a power radiated from the source. Let place a specially designed scatterer in the region $y < 0$. Then an asymmetric radiation pattern with respect to the $y = 0$ plane can be formed with its main lobe directed downward, see Fig. 6 (similar trick is used in the Uda-Yagi dipole antennas). In doing so, the major portion of energy is directed into lower half-space. Further, it may be absorbed in an ordinary way. Once the tangential components of the electric and magnetic fields are calculated in the plane $y = 0$, one can evaluate the desired distribution of the equivalent surface impedance of such a system.

Total transition of the point source radiation into a half-space

The system shown in Fig. 6 may be further complicated. Evidently, it is possible to make the field cancellation in the upper half-space more complete and, correspondingly, to increase the portion of the energy absorbed in the lower half-space by increasing a number of auxiliary scatterers. The question arises: what *maximum* portion of energy emitted by source can be directed into lower half-space without using any additional devices (say, mirrors) in the upper half-space, at $y > y_0$.

It will be shown below that one can create even such a passive system which secures *total* cancellation of the source field in the upper half-space and, correspondingly, transfers the whole of the emitted energy into the lower half-space.

Consider an example of designing such a system, firstly, on a qualitative level.

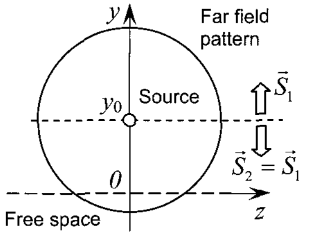


Fig. 5

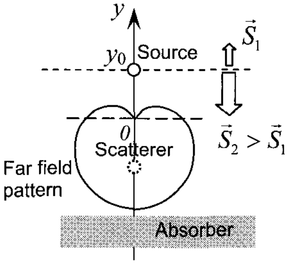


Fig. 6

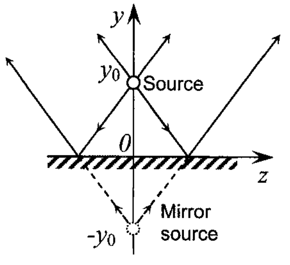


Fig. 7

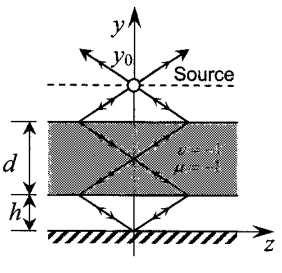


Fig. 8

Let a filamentary source with a single x-directed component of the electrical current be placed in the point y_0 over the conducting half-plane $y = 0$, Fig. 7. As known, in this case the secondary field can be interpreted as produced by the mirror source, the currents in filament and in its image are of the same magnitude but their phases are opposite to each other. In other words, the sign of the wave phase is reversed when reflection from the conductor occurs. Let a focusing flat plate (Veselago's lens [8]) with a thickness of $d = y_0/2$ made of the metamaterial with $\varepsilon = -1$, $\mu = -1$ be inserted between the source and the plane at the altitude h so as $0 < h < y_0/2$. Then the focusing point and its mirror image coincide with each other right at the surface of the conducting plate (see, for example, the ray picture in Fig. 8). Once the total phase advance along ray paths is calculated bearing in mind the negative phase velocity of the wave traveling through the plate and the phase reversal of the field due to the reflection from the conducting plane, one can discover that in the region $y > y_0$ the incident and secondary fields mutually cancel each other. In an ideal case, when electromagnetic losses in the plate are infinitesimally small, the total field in the upper half-space tends to zero.

Rigorous solution of the corresponding boundary problem results in the same conclusion. This is illustrated by Fig. 9 and Fig. 10, which show the absolute values of the total field in the vicinity of the source (in the plane perpendicular to the filament of electrical current). Contour plots are given in Fig. 9, and corresponding 3D images of the field distribution are shown in Fig. 10.

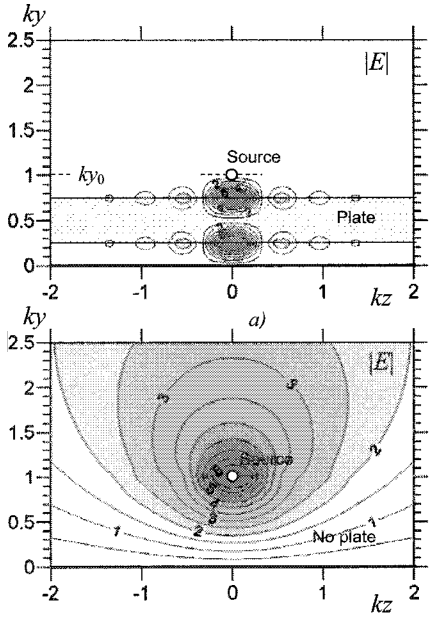


Fig. 9 b)

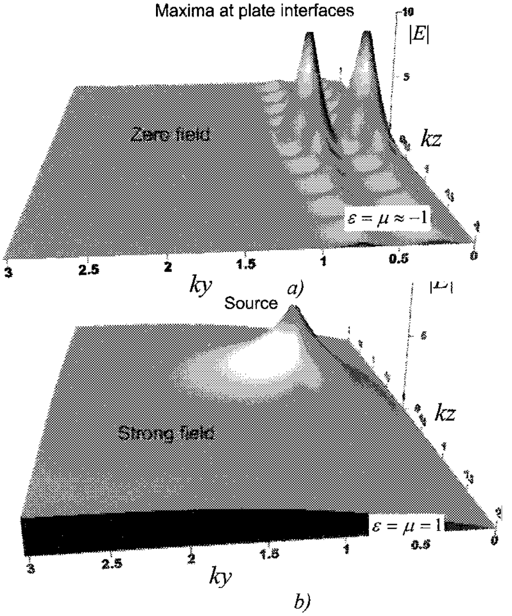


Fig. 10

Upper figures (*a*) depict the results obtained at $ky_0 = 1$, $d = 2h = y_0/2$, $\varepsilon = \mu = -1 - i0.001$ (time dependence is chosen as $\exp(i\omega t)$), geometry of the problem corresponds to Fig. 8. Lower figures refer to the case of plate absence, when $\varepsilon = \mu = 1$. They are given for reference purposes. Note, in the presence of the metamaterial plate the field in the region $y > y_0$ is almost equal to zero in contrast to the second case, when the field of the filamentary source does not attenuate. It is seen most clearly on the cross sections of 3D images of the field distribution, Fig. 11 (*a*: no plate inserted, *b*: the case of the geometry shown in Fig. 8).

Open resonator

The regions with high field concentration due to accumulating reactive energy are worth noting in the figures (see Fig. 9*a,* Fig. 10*a*). They arise next to the metamaterial plate faces while field compensation in upper half-space occurs. These maxima reach especially great values in the case of the plate arrangement side-by-side to the conducting surface, $h = 0$, Figs. 11*c*, *d*. Thus, the structures shown in Fig. 8 and Fig. 11*c* may serve as prototypes for designing *novel open resonators* without usual restrictions on the thickness of the system in terms of wavelength. Note, previously a different idea of a "thin" metamaterial-based resonator of "closed" type was suggested [9] (the metamaterial sheet was sandwiched between a pair of conducting plates). Other design of an open resonator is also known [10], it is based on the negative refraction property of photonic crystal or metamaterial prisms.

Correspondence to the "superresolution" phenomenon. Effect of losses.

One of the specific features of the Veselago's lens is the ability to produce an image with extremely fine details as its resolution is not restricted with so called "diffraction limit". This surprising fact was firstly pointed out by Prof. Pendry [11]. Later it was shown that the absorption in metamaterial plays a crucial role in view of achieving superresolution in practice. And the smaller the plate thickness (in wavelengths), the higher is the upper level of losses to secure desired resolution (see, e.g., [12]).

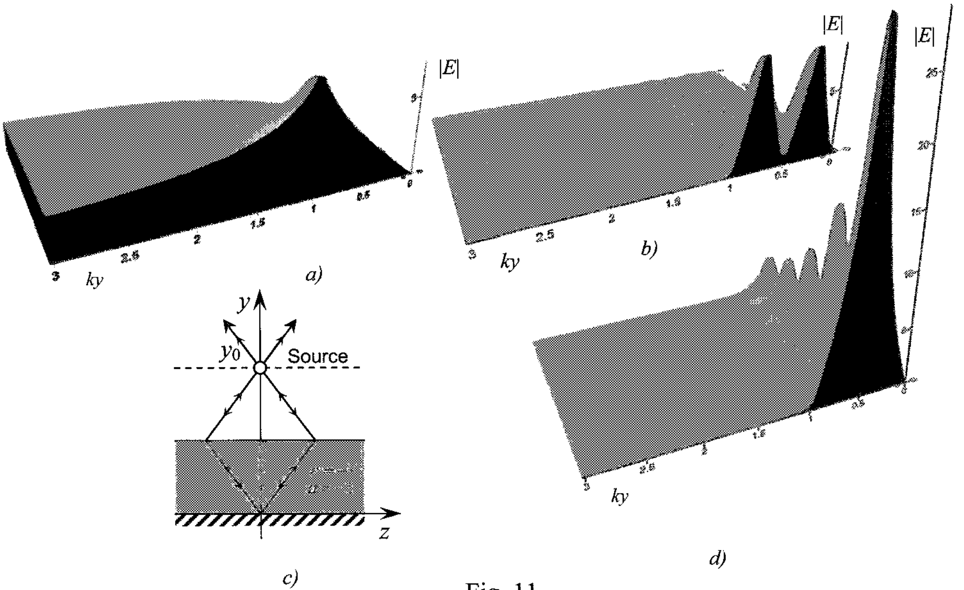


Fig. 11

Similar conclusions can be made regarding the performance of the systems under consideration. Even if one tends to compensate only propagating modes of the far field in upper half-space, rather strict requirements should be placed to the quality of metamaterial. But to attain the *near field* compensation in the vicinity of the source (around y_0 point), the mirror image should be developed with "superresolution", which is achievable only with extremely low losses in the plate. Though, at small ky_0 and kd one may expect rather good results even using existing metamaterials with noticeable absorption, as was in the case of electrically thin focusing plate [12]. Passing on to the greater values of ky_0 , the near field is much more difficult to compensate, and this is illustrated in Fig. 12 (geometry of the Fig. 8, $d = 2h = y_0/2$, $ky_0 = 14$).

Electromagnetic wave absorber with special angular properties

Finally, note that metamaterials may be efficiently used to create *novel absorbers* of the electromagnetic energy of a plane wave. Their special properties may be achieved, particularly, due to arranging a wave path so as to cross the metamaterial structure with the result of phase advance compensation. An example of the RAM design usable under the incidence of perpendicularly polarized (TM) plane wave is shown in Fig. 13. Provided the electromagnetic response of the semi-infinite film, particularly, its transition and reflection coefficients were properly chosen, the wave reflected from the film cancels the wave penetrated into and returned back from the region $y < y_0$. This latter wave got a negative phase correction when propagated in the metamaterial plate and additional phase reversal because of the reflection from the conducting plane. It is interesting that total phase advance of that wave is equal to π independently on the incidence angle. Therefore, it is possible to achieve a very broad angular range in which such an absorber should operate efficiently, in contrast to classical designs, like Salisbury screen [1]. In fact, only deviations of semi-transparent film properties impose certain limits to the angular performance. Finally, as there are no fundamental physical restrictions on the thickness of the described absorber, it can be made electrically thin (at least, in principle), as well as earlier suggested system of complementary metamaterials [13].

Conclusion

Thus, a way to attain nearly optimal absorber properties originating from energy considerations was suggested, the technique is based on a model problem solution for the point source excitation of an impedance plane. Next, it was shown that the metamaterials provide a variety of new opportunities in designing novel absorbers and resonators, the latter may be even open. The paper reports about an important (though not so evident) result of potential total absorption of the radiated field of omnidirectional point source by a flat surface with properly chosen distribution of the impedance. Such a surface may be engineered with the use of the metamaterials.

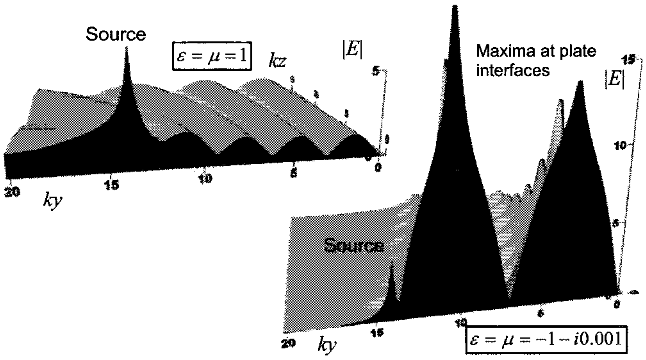


Fig. 12

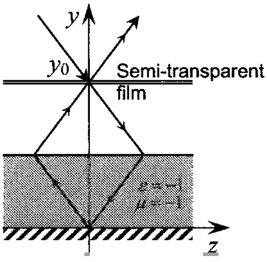


Fig. 13

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