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WIDE-ANGLE ABSORPTION BY THE USE OF A METAMATERIAL PLATE

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Abstract—The problem regarding top possible (hopefully, total) field suppression of a filamentary source placed above nonuniform impedance plane is discussed. New designs of the electromagnetic field absorbers and resonators are suggested which may be engineered with the use of metamaterials.

1. INTRODUCTION — ABSORPTION OF THE ENERGY OF A POINT SOURCE BY A HALF-SPACE

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 with the aim to *minimize* the signal losses.

Now certain practical needs [1] set 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. 1.

Calculations showed that even at some "optimal" but constant value of Z the integral of the real part of the Poynting vector taken over the surface $y = 0$ (that is, $z_0 = -\infty, \ldots, +\infty$) does not exceed a half of radiated power. However it is evident that the lower half-space can absorb more than one half of radiated power provided the

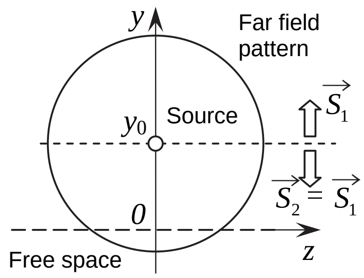

Figure 1.

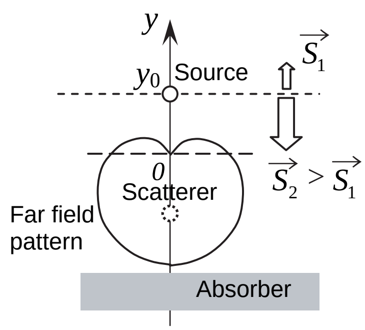

Figure 2.

impedance distribution is inhomogeneous. For example, 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. 2 (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.

2. TOTAL TRANSMISSION OF THE POINT SOURCE RADIATION INTO A HALF-SPACE

The system shown in Fig. 2 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 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. 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. 3. 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 opposite to each other. In other words, the sign of the wave is reversed when reflection from the conductor occurs. Let a focusing flat plate (Veselago's lens [2]) 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 occurs right at the surface of the conducting plate (see, for example, the ray picture in Fig. 4).

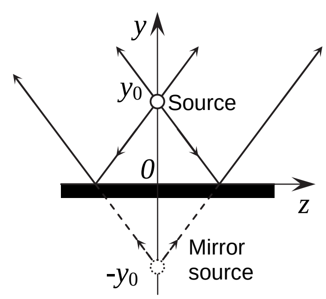

Figure 3.

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 field reversal 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. 5 and Fig. 6, which show the absolute values of the total field in the vicinity of the

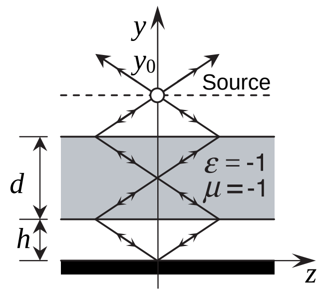

Figure 4.

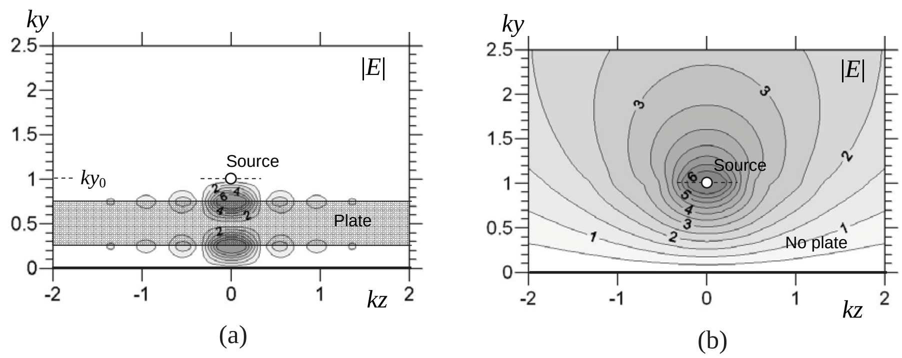

Figure 5.

source (in the plane perpendicular to the filament of electrical current). Contour plots are given in Fig. 5, and corresponding 3D images of the field distribution are shown in Fig. 6.

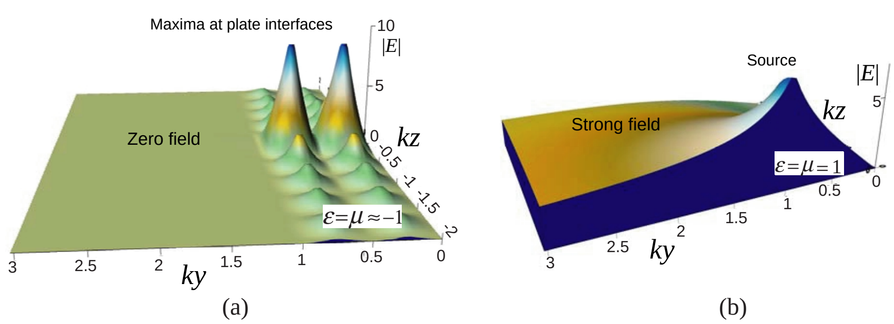

Figure 6.

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. 4. Figs. (b) 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.

Of course, microwave experiments on the discussed phenomena with a linear antenna operating as a source should indicate a strong reflected wave in the antenna feeder. This wave can be easily suppressed by a number of techniques commonly used in microwave engineering. Moreover, in a realistic case of easy to manufacture metamaterial plate with a rather high losses, say, $\varepsilon = \mu = -1 - i0.1$, matching the antenna to a feeder is better while the conclusions remain the same. As calculations show, the major portion of energy, as much as 99.4% is transferred into the lower half-space and dissipates there.

3. OPEN RESONATOR

The regions with high field concentration due to accumulating reactive energy are worth noting in the figures (see Fig. 5(a), Fig. 6(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, $h = 0$, Fig. 7. Thus, the structures shown in Fig. 4 and Fig. 7(a) 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 [3] (the metamaterial sheet was sandwiched between a pair of conducting plates). Other design of an open resonator is also known [4], it is based on the negative refraction property of photonic crystal or metamaterial prisms.

4. 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 [5]. 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

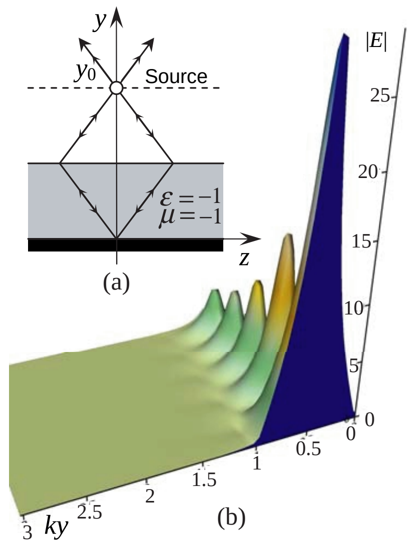

Figure 7.

wavelengths), the higher is the upper level of losses to secure desired resolution (see, e.g., [6]).

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 [6]. Passing on to the greater values of ky_0, the near field is much more difficult to compensate, and this was proven by calculations.

5. 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

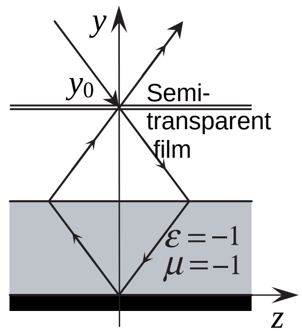

Figure 8.

of phase advance compensation. An example of the RAM design usable under the incidence of perpendicularly polarized (TM) plane wave is shown in Fig. 8. Provided the electromagnetic response of the semi-transparent film, particularly, its transmission 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 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 [7].

Our experimental investigations (Fig. 9) support these theoretical suggestions.

The experimental setup is schematically shown in Fig. 9(a). By means of a dihedral corner one face of which is lined with a tested coating the angular dependency of its reflection coefficient can be measured via registering the power of the reflected wave in the course of the corner rotation. An example of the measured reflected power (in dB) is depicted in Fig. 9(b), curve 1 corresponds to the uncoated corner, curve 2: metamaterial-based multilayer coating is arranged as suggested in this section, curve 3: only semi-transparent film is placed parallel to the corner face, curve 4: only metamaterial layer is present

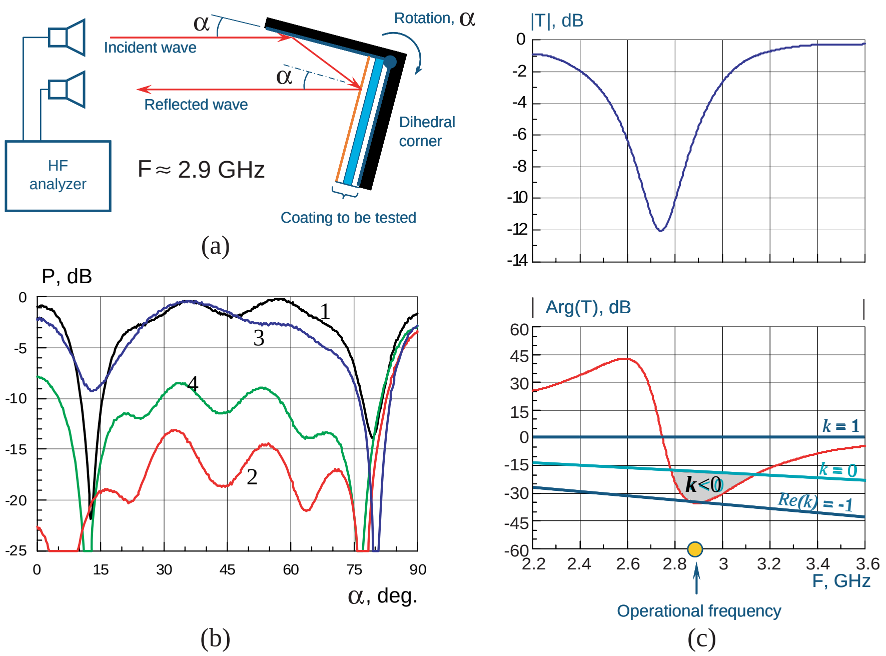

Figure 9.

on the face. The metamaterial sample was prepared using right- and left-handed helixes as resonant inclusions, the details of the design are given in [8]. The superiority of the sandwiched structure (curve 2) is clearly seen, one can observe a broad angular range of the efficient absorption. Note, the operational frequency was chosen in such a way as to secure the negative phase advance of the wave penetrated into the metamaterial. To that purpose, the transmission coefficient of the metamaterial slab was measured beforehand; the results are shown in Fig. 9(c).

6. CONCLUSION

Thus, the obtained results show that the energy radiated by an omnidirectional (point) source can be completely absorbed by a flat surface with special equivalent impedance. In order to suppress both propagating and evanescent components such a surface should be engineered with the use of metamaterials. However, partial compensating and absorbing essentially propagating modes may be achieved by some other means, for example, using a system of auxiliary scatterers combined with a suitable absorber. Photonic crystals or stacked frequency selective surfaces are also good candidates for that purposes.

Some new opportunities originating from the discussed phenomenon are presented as well. Besides the evident option to use metamaterial layer in order to solve the electromagnetic compatibility problems, we suggest a new design of an open resonator excited by a point source. A new approach to design radio absorbing interference coatings to operate under a plane wave illumination is also introduced. The approach enables one to obtain some specific features of the absorber, e.g., wide angular operational range at small electrical thickness. The latter becomes possible thanks to the fact that the required (e.g., effective negative) phase advance for mutual compensation of the waves reflected from the media interfaces is achieved by the application of a backward wave medium (metamaterial) instead of arranging thick layers of ordinary coating with a subsequent narrowing the angular range. Finally, a possible design of a wide-angle metamaterial-based microwave absorber is shown and experimentally tested.

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