

On the Parametric Version of Black Body

Vladimir Arabadzhi*

Institute of Applied Physics, 603950 GSP-120 Nizhny Novgorod, Ulianov st. 46, Russian Federation, Russia.

***Correspondence:**

Vladimir Arabadzhi, Institute of Applied Physics, 603950 GSP-120 Nizhny Novgorod, Ulianov st. 46, Russian Federation, Russia.

Received: 20 December 2018; **Accepted:** 15 January 2019

Citation: Vladimir Arabadzhi. On the Parametric Version of Black Body. Nano Tech Appl. 2019; 2(1): 1-6.

ABSTRACT

In the time representation, the parametric microstructure (material) filling the radio absorbing shell of the protected body is analyzed analytically. This passive microstructure provides absorption of any (in frequency and direction) radio wave perturbations which have come to the zone of parameters modulation (this is the ideal of the “black body”). Ultra-high spatial-temporal resolution in the control of this structure provides effective absorption in a thin (in comparison with the incident wavelength) shell. Absorption in a thin parametric shell occurs due to the transfer of the energy of the incident wave to the area of high-frequencies (much larger than, for example, traditional harmonics of the absorbed wave). It is shown that: (a) the alternative parametric version (as opposed to the traditional one) of “black body” can have both large and arbitrarily small wave dimensions, as well as an arbitrary shape (smooth or non-smooth); (b) “black shell” can be of thickness much less than minimum length of incident wave; (c) the outer scattering properties of the “black shell” and “black body” (when the entire volume of the body is filled with the material of the “black shell”) are identical to each other.

Keywords

Instant Simultaneous Cutting of the Instantaneous Spatial Distribution of the Wave Field Along a Thin Contour of Boundary Conditions .

Goals

We will mean absorption as the conversion of the energy of an absorbed wave into forms of energy that are fundamentally different from the absorbed wave: for example, the energy of water waves into electric energy, however in most cases into heat, due to the dissipative parameters of some absorbing shell. Our goal is to design “black” shell for the body of arbitrary shape and wave dimensions (large and small wave dimensions jointly)

$$\bar{D} / \lambda_{max} \ll 1 \cap \bar{D} / \lambda_{min} \gg 1 \tag{1}$$

in the frequency range $\omega_{min} \leq \omega_I \leq \omega_{max}$ (at $\omega_{max} / \omega_{min} \gg 1$) and wavelength range $\lambda_{min} \leq \lambda_I \leq \lambda_{max}$ (where ω_I - incident wave frequency, λ_I - incident wave length, $\lambda_{min} = 2\pi c / \omega_{max}$, $\lambda_{max} = 2\pi c / \omega_{min}$, \bar{D} - characteristic geometric dimension of body to be “black”, c - speed of light) and for arbitrary

$$\forall \mathbf{w}_I \tag{2}$$

directions \mathbf{w}_I ($|\mathbf{w}_I| = 1$) of incident waves with arbitrary shape of leading edge by the means of absorbing shell of small thickness jointly satisfying the conditions (arbitrarily low gabarits of absorbing shell)

$$L \ll \lambda_{min} \cap L \ll \bar{D} \tag{3}$$

Let us specify the geometric definition of an absorbing shell: it is the set $\mathbf{L} = \mathbf{D} - \bar{\mathbf{D}}$ of points of the layer \mathbf{L} between the outer surface $S \subset \mathbf{D}$ of the shell and its inner surface $\bar{S} \subset \bar{\mathbf{D}}$, where \mathbf{D} is the space inside the outer surface S , $\bar{\mathbf{D}}$ - the space occupied by the protected body itself with surface \bar{S} . The thickness of the absorbing shell will be called the minimum distance between the points of the surfaces S and \bar{S} , i.e. $L = \min_{\mathbf{r}_1 \in S, \mathbf{r}_2 \in \bar{S}} |\mathbf{r}_1 - \mathbf{r}_2|$. We can call conditions (1)-(3) the definition of an ideal black shell.

Known Approaches to Black Body Problem

The earliest version of the “black body” was a pinhole camera (Figure 1a): a cavity with a characteristic size L (dimensions) and with a hole (aperture) with a characteristic size $\bar{D} < L$. Each ray entering the aperture experiences a multitude of reflections (with small relative power losses on each reflection) from the inner surface of the cavity to its possible exit back out through

the same aperture (with almost complete loss of power). This is the principle of black body with absorption cross-section $\sigma_A \sim \bar{D}^2$. However, a beam is a special type of wave from geometric optics, i.e. $\lambda_l \ll \bar{D}$ only for (contrary to condition (1)). In addition: the black body is only a little hole in a much larger cavity. A cavity is only a necessary (large-sized, contrary to condition (3)) device for providing a black body mode; such a black body has no volume and is not black for the rays falling from the back side (contrary to condition (2)).

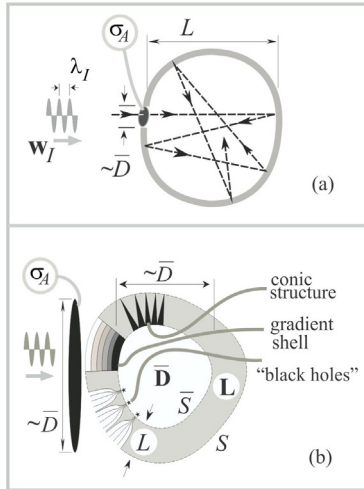


Figure 1: Main famous types “black body”: pinhole camera (a); absorbing shell (b).

With arising of dissipative materials (Figure 1-b), it became possible to create absorbing coatings (shells) of bodies that were supposed to be made black (moreover, with an absorption cross-section $\sigma_A \sim \bar{D}^2$ closest (if $L < \bar{D}$) to the geometric projection of the protected body with surface \bar{S} on the flat leading edge of the incident wave, see Figure 1-b), that is, without creating backscattering. The impedance of the shell material must be equal to the impedance of the external environment with a relatively small difference, due to only a small absorption of the wave in the shell material. The weakness of absorption is needed so that the wave is reflected from the outer surface of the shell as little as possible, and the large wave thickness of the shell ($L > \lambda_l$ or $L > \lambda_{max}$) is needed so that the wave can, with weak absorption, almost completely attenuate along a propagation path equal to the thickness of the shell. Weak bulk absorption guarantees the absence of interaction between individual parts of the absorbing medium via wave field and, as a consequence, the uniformity of absorption in the direction \mathbf{w}_l of the incident wave and in its frequency ω_l . This is the simplest design of the absorbing coating (similar to window tinting). Many researchers have tried to find a structures (constant in time, and with field representation by complex amplitudes at any frequency) of an absorbing shell (gradient shells, conic structures [1], black holes [2] and other attempts to find a stationary absorbing structure) that would satisfy the conditions (1)-(3) simultaneously.

The main difficulty (in 2D, 3D problems) is that any wave to be

absorbed (or for conversion into heat) needs time (more or equal to its period) and distance (more or equal to its wavelength) to have time to make a work (if we do not make conversion its frequency, i.e. if medium parameters are constant in time) on the absorber. Otherwise wave will “slip away” from absorber: it will be reflected or pass through.

We must note, that in the case of a resonant (that is, narrowband and “physically compact”) absorber, the role of the “actual dimensions of the absorber” is played by the reactive field region. In addition, the group of resonant absorbers has a pronounced spatial directionality breaking the conditions (1)-(3).

Now remind that in all these years of research on optimizing absorbing shells with parameters that are constant in time, microelectronic technologies (designed for computational purposes and according the law of Gordon Moore) have been intensively developed: the miniature and rate of the element base (or the spatial-temporal resolution). On the other hand wavelengths that were intended to be absorbed by the “black” shells remained the same due to the constant conditions of the long-range propagation of these waves. This work is an attempt to use the successes of microelectronics to satisfy conditions (1)-(3) jointly.

Main Principle of Approach

Let’s consider the free spatial area D (square of dimension L_{VR} in Figure 2a) filled with the running incident wave field. Any simply connected spatial domain (in particular, arbitrarily small compared to the wavelength) of a traveling wave field is also a traveling wave initially. And if this area of space is suddenly (in the moment $t = 0$) instantly (during the time $\tau_{sw} \ll L_{VR}/c$) isolated by an impenetrable boundary condition (very thin boundary), then the field that has entered the “cage” tries to continue its run. Because the points of the field inside the “cage” will not have time to “find out” anything about what happened in the moment $t = 0$. And if this “cage” (resonator) does not have a zero natural frequency (see below), then only oscillations will exist in it, the frequency of which is a multiple of the inverse of the travel time of the wave between the opposite boundaries of the “cage” (resonator). In other words, in the moment $t = 0$ the boundary conditions pierce instantly the instant spatial distribution of the wave field along the contour of the square (Figure 2-a), and the problem of wave propagation in free space splits into two: (a) the problem of diffraction of an incident wave on an opaque (with any internal filling) outer boundary conditions on the surface S of the square (cube) (Figure 2b); (b) the problem of damped oscillations of a field inside a square (cube) or a resonator with impermeable internal boundary conditions on the surface S (Figure 2c) and initial conditions in the form of the field distribution of the incident wave in the moment $t = 0$. This process of instantaneous piercing of a smooth field of an incident wave by a thin contour of reflecting boundary conditions (“instant metallization”) means the transfer of the field energy of the incident wave from low frequencies (section 1) to the ultrahigh frequency region $|\omega| \sim n\pi c / L_{VR}$ ($n = 1, 2, \dots$).

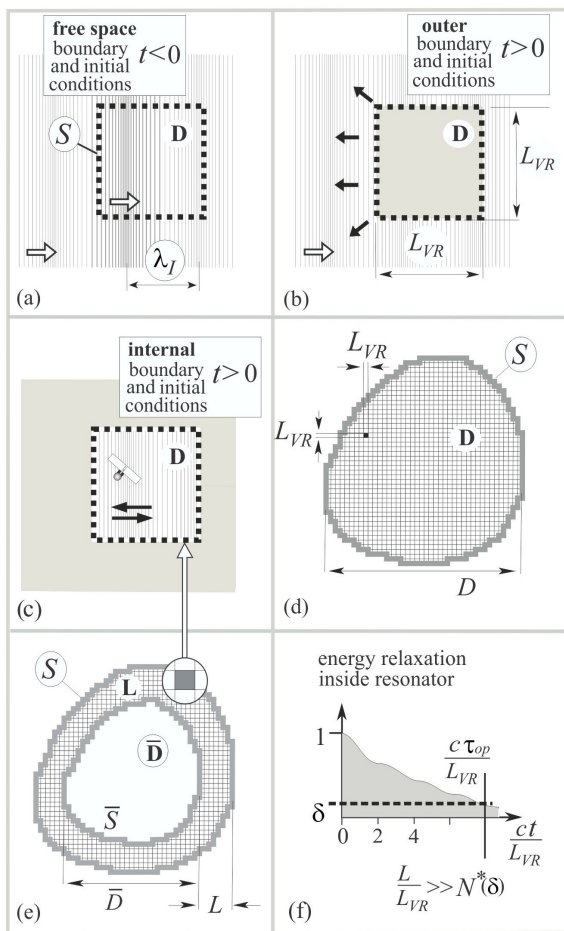


Figure 2: The separation at the time $t = t_0$ of the problem of diffraction of the incident wave (a) with the initial conditions on the external (b) and internal (c). Black body (d), black shell (e), field energy in virtual resonator (f).

In Figure 2d shows an area (with an external surface S) filled with cubic cells (with size) with thin walls (of thickness $\sim L_0 \ll L_{VR}$) of controlled transparency (with reflection coefficient $|R_w(t)|$) similar to that shown in Figure 2c. This structure resembles a foam with flat walls between cells, which are not necessarily cubes (cubes only for drawing simplicity), but generally convex polyhedrons (with a characteristic spatial scale $\sim L_{VR}$) in contact with each other, separated from one another by their own walls (faces of a polyhedron). In Figure 2f shows a typical graph of the decay of the field energy of oscillations in a resonator, when the oscillations were caused by some initial field distribution in the moment $t = 0$. The time inside the resonator (i.e. with the module of the wall reflection coefficient $|R_w(t)| = 1$) is measured by the number ct / L_{VR} of wave paths along its length $\sim L_{VR}$. Suppose that by the time $t^* > 0$ of oscillation it can be considered damped, if their energy has dropped to a level $\delta \ll 1$, and the wave at the same time managed to make $N^*(\delta) = t^*c / L_{VR} \gg 1$ runs. Then, when the resonator is opened (that is $|R_w(t)| = 0$, when $t > t^*$), the field in the resonators of the structure shown in Figure 2d will not contribute to the scattering field of the incident wave. The contribution to the scattering in this case will give only a reflection of the incident wave from the outer surface of the structure in the time interval

$0 < t < t^*$ of the opacity of the walls. Further, we will periodically repeat the locking of the structure walls (i.e., install $|R_w(t)| = 1$) in Figure 2d with a period T in the intervals $nT < t < nT + \tau_{op}$ ($n = 1, 2, 3, \dots$), where $\tau_{op} = t^*$, leaving the walls transparent in the intervals $nT + \tau_{op} < t < (n+1)T$ of duration $\tau_{tr} = T - \tau_{op}$. It is easy to see that at $\tau_{tr} \gg \tau_{op}$ and $cT \ll D$ the structure presented in Figure 2d, practically will not scatter the incident wave on average at each modulation period T , and such a structure can be called a “black body” we neglected here the duration $\tau_{sw} \ll \tau_{op}$ of switching. In addition, the incident wave practically can’t penetrate to depth $L = cT$ in structure. This means that at a depth $L = cT$, instead of resonators, we can place arbitrary body \bar{D} bounded by the surface \bar{S} (Figure 2e). At the same time, nothing will change outside the surface, i.e. layer L can be called the “black shell” of the body \bar{D} . It is also easy to verify that (within the framework of the parametric structure considered), a reduction in the dimensions of the resonators and a corresponding acceleration in the modulation of the reflection coefficient of their walls will make the black shell as thin as desired compared to the incident wavelength λ_I , and body \bar{D} size, i.e. fulfill conditions (1) - (3).

Now let us briefly describe the formulation of the problem of diffraction of waves on a parametric black body. First of all, we note that the traditional formulation of the problem in the form of a wave equation, boundary conditions, and complex field amplitudes is impossible in this case. Scattering on a parametric black body is represented by the following sequence of problems with initial conditions. At the moment $t = 0$ the field outside the surface S is given \sim , and inside the surface the field is zero. Over time τ_{tr} the external field spreads unhindered inside the surface S to a depth $\tau_{tr}c$. In the course of time $\tau_{op} \ll \tau_{tr}$ (very quickly), the field penetrated into the area L of modulation of the transparency of the walls, turning into heat, becomes zero. Over time τ_{tr} the field distribution outside S again freely spreads inward S to a depth $\tau_{tr}c$. And so on... It should be noted that the propagation of the field into the surface S leads to a change in the external field as well.

On the Possible Practical Implementation

In Figure 3a shows the possible construction of a virtual resonator (a) - the main functional element of the “black” shell L and the construction (b) of one wall of controlled transparency (metal needles of length $L_{\parallel} \ll L_{\#} \ll L_{VR}$ and diameter $L_0 \ll L_{\parallel}$) interconnected by optoelectronic keys, Figure 3b). We call this resonator virtual because that it is transparent the main time in each modulation period, that is, as if it does not exist. A resonator with reflective (opaque) walls exists a short duration τ_{op} in each period. Compact absorbing resonantly loaded dipoles (of length $L_D \ll L_{VR}$) are placed at different points (in the maximums of resonator’s modes) inside the resonator and tuned to different polarizations and frequencies of the resonator’s modes. These dipoles are converting wave energy into heat directly. The full cycle of operations (repeated with a period $T = \tau_{tr} + \tau_{op} + 2\tau_{sw}$) in the parametric foam structure consists of the following four intervals: (a) a “transparent” interval with duration τ_{tr} and modulus of wall reflection coefficient $|R_w|_{tr} \ll 1$; (b) switching interval with duration $\tau_{sw} \gg \tau_{tr}$; (c) an “opaque” interval with duration τ_{op}

(lifetime of virtual resonator $\tau_{sw} \ll \tau_{op} \ll \tau_{tr}$) and modulus of wall reflection coefficient $|R_w|_{op}$ satisfying the condition $|1 - |R_w|_{op}| \ll 1$; (d) switching interval with duration $\tau_{sw} \gg \tau_{op}$. Thus, the black shell **L** absorbs (i.e. the field zeroing inside **L**) during the time τ_{op} any wave disturbance that enters (without scattering) the zone **L** modulation of parameters (walls transparency) during the time τ_{tr} , and above sequence (a)–(d) operations repeated with period T .

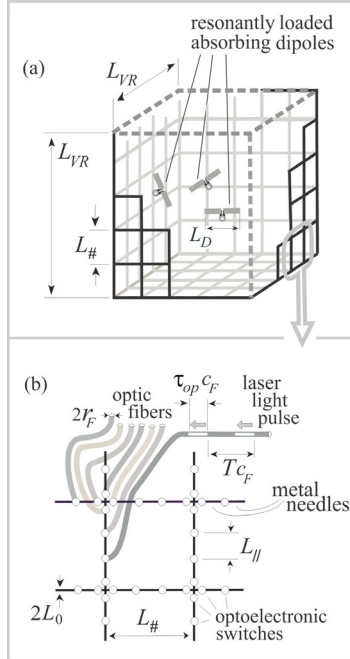


Figure 3: The construction of virtual resonator (a) and its wall (b) (-light speed in fiber).

Cyclical Wave-Bolt

As a prototype of the structure presented in Figure 2d, Figure 2e we consider briefly a one-dimensional structure (“cyclical wave-bolt”[3]), which is a train of walls of controlled transparency (with a thickness L_0 and ideally controlled reflection coefficient $R_w(t)$, i.e. $|R_w|_{tr} = 0$, and $|R_w|_{op} = 1$), which are equidistant (with a spatial period $L_{VR} \ll L_0$) located in the path of the incident wave. Any two adjacent walls of controlled transparency are a virtual resonator with length L_{VR} and own frequencies $\omega \geq c\pi / L_{VR}$. Figure 4 shows the parameters of the “one-dimensional” absorbing shell: the placement of the walls in space (Figure 4a); the modulus of the reflection coefficient of one wall as a function of time (Figure 4b); estimate [3] of the minimum average over the period of the modulus of the reflection coefficient (Figure 4c).

$$|\Gamma| \leq \ln(A) / A, \quad (4)$$

with

$$\tau_{op} / \tau_{tr} = \ln(A) / A \ll 1, \quad (5)$$

where

$$A = (M_x / M_t) \alpha, \quad (6)$$

$$M_t = T / \tau_{op} \gg 1 \quad (7)$$

is the microstructuring coefficient in time,

$$M_x = L / L_{VR} \gg 1 \quad (8)$$

is the microstructuring coefficient in space, is the decay damping factor of a wave over a single path across the resonator (until we specify the damping mechanism (wave absorption by walls, leakage high-frequency field components through the resonator walls, wave absorption in the cavity environment, wave absorption by resonator dipoles, etc.).

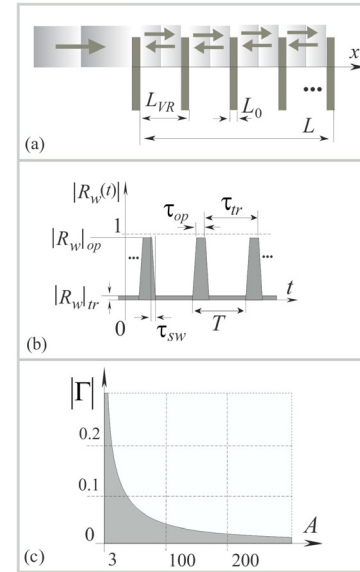


Figure 4: Spatial placement of walls of controlled transparency (a), modulus of reflection coefficient of each wall (b), modulus of temporally averaged reflection coefficient of cyclical wave-bolt (c).

Transparency–Reflection

Below we consider the possible characteristics of the walls of transparency controlled.

Reflection

Good reflection of the wall for wavelength $\lambda \sim L_{VR} / 2$ is necessary to make the waves to run many times inside the virtual resonator through the absorbing dipole, converting wave energy into heat. Let any flat linearly polarized electromagnetic wave (with electric vector \mathbf{E}_i , magnetic vector \mathbf{H}_i and propagation vector \mathbf{W}_p ($|\mathbf{w}_i| = 1$) and wavelength λ) normally fall on a flat infinite array of equidistantly spaced (with a period L_{\parallel}) infinite parallel metal wires (with radius L_0 , Figure 5a) and wave's electric vector \mathbf{E}_i is parallel to wires (Figure 5a). When $L_{\parallel} / \lambda < 1/4$ and $(L_{\parallel} / \lambda) \ln(L_0\pi / L_{\parallel}) \ll 1$ (with uncut wires), the reflection coefficient of the incident wave from such array is close to unity, so this array becomes equivalent to metal plane (this allows the use of metal grids as radar reflectors). Since the array (wall) must reflect the waves inside the resonator, we accept $\lambda = L_{VR} / 2$ and obtain the following condition of good reflection from array

$$|1 - |R_w|_{op}| \approx 2(L_{\parallel} / L_{VR}) |\ln(L_0\pi / L_{\parallel})| \ll 1 \quad (9)$$

In other words, a good reflection means that the current $J_{\#0}$ in one wire of the grid is equal (close) to the current in the strip with the width of the metal plane (Figure 5a).

Transparency

The transparency of the walls is necessary for the free penetration

of the external wave field into the parameter modulation zone **L**. When the optoelectronic switches becomes simultaneously “switched on” in a short time τ_{sw} , this is equivalent to the “instantaneous and simultaneous metallization” of the faces of polyhedrons (or walls of virtual resonators). In the approximation of above well-reflecting grid of wires, the following phenomenon takes place: decreasing of $L_{\#}$ leads to decreasing of current $J_{\#0}$, as if the conductors “know” what current is needed for good reflection. This is due to the interaction of wires (essentially adjacent wires, interaction parameter $\vartheta \rightarrow \pi$, Figure 5a). On the other hand, the incident wave excites in a solitary metal wire a current J_0 , which is $\sim (\lambda / L_{\#}) / |\ln(L_0 \pi / \lambda)|$ times less than the current $J_{\#0}$ in each linear wire in the grid (Figure 5b). And it also points to the interaction of wires in the grid. In other words, the wires are reflected in each other (creating a lot of images) like cylindrical mirrors. Thus, by breaking the mirrors (metal wires) into many small pieces (by simultaneous “switching off” the optoelectronic switches), we will make the images small and their interaction insignificant: as a result, the incident wave creates a current in the grid of lumped wires (interaction parameter $\vartheta \leq L_{\parallel} / L_{\#} \ll 1$, Figure 5-c) that is close to the current in a solitary lumped wire (Figure 5d). The transparency of the walls is necessary at the frequency of the incident wave, on which the metal structure of the virtual resonator wall responds quasistatically (Figure 5d), and we get the upper estimate of the reflection coefficient:

$$|R_w|_{tr} \leq (L_{\parallel} / L_{\#}) C_{sw} \omega_{max} \sqrt{\epsilon_0 / \mu_0} \ll 1 \quad (10)$$

where C_{sw} is pass-through capacitance of optoelectronic switch, ϵ_0 and μ_0 are the electric and magnetic constants of vacuum correspondingly, ω_{max} is maximum frequency of incident waves (see section 1).

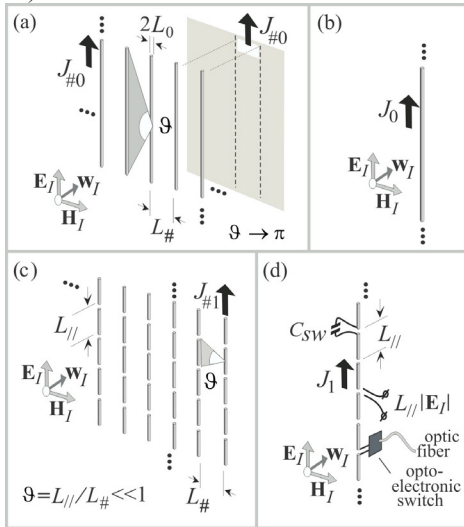


Figure 5: Excitation by a falling plane wave of currents in metal wires.

Optic Fibers

For a certain characteristic wavelength λ_F of laser light in a fiber (for example, $\lambda_F = 6.5 \times 10^{-7} \text{m}$), the condition of a lot of periods of a light wave on the switching interval is necessary (switching occurs after a change in the time average laser intensity)

$$c_F \tau_{sw} \gg \lambda_F \quad (11)$$

(where c_F is the speed of light in the fiber) and the conditions of multiple wavelengths of light on the fiber radius r_F (single mode in the fiber)

$$c_F / \lambda_F > 3 \quad (12)$$

Airiness inside the virtual resonator

Metal wires of arbitrarily small thickness and length are capable of generating an undesirable field with a cross-sectional size far exceeding the geometric dimensions of the conductor. Therefore, to control the switches selected glass optical fibers. Glass parts create a field of scattering proportional to only the relative average volume of the glass (relative to the air volume of the resonator $\sim L^3_{VR}$ in the ideal). To power the optoelectronic switches, you can also use the time-average level of light intensity in the fiber. However, it is necessary to require that the relative volume of glass in the resonator should be small, i.e.

$$(\Delta V / V)_F \approx 12\pi r_F^2 / (L_{\parallel} L_{VR}) \ll 1 \quad (13)$$

where $r_F \approx 3.5 \times 10^{-6} \text{m}$ - characteristic radius of one-mode optic fiber. All fibers inside the resonator have the same length so that the switches should be triggered simultaneously. Now we require the smallness of relative total volume of all smallest metal details (of length L_{\parallel} and radius L_0) in VR, i.e. the condition:

$$(\Delta V / V)_M \approx 12\pi L_0^2 / (L_{\#} L_{VR}) \ll 1 \quad (14)$$

Plasmonic aspects

The considered model uses ultra-fast operations with metal pieces. We assume that it is possible to set (during the time much smaller then τ_{sw}) classical boundary condition on the metal surface (zero of the tangential component of the electric field). But at arbitrarily high switching frequencies, the properties of the electrons of a metal as a gas may enter the game. Therefore, we need to formulate the conditions under which the switch would represent a sequential change in time of the static charge distributions on the metal surface. At 300⁰ Kelvin, the characteristic Maxwell’s relaxation time of some perturbed charge distribution in the metal to the equilibrium distribution is $\tau_M = 1.25 \times 10^{-15} \text{s}$, and the plasma wavelength in the metal is $\lambda_p \approx 4 \times 10^{-7} \text{m}$. Thus, to ensure the static nature of processes in metal elements with a length L_{\parallel} , the following conditions must be met:

$$\tau_{sw} \gg \tau_M, L_{\parallel} \gg \lambda_p \quad (15)$$

Conclusion

Thus, having satisfied conditions (5), (9)-(15) together (based on high space-time resolution technologies) conditions (1)-(3) can also be jointly satisfied. Absorbing elements of the parametric shell (virtual resonators) do not interact through the wave field (unlike the systems with parameters constant in time) and this guarantees the uniformity of absorption in frequency ω_I and direction w_I of the incident wave. The above model under consideration is a problem with initial conditions (time representation, ultrawideband), because traditional representation of the problem by complex amplitudes leaves this solution out of sight. The described parametric system is passive, since the right-hand sides of the boundary conditions and the wave equation are zero. Parametric control of structure can’t add instability (can’t add

energy to wave field) because we control the dissipative parameter – switch's conductivity. We called the above structure covering material of thickness L , because: (a) the structure is homogeneous both in composition (virtual resonators) and in the type of control (simultaneous switching) and breakdown of any several elements does not entail the inefficiency of the whole structure, (b) any part of this structure of size $D > L$ (if $A \gg 1$ and $\ln(A)/A \ll 1$) save its same absorbing properties. This article presents the brief evolution of ideas about a completely absorbing black body: from the pinhole camera (where black is only a small hole in a relatively large cavity with multiple reflections) to a parametric version of a black body (with virtual resonators for multiple reflections). The parametric version of the black body, based on the miniature and quickness of the structure, provides the possibility of multiple reflections for

absorption, similar to ancient pinhole camera (virtual resonator is analog of pinhole camera's cavity). And the virtual resonator (as the main functional element of above structure) is some special nano-electronic chip which does not process signals, but is a direct participant in wave processes.

References

1. Aviation Week and Space Technology. 1970; 92: 201.
2. Cheng Q, Cui TJ, Jiang WX, et al. An electromagnetic black hole made of metamaterials. Arxiv Org. 0910.2159v2, 2010.
3. Arabadzhi V. Solutions to Problems of Controlling Long Waves with the Help of Micro-Structure Tools. Bentham Science Publishers Ltd. 2011; 69-85.