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PRESSURE OF ELECTROMAGNETIC RADIATION ON A LINEAR VIBRATOR†

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Nowadays the pressure of electromagnetic radiation in the optical range is widely used in laser traps (so called optical tweezers or single-beam gradient force trap) to control the position of microparticles, biological cells and other microscopic objects. This is possible by focusing the laser radiation into the area of several micrometers in size. The intensity of the radiation in the area is sufficient to hold particles in the beam and manipulate them. We are interested to research similar possibility in the microwave range of wavelengths. However we had faced a number of difficulties in this range: the size of the focal region is much larger, the radiation intensity is less, and to control microscopic objects by means of radiation pressure very high powers are required. And we decided to consider the known effect of a very strong interaction of thin conducting fibers (metal, semiconductor, graphite) with microwave radiation. The efficiency factor of radiation pressure on such objects reaches values of several hundreds and thousands. This can be used to control objects in the form of electrically thin metal conductors by means of radiation pressure. Methods for calculating the pressure of electromagnetic radiation on an infinitely long circular cylinder are known. In this paper we propose a method for calculating the radiation pressure on a circular cylinder (vibrator), the length of which is comparable to the radiation wavelength. We have found out that when the vibrator length is close to half the wavelength, the radiation pressure efficiency factor is much larger than for an infinite cylinder. We have obtained the dependence of the radiation pressure efficiency factor on the length and diameter of an absolutely reflecting and impedance vibrator. It decreases with decreasing conductivity. An infinite cylinder at a certain value of conductivity has a maximum of the radiation pressure efficiency factor.
Key words: microwave radiation, thin conductors, impedance vibrator, radiation pressure.
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Electromagnetic radiation presses on an object located in free space with the force determined by the following formula

$$F = \frac{P}{c} Q_{pr}, \tag{1}$$

where P is the power of the radiation that hits the object, c is the speed of light, Q_{pr} is the efficiency factor for radiation pressure. For a completely absorbing body $Q_{pr} = 1$ and for a reflecting plane $Q_{pr} = 2$. The radiation pressure on objects of a more complex shape (a sphere, a cylinder, an ellipsoid, a linear vibrator) can be found in two ways:

1. Having solved the problem of diffraction of an electromagnetic wave on an object (having found the distribution of fields in the object vicinity) and having calculated the forces and moments of forces acting on the object by the help of the Maxwell tension tensor. This method was first used by P. Debye in 1909 in his work on the pressure of light on a sphere [1], and then by G. Thilo in 1920 in his work on the pressure of light on an infinite circular cylinder [2]. They both had got the expressions for the radiation pressure efficiency factors in the form of series, the terms of which are expressed through the Bessel and Hankel functions.

2. Having found the strength of the currents interaction in an object with magnetic field in its vicinity. This method seems to be simpler, since it is related to the well-known problems on currents arising in a receiving linear antenna, but in fact it still requires solving the problem of wave diffraction on the antenna.

The problem on a linear vibrator of finite length is three-dimensional, in contrast to the two-dimensional problem for an infinite cylinder, and was actively researched in the middle of 20th century during the period of intensive development of radiolocation. The results of its solution for the cross section of radar scattering were obtained in a series of papers [3-5] and the book [6] summarizing them. Scattering by a thin conductor and the cross section of radar scattering were researched in These works. The authors have considered the cases when the vibrator length did not exceed the radiation wavelength. The distribution of currents induced in the conductor by the field of the incident plane wave was found through an approximate solution of the integral equation. The main term in the obtained solution was substituted into the integral that determines the electric field in the far zone, and the value of the backscattering cross section was calculated. The methods used by the authors differed mainly in the form of used zero approximation for the current and in the methods of subsequent calculation of the integrals. The results obtained through these methods are consistent with each other and with the results of experiments with vibrator lengths not exceeding one wavelength [7,8]. For longer vibrators zero approximation for currents is not sufficient. In [6] the authors had expanded the field of

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application of the theory onto vibrators with a length of several wavelengths by complex calculations, which are essentially equivalent to the usage of currents expressions with an accuracy of the first order. We did not found any published results of further researches in recent time.

Difficulties in solving these problems are created by the vibrator edges causing the reflection of currents from them. The solution of some problems of diffraction by such objects is given in [9, 10]. In books on antenna theory the problems of calculating currents in a receiving antenna are considered [11, 12]. But as a rule, only electromotive force at the antenna output is determined in them. The case closest to ours is considered in the paper [13] where a method for the numerical solution of the problem of electromagnetic scattering on a thin dielectric cylinder of a finite length is proposed and the results of numerical calculations are presented. To facilitate the solution of the problem, it was assumed that there are spherical rounding at the ends of the cylinder reducing the reflection of the wave.

In [14] the authors had proposed to use the results of problem solution of the electromagnetic wave diffraction on an ellipsoid. In [15-17], the problems of radiation pressure and torques acting on ellipsoids and systems of ellipsoids located in a rectangular waveguide are considered. These problems have been solved by the authors during the development of ponderomotive microwave measuring devices. Limitation in them is the condition of smallness of the size of objects in comparison with the wavelength.

The paper [18] analyzes the magnitude of the ponderomotive action of a plane electromagnetic wave on a thin vibrator with weakly perturbed surface impedance. The currents in the vibrator were calculated by the methods given in [19]. When solving the integral equation for the current in the vibrator the authors took into account the disturbances in the impedance distribution by averaging its value over the vibrator length. During the simulation the vibrators with distributed reactive impedance were researched. It is shown that such impedance scatterers experience a lower wave pressure force under resonance conditions than ideally conducting vibrators.

Below we will be using the results obtained in the mentioned papers.

Research is underway on the use of radiation pressure in technology. In work [20] studies micromachines, in [21] studies laser material processing. The features of the radiation pressure in thin films are studied in [22].

PONDEROMOTIVE FORCE ACTING ON THE VIBRATOR

The geometry of the problem is shown in Figure 1. A plane wave is incident on a thin vibrator with a length of $2L$ in the direction opposite to the direction of the Oz axis:

$$E_y = E_0\, e^{ik_1 z}, \qquad H_x = -\frac{E_0}{Z_0} e^{ik_1 z}$$

where k_1 is the wave number for the surrounding space, E_0 is the electric field strength of the incident wave, Z_0 is the wave impedance of free space.

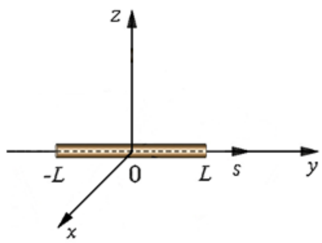

Figure 1. Geometry of the problem

The force f acting on a conductor element of length ds in a magnetic field with an intensity H, through which an electric current J flows, is determined by the following formula:

$$f(s) = \frac{1}{2}\mathrm{Re}\left\{J(s)\cdot \mu_0 H^*\right\} ds\,. \tag{2}$$

Expressions for the current and magnetic field are complex:

$$J(s) = J_0\, e^{i(\psi+\omega t)}, \quad H = H_0 e^{i(k_1 z+\omega t)}\,.$$

Here J_0, H_0 are modulus of the complex quantities J and H, ψ is the argument of the complex expression for the current, the * sign denotes the complex conjugate quantity. Having substituted them in (2) we obtain

$$\begin{aligned} f(s) &= \frac{1}{2}\mathrm{Re}\left\{J_0\, e^{i(\psi+\omega t)}\cdot \mu_0 H_0{}^{-i(k_1 z+\omega t)}\right\} ds = \frac{\mu_0 H_0}{2}\mathrm{Re}\left\{J_0\, e^{i(\psi-k_1 z)}\right\} ds = \\ &= -\frac{\mu_0 E_0}{2Z_0}\mathrm{Re}\left\{J_0\, e^{i(\psi-k_1 z)}\right\} ds \approx -\frac{\mu_0 E_0}{2Z_0}\mathrm{Re}\left\{J_0\, e^{i\psi}\right\} ds = -\frac{\mu_0 E_0}{2Z_0}\mathrm{Re}\left\{J(s)\right\} ds \end{aligned} \tag{3}$$

The force acting on the vibrator can be obtained by integrating expression (3) along the *Oz* axis along the vibrator:

$$F = -\frac{\mu_0 E_0}{2Z_0} \int_{-L}^{L} \mathrm{Re}\{J(s)\} ds \tag{4}$$

The reader can see that it depends only on the real part of the current in the vibrator.

Having calculated the force *F*, we can use expression (1) to find the efficiency factor of the radiation pressure:

$$Q_{pr} = \frac{F\,c}{P}. \tag{5}$$

Vibrator current

In order to use formula (4) to calculate the force with which the radiation presses on the vibrator, we need to find the distribution of the current along the vibrator. The needed expression was obtained in [21]:

$$J(s) = \alpha \frac{i\omega E_0}{k\tilde{k}} \left\{ 1 - \cos\tilde{k}(s+L) - \frac{\sin\tilde{k}(s+L) + \alpha P^s(s)}{\sin 2\tilde{k}L + \alpha P^s(L)} \left(1 - \cos 2\tilde{k}L\right) \right\}, \tag{6}$$

where *s* is the coordinate directed along the vibrator. The expression includes:

$$P^s(s) = \int_{-L}^{s} \left[\frac{e^{-ikR(s',-L)}}{R(s',-L)} + \frac{e^{-ikR(s',L)}}{R(s',L)} \right] \sin\tilde{k}(s-s') ds',$$

$\alpha = \frac{1}{2\ln[r/2L]}$ is a small parameter, E_0 is the electric field amplitude of incident wave, $R(s',s) = \sqrt{(s'-s)^2 + r^2}$, $\tilde{k}^2(s) = k_1^2\left[1 + i\alpha\omega\varepsilon_1 z_i(s)/k_1^2\right] = k_1^2\left[1 + i2\alpha\bar{Z}_S(s)/(\mu_1 kr)\right]$, $z_i(s)$ is resistance per unit length, Ω/m, $\bar{Z}_S(s) = 2\pi r z_i(s)/Z_0$, $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\ \Omega$ is the wave impedance in free space, $k_1 = k\sqrt{\varepsilon_1\mu_1}$, $k = 2\pi/\lambda$, is wavelength in free space, λ is circular frequency.

Expression (6) is valid for vibrators with a length of less than λ. It is written in the Gauss system of units. Therefore, before using formula (4) to calculate the ponderomotive force, the values of the electric field E_0 and the current *J*(*s*) must be converted to SI. It is reasonable to calculate the value of $\tilde{k}(s)$ directly in SI units.

Radiation pressure on an absolutely reflective vibrator

For an absolutely reflecting vibrator, $z_i(s) = 0$. Figure 2 shows the dependence of the efficiency factor of radiation pressure with a wavelength of 8 mm on an absolutely reflecting vibrator on the length of the vibrator for several diameters, calculated according to formulas (1) - (6). The abscissa shows the values of 2*L*/λ; the ordinate indicates the radiation pressure efficiency factor Q_{pr}.

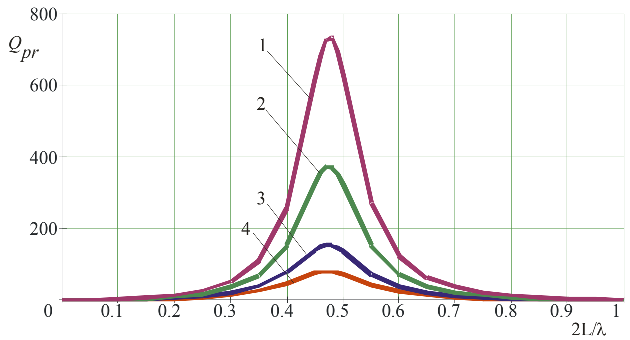

Figure 2. Dependence of the efficiency factor of radiation pressure on an absolutely reflecting vibrator on its electrical length and diameter 1 – *D* = 10 μ, 2 – *D* = 20 μ, 3 – *D* = 50 μ, 4 – *D* = 100 μ

The following features are visible:

1) There is a resonance at which the radiation pressure rises strongly. It occurs when the vibrator length is slightly less than half the wavelength (2*L*/λ = 0.48)

2) When the length of the vibrator is equal to the wavelength (2*L*/λ = 1) the radiation pressure is zero.

For the comparison, we took the graph (Figure 3) from [9], which shows the dependence of the effective cross-section of backscattering σ_l of a linear vibrator on its length. The solid line is calculation results; dots are experimental data.

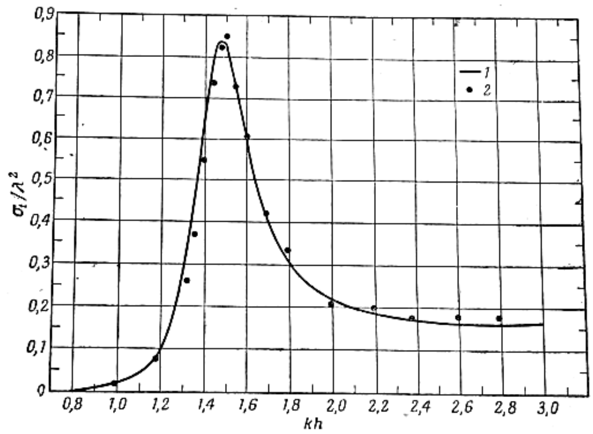

Figure 3. Dependence of the effective cross-section of backscattering of a linear vibrator on its length

The vibrator is a steel-silvered rod with a radius of 0.35 mm. The wavelength of radiation is 10 cm.

There is a resonance at $kh = 1.5$, where h is a half of the vibrator length, therefore, $2h/\lambda = 0.48$. It coincides with the resonance condition for the radiation pressure. This is normal, since the radiation pressure depends on the magnitude and direction of the scattered field.

The backscattering efficiency factor defined as the ratio of the effective backscattering cross section to the vibrator geometric cross section is

$$Q_{rev\,sca} = \frac{\sigma}{S} = 253.$$

The radiation pressure efficiency factor calculated from the vibrator data is

$$Q_{pr} = 121.$$

These values are of the same order of magnitude, which confirms the correctness of the method for calculating the radiation pressure.

But it can be seen in Fig. 3 that for vibrator length equal to the radiation wavelength, the effective cross-section of backscattering is not zero. This is probably due to the fact that the current calculation method can only be applied to vibrators whose length is shorter than the wavelength.

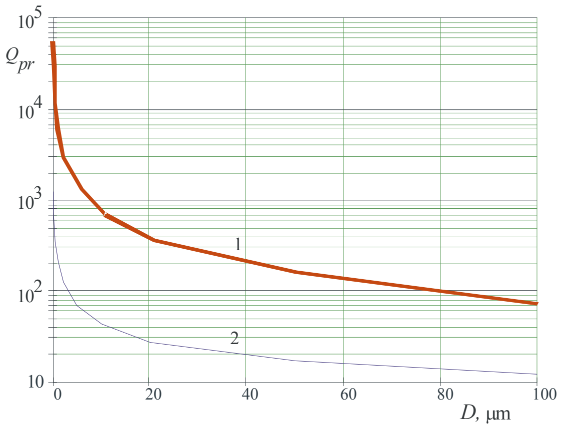

Figure 4. Dependence of the efficiency factor of the radiation pressure on the vibrator on its diameter
1 - half-wave vibrator, 2 - electrically long vibrator

Figure 4 shows the dependencies of the efficiency factor of radiation pressure on an absolutely reflecting vibrator on its diameter. Curve 1 shows the dependence for a half-wave vibrator at a resonance; curve 2 shows the dependence for an infinitely long cylinder of the same diameter.

Curve 2 is plotted by means of the approximate formula for an E-polarized wave [23]:

$$Q_{pr} = \frac{\pi^2}{2\rho(\ln\rho)^2},$$

where $\rho = \pi D/\lambda$.

The formula can be obtained when only the first terms of the series for the radiation pressure efficiency factor [2] and the Bessel and Hankel functions are taken into account.

Both curves in Figure 4 show that the radiation pressure efficiency factor grows indefinitely when vibrator diameter decreases.

The fact that the efficiency factor of the radiation pressure on the vibrator increases when its diameter is reducing does not mean that the force acting on the vibrator increases. The power of the radiation incident on the vibrator decreases. Figure 5 shows the dependence of the force on the diameter, calculated under the following conditions: I = 40,000 W/m^2 is the average radiation intensity at the output of a waveguide with a cross section of 7.2×3.4 mm at a power of 1 W, $2L$ = 4 mm is the vibrator length, $\lambda = 8\ mm$ mm is the radiation wavelength.

The acting force is determined by the formula

$$F = \frac{PQ_{pr}}{c} = \frac{2IDLQ_{pr}}{c}$$

The reader can see that the force acting on the vibrator tends to zero when the diameter is decreasing, although the radiation efficiency factor increases indefinitely.

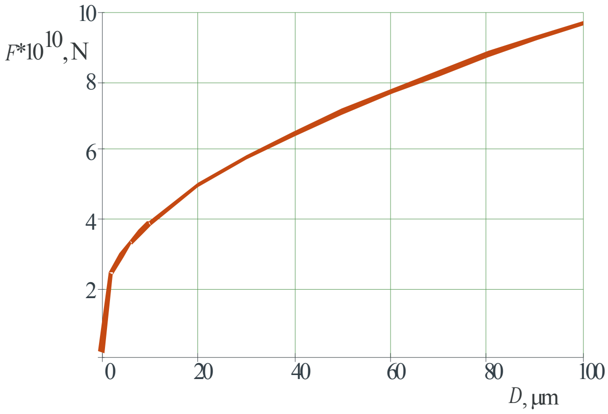

Figure 5. Dependence of the force acting on the vibrator on its diameter

Surface impedance of the vibrator

The surface resistance of metal has an inductive character and is determined by the following expression [24]:

$$Z = \sqrt{\frac{\pi c \mu_0}{\lambda\sigma}}(1+i), \tag{7}$$

where σ is the electrical conductivity of metal. Units for the surface resistance are Ω/m^2. The surface resistance of copper (σ = 5.8×10^7 1/(Ω×m)) at a wavelength of 8 mm equals to Z = 0.0505 (1 + i) Ω/m^2.

We had defined the surface resistance of the vibrator per unit length z_i in the following manner: a square on the surface of a round conductor of radius r has a side equal to 2πr. Thus, a vibrator with a length of 2πr has a resistance defined by formula (7). Then the surface resistance of the vibrator per unit length is equal to

$$z_i = \frac{Z}{2\pi r}.$$

For a copper vibrator with a radius of r = 50 μm at a wavelength of 8 mm

$$z_i = 161\ (1+i)\ \Omega/\text{m}.$$

The expression for the current in the vibrator includes the parameter

$$\tilde{k} = k_1\sqrt{1 + i\frac{2\alpha \bar{Z}_s(s)}{\mu_1 kr}},$$

where $k_1 = k\sqrt{\varepsilon_1 \mu_1}$, $k = 2\pi/\lambda$ = 786m^{-1}, ε_1, μ_1 are relative dielectric and magnetic permeabilities of the environment ($\varepsilon_1 = 1$, $\mu_1 = 1$),

$\alpha = \dfrac{1}{2 ln\dfrac{r}{2L}} = -0.114$ at L =2 mm ($2L/\lambda = 0.5$).

$\bar{Z}_s(s) = \dfrac{2\pi r z_i}{Z_0} = 0.000134(1+i)$

$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi$ Ω is the wave impedance in free space.

We have obtained:

$$\tilde{k} = 786 - 0.306i \ \text{m}^{-1}, \tag{8}$$

The reader can see that the difference from $k_1 = k = 786$ m^{-1}, which is characteristic of an absolutely reflecting vibrator when $z_i = 0$, is very small. This is normal, since the conductivity of copper is very high and its reflection coefficient at a wavelength of 8 mm differs little from 1.0 (approximately 0.999).

Radiation pressure on the impedance vibrator

We had explored the impact of the conductivity of the vibrator material on the radiation pressure. We have found out that the radiation pressure on the copper vibrator, with an accuracy of tenths of a percent, coincides with the radiation pressure on the absolutely reflecting vibrator. But when the length of the vibrator is equal to the wavelength, the efficiency factor of the radiation pressure on the copper vibrator is not zero, while being a very small value. For a vibrator with a diameter of 10 microns, it is approximately 0.0004.

We had made the comparison of the radiation pressure on an infinitely long cylinder calculated by the formulae [2] (Fig. 6), and the radiation pressure on a half-wave vibrator calculated by the formulae given in the actual paper (Fig. 7). It is can see that for vibrator diameters larger than several micrometers, the radiation pressure on the absolutely reflecting vibrator and on the copper vibrator are almost equal. This is an expected result, since the radiation reflection coefficient with a wavelength of 8 mm from copper is approximately 0.999. Nevertheless, for diameters less than 2 microns, the radiation pressure on an infinite copper cylinder becomes greater than on an absolutely reflecting cylinder. At a certain diameter it reaches a maximum and then, with a decrease in the diameter, drops to zero. The maximum is a consequence of the effect of strong interaction of electromagnetic radiation with very thin cylinders, the diameter of which is comparable to the thickness of the skin layer in the cylinder material [23]. The efficiency factor of the radiation pressure on an absolutely reflecting cylinder increases indefinitely with a decrease in its diameter.

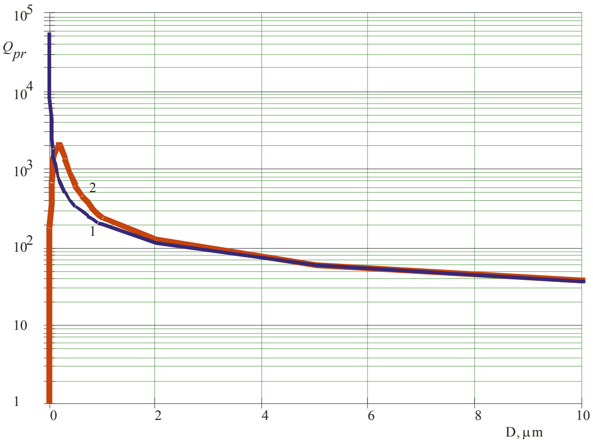

Figure 6. Dependence of the radiation pressure efficiency factor on an electrically long vibrator on its diameter
1 - absolutely reflective vibrator, 2 - copper vibrator

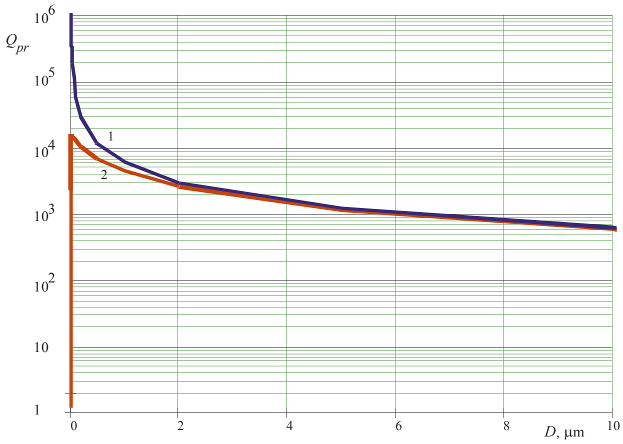

Figure 7. Dependence of the radiation pressure efficiency factor on a half-wave vibrator on its diameter
1 - absolutely reflective vibrator, 2 - copper vibrator

The calculation results for a half-wave vibrator are different (Fig. 7). The radiation pressure efficiency factor for a copper vibrator is always less than the one for an absolutely reflective vibrator. The maximum pressure exists, but at extremely small diameters of thousandths of a micrometer. For such diameters, the calculations we have presented above may be incorrect because in this range of sizes and at larger diameters the physics of the processes may differ.

It is likely that the difference in the dependences of the radiation pressure on the long vibrator and half-wave vibrator on the diameter is explained by the limitations on the method for calculating the current in the vibrator.

We had examined the dependence of the radiation pressure efficiency factor on the conductivity of the vibrator material and the type of impedance (inductive or capacitive). We have assumed that the values of the real and imaginary parts of the impedance in both cases were determined by formula (7), and its type is determined by the sign in front of the imaginary part. Figure 8 represents the dependencies for a vibrator with a diameter of 10 μm. Curves 1 and 2 show that when the conductivity decreases the efficiency factor of the radiation pressure decreases too regardless of the conductivity nature. For a vibrator with capacitive impedance, the radiation pressure efficiency factor is slightly higher than for a vibrator with inductive impedance. Dots on the curve 1 represent different materials. The radiation pressure efficiency factor is much less for an infinitely long metal cylinder than for a resonant half-wave vibrator. It also decreases when the conductivity is decreasing. But at some of conductivity value, there is a maximum which is caused by the effect of strong interaction of thin conductive fibers with microwave radiation. There is no such maximum on the graphs for a half-wave vibrator.

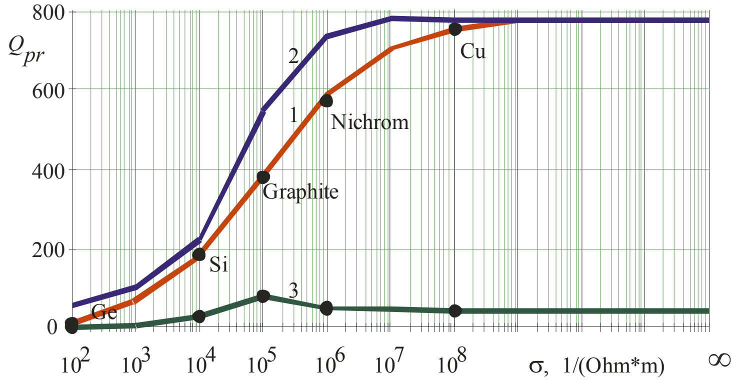

Figure 8. Dependence of the efficiency factor of the radiation pressure on the conductivity of the vibrator (diameter 10 μm)
1 - Inductive half-wave vibrator, 2 - capacitive half-wave vibrator, 3 - infinitely long metal cylinder

Figure 9 shows the same dependences but for a vibrator with a diameter of 100 μm. Their shape is the same as in Figure 8, but the values of the radiation pressure efficiency factor are much less, and the position of the maximum for an infinitely long cylinder is different. This can be explained by the fact that the condition for the maximum is the approximate equality of the cylinder diameter and the thickness of the skin layer in it [23].

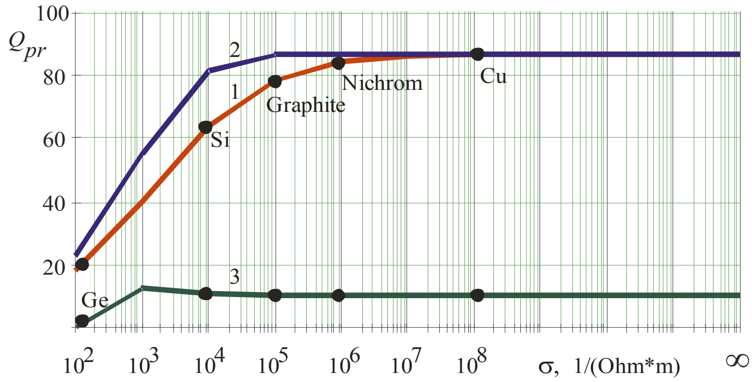

Figure 9. Dependence of the efficiency factor of the radiation pressure on the conductivity of the vibrator (diameter 100 μm)
1 - inductive half-wave vibrator, 2 - capacitive half-wave vibrator, 3 - infinitely long metal cylinder

CONCLUSIONS

1. We have proposed a method for calculating the efficiency factor of radiation pressure on an impedance linear vibrator, the length of which does not exceed the radiation wavelength.

2. We have found out that the resonance occurs when the length of the vibrator is close to half the wavelength. The radiation pressure efficiency factor reaches values tens of times larger for an infinitely long cylinder of the same diameter. With a vibrator length equal to the wavelength, the radiation pressure efficiency factor is very small, and for an absolutely reflecting cylinder it is equal to zero.

3. We have established that with a decrease in the diameter of an impedance vibrator of a finite length, the radiation pressure efficiency factor increases indefinitely, in contrast to an infinite cylinder of the same diameter, in which it reaches a certain maximum, and then decreases to zero. The maximum is explained by the existence of the effect of strong interaction of very thin conducting fibers with electromagnetic radiation.

4. We have discovered that an increase in the efficiency factor of radiation pressure on thin vibrators does not mean an increase in the force with which radiation presses on them. This is due to the fact that with a decrease in the diameter, the energy of the radiation hitting the vibrator decreases, and the force decreases too.

5. We have detected that with a decrease in the conductivity of an impedance vibrator of a finite length, the radiation pressure decreases monotonically, regardless of the type of the impedance (inductive or capacitive). The radiation pressure on an infinitely long cylinder reaches a maximum in a certain region, which is explained by the existence of the effect of strong interaction of radiation with very thin conducting fibers.

6. To summarize the results of our research we want to say that the effect of large values of the radiation pressure efficiency factor on thin conductive vibrators can be used to levitate and control the movement of targets in the microwave range, similar to how it is done in the optical range with the help of lasers.

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ТИСК ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ НА ЛІНІЙНИЙ ВІБРАТОР

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В теперішній час тиск електромагнітного випромінювання в оптичному діапазоні широко використується в лазерних пастках (так званих оптичних пінцетах або однопроменевих градієнтних силових пастках), для управління положенням мікрочастинок, біологічних клітин та інших мікроскопічних об'єктів. Це можливо, завдяки фокусуванню лазерного випромінювання в область розміром в кілька мікрометрів. Інтенсивність випромінювання в ній є достатньою для утримання частинок у промені та маніпуляцій з ними. Ми вважаємо, що буде доцільно дослідити таку можливість й у мікрохвильовому діапазоні довжин хвиль. Однак, у цьому діапазоні розміри фокальної області набагато більші, інтенсивність випромінювання тут менша, і для управління малими об'єктами за допомогою тиску випромінювання необхідні дуже великі потужності. Ми вирішили використати відомий ефект дуже сильної взаємодії тонких провідних волокон (металевих, напівпровідникових, графітових) з мікрохвильовим випромінюванням. Фактор ефективності тиску випромінювання на такі об'єкти досягає значень у кілька сотень та тисяч. Це можна використовувати для керування об’єктами у вигляді електрично-тонких металевих провідників за допомогою радіаційного тиску. Відомий метод розрахунку тиску електромагнітного випромінювання на нескінченно довгий круговий циліндр. У цій статті ми пропонуємо метод розрахунку тиску випромінювання на круговий циліндр (вібратор), довжина якого порівняна з довжиною хвилі випромінювання. Ми з’ясували, що коли довжина вібратора близька до половини довжини хвилі, фактор ефективності тиску випромінювання набагато більший, ніж для нескінченного циліндра. Ми отримали залежність фактора ефективності тиску випромінювання від довжини та діаметра абсолютно відбиваючого та імпедансного вібратора. Він зменшується при зменшенні провідності. Нескінченний циліндр при певному значенні провідності має максимум фактора ефективності радіаційного тиску.

Ключові слова: мікрохвильове випромінювання, тонкі провідники, імпедансний вібратор, тиск випромінювання.