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PRESSURE OF ELECTROMAGNETIC RADIATION ON A THIN LINEAR VIBRATOR IN A WAVEGUIDE[†]

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The problem of electromagnetic wave pressure on a thin conductive vibrator located in a rectangular waveguide is solved. Wave H_{10} falls on the vibrator. The vibrator is located perpendicular to the wide wall of the waveguide. The current in the vibrator arising under the action of the electric field of the wave is calculated. The current distribution along the vibrator is almost uniform. The current in the microwave range depends little on the vibrator conductivity. Two components of the magnetic field - longitudinal and transverse exist in the H_{10} wave. When these components interact with the current in the vibrator, forces arise, acting on the vibrator across the waveguide and along it. The magnitude of the longitudinal force is greatest when the vibrator is located in the middle of a wide wall. It is almost 2 times greater than the force acting on the vibrator in free space at the same average radiation intensity, When the vibrator length is close to half the radiation wavelength, the force is maximum. The transverse force is determined by the interaction of the current in the vibrator with the longitudinal component of the magnetic field in the waveguide. It is maximum when the vibrator is located at the distance of ¼ of the length of the wide wall from its middle. If the length of the vibrator is less than half the wavelength of the radiation, the force is directed towards the axis of the waveguide, otherwise - in the opposite direction. The possibility of using microwave radiation pressure to create micromachines and to control the position of the vibrator in space has been evaluated. This requires a radiation power of several watts.
Keywords: electromagnetic wave, conducting vibrator, radiation pressure, waveguide, longitudinal force, transverse force.
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The pressure of electromagnetic radiation is one of the fundamental physical phenomena. Its use is an actual direction of modern optics, laser physics and electrodynamics.

The ability to control the movement of bodies using the pressure of light or other electromagnetic radiation was recognized as possible after the experiments of P.N. Lebedev, in which he measured the pressure of light on solids and gases. For a long time, it seemed that the smallness of the light pressure, in the words of J. Poynting "...excludes it from consideration in earthly affairs". The situation has changed with the appearance of lasers. This is due to the possibility of sharp focusing of the laser beam, when the diameter of the focal spot is comparable with the dimensions of the light wavelength.

A. Ashkin, 2018 Nobel Prize winner, proved that the light pressure produced by a laser beam is sufficient to capture, hold in a given place, levitate and move micron-sized particles [1]. The existence of a transverse force was also proved, which pulls the particle into the center of the beam. Based on these works, devices were subsequently developed to control the position and movement of microparticles – "laser tweezers" [2-4]. Technical applications of the ponderomotive action of microwave and optical radiation in metrology and the design of ponderomotive microwave power meters are described in the monograph [5].

Currently applied not only the pressure of the wave on the object, but also the occurrence of a torque in the case of waves polarized in a circle. It was shown in [6] that the laser beam can rotate the microparticles.

In the microwave range, the operation of objects with the help of radiation pressure meets with great difficulties. This is due to the fact that the diameter of the focal spot is comparable to the wavelength. In the microwave region, this size is about 1 cm. Objects of this size are difficult to hold by radiation pressure. And small part of the beam energy falls on small objects in the microwave beam, and therefore the mechanical action on them is weak. So, in order to obtain fields, the magnitude of which is sufficient to operation objects, very large radiation powers are needed.

But in this range, thin vibrator wires can be used as targets. It was shown in [7-9] that the scattering, absorption and pressure of electromagnetic radiation on conducting fibers, the diameter of which is much smaller than the wavelength, are very large. Figure 1 shows the dependences of scattering (dashed line), absorption (thin solid line), and radiation pressure (thick solid line) on the thickness of the nickel wire at a radiation wavelength of 10 cm. The abscissa axis shows the values of the wire diameter in micrometers, the ordinate axis shows the values of the scattering efficiency factors Q_{sca}, absorption Q_{abs}, and radiation pressure Q_{pr}. These parameters are often used to characterize the interaction between electromagnetic radiation and objects [10, 11].

The force with which radiation presses on an object is determined by the formula:

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$$F_{pr} = \frac{P}{c} Q_{pr} .$$

Here P is the power of the radiation that hit the object, c is the speed of light in the environment, Q_{pr} is the radiation pressure efficiency factor.

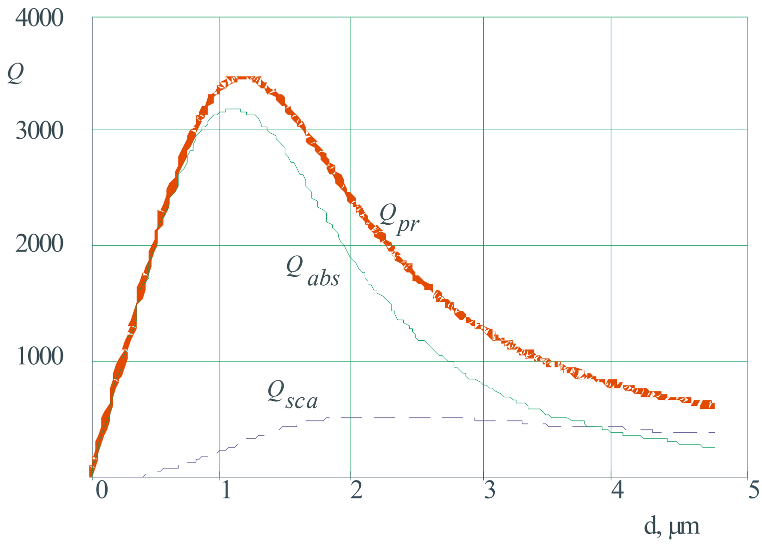


Figure 1. Efficiency factors of scattering, absorption, and radiation pressure on a thin metal wire

For a fully absorbent surface Q_{pr} = 1, for an absolutely reflective surface Q_{pr} = 2. Figure 1 shows that for a metal wire with a diameter of about 1 μm, the radiation pressure efficiency factor can reach very large values – up to several thousand. This can be used to levitate or move such objects in space.

Some new effects are observed in the interaction of electromagnetic radiation with vibrators of finite length. The pressure of a plane electromagnetic wave on a thin metal vibrator in free space was theoretically studied in [12]. When the length of the vibrator is close to half the wavelength of the radiation, resonance is observed, and the radiation pressure on this vibrator increases compared to the pressure on an infinitely long conductor. Radiation pressure efficiency factor increases with decreasing vibrator diameter.

The paper [13] describes an experiment on measuring the pressure of radiation with a wavelength of 8 mm on thin copper vibrators located in free space.

A vibrator in free space is subjected to a longitudinal force in the direction of propagation of the incident wave. If the vibrator is located in the waveguide, the configuration of the electric and magnetic fields near it is more complex than in free space. The direction and magnitude of the forces acting on it are different. Therefore, it is of interest to study such a case.

LINEAR VIBRATOR IN A RECTANGULAR WAVEGUIDE

The geometry of the problem is shown in Figure 2. A vibrator with a length of 2L is located in a rectangular wave-guide perpendicular to the wide wall. The wave type is H10, a and b are the lengths of the wide and narrow walls. The electric field vector in the H10 wave is parallel to the vibrator axis, the magnetic field lines are perpendicular to it.

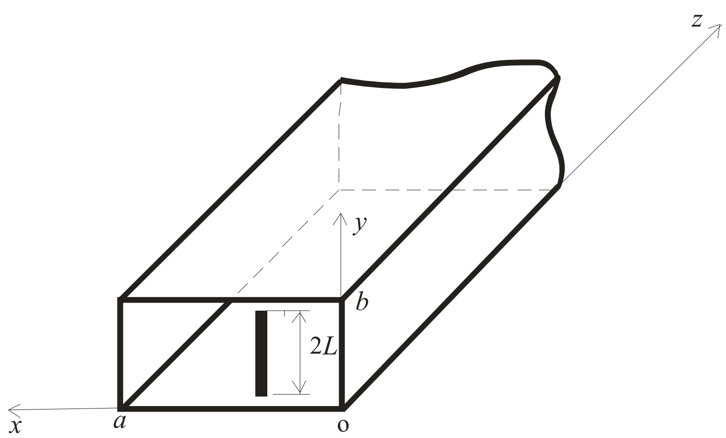


Figure 2. Vibrator in the waveguide

The fields in the waveguide are described by the following expressions:

$$E_y = E_0 \sin\left(\frac{\pi x}{a}\right)\exp(-ik_1 z),$$
$$H_x = -\frac{E_0}{Z_c}\sin\left(\frac{\pi x}{a}\right)\exp(-ik_1 z), \quad H_z = i\frac{\lambda_w}{\lambda_{kp}}\frac{E_0}{Z_c}\cos\left(\frac{\pi x}{a}\right)\exp(-ik_1 z). \tag{1}$$
$$k_1 = \frac{2\pi}{\lambda}, \quad \lambda_w = \frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{\lambda_{kp}}\right)^2}}, \quad Z_c = \frac{Z_0}{\sqrt{1-\left(\frac{\lambda}{\lambda_{kp}}\right)^2}}, \quad \lambda_c = 2a.$$

Here λ_w is the wavelength in the waveguide, λ_c is the critical wavelength.

The power of the wave propagating in the waveguide:

$$P_0 = \frac{1}{2}\mathrm{Re}\int_{S_0} E_y H_x^* dS = \frac{E_0^2}{4Z_c}ab. \tag{2}$$

Integration is performed over the cross-sectional area of the waveguide

The radiation intensity distribution along the x coordinate (wide wall of the waveguide) is as follows

$$I(x) = \frac{2P_0}{ab}\sin^2\frac{\pi x}{a}. \tag{3}$$

The strength of the electric field in the middle of a wide wall is:

$$E_0 = \sqrt{\frac{4P_0 Z_c}{ab}}. \tag{4}$$

Along a narrow wall (the coordinate y) the intensity of the wave does not change.

Two magnetic field components, H_x and H_z, exist in the waveguide with the H_{10} wave. Therefore, there are two components of the force acting on the vibrator – F_z and F_x.

In a waveguide with a wave H_{10}:

$$\vec{F} = \left(\vec{J}\times\vec{B}\right)\cdot 2L = 2L\mu_0\begin{vmatrix}\vec{i} & \vec{j} & \vec{k}\\ 0 & J_y & 0\\ H_x & 0 & H_z\end{vmatrix} = 2L\mu_0\left(\vec{i}J_y H_z - \vec{k}J_y H_x\right).$$

Force directed along the *z*-axis (longitudinal force):

$$F_z = -\frac{\mu_0}{2}\int_{-L}^{L}\mathrm{Re}\left\{J_y(s)\cdot H_x^*\right\}ds, \tag{5}$$

Force directed along the *x*-axis (transverse force):

$$F_x = \frac{\mu_0}{2}\int_{-L}^{L}\mathrm{Re}\left\{J_y(s)\cdot H_z^*\right\}ds \tag{6}$$

Electric current in the vibrator

The current in the vibrator is determined by the strength of the electric field in the wave incident on it, regardless of whether it is a plane wave in free space or an H_{10} wave in a waveguide. Therefore, to calculate the wave pressure on the vibrator in the waveguide, we will use the method of calculating the magnitude of the current in the vibrator, described in [12].

The current is determined by the following expression:

$$J(x,s) = \alpha\frac{i\omega E}{k\tilde{k}}\left\{1-\cos\tilde{k}(s+L) - \frac{\sin\tilde{k}(s+L)+\alpha P^s(s)}{\sin 2\tilde{k}L + \alpha P^s(L)}\left(1-\cos 2\tilde{k}L\right)\right\}\sin\left(\frac{\pi x}{a}\right). \tag{7}$$

It differs from the same expression in the work [12] by the factor $\sin(\pi x/a)$, which takes into account the change in the electric field strength along the wide wall of the waveguide.

Here:

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

$\alpha = \dfrac{1}{2\ln\left[r/(2L)\right]}$ is the small parameter ($\alpha \ll 1$),

E is the electric field of the incident wave at the location of the vibrator,

$$R(s',s)=\sqrt{\left(s'-s\right)^2+r^2},$$

$$\tilde{k}^2(s)=k_1^2\left[1+i\alpha\omega\varepsilon_1 z_i(s)/k_1^2\right]=k_1^2\left[1+i2\alpha\bar{Z}_S(s)/(\mu_1 kr)\right]$$

$z_i(s)$ is the linear resistance, Ohm/m,

$$\bar{Z}_S(s)=2\pi r z_i(s)/Z_0,\quad z_i=\frac{Z}{2\pi r},\quad Z=\sqrt{\frac{\pi c\mu_0}{\sigma\lambda}}(1+i),$$

$Z_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}$ = 377 Ohm is the wave impedance of free space, $k_1=k\sqrt{\varepsilon_1\mu_1}$ $k=\frac{2\pi}{\lambda_w}$, ε_1 and μ_1 are the relative dielectric and magnetic permeability of the environment, λ_w is the wavelength in the waveguide, ω is the circular frequency. Values *E, k, Z* are taken for the medium in the waveguide, $\varepsilon_1=1$, $\mu_1=1$.

Expression (7) is valid for vibrators with a length less than λ. It is written in the Gaussian unit system.

Calculations were performed for the case when radiation with a frequency of 37.5 GHz propagates in a rectangular waveguide (the wavelength in free space is 8 mm). A thin copper vibrator is located in the waveguide perpendicular to the wide wall.

The standard size of the cross section of such waveguide is:

$$a = 7.2\text{ mm},\ b = 3.4\text{ mm}.$$

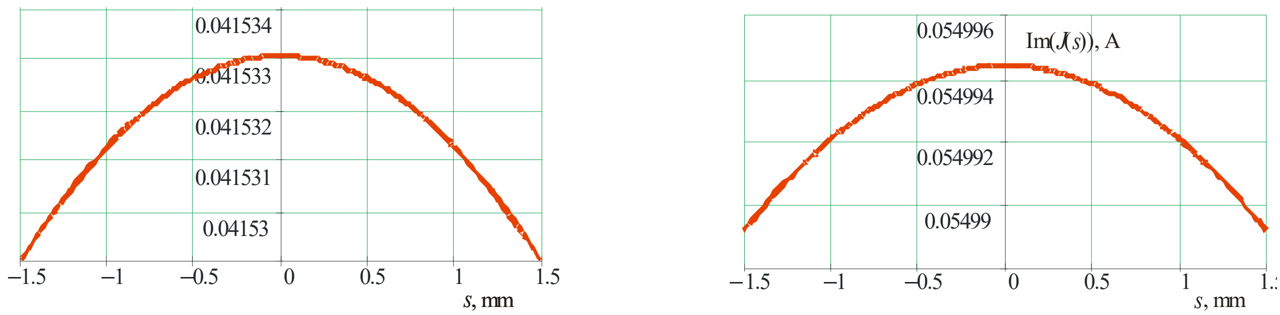
The wavelength in the waveguide is 9.62 mm. Therefore, assuming that the largest length of the vibrator is 3 mm, we can evaluate its properties for the largest relative length $2L/\lambda_w=0.312$.

In calculations, the transverse dimensions of the waveguide were taken as follows:

$$a = 7.2\text{ mm},\ b = 10\text{ mm}.$$

Higher types of waves can arise in such waveguide. But if you take measures against the occurrence of these waves, then you can evaluate the effect of the main type of wave on a vibrator with a relative length of up to $2L/\lambda_w=1$.

Figure 3 shows the distribution real and imaginary parts of the current along the vibrator by power 1 W. A copper vibrator with a diameter of 100 μm and a length of 3 mm is located perpendicular to the wide wall. The current value in amperes is shown for the case when the vibrator is located in the middle of a wide wall, at the maximum electric field.



a) b)

Figure. 3. The vibrator current
a – real part, b – imaginary part

The current distribution is uneven, with a maximum in the center. But the current changes are very small - in the sixth place after the decimal point. The average value of the current along the length of the vibrator is

$$J_{cp}=0.042+0.055i\ \ A$$

This current almost 2 times less than the current in the same vibrator and the same electric field in free space, where it is equal

$$J_{cp}=0.071+0.052i\ \ A$$

Figure 4 shows the dependences of the real and imaginary parts of the current in the vibrator on its length. The real part of the current has a maximum when the length of the vibrator is close to half the wavelength of the radiation. The imaginary part changes sign near the point $2L/\lambda_w=0.5$. The resistance of a short vibrator is inductive, while that of a long vibrator is capacitive.

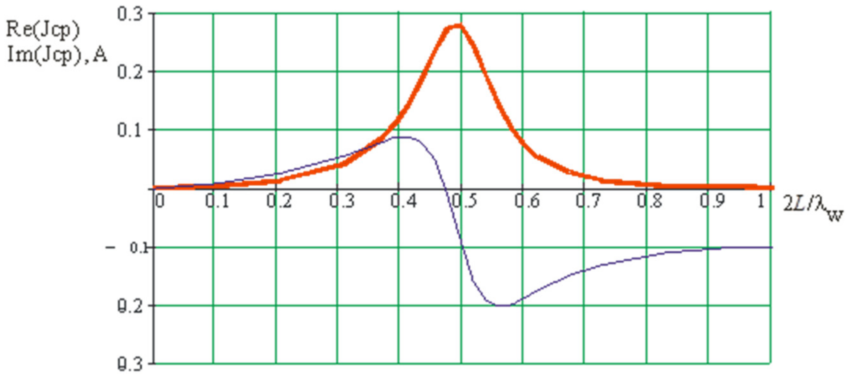


Figure 4. Dependence of the current in the vibrator on its length

Table 1 shows the current values in vibrators made of materials with different conductivity. Conductivity determines the value of the surface resistance *Z*, the thickness of the skin layer δ and current *J*.

Table 1. The dependence of the current in the vibrator on the conductivity of the material

Material	σ, 1/(Ohm·m)	*Z*, Ohm/square	δ, μm	*J*, *A*
Copper	$5.88\cdot10^7$	0.050 (1+*i*)	0.34	0.071+0.052*i*
Nickel	$1.45\cdot10^7$	0.103 (1+*i*)	0.68	0.077+0.057*i*
Platinum	$9.52\cdot10^6$	0.125 (1+*i*)	0.84	0.078+0.057*i*
Graphite	$1.4\cdot10^5$	1.028 (1+*i*)	6.95	0.080+0.053*i*

It can be seen that the current is almost independent of conductivity, which differ by more than 400 times. This is explained by the fact that with a decrease in conductivity, the surface resistance increases, which makes it difficult for the current to flow. But the thickness of the skin layer increases, which facilitates its flow.

Longitudinal force acting on the vibrator

Substitution in formula (5) of expressions for current *J(s)* and the components of the magnetic field H_x gives the following expression for the longitudinal component of the force acting on the vibrator:

$$F_z(x) = \frac{E_0}{2c}\frac{\lambda}{\lambda_w}\sin\left(\frac{\pi x}{a}\right)\int_{-L}^{L}\mathrm{Re}\{J(s)\}ds\,. \tag{8}$$

The form of the formula is almost the same as for the force acting on the vibrator in free space [12]. The difference is in the presence of factors showing that the force depends on the *x*-coordinate and on the wavelength.

The current changes along the vibrator are very small. Therefore, the average value of the current can be used, so that formula (8) becomes:

$$F_z(x) = \frac{E_0 L}{c}\frac{\lambda}{\lambda_w}\sin\left(\frac{\pi x}{a}\right)\mathrm{Re}\{J_{cp}\} \tag{9}$$

Figure 5 shows the dependence of the force acting on the vibrator on its position in the waveguide. The calculations were made for a copper vibrator with diameter of 100 μm and length of 3 mm, located in waveguide with cross section of 7.2×3.4 mm². The radiation wavelength in free space is 8 mm, the radiation power is 1 W.

Radiation pressure is the greatest when the vibrator is located in the middle of the wide wall of the waveguide, where the electric field strength is maximum, and it drops to zero near the narrow walls. The dependence of the force on the *x* coordinate is close to the $\sin^2 x$ function. The force is directed in the positive direction of the *z*-axis, in the direction of wave propagation.

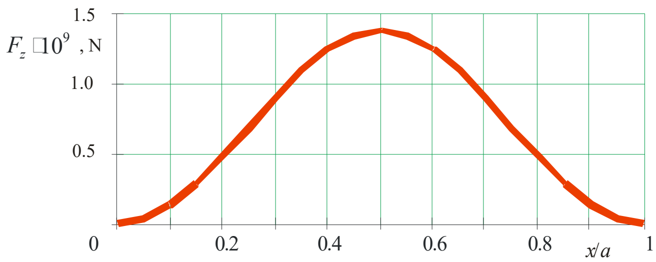


Figure 5. Dependence of the longitudinal force acting on the vibrator on its position in the waveguide

Figure 6 shows a graph of the efficiency factor of the radiation pressure on the vibrator as a function of its length. The vibrator is copper, its diameter is 100 μm. Curve 1 is shown for a vibrator in a waveguide with an H_{10} wave, which is located perpendicular to the wide wall in its middle, curve 2 is for the same vibrator in free space. Parameter $2L/\lambda_w$

plotted along the abscissa axis. In this parameter λ_w is the wavelength in the waveguide for curve 1, the wavelength in free space for curve 2. It is remarkable that the efficiency factor of the radiation pressure on the vibrator in the waveguide can be 2 times greater than on the vibrator in free space, and reach a value of 123. But for this, it is necessary that its length be approximately half the wavelength in the waveguide. Thus, at a radiation frequency of 37.5 GHz (the wavelength in free space is 8 mm, in the waveguide – 9.62 mm), the length of the vibrator should be 4.7 mm. This means that the length of the narrow wall of the waveguide must be at least 5 mm instead of the standard value of 3.4 mm.

The arrow on the abscissa shows the radiation pressure efficiency factor for a vibrator 3 mm long, which can be placed in a standard waveguide 7.2×3.4 mm^2. It is equal to 18.2. This is much less than the maximum possible value. Therefore, it is advisable to use waveguides with non-standard cross-sectional dimensions, with a large vertical wall *b* to effectively use the radiation pressure.

The positions of the maxima of the radiation pressure efficiency factors on curves 1 and 2 do not coincide. For a vibrator in free space the maximum is at $2L/\lambda_w = 0.48$, for a vibrator in a waveguide it's located at $2L/\lambda_w = 0.49$.

The radiation pressure efficiency factor increases without limit, tending to infinity as the vibrator diameter decreases. However, this does not mean that the force acting on the vibrator increases, since the power of the radiation that hit the vibrator decreases in this case. The force acting on the vibrator decreases with a decrease in its diameter [12].

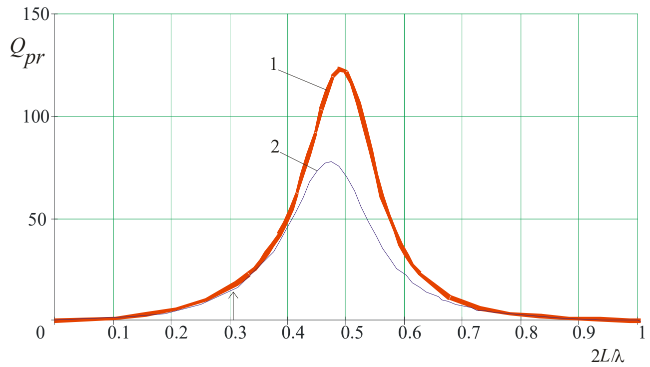


Figure 6. Dependence of the radiation pressure efficiency factor on the vibrator on its length
1 - vibrator in the waveguide, 2 - vibrator in free space

Transverse force acting on the vibrator

We use formula (6) in this case. Substituting into it the expression for the H_z component from formula (1), we obtain:

$$F_x(x) = \frac{E_0}{2c}\frac{\lambda}{\lambda_{kp}}\cos\left(\frac{\pi x}{a}\right)\int_{-L}^{L}\mathrm{Im}\{J(s)\}\,ds. \qquad (10)$$

Taking into account the small change in the current value along the vibrator, we can write:

$$F_x(x) = \frac{E_0 L}{c}\frac{\lambda}{\lambda_{kp}}\cos\left(\frac{\pi x}{a}\right)\mathrm{Im}\{J_{cp}\}. \qquad (11)$$

The results of calculations using this formula are shown in Figure 7. The transverse force is zero in the middle of the waveguide and near its walls. The force maxima are located at *x* = *a*/4 and *x* = 3*a*/4. The force is always directed towards the middle of the waveguide, i.e. the vibrator is drawn into the region of maximum field intensity.

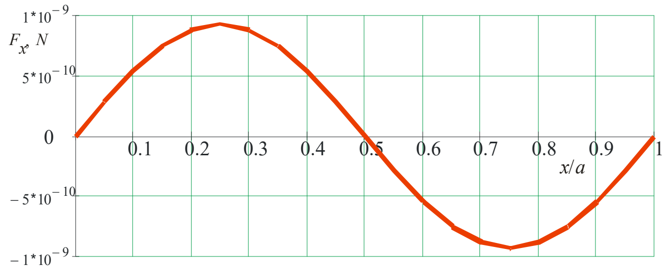


Figure 7. Dependence of the transverse force acting on the vibrator, on its position in the waveguide

Figure 8 shows the dependence of the transverse force on the length of the vibrator. The vibrator is located at the maximum of the magnetic field (*x* = *a*/4). The maximum force is located at $2L/\lambda_w$ = 0.41. This value does not match either the value for the longitudinal force in free space $2L/\lambda_w = 0.48$), nor with the value for the longitudinal force in the waveguide ($2L/\lambda_w = 0.49$), although it does not differ much from them.

The force changes sign at $2L/\lambda_w = 0.475$: the longer vibrator is pushed out of the region of high field intensity. The maximum of buoyancy force is located at $2L/\lambda_w = 0.56$. It is approximately 3 times greater than the maximum of the positive force. Further, the force decreases in magnitude, but it does not reach zero at $2L/\lambda_w = 1$, as in the case of the longitudinal force.

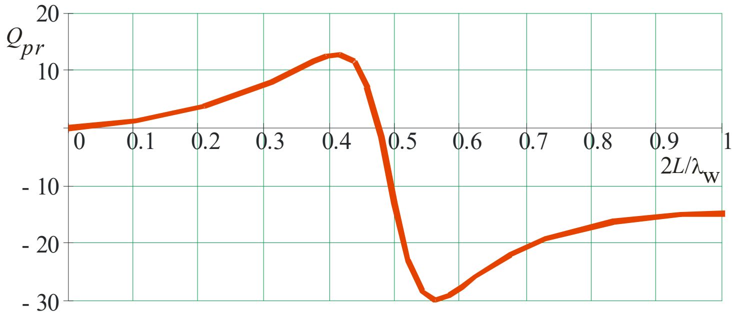


Figure 8. Dependence of the transverse force acting on the vibrator in the waveguide, on its length

Forces acting on the vibrator in waveguides of various sections

The forces acting on the vibrator in a waveguide with a cross section of 7.2×3.4 mm^2 were calculated above. It is of interest to estimate the forces acting on a vibrator located in a waveguide with a different cross section at the same radiation power for wavelengths corresponding to the waveguide cross section. There are two factors here:

1. The radiation pressure efficiency factor Q_{pr} increases by increasing in the wavelength and the same vibrator diameter so the force acting on the vibrator increases [12].
2. At the same radiation power in a waveguide with a larger cross section, the radiation energy density decreases, so the force acting on the vibrator decreases.

We assume that the vibrator is made of copper, has a diameter of 100 μm and a length equal to the length of the short wall of the waveguide. Let's find the magnitude of the forces:

1. longitudinal force F_z acting on a vibrator located in the middle of a wide wall at the maximum radiation intensity;
2. transverse force F_x acting on a vibrator located at the maximum of the magnetic field H_z (for $x = a/4$ or $x = 3a/4$).

The power of radiation in the waveguide is equal $P_0 = 1$ W. The results of calculations are shown in Table 2.

Table 2. Forces acting on a vibrator in a waveguide

Cross section of waveguide, mm^2	Wavelength, cm	Longitudinal force $F_z \cdot 10^{10}$, N	Transverse force $F_x \cdot 10^{10}$, N
7.2×3.4	0.8	26.8	9.59
23×10	3	6.68	6.55
28×12	3.5	6.74	6.14
	5	2.38	8.77
58×25	5.45	26.1	6.91
	10	2.00	6.91
	10.7	1.69	8.75
72×34	10	4.35	6.31

The forces in all waveguides are approximately the same, despite the large difference in the sizes of the latter. This is explained by the presence of counteracting factors mentioned above.

On the possibility of manipulations with targets in the form of thin vibrators in the microwave range

Let us evaluate the possibility of manipulations on thin vibrators using microwave radiation pressure: their displacement in space and levitation. Let us consider the case when the target is a copper vibrator, it diameter is 100 μm and a length of 3 mm. It is located in the waveguide with cross section of 7.2×3.4 mm^2. Power of radiation is 1 W. Table 2 shows, that the longitudinal force acting on the vibrator is equal $26.8 \cdot 10^{-10}$ N, the transverse force is $9.59 \cdot 10^{-10}$ N.

The mass of this vibrator is $m = 1.65 \cdot 10^{-7}$ kg. The acceleration of the target is:

$$a = \frac{F}{m} = 0.0163 \text{ m/s}^2.$$

The target will move a distance of about 8 mm in 1 s, when it move by this acceleration. This is quite a noticeable distance. It can be seen that microwave radiation pressure can be used to move millimeter-sized wire targets.

The radiation power required to keep such a target on the weight (levitation) can be estimated from the expression for the ponderomotive force

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

Force required for levitation is equal $F = mg = 1.62 \cdot 10^{-6}$ N. This is the weight of the target. The radiation pressure efficiency factor on a vibrator 3 mm long is $Q_{pr} = 18.2$. The power required for levitation is approximately 27 watts. This is a high power, but quite achievable in modern microwave technology.

CONCLUSION

1. A thin wire vibrator in the waveguide experiences radiation pressure.
2. There is a longitudinal component of the ponderomotive force directed towards the propagation of the wave and a transverse component directed towards the middle of the waveguide cross section.
3. The forces depend little on the conductivity of the vibrator material and the size of the waveguide cross section.
4. The magnitudes of the ponderomotive forces acting on thin metal vibrators are sufficient to control their position and move in space. Microwave radiation can be used to move such objects in space and keep them in a given place, similar to how it is done in the optical range using lasers.

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REFERENCES

[1] A. Ashkin, Pressure of laser radiation, Uspekhi fizicheskikh nauk. **110,** 101-116 (1973).
[2] S. Kawata, and T. Sugiura, "Movement of micrometer-sized particles in the evanescent field of a laser beam", Opt. Lett. **17**, 772 (1992). https://doi.org/10.1364/OL.17.000772
[3] A. Pralle, M. Prummer, E.-L. Florin, E.H.K. Stelzer, and J.K.H. Hörber, "Three-Dimensional High-Resolution Particle Tracking for Optical Tweezers by Forward Scattered Light", Microscopy research and technique. **44**, 378 (1999). https://doi.org/10.1002/(SICI)1097-0029(19990301)44:5%3C378::AID-JEMT10%3E3.0.CO;2-Z
[4] R.M. Simmons, J.T. Finer, S. Chu, and J.A. Spudich, "Quantitative measurements of force and displacement using an optical trap", Biophysical Journal. **70**, 1813 (1996). https://doi.org/10.1016/S0006-3495(96)79746-1
[5] R.A. Valitov editor, *Ponderomotive action of electromagnetic field (theory and application)*, (Moscow, Sov. Radio, 1975). pp. 232 p. (in Russian).
[6] V.G. Volostnikov, S.P. Kotova, N.N. Losevsky, and M.A. Rakhmatulin, "Manipulation of micro-objects using beams with non-zero orbital momentum", Quantum Electronics, **32**, 565 (2002). https://doi.org/10.1070/QE2002v032n07ABEH002248
[7] V.M Kuz'michev, N.G Kokodiy, B.V Safronov, and V.P Balkasin, "Values of the absorption efficiency factor of a thin metal cylinder in the microwave band", Journal of Communication Technology and Electronics, **48**, 1240 (2003).
[8] A. Akhmeteli**,** N. Kokodiy, B. Safronov, I. Priz, and A. Tarasevitch, "Efficient non-resonant absorption of electromagnetic radiation in thin cylindrical targets: Experimental evidence", Proc. of SPIE, **10185**, 101850I (2017). https://www.scopus.com/record/display.uri?eid=2-s2.0-85022326725&origin=resultslist
[9] N.G. Kokodii, M.V. Kaydash, and V.A. Timaniuk, "Interaction of electromagnetic radiation with a thin metal wire in the case of a glancing incident wave", Journal of Communication Technology and Electronics, **62**, 205 (2017). https://elibrary.ru/item.asp?id=28918056
[10] H.C. van de Hulst. *Light Scattering by Small Particles*. (NY, London, 1957). 536 p.
[11] M. Kerker, *The scattering of light and other electromagnetic radiation*. (Academic Press, NY and London, 1969). pp. 671.
[12] M.G. Kokodii, S.L. Berdnik, V.O. Katrich, M.V. Nesterenko, and M.V. Kaydash, Pressure of electromagnetic radiation on a linear vibrator, East European Journal of Physics, **4**, 172 (2021). https://doi.org/10.26565/2312-4334-2021-4-23
[13] M. Kokodii, S. Berdnik, V. Katrich, M. Nesterenko, I. Priz, A. Natarova, V. Maslov, and K. Muntian, Measurement of microwave radiation pressure on thin metal fibers, Ukrainian Metrological Journal, **4**, 45 (2021), https://doi.org/10.24027/2306-7039.4.2021.250413

ТИСК ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ НА ТОНКИЙ ЛІНІЙНИЙ ВІБРАТОР В ХВИЛЕВОДІ

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Розв'язано задачу тиску електромагнітної хвилі на тонкий провідниковий вібратор у хвилеводі з модою H_{10}. Вібратор розташований перпендикулярно до широкої стінки хвилеводу. Розраховано силу струму у вібраторі, який виникає під дією електричного поля хвилі. Розподіл струму вздовж вібратора майже рівномірний. Струм у мікрохвильовому діапазоні мало залежить від провідності вібратора. У хвилі H_{10} існують дві складові магнітного поля - поздовжня і поперечна. При взаємодії цих компонентів зі струмом у виникають сили, які діють на вібратор поперек хвилеводу і вздовж нього. Величина поздовжньої сили найбільша, коли вібратор розташований посередині широкої стіни. Вона майже в 2 рази перевищує силу, яка діє на вібратор у вільному просторі при тій же середній інтенсивності випромінювання. Коли довжина вібратора близька до половини довжини хвилі випромінювання, сила максимальна. Поперечна сила виникає при взаємодії струму у вібраторі з поздовжньою складовою магнітного поля в хвилеводі. Вона максимальна, коли вібратор розташований на відстані ¼ довжини широкої стіни від її середини. Якщо довжина вібратора менше половини довжини хвилі випромінювання, сила спрямована в бік осі хвилеводу, інакше - у протилежний бік. Оцінена можливість використання тиску мікрохвильового випромінювання для створення мікромашин і управління положенням вібратора в просторі. Для цього потрібна потужність випромінювання в кілька ват.

Ключові слова:електромагнітна хвиля, провідниковий вібратор, тиск випромінювання, хвилевод, поздовжня сила, поперечна сила.