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PRESSURE OF ELECTROMAGNETIC RADIATION ON VERY THIN CONDUCTORS

Background.. We use the mechanical action of laser radiation in the optical range for levitation, holding and moving of microparticles. We use that fact that the radiation beam presses on the particle, pulls it into a region of high field intensity and holds it there. We use the effect of strong absorption and scattering of microwave radiation by very thin conductors - metal wires, graphite and semiconductor fibers, to overcome difficulties caused by comparable large focal spot of the beam in the microwave range.

Objectives. To provide an analysis of the possibility of levitation and control of the movement of thin metal targets, which can be metal conductors with a diameter of several micrometers and a length of several millimeters, using microwave radiation without focusing on the target.

Results. We provide a theoretical analysis of the effect of microwave radiation strong pressure on thin conductors. We derive a condition for the maximum of radiation pressure - the relationship between the radiation wavelength, the diameter of wire and its conductivity. Also, we provide results of measurement of forces acting on thin conductors. For such purpose, we have used a torsion bar scales with a wire suspension with a diameter of several micrometers and an optical rotation angle reading. We show the good agreement between the calculation and experimental results.

KEY WORDS: radiation beam pressure, thin fiber, wire, levitation

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INTRODUCTION

The pressure of electromagnetic radiation on material bodies (ponderomotive effect) was predicted by J. Maxwell in his treatise on electromagnetism (Maxwell 1873). It was first measured by P.N. Lebedev (Lebedev 1901), and his experiments had a strong influence on the development of physics in the late 19th - early 20th centuries.

For a long time, it seemed that the smallness of light pressure, in the words of J. Poynting, "excludes it from consideration in earthly affairs" (Poynting 1910). But in the 1950s, intensive research began on the use of microwave radiation pressure to measure power in waveguide paths. As a result, there were created instruments for high accuracy radiation power measurement in the centimeter and millimeter ranges (Cullen 1952, Barlow 1966, Barlow et al. 1970, Valitov 1959, Orlov 1962). Then there were developed instruments for measurement of laser radiation (Kokodii et al. 1988).

An engine was built - a device where a carousel with flat wings rotates under the influence of microwave radiation pressure in a waveguide (Valitov et al. 1961). It was the world's first device that used radiation pressure to perform work and move bodies in space.

Ponderomotive devices did not become widespread, and the pressure of electromagnetic radiation remained as some interesting physical effect without much practical application.

The situation changed radically with the advent of lasers with high radiation coherence and the ability to focus the beam into a spot whose dimensions are comparable to the light wavelength (sharp focusing). A. Ashkin, Nobel Prize winner in 2018, in experiments conducted in the 1970s, showed that the light pressure produced by a laser beam is sufficient to capture, hold and move micron-sized particles (Ashkin 1970, Ashkin 1973).

Ashkin exposed green light from argon laser (λ = 514.5 nm) onto transparent polymer spheres with a diameter of 0.59 - 2.68 μm, suspended in water. A focused beam of light on a sphere with a diameter of 2.68 μm creates a force $F \approx 6.67\times10^{-10}$ N. This force in the biological microcosm is very large. According to Newton's law, it creates an acceleration of a biological cell of 9.5×10^{-18} kg mass equal to 7×107 m/s^2, which is million times greater than the acceleration of free fall on Earth (g = 9.8 m/s^2)!

He has also showed that there is a transverse force that draws a refractive particle into a region of high light intensity - towards the axis of the beam from its periphery. His research became the basis for the creation of now widely known optical (laser) tweezers, which can be used to hold or move of microparticles, biological cells and individual atoms (Shwarz et al. 2021, Andriyanov et al. 2019, Tashtimirova et al. 2021, Jones et al. 2015, Padgett et al. 2010).

He has also made experiments on optical levitation, where the force of light pressure lifted and held micron-sized particles in the air.

The success of these experiments is explained by the fact that the focal region of the laser beam has dimensions comparable to the wavelength of visible light (several micrometers). The radiation intensity there is very high even with a beam power of several milliwatts, and the light pressure force is sufficient to manipulate micron-sized particles, which in such case receive all the power of the light beam.

The same research has begun in the microwave range, which is also interesting for use in science and technology. But in this range, solving the problem of manipulation objects using radiation pressure encountered great difficulties. This is due to the fact that the size of the focal spot is of the same order as the radiation wavelength. In the microwave range, this size is about 1 cm. It is impossible to focus a microwave beam more strongly under normal conditions. In order for the entire beam energy to reach the object, it must have the same dimensions. But objects of such dimensions have large mass, and it is difficult to manipulate them using radiation pressure. If the objects are small, just a small part of the beam power hits them, and therefore the effect on them is weak. To obtain fields whose magnitude is sufficient to manipulate objects, very high radiation powers are required.

But in works (Pettit et al. 2019, Kuzmichev et al. 2003, Akhmeteli et al. 2015, Kokodii et al. 2017, 2023, 2023, Kalambet et al. 2020) it was discovered that in the microwave range there is an effect of strong absorption and scattering of radiation by thin wires, which diameter is much smaller than the incident radiation wavelength. The values of absorption and scattering efficiency factors characterizing the interaction between wave and object can reach several hundreds and thousands. It can be expected that the radiation pressure efficiency factor in these cases will also be large. This will be described in detail in subsequent sections of such paper.

TASK STATEMENT

The force with which electromagnetic radiation presses on an object can be determined by the formula

$$F_{pr} = \frac{P}{c} Q_{pr} . \tag{1}$$

Here P is the radiation power, which hits the object, c is the light velocity, Q_{pr} is the radiation pressure efficiency factor. For example, for a completely absorbing surface $Q_{pr} = 1$, for an absolutely reflective plate $Q_{pr} = 2$.

For a circular cylinder on which a plane electromagnetic wave is incident normal to its axis, the radiation pressure efficiency factor is determined by the formulas (Kerker 1969, Van de Hulst 1981):

$$Q_{pr}^{E} = \frac{2}{\rho} \sum_{l=0}^{\infty} \mathrm{Re}\left(b_l + b_{l+1}^{*} - 2 b_l b_{l+1}^{*} \right), \tag{2}$$

$$Q_{pr}^{H} = \frac{2}{\rho} \sum_{l=0}^{\infty} \mathrm{Re}\left(a_l + a_{l+1}^{*} - 2 a_l a_{l+1}^{*} \right). \tag{3}$$

The superscripts E and H indicate the direction of polarization of the wave - along the axis of the cylinder (E-wave) or perpendicular to it (H-wave).

Coefficients b_l and a_l depend on the cylinder diameter D, wavelength λ and complex refractive index $m = n - ik$:

$$b_l = \frac{m\,J_l^{'}(m\rho)\,J_l(\rho) - J_l(m\rho)\,J_l^{'}(\rho)}{m\,J_l^{'}(m\rho)\,H_l^{(2)}(\rho) - J_l(m\rho)\,H_l^{(2)'}(\rho)}, \qquad (4)$$

$$a_l = \frac{m\,J_l(m\rho)\,J_l^{'}(\rho) - J_l^{'}(m\rho)\,J_l(\rho)}{m\,J_l(m\rho)\,H_l^{(2)'}(\rho) - J_l^{'}(m\rho)\,H_l^{(2)}(\rho)}, \qquad (5)$$

Here $\rho = \frac{\pi D}{\lambda}$, $J_l(z)$ is the Bessel function, $H_l^{(2)}(z)$ is the Hankel function of the 2nd kind, the prime denotes the derivative of the function with respect to the entire argument.

RADIATION PRESSURE ON A THIN METAL CYLINDER

A feature of the dependencies presented in Fig. 1 is a strong increase of the radiation pressure efficiency factor in the case of E-polarization on thin conducting cylinders - metal wires and semiconductor fibers. In the microwave range for wires of nano- and micrometer diameters, its value reaches several hundreds and thousands.

In Fig. 2 presented is the dependence of the radiation pressure efficiency factor for a copper wire on the parameter ρ (curve 1). One can see that at a certain value of this parameter, at the maximum, it is greater than 2000. It is interesting, that it can be greater than the radiation pressure efficiency factor for an absolutely reflective cylinder (curve 2), although the radiation pressure on a flat surface with a finite reflection coefficient always less than the pressure on absolutely reflective surface.

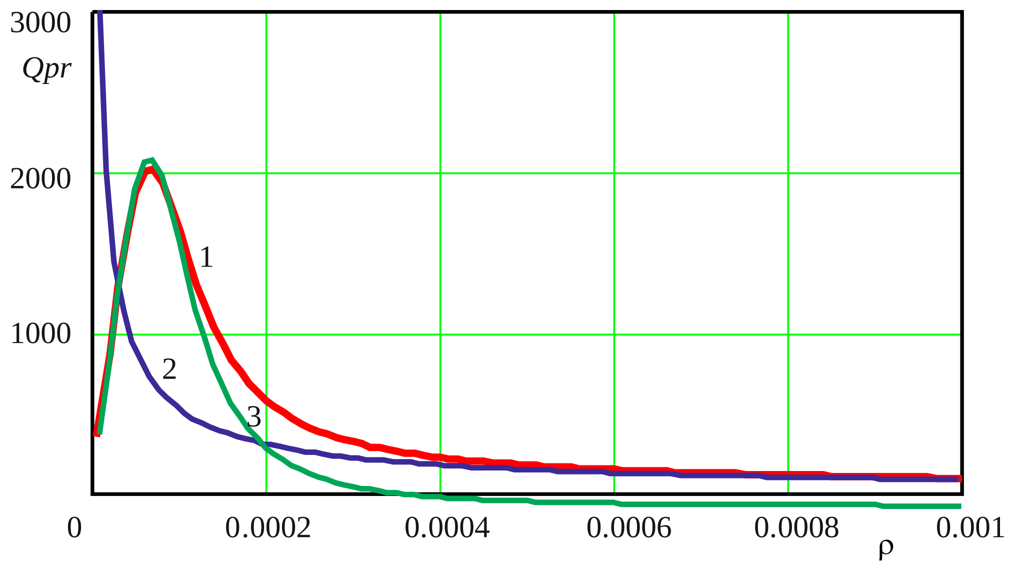

Fig. 2. Radiation pressure efficiency factor dependencies on ρ for:
in the microwave range
1) thin copper wire, 2) absolutely reflective wire,
3) thin copper wire, calculated using approximate formula.

Let us find the coordinate and value of the maximum of the radiation pressure efficiency factor. For this, one can use the fact that for a very thin wire the conditions $\rho \ll 1$, $|m\rho| << 1$ are satisfied, and in series (2) and (3) one can use only the first term, and in the coefficients b_l – the first term of the expansion into series of Bessel and Hankel functions. Let us describe the case of the E-wave. After some transformations, we obtain the following expression for the radiation pressure efficiency factor, which well describes the trajectory of the function $Q_{pr}^{E}(\rho)$ in the region of its maximum (curve 3 in Fig. 2):

$$Q_{pr}^{E}=\frac{\pi n^{2}\rho}{1+\left(n^{2}\rho^{2}\,ln\rho\right)^{2}}\quad(6)$$

Here n is the real part of the complex refractive index. According to Drude theory, the complex refractive index of a metal in the infrared and microwave regions of the spectrum is determined as

$$m=\sqrt{\frac{\sigma}{2\omega\varepsilon_0}}\left(1-i\right),\quad(7)$$

where σ is conductivity, ω is circular frequency, $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m is the dielectric constant of free space.

Position of the maximum can be found by differentiating of the expression (6). As result we obtain the following equation for determining the coordinates of the maximum,

$$1-3n^{4}\rho^{4}\,ln\left(\rho\right)^{2}-2n^{4}\rho^{4}\,ln\left(\rho\right)=0\,.$$

The last term in this equation is much smaller than the other and can be neglected. Thus, the equation becomes the following form:

$$1-3n^{4}\rho^{4}\,ln\left(\rho\right)^{2}=0\quad(8)$$

It has three roots:

$$\rho_{1max}=exp\left(\frac{1}{2}LambertW\left(\frac{2}{\sqrt{3}n^{2}}\right)\right),$$

$$\rho_{2max}=exp\left(\frac{1}{2}LambertW\left(-\frac{2}{\sqrt{3}n^{2}}\right)\right),$$

$$\rho_{3max}=exp\left(-1,-\frac{1}{2}LambertW\left(-\frac{2}{\sqrt{3}n^{2}}\right)\right),$$

where LambertW(x) is the Lambert function. It was introduced into the MAPLE mathematical computer system by the developers of this program (Corless et al. 1996), and then into the MATHCAD, MATLAB, MATHEMATICA programs. Three roots correspond to three branches of this function. The physical meaning in our problem has a third root. It shows the exact value of the position of the maximum on curve 3 of the $Qpr(\rho)$ dependence in Fig. 2. But it is difficult to use the LambertW(x) function due to its lack of knowledge. Therefore, we have found an approximate solution of equation (8). One can use a fact that it is easy to construct a graph of $n(\rho)$, which covers the range of refractive index values for conductors in the infrared and microwave regions of the spectrum. From it one can find the inverse function $\rho(n)$, which is very simple,

$$\rho_{max}=\frac{1}{4n}\,.\quad(9)$$

This formula well describes the position of the radiation pressure efficiency factor maximum for conductors in the microwave range. It can be rewritten in the following form,

$$D_{max}=\frac{\lambda}{4\pi n}\approx0.1\lambda_i\,,\quad(10)$$

where D is the diameter of the conductor, λ is the radiation wavelength in free space, and $\lambda_i=\lambda/n$ is the wavelength inside the conductor. Thus, the condition for maximum is a diameter value that is approximately 10 times smaller than the radiation wavelength in the conductor. For example, for copper at a wavelength of $\lambda=8$ mm, the maximum will be for a conductor diameter of 170 nm. For graphite, the maximum will be for a conductor diameter of 3.5 microns.

The graph shows that the effect of microwave radiation on cylindrical metal nanoparticles is very strong. This can be used to retain and transportation such particles using microwave radiation, similar to laser tweezers in the optical range (Kokodii et al. 2020).

Putting expression (9) into (6) gives the value of the radiation pressure efficiency factor maximum,

$$Q_{abs\,\max}\approx\frac{n}{2}=\frac{1}{4}\sqrt{\frac{\sigma\lambda}{\pi c\,\varepsilon_0}}\,.$$

In our example, the value of the radiation pressure efficiency factor at the maximum is large – about 2000. The maximum is at very small diameter values – about 200 nm. But even in the micrometer range of diameter values, the radiation pressure efficiency factor is large. For a copper cylinder with a diameter of 30 microns, it is equal to 28, which is also a large value.

The cylinder as an object of interaction with electromagnetic radiation is unique. The effect of strong interaction of thin cylinders with radiation was studied in detail in (Kokodii et al. 2024).

EXPERIMENT

We have made an experiment, where a target made of several metal wires has been moved in space. We have also measured the force of the electromagnetic radiation which moved a target.

We have used a torsion bar scale as the measuring transformer. The scheme of the experimental setup is presented in Fig. 4. A rocker arm 2 of a 50 mm length is suspended on tungsten wire 1 with a diameter of 8 microns and a length of 150 mm. At the edges of the rocker there are located receiving elements 3 and 4. One of them is an aluminum foil plate with dimensions $15\times15\times0.15$ mm. Its radiation pressure efficiency factor is Q_{pr} = 2. It was used for reference measurements. Another receiving element is a grating from copper wires with a diameter of 300 microns, located at distance 1 mm from one another. To measure the movement of the mobile system under the influence of radiation pressure, a laser beam 6 was directed at mirror 5. After reflection, the beam fell on scale 7. The beam offset *l* on the scale is related to the rotation angle α of the mobile system by the relation,

$$l = 2\alpha L\ ,$$

where *L* is the distance from the mirror to the scale.

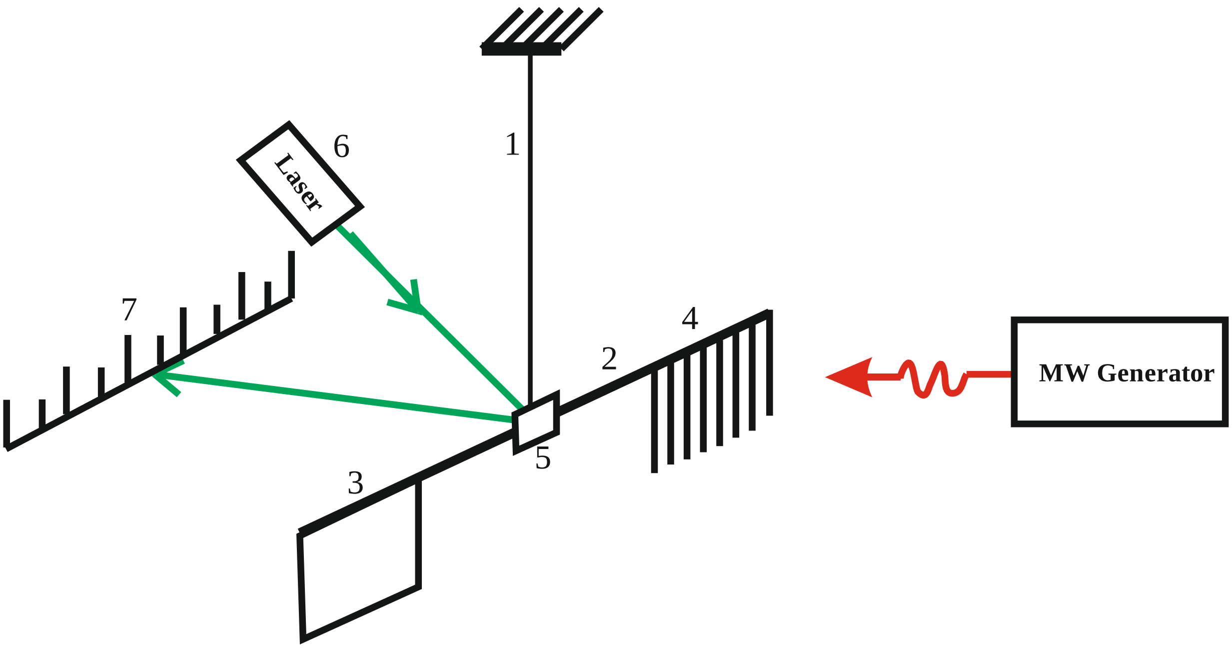

Fig. 4. Scheme of the experimental setup
1 – suspension, 2 – rocker arm, 3 – flat receiving element,
4 – grating receiving element, 5 – indicator mirror, 6 – laser,
7 - scale

Radiation with 8 mm wavelength was directed to the receiving element. The power of incident radiation on the receiver was *P* = 32 mW. Under the influence of the pressure of this radiation, the system has been rotated through an angle α = 1.54°. This angle can be determined by the formula

$$\alpha = \frac{M}{W}\ , \tag{13}$$

where $M = Fr$ is the torque acting on the system, *F* is the force applied to the receiving element, *r* is the arm of the force (the distance from the suspension to the middle of the receiving element), *W* is the specific counteracting moment of the suspension.

The specific counteracting moment of the suspension is determined by the relation following from solid mechanics,

$$W = \frac{\pi d^4 G}{32h} = 3.58\cdot10^{-10}\ \frac{N\cdot m}{rad}\ ,$$

where d = 8 μm is the diameter of the suspension, h = 150 mm is its length, G = 151 GPa is the shear modulus of tungsten.

The torque acting on the mobile system, according to (13), is equal to

$$M = \alpha W = 9.62 \cdot 10^{-12}\ N \cdot m / rad\ .$$

A force acting on the receiving element is,

$$F = \frac{M}{r} = 5.50 \cdot 10^{-10}\ \text{N}.$$

Here r = 17.5 mm is the arm of the force, that is, the distance from the suspension to the middle of the receiving element.

A force acting on each wire is,

$$F_1 = \frac{F}{N} = 3.44 \cdot 10^{-11}\ \text{N},$$

where N = 16 is number of wires.

According to equation (1), the radiation pressure efficiency factor is equal to

$$Q_{pr} = \frac{F_1 c}{P_1} = 5.16\ .$$

Here $P_1 = F_1/N$ = 0.002 W is the power incident on each wire.

Calculations using equation (2) give the value Q_{pr} = 5.39. The difference between theory and experiment is 4%. This is a good coincidence, considering the inaccuracy of estimating the power incident on each wire, the theoretical determining of the mechanical parameters of the suspension, and other factors.

CONCLUSIONS

We have studied the effect of very strong microwave radiation pressure on thin metal conductors. The radiation pressure efficiency factor on them can reach several hundreds and thousands.

We have determined the conditions for maximum radiation pressure - the relationship between the radiation wavelength, the diameter of the conductor and its conductivity.

We have shown a possibility of a levitation of targets in the form of metal wires with a diameter of several microns and a length of several millimetres, as well as control of their movement in space for the radiation power of several watts.

We have also measured the force acting on a thin metal wire by microwave radiation.

STATEMENTS AND DECLARATIONS

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ТИСК ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ НА ДУЖЕ ТОНКІ ПРОВІДНИКИ

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Актуальність. Механічна дія лазерного випромінювання в оптичному діапазоні використовується для левітації, утримання і транспортування мікрочастинок. Тут використовується те, що пучок випромінювання тисне на частинку, втягує її в область великої інтенсивності поля й утримує її там. У мікрохвильовому діапазоні створення подібних пристроїв зустрічає великі труднощі, пов'язані з тим, що дифракція не дає змоги здійснити гостре фокусування пучка, тому діаметр фокальної плями виходить не меншим за 1 сантиметр. Неможливо отримати таку велику концентрацію енергії випромінювання, як в оптичному діапазоні, де діаметр фокальної плями може бути не більшим за 1 мікрометр.

Мета роботи Ці труднощі можна подолати, якщо використовувати ефект сильного поглинання і розсіювання мікрохвильового випромінювання дуже тонкими провідниками - металевими дротами, графітовими і напівпровідниковими волокнами.

Матеріали та методи. У статті проведено теоретичний аналіз ефекту сильного тиску мікрохвильового випромінювання на тонкі провідники. Виведено умову максимуму тиску випромінювання - співвідношення між довжиною хвилі випромінювання, діаметром провідника та його провідністю. У максимумі фактор ефективності тиску мікрохвильового випромінювання дуже великий - сотні й тисячі.

Результати. Проведено аналіз можливості левітації та керування рухом тонких металевих мішеней за допомогою мікрохвильового випромінювання. Мішенями можуть бути металеві провідники діаметром кілька мікрометрів і довжиною кілька міліметрів. Фокусувати випромінювання на мішень немає необхідності. Проведено вимірювання сил, що діють на тонкі провідники. Для цього використано торсіонні ваги з підвісом із дроту діаметром кілька мікрометрів і оптичним відліком кута повороту. Результати розрахунків і результати експерименту добре збігаються один з одним.

КЛЮЧОВІ СЛОВА: тиск пучка випромінювання, тонке волокно, дріт, левітація.

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