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Measurement of microwave radiation pressure on thin metal fibers

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Abstract

The pressure of electromagnetic radiation in the optical range is widely used to hold microparticles in a given place and control their movement. This is possible by focusing the laser radiation into an area with the dimension of several micrometers. The intensity of radiation in this area is large and sufficient to retain micro-particles in the laser beam and manipulate them. Nowadays, intensive research is underway on the use of microwave and terahertz radiation and the possibility of applying radiation pressure in these ranges. But in the microwave range, the focal spot dimension is much larger than in the optical one. Therefore, control of the objects whose dimensions are comparable to those of the focal spot using the radiation pressure requires very high power. For the objects with small dimensions, a small amount of radiation energy falls on them, and the acting force decreases. However, it is known that thin conductive fibers interact very strongly with microwave radiation. This can be used to levitate short thin metal fibers (vibrators), hold them in predicted place and control their position in space.

The paper describes the measurements of the pressure of microwave radiation with a wavelength of 8 mm on thin copper fibers. Torsional balance is used for this purpose. In the metal case on a suspension from a tungsten fiber with a diameter of 8 microns there is located the rocker arm with 50 mm length with receiving elements in the form of system of copper fibers with a diameter of 300 microns and 15 mm length. Microwave radiation was directed to one of the receiving elements using a horn. The calibration of torsion balance, the measurement process, and the evaluation of the resulting error are described. The measurements gave the value of the efficiency factor of the radiation pressure Q_{pr} = 4.86. This agrees satisfactorily with the results of calculations Q_{pr} = 5.39. The difference is 10%.

Keywords: microwave radiation; thin fibers; radiation pressure; measurement.

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Introduction

Pressure of electromagnetic radiation is one of the fundamental physical phenomena. Until the invention of lasers, it seemed that smallness of the light pressure excludes it from using for manipulation of objects. With the invention of lasers, the situation changed radically. This is due to the possibility of focusing a laser beam into the spot whose dimensions are comparable to the light wavelength. A. Ashkin in his experiments [1, 2] has shown that the laser beam pressure is sufficient to grip, retain and move the micron-size particles (laser pincer). A. Ashkin has also demonstrated the optical levitation of particles in the air.

In the microwave range the driving of objects with the radiation pressure and the implementation of levitation occur with great difficulties. The dimensions of the focal spot are of the order of radiation wavelength (about 1 centimeter). Objects of such dimensions have a large mass and it is difficult to keep them with the radiation pressure. If the objects are small, only a small part of the energy of focused radiation falls on them, and its pressure is weak. Therefore, an extremely large radiation power is necessary to obtain the fields, which magnitude is sufficient to drive objects.

But with using targets in the form of thin conducting fibers (metal, semiconductor, graphite), it is possible to use the effect of a very strong interaction between electromagnetic radiation and such objects. In works [3–5] absorption and scattering of microwave radiation of centimeter and millimeter ranges by metal and graphite fibers with diameter of several dozen micrometers were investigated. The absorption efficiency factor of such targets reaches several hundreds, that is, their effective absorption cross-section is much larger than the geometric cross-section. There is a reason to expect that the radiation pressure efficiency factor is also very large.

Radiation pressure efficiency factor

The radiation pressure force on the object is determined by the formula

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

where P is the incident radiation power, c is the light velocity, Q_{pr} is the radiation pressure efficiency factor.

The radiation pressure efficiency factor on a very thin metal fiber must be large, because it is determined by absorption and scattering of radiation, which are also very large. Therefore, it is possible to use targets in the form of thin fibers as objects for driving and levitation.

The radiation pressure efficiency factor on the fiber can be calculated by the formulas following from the problem of the electromagnetic wave diffraction on the cylinder [6–8].

For a normal incidence the formulas are

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

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

Indexes E, H and coefficients b_l, a_l correspond to the two types of polarization:

E-polarization, when the electric field vector is parallel to cylinder axis, and H-polarization, when the magnetic field vector is parallel to cylinder axis.

Fig. 1 presents dependencies of the radiation pressure efficiency factor for some thin fibers at the radiation wavelength of 8 mm, calculated by formulas (1) and (2).

With the reducing of conductivity, the radiation pressure decreases in a maximum, and the maximum shifts towards larger diameters. Further, the effectiveness factor decreases for all diameters, but for thicker fibers it is larger than for thin ones.

High values of the radiation pressure occur only in the E-polarization case. In the H-polarization the radiation pressure efficiency factors are small.

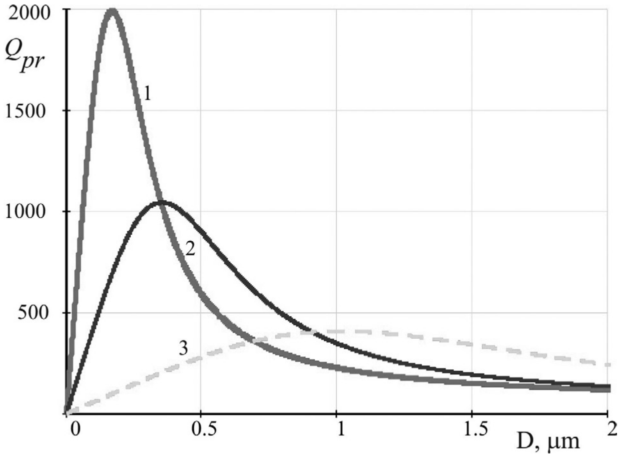

Fig. 1. Radiation pressure efficiency factor as a function of the diameter of fiber, 1 – copper; 2 – nickel; 3 – constantan

Experimental facility

For measurements we have used a torsion balance, which is schematically presented in Fig. 2. A weigh beam 2 of 50 mm length is connected to the tungsten suspension 1 with diameter of 8 μm and length of 150 mm. At its edges there are located the receivers 3 and 4. During measurements one of them is illuminated by the microwave radiation beam 5. The entire system is located in a metal case with windows for transition of microwave radiation and laser beam 6 for measuring of the beam deflection angle from the equilibrium position. The indication system consists of a mirror 7 attached to the weigh beam, laser 8 and reference scale 9. The moving system can be installed in the required position with the device 10. A calibration load 11 is shown below the system.

We have used two types of receivers:

1. In the control measurements we have used plates made of aluminum foil with the dimensions 15×15×0.15 mm. The radiation pressure efficiency factor on such receiver is $Q_{pr} = 2$.
2. A grating from the copper fibers with diameter of 0.3 mm. We have used the grating with randomly located fibers to exclude diffractive interaction between them, and the radiation pressure can be considered equal to the sum of the forces acting on each element.

We have used the backward-wave tube with a wavelength of 8 mm as a source of radiation. The radiation power was controlled by the thermistor wattmeter, which was connected to the waveguide transmission line through a directional coupler with a transitional attenuation of 20 dB. The waveguide was with cross-section of 7.2×3.4 mm and at the end it had a horn with 20×15 mm mouth and 60 mm length. The receiver was located at a distance of 3 mm from the horn mouth.

Calibration of the measurement system

The deflection angle of a moving system from the equilibrium position under the influence of radiation pressure is determined by the torsion moment M_{pr},

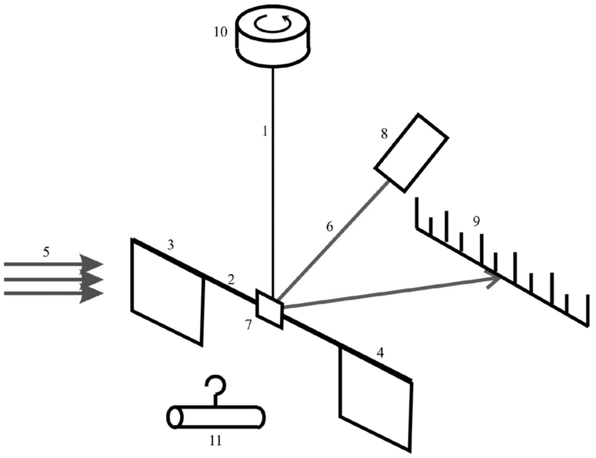

Fig. 2. A torsion balance

which is created by radiation, and the opposite suspension moment M.

The torsion moment:

$$M_{pr} = F_{pr}\, r = \frac{P}{c} Q_{pr}\, r, \tag{3}$$

where F_{pr} is the radiation pressure force on the receiver, r is the distance from the rotation axis of the moving system to the center of the receiver. At this point the force effects on the moving system.

The opposite moment:

$$M = W\alpha, \tag{4}$$

where W is the specific opposite suspension moment (suspension rigidity), α is the deflection angle of a moving system from the equilibrium position.

From the condition of equality of these moments it follows that the deflection angle of the system under the influence of the radiation pressure is

$$\alpha = \frac{P Q_{pr}\, r}{cW}. \tag{5}$$

Deflection of the light indicator on the reference scale at small angles:

$$l = 2\alpha L,$$

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

The calibration of the system is based on the ratio between the period of torsional oscillations T, the moment of inertia of the system J and the suspension rigidity W [9]:

$$T = 2\pi\sqrt{\frac{J}{W}}.$$

We have measured the period of oscillations of a free moving system T and the period T_1 of oscillations of a system with a load with a known moment of inertia J_1. With solving the resulting system of equations, one can find the moment of inertia of the system J and the suspension rigidity W:

$$J = \frac{J_1 T^2}{T_1^2 - T^2}, \qquad W = \frac{4\pi^2 J_1}{T_1^2 - T^2}.$$

Measurements of the oscillation periods T and T_1 gave the following results:

$T = 118 \pm 1$ s, $T_1 = 172 \pm 1$ s.

The load presented in Fig. 2 is a copper rod with the following parameters:

$m = 1.89 \pm 0.01$ g, $l = 30 \pm 0.2$ mm.

The moment of inertia of the load is determined by the formula

$$J_1 = \frac{ml^2}{12}.$$

Its significance $J_1 = (1.42 \pm 0.02)\cdot 10^{-7}$ kg·m². The error of its calculation was found by the method of calculation the error of the result of indirect measurements.

The working equation (5) does not include the moment of inertia of the system. Therefore, in our calculations we estimate just the error of determining the suspension rigidity. Calculations give the following values:

$W = 3.58\times10^{-10}$ N·m/rad, $\Delta W = 0.01\times10^{-10}$ N·m/rad.

The relative error in determining of the suspension rigidity is 3%.

Measurement of the radiation pressure

1. *Control measurements*

We have used a moving system with aluminum plates as receivers.

Radiation power at the output of the generator is $P_0 = 0.1$ W. The radiation intensity at the output of the horn with dimensions of the mouth $S_0 = 20\times15$ mm is $I_0 = \frac{P_0}{S_0} = 333$ W/m². At 3 mm distance from the horn, where the receiver is located, the intensity due to the divergence of the radiation beam decreases and has the value of $I = 281$ W/m². On the receiver with a 15×15 mm surface area falls the power of $P = 0.063$ W.

The radiation pressure efficiency factor on the plate is $Q_{pr} = 2$. The arm of the force is considered equal to the distance from the system rotation axis to the center of the receiver, $r = 17.5$ mm. Substitution of these data into (5) gives us the deflection angle of the system

$\alpha = 0.0326$ rad $= 1.87°$.

The scale of the indicator device was located at a distance $L = 0.85$ m from the indicator mirror on the moving system. Deflection of the indicator light on the scale was $l = 53$ mm. This corresponds to the angle $\alpha = 1.78°$. The results of the experiment differ from the theoretical ones by 5%.

Values of the quantities used in calculations and results of the calculations and measurements were written with an excessive number of decimal digits. Estimation of the measurement error and determination of the number of reliable decimal digits in the results will be made below.

The measurements have shown the operability of the experimental facility, the absence of the thermal effects associated with the heating of the parts of the measuring transducer, and the correctness of the calibration of the torsion balance.

2. *Measurement of the radiation pressure on thin fibers*

We have used a system of copper fibers with 300 μm diameter as a receiver. The radiation pressure efficiency factor on a single fiber, calculated by equation (1) is $Q_{pr} = 5.39$. The low value of Q_{pr} can be explained by the fact that the wires have a relatively large diameter, but it still fulfills the condition of a thin fiber ($D << \lambda$). The power of the generator was insufficient for work with thinner fibers. At the output of the generator $P_0 = 0.15$ W. The radiation intensity in the horn mouth is 500 W/m², on the receiver which is located at 3 mm distance from the horn it is $I = 420$ W/m^2. The power by one fiber is

$$P_1 = IDl = 0.0189 \text{ W}.$$

Here $D = 300\,\mu$m, this is fiber diameter, $l = 15$ mm, this is fiber length.

The number of fibers in the receiver is $N = 18$. Therefore, the receiver is illuminated by the power of

$$P = P_1 N = 0.0340 \text{ W}.$$

The deflection angle of a moving system under the radiation pressure is theoretically determined by equation (5):

$$\alpha = \frac{PQ_{pr}\,r}{cW} = 0.0298 \text{ rad} = 1.71°.$$

The indicator scale was located at a distance of $L = 0.65$ m from the mirror on the moving system. The deflection of the indicator light on indicator scale is $l = 35$ mm. This corresponds to the angle $\alpha = 1.54°$. The experimentally determined radiation pressure efficiency factor is $Q_{pr} = 4.86$. The coincidence with the calculated one ($Q_{pr} = 5.39$) is satisfactory. The difference between them is 10%.

Calculation errors

From (3) and (4) it follows

$$Q_{pr} = \frac{cWl}{2LPr}.$$

The main sources of errors:

1. The error in determining the stiffness of the suspension rigidity, which is $\Delta W/W = 3\%$.
2. The absolute error of indication of moving system deflection $\Delta l = 2$ mm. When the values of deflection are about 40 mm, the relative error is $\Delta l/l = 5\%$.
3. The absolute error of measuring the distance from the indicator mirror of the moving system to the scale is also about 2 mm. When the distance value is $L = 600 \ldots 800$ mm relative error is $\Delta L/L < 1\%$.
4. The relative error of measuring the radiation power with a thermistor wattmeter is 5%. To the error of determining the power P, which falls on the receiver, contributes the error of determining the part of the power that has passed through it due to the divergence of the beam from the horn. Therefore, the total error $\Delta P/P$ is 10%.
5. The distance r from the moving system rotation axis to the point of application of a force on the receiver could not be accurately determined in our experiments. It was assumed that $\Delta r = 2$ mm, therefore the relative error is about 10%.

The error of determining the radiation pressure efficiency factor can be estimated by the equation:

$$\frac{\Delta Q_{pr}}{Q_{pr}} = \sqrt{\left(\frac{\Delta W}{W}\right)^2 + \left(\frac{\Delta l}{l}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta r}{r}\right)^2}.$$

Substituting here the numerical values of partial errors gives

$$\frac{\Delta Q_{pr}}{Q_{pr}} = 15\%.$$

Thus, the experiment gives the following value of the radiation pressure efficiency factor

$$Q_{pr} = 4.9 \pm 0.7.$$

With a confidence probability of 95%, the estimated value of $Q_{pr} = 5.39$ is in the confidence range.

Conclusions

1. Thin metal conductors ($D << l$) strongly interact with microwave electromagnetic radiation.
2. Theoretical analysis shows that the radiation pressure efficiency factor on the fibers of micrometer diameter reaches values of several hundred at the maximum. For thicker fibers it decreases, but for diameters of tens and hundreds of micrometers, it is still significantly larger than one.
3. For the first time it has been performed an experiment for the microwave radiation pressure efficiency factor measurement on thin fibers. The relatively large diameter of the fibers is due to the low power of the generator. The results of measurements are reliably consistent with the results of theoretical calculations and show the possibility of using targets in the form of thin fibers as objects for manipulation of them using the microwave radiation pressure.

Вимірювання тиску мікрохвильового випромінювання на тонкі металеві волокна

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Анотація

Тиск електромагнітного випромінювання в оптичному діапазоні широко застосовується для утримання мікрочастинок і керування ними. Це досягається завдяки можливості фокусування лазерного випромінювання в область розміром у декілька мікрометрів. Інтенсивність випромінювання в ній достатня для утримання мікронних частинок у промені лазера і маніпуляцій з ними. Зараз проводяться інтенсивні дослідження щодо використання мікрохвильового й терагерцового випромінювань та можливості застосування тиску випромінювання в цих діапазонах. Але в мікрохвильовому діапазоні розміри фокальної області набагато більші, ніж в оптичній. Тому для керування об’єктами, розмір яких порівняний із розміром фокальної області, за допомогою тиску випромінювання необхідні дуже великі потужності. При малих розмірах об’єктів на них потрапляє невелика кількість енергії випромінювання, і діюча сила зменшується. Однак, відомо, що тонкі провідникові волокна дуже сильно взаємодіють з мікрохвильовим випромінюванням. Це може бути використано для левітації коротких тонких металевих волокон (вібраторів), утриманні їх у заданому місці та керуванні їхнім положенням у просторі.

У статті описано вимірювання тиску мікрохвильового випромінювання з довжиною хвилі 8 мм на тонкі мідні волокна. Для цього використано крутильні ваги. У металевому корпусі на підвісі з вольфрамового волокна діаметром 8 мкм розташовано коромисло довжиною 50 мм із приймальними елементами у вигляді системи мідних волокон діаметром 300 мкм і довжиною 15 мм. На один із приймальних елементів за допомогою рупора спрямовувалось мікрохвильове випромінювання. Описано калібрування крутильних ваг, процес вимірювань та оцінку похибки результатів. Вимірювання дали значення фактора ефективності тиску випромінювання $Q_{pr} = 4.86$. Це задовільно узгоджується з результатами розрахунків $Q_{pr} = 5.39$. Різниця становить 10%.

Ключові слова: мікрохвильове випромінювання; тонкі волокна; тиск випромінювання; вимірювання.

Измерение давления микроволнового излучения на тонкие металлические волокна

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Аннотация

Давление электромагнитного излучения в оптическом диапазоне используется в лазерных ловушках (“оптических пинцетах”) для управления положением мишеней (микрочастиц, биологических клеток и др.). Это возможно благодаря фокусировке лазерного излучения в область размером в несколько микрометров. Интенсивность излучения в ней достаточна для удержания частиц в луче и манипуляций с ними. В микроволновом диапазоне диаметр фокального пятна намного больше, и для управления объектами с помощью давления излучения необходимы очень большие мощности. Но известен эффект очень сильного взаимодействия тонких проводящих волокон с микроволновым излучением. Фактор эффективности давления излучения на такие объекты достигает значений в несколько сотен. Это может быть использовано для левитации объектов в виде тонких металлических волокон и для управления их положением в пространстве.

В статье описано измерение давления микроволнового излучения с длиной волны 8 мм на тонкие медные волокна. Для этого использованы крутильные весы. Описана калибровка крутильных весов, процесс измерений и оценка погрешности результата. Эксперимент подтвердил выводы теории.

Ключевые слова: микроволновое излучение; тонкие волокна; давление излучения; измерения.

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