Efficient non-resonant absorption of electromagnetic radiation in thin cylindrical targets: experimental evidence

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ABSTRACT

A theoretical possibility of non-resonant, fast, and efficient (up to 40 percent) heating of very thin conducting cylindrical targets by broad electromagnetic beams was predicted in [Akhmeteli, arXiv:physics/0405091 and 0611169] based on rigorous solution of the diffraction problem. The diameter of the cylinder can be orders of magnitude smaller than the wavelength (for the transverse geometry) or the beam waist (for the longitudinal geometry) of the electromagnetic radiation. Experimental confirmation of the above results is presented [Akhmeteli, Kokodiy, Safronov, Balkashin, Priz, Tarasevitch, arXiv:1109.1626 and 1208.0066, Proc. SPIE 9097, Cyber Sensing 2014, 90970H (June 18, 2014); doi:10.1117/12.2053482].

Keywords: electromagnetic beams, efficient absorption, thin cylinder, diffraction

1. INTRODUCTION

In this experimental work, we show significant (up to 36%) absorption of broad electromagnetic beams in thin cylindrical targets (the diameter is two to three orders of magnitude less than the characteristic transverse dimension of the beam). This new physical effect can be used in numerous applications, including pumping of active media of short-wavelength lasers. For example, an exciting possibility of efficient heating of nanotubes by femtosecond laser pulses is discussed in Ref.[1] A theoretical possibility of non-resonant, fast, and efficient heating of extremely thin conducting cylindrical targets by broad electromagnetic beams was described in Ref.[2] (see also Refs.[1,3] and references there). In earlier work, either the conditions of efficient absorption in thin targets were resonant and thus difficult to use for practical plasma heating (Ref.[4]), or it was not noted that the power absorbed in a thin target can be comparable to the power in the incident wave (Refs.[5,6,7,8]).

The effect has the following physical mechanism: the absorption in the cylindrical target causes a deep fall in the field distribution, and this fall causes diffractive diffusion of the field towards the axis from a relatively large volume of the beam.

We consider two different geometries of target irradiation: the transverse geometry (Fig. 1) and the longitudinal geometry (Fig. 2).

2. TRANSVERSE GEOMETRY

Efficient heating takes place for converging axisymmetric cylindrical waves (under some limitations on the real part of the complex permittivity of the cylinder) if the diameter of the cylinder and the skin-depth are of the same order of magnitude and the electric field in the wave is directed along the common axis of the cylinder and the wave (see the exact conditions in Refs.[1,3] , where these conditions are derived based on a rigorous solution of the problem of diffraction of an electromagnetic beam on a cylinder). Similar conditions were derived earlier in Ref.[5] , but for the case of a plane wave diffracting on the cylinder, where heating is very inefficient. The

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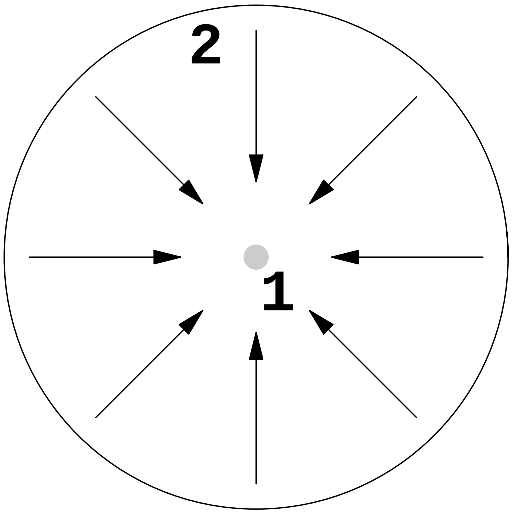

Figure 1. Transverse geometry (the axes of a converging cylindrical wave and a cylinder coincide; there is no energy flow along the axis; the wavelength is considered the transverse dimension of the beam). 1 – cylindrical target; 2 - incident converging cylindrical electromagnetic wave .

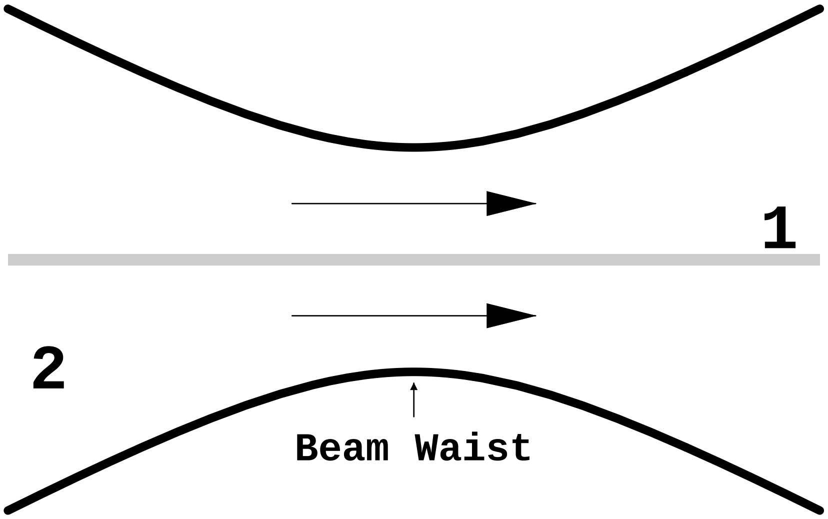

Figure 2. Longitudinal geometry (the axes of a Gaussian beam and a cylinder coincide; the energy flows mainly along the axis). 1 – cylindrical target; 2 – incident Gaussian electromagnetic beam (energy flows from left to right).

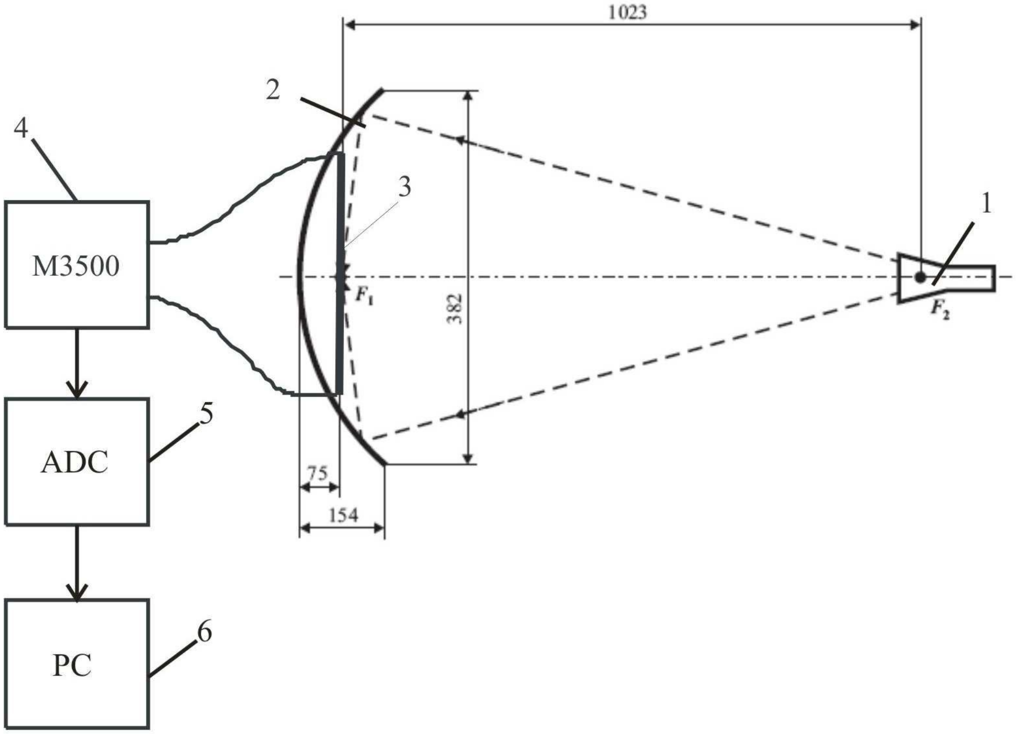

Figure 3. The experimental setup, transverse geometry (not to scale). The dimensions are in millimeters. Microwave radiation ($\lambda \sim 8mm$) from the horn 1 is focused by the ellipsoidal reflector 2 on an 11μ carbon fiber 3 . 4 Multimeter 5. ADC 6 PC.

experimental results of Ref.[6] , motivated by the theoretical results of work [5] , were obtained for absorption of microwave H_{01} mode at the output of a waveguide, and overall heating efficiency was not assessed. In the present experiment, we demonstrate efficient heating of a thin fiber by an electromagnetic beam in free space, thus confirming the predictions of Refs.[1–3]) (preliminary results for a somewhat problematic configuration were presented in Ref.[9]). The experimental results are in satisfactory agreement with theoretical computations.

The experimental setup is shown schematically in Fig. 3.

A thin fiber is placed in focus F_1 of the ellipsoidal reflector. The internal surface of the reflector is a part of an ellipsoid of revolution defined by the equation:

$$\frac{x^2}{a^2} + \frac{y^2 + z^2}{b^2} = 1, \tag{1}$$

where $a \approx 586$ mm is the major semiaxis and $b \approx 287$ mm is the minor semiaxis of the relevant ellipse. The distance between the foci F_1 and F_2 is approximately 1023 mm. A horn with aperture 31 x 22 mm^2 and length 130 mm is placed in focus F_2 (the distance between the horn aperture and the focus is 65 mm). The wide side of the horn is horizontal. The horn is connected to a waveguide with dimensions 7.2 x 3.4 mm^2 with mode H_{10}. The wavelength of the electromagnetic radiation was about 8 mm, and the power was about 1 W. Typically, most of the power is collected by the reflector and focused in focus F_1.

A thermal image of the heated fiber is shown in Fig. 4.

To measure the power absorbed by a cylindrical target irradiated by a continuous microwave beam, the target's electrical resistance was measured before and during irradiation. When the fiber in the focus is heated

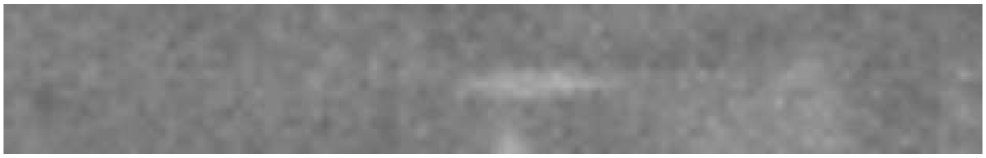

Figure 4.

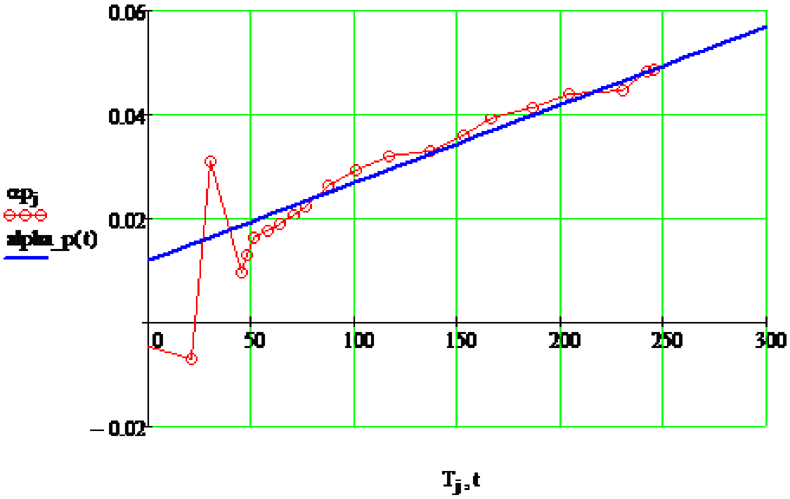

Figure 5.
Temperature coefficient of convective heat transfer ($P = \alpha_p L \Delta T$) vs. temperature (deg. C).

by the radiation, the initial resistance of the fiber R_0 changes by ΔR. The average fiber temperature increase ΔT corresponding to ΔR was calculated as

$$\Delta T = \frac{\Delta R}{\alpha_r R_0}, \tag{2}$$

where α_r is the temperature coefficient of resistance. This coefficient was measured for a 275 mm fiber to be $-0.000340K^{-1}$. The resistivity was measured to be $1.2 \cdot 10^{-5}\Omega m$.

On the other hand, the steady state fiber temperature increase depends on the absorbed power P_a and the conditions of heat exchange with the environment. We assume that, after a short transient process, all the power absorbed in the fiber is transferred to the surrounding air through convection (the contribution of conductive heat transfer through the ends of the fiber is relatively small, as the fiber is very thin). According to Newton's law of cooling (Ref.[10]),

$$q\text{"} = h(T_s - T_\infty), \tag{3}$$

where q" is the convective heat flux, T_s and T_∞ are the temperatures of the fiber surface and of the ambient air at infinity, respectively, and h is the convection heat transfer coefficient. We assume that temperature is approximately constant in any transverse section of the fiber, as the latter is very thin, and its thermal conductivity is relatively high. Thus, on average(cf. Ref.[6]),

$$\Delta T = \frac{P_a}{a_p L}, \tag{4}$$

where L is the length of the fiber and a_p is the linear convection heat transfer coefficient. For the carbon fiber of diameter 11μ, this coefficient was measured using a direct current. Under the conditions of the experiment, this coefficient was found to depend significantly on the temperature (Fig. 5).

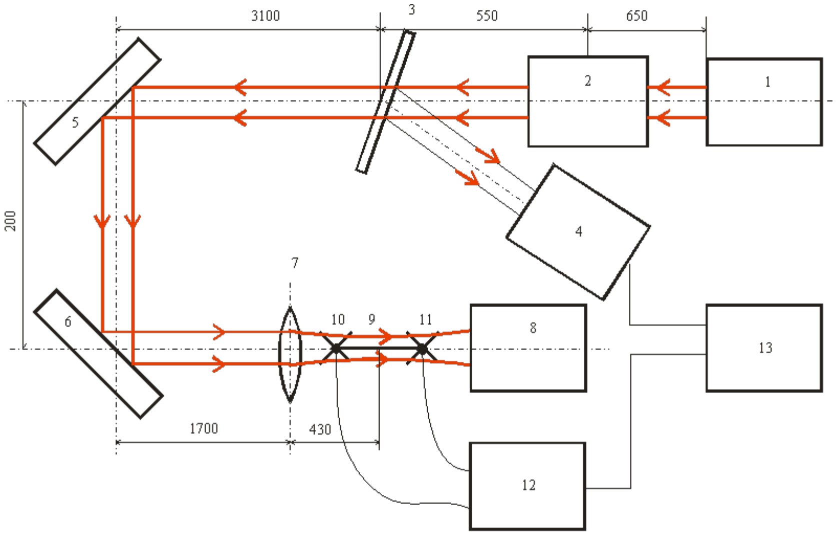

Figure 6.
1. CO2 laser 2. Polarization attenuator 3. Beam splitter 4. Laser power meter 5. Mirror 6. Mirror 7. Lens 8. Absorber 9. Wire 10. Cross-wire 11. Cross-wire 12. Multimeter 13. PC.

Different methods used to take into account these circumstance (to be described elsewhere) yielded somewhat different results for the efficiency of absorption: 12-14%.

Theoretical computations of heating efficiency were performed as follows.

The feed horn fields (incident on the reflector) were computed using the formulas for the far zone of a pyramidal horn.[11] The reflected fields for the ellipsoidal reflector were estimated using methods of physical optics,[12] as the radii of curvature of the reflector are much greater than the wavelength everywhere. Absorption of the reflected field of the ellipsoidal reflector in the fiber in the focus of the reflector was computed using the rigorous solution of the problem of diffraction of electromagnetic field on a homogeneous cylinder (Ref.[13]), which has a simpler form in the case of axisymmetrical field (non-axisymmetrical field is not efficiently absorbed in a very thin cylinder). The efficiency of absorption was calculated to be 9%, in good agreement with the experimental results.

3. LONGITUDINAL GEOMETRY

The experimental setup is shown schematically in Fig. 6.

The CO_2 laser emits infrared radiation (the wavelength λ is 10.6 micron). The thin wire was mounted using crosswires in vertical planes at each end. Each crosswire consisted of two mutually orthogonal thin nickel wires (length – about 60 mm, diameter – 50 micron). The wires were placed at 45° to the vertical. The horizontal wire was placed upon these crosswires and had to be pulled taut to ensure its stability in the course of heating. A photograph of a heated wire is shown in Fig. 7.

The parameters of the horizontal wire are given in Table 1.

Material	D, μm	L, m	α_r, K^{-1}	α_p, W/(m·K)
Pt	20	1.1	$4 \cdot 10^{-3}$	$4 \cdot 10^{-2}$

Table 1. Wire material, diameter D, length L, temperature coefficient of resistance α_r, linear heat exchange coefficient α_p.

The linear heat exchange coefficient depends weakly on the material and the wire diameter in this range of parameters. It was measured through heating the wire with direct current.

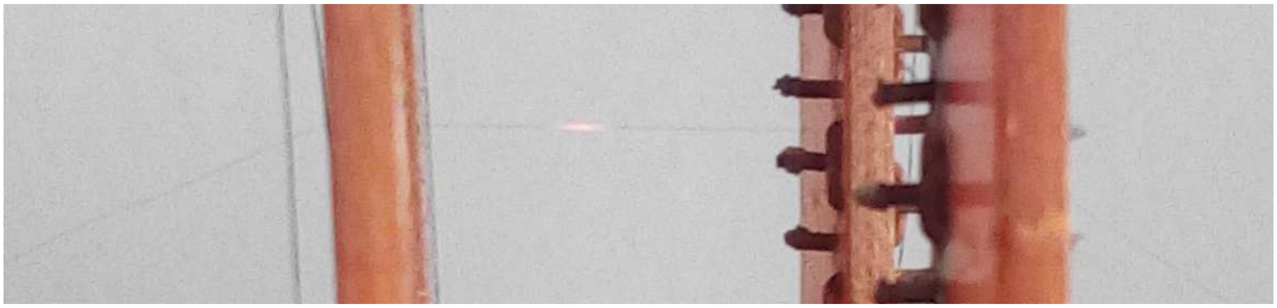

Figure 7.
Longitudinal geometry. Heated wire (for a 400 mm lens focus length and a beam waist's width of about 0.3 mm).

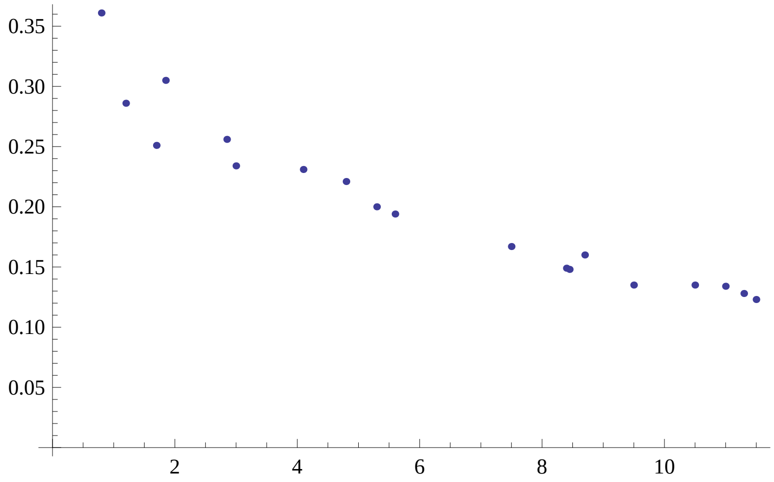

Figure 8. Absorption efficiency vs beam power, W.

The beam is focused by a ZnSe lens (the focal length f is 1700 mm). The electrical resistance of the wire is measured with an ohmmeter. The parameters of the beam and the wire provide efficient absorption for the platinum wire (case 2.1.2.1, Eq. (167) of Ref.[1] , version 1).

The results of the experiments are presented in Fig. 8.

The measured absorption efficiency was compared to the absorption efficiency of 0.58 computed using the precise theoretical method for a gaussian beam of Refs.[1,3,14]). Thus, the experimental results are in qualitative agreement with the theoretical predictions derived for gaussian beams. It should be emphasized that the efficiency achieved in the experiment is quite high, as the measured width of the beam's waist (1.2 mm at 1/e intensity level) is two orders of magnitude greater than the wire diameter (20 micron).

The exact cause of the nonlinearity (significant dependence of the absorption efficiency on the beam power) has not been established yet, but variation of the air refraction index due to convective flows from the heated wire is a candidate, as the following observation suggests: we directed a laser beam in the visible range along the wire, and the beam's structure (observed on a screen behind the wire) changed when the CO_2 laser beam was switched on and off. No such change of structure was observed when the visible beam was deflected away from the wire. The nonlinearity can also be caused by the dependence of the linear convection heat transfer coefficient on the temperature.

4. CONCLUSIONS

The results of the experiments on target irradiation in the transverse and the longitudinal geometries demonstrate the feasibility of efficient heating of thin cylindrical targets with broad electromagnetic beams with transverse dimensions several orders of magnitude greater than the diameter of the target. To this end, there needs to be a match between the diameter of the target, its conductivity, and the wavelength. However, the conditions of efficient heating are non-resonant and therefore very promising for numerous applications. The heating efficiency of tens percent can be achieved for very thin targets.

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