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# Periodic generation of submerged jets during laser heating of the fiber tip

© V.I. Yusupov

Institute of Photon Technologies, Federal Scientific Research Center „Crystallography and Photonics“, Russian Academy of Sciences, Troitsk, Moscow, Russia

E-mail: iouss@yandex.ru

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It has been experimentally found that when the tip of an optical fiber with an absorbing coating is heated by continuous laser radiation with a wavelength of 0.97 $\mu$m, submerged jets are periodically generated in water. Each such jet is formed as a result of the collapse of a gas-vapor bubble arising from the explosive boiling of water. The mechanisms of formation of bubbles and jets are discussed.

**Keywords:** laser radiation, optical fiber, absorbing coating, explosive boiling, submerged jet.

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The research interest in submerged jets formed due to the cavitation collapse of laser-induced gas-vapor bubbles has been on the rise lately (see [1–4] and references therein). On the practical side, this interest stems from the need for efficient cooling of micro- and nanoelectronic components [5], selective cleaning of various surfaces [6], and perfecting the bioprinting technology [4,7] and from various medical applications, which range from kidney stone destruction [8] to surgical treatment of different types of diseases [9].

Research groups have conducted a detailed experimental examination and simulation of the stages of formation of submerged jets in water induced by the absorption of continuous or pulsed laser radiation in the bulk of liquid in the vicinity of an tip of an optical fiber [1–3,10–13]. It was found that explosive water boiling occurs at the first stage due to significant superheating, and the superheated region decomposes into vapor (compressed to high pressures) and liquid microdroplets. This results in the formation of a rapidly growing gas-vapor bubble, which collapses after reaching its maximum size. The collapse of this non-equilibrium bubble with no symmetry induces the formation of a submerged jet directed from the fiber tip toward free liquid. The velocity of such jets varies from several centimeters per second to several tens or hundreds of meters per second.

There is a certain interest in examining the possibility of generation of submerged jets in the process of absorption of laser radiation in a thin absorbing layer on a fiber tip (rather than in the bulk of liquid). Such fibers with absorbing coatings are used, e.g., in certain advanced medical technologies to intensify hydrodynamic processes [9,14]. It is demonstrated in the present study that submerged jets are generated periodically in water due to explosive boiling in the process of heating of an tip of an optical fiber with an absorbing coating by continuous laser radiation.

An LS-0.97 fiber laser device (IRE-Polyus, Russia) operating at wavelength $\lambda = 0.97\,\mu$m and coupled with an optical fiber with a light-conducting quartz core $400\,\mu$m in diameter was used in experiments. The tip of this fiber was coated with a thin layer of amorphous carbon by bringing it into brief (several seconds) contact with wood under continuous laser irradiation with $P = 2$ W. This procedure allowed us to obtain a coating with reproducible characteristics that absorbed $k = 30 \pm 5\%$ of the laser radiation energy. The fiber was introduced horizontally into a transparent cell $7 \times 5 \times 3$ cm in size filled with water kept at 22°C. The immersion depth was 20 mm.

Dynamic processes in liquid were studied by high-speed video recording and wideband acoustic signal detection. A Fastcam SA-3 high-speed camera (Photron, Japan) with frontal illumination (in transmission) operated at 20 000 fps was used for this purpose. A GDS 72304 (GW Instek) memory oscilloscope was used to record acoustic signals within the 0–500 kHz range from a wideband hydrophone type 8100 (Brüel & Kjær). The angle between the fiber axis and the hydrophone axis was 90°, and the distance between the fiber tip and the sensing hydrophone element was 15 mm.

A noise-like acoustic signal associated with water boiling at the fiber tip with the absorbing coating emerges $t = 0.2$ s after the application of laser radiation with $P = 4$ W (Fig. 1, *a*). Examining the presented fragment of this signal (Fig. 1, *b*), one can see that it consists of fairly short decaying pulse trains of various amplitude and length ($\tau \sim 4-8$ ms) with a $\Delta t$ time interval between them, which is normally longer (or significantly longer) than $\tau$.

Figure 2 shows high-speed video frames illustrating the stages of formation and collapse of a bubble in water at the fiber tip with the absorbing coating heated by continuous laser radiation. The working part of the fiber surrounded with vapor-gas bubbles from all sides is seen in these frames.

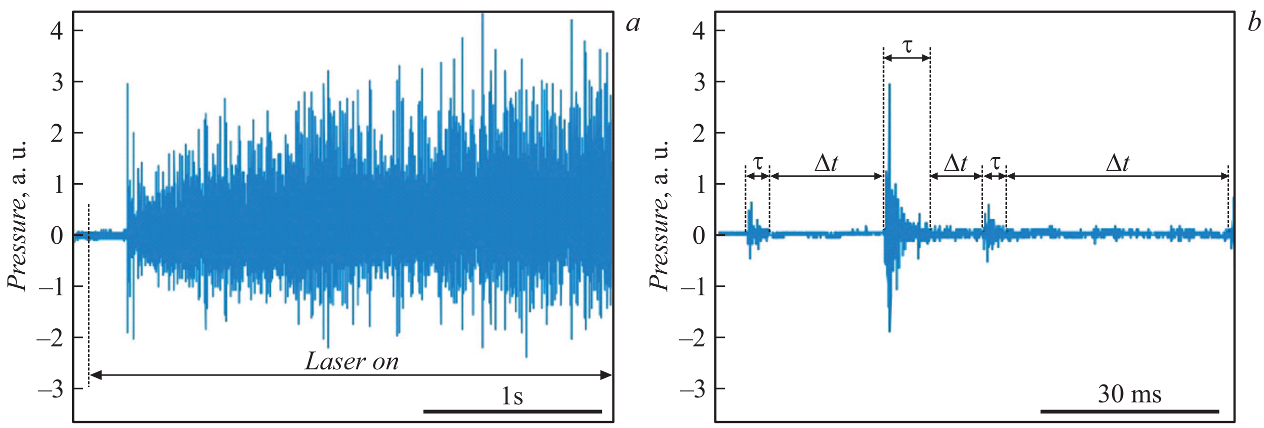


**Figure 1.** Acoustic signal induced by water boiling at the fiber tip with an absorbing coating heated by continuous laser radiation. *a* — Emergence and evolution of the signal after the application of laser radiation, *b* — acoustical signal fragment. The lengths of decaying pulse trains ($\tau$) and intervals between them ($\Delta t$) are indicated. $P = 4$ W.

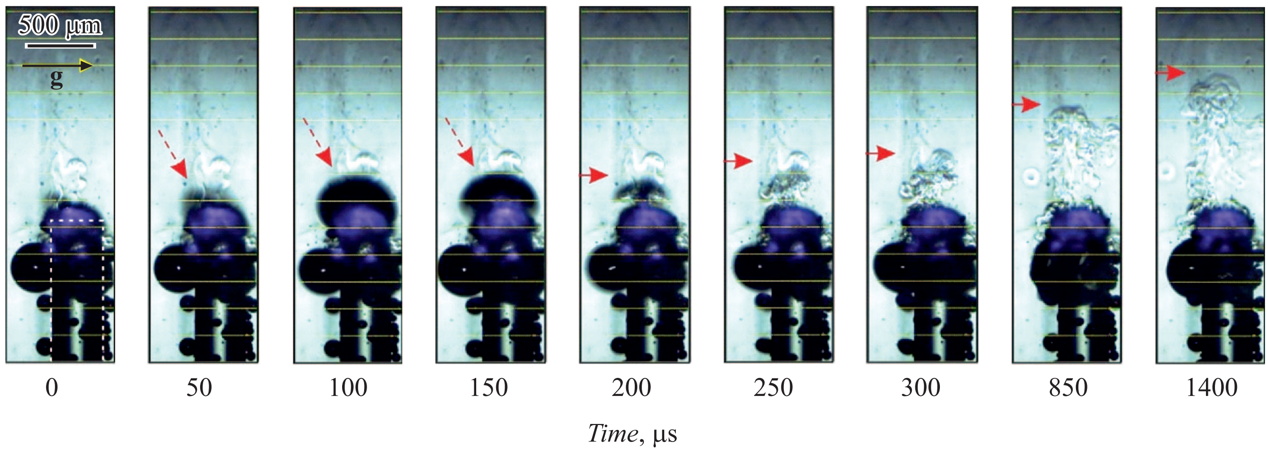


**Figure 2.** High-speed video frames captured at the moment of formation of a submerged jet under laser heating of the fiber tip with an absorbing coating. Numbers indicate time (in $\mu$s). The inclined arrow points at the forming and collapsing bubble. The horizontal arrow marks the submerged jet front. The dashed outline in the first frame represents the end fiber part. Vector **g** denotes the direction of gravitational acceleration. Horizontal lines are spaced 200 $\mu$m apart.

These bubbles were found to be stationary. Their formation is associated with the release of dissolved gases induced by fiber heating.

The first three frames in Fig. 2 demonstrate that a bubble (indicated with an inclined arrow) grows within this time interval near the fiber tip. Its cross section at $t = 100\,\mu$s is an ellipse with an axis length of $\sim 480\,\mu$m (along the optical axis) and $\sim 630\,\mu$m (transverse to it). The bubble then starts shrinking and collapses at $t = 200\,\mu$s, ejecting a mushroom-shaped submerged jet toward free liquid. The diameter of the base („stem") of this mushroom-shaped formation is $\sim 140\,\mu$m, the „cap" diameter is $\sim 400\,\mu$m, and its height is $\sim 230\,\mu$m.

Subsequent frames ($t > 200\,\mu$s) illustrate the propagation of the submerged jet front (horizontal arrows) away from the fiber tip. The frame captured at $t = 200\,\mu$s allows one to determine the initial jet velocity, which was estimated at $\sim 7$ m/s, at a distance of $\sim 200\,\mu$m from the tip; this velocity decreases gradually to 0.5 m/s at a distance of $\sim 1$ mm ($t = 1.4$ ms).

Similar growing and collapsing bubbles of a much greater size are detected at the fiber tip if laser radiation is absorbed strongly in water [9] or an aqueous dye solution [13]. In the case of continuous laser irradiation, these hydrodynamic processes are initiated via thermal cavitation [15]. The temperature of a small volume of water absorbing laser energy may exceed considerably its saturation temperature (100°C at $p = 1$ atm), thus initiating explosive water boiling. It is known that such processes are accompanied by the generation of pulsed acoustic signals [16].

Note that the optical fiber was introduced horizontally into the experimental cell. This is typical, e.g., for modeling of similar effects in medicine [17]. Convection triggered in this geometry induces the formation of larger stationary bubbles on the top fiber surface and the upward deflection of submerged jets generated at the tip. It can be seen in

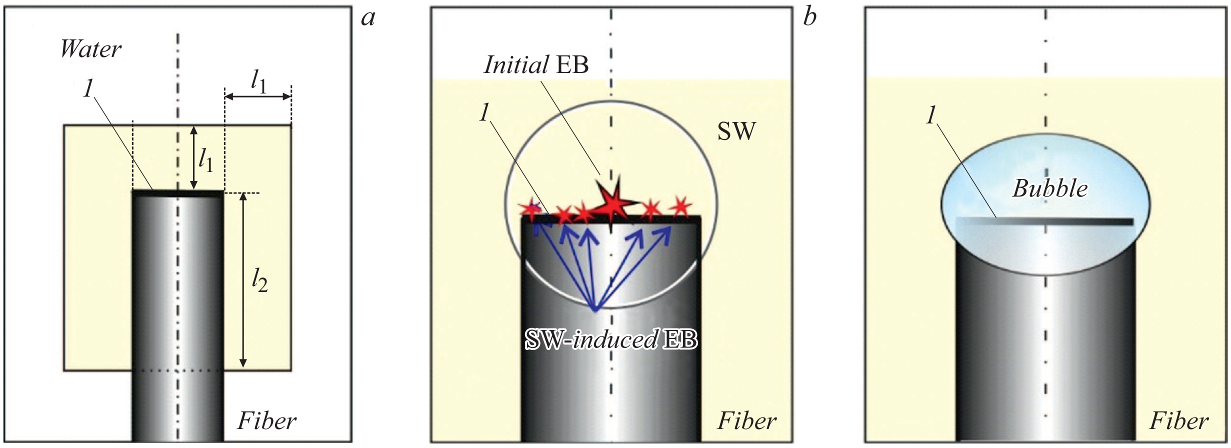


**Figure 3.** Diagram illustrating the processes at the fiber tip that precede the formation of the first bubble after the application of laser radiation. *a* — Superheated water region (shaded area), *b* — initial explosive boiling (*Initial* EB), which is accompanied by the generation of a shock wave (SW), and SW-induced explosive boiling (SW-*induced* EB), *c* — formed bubble prior to the onset of its collapse. The arrow numbered *1* indicates the thin absorbing coating on the fiber tip.

Fig. 2 that larger stationary bubbles do indeed form to the right of the fiber, and the influence of convection on the jet direction is insignificant.

Absorbing laser radiation, the thin absorbing layer on the fiber tip becomes a heating source. The redistribution of released heat between the absorbing layer, the fiber, and surrounding liquid governs the hydrodynamic processes near the fiber tip with the absorbing coating. Let us estimate the magnitude of temperature rise $\Delta T$ in the region of the fiber tip at the moment of emergence of intense acoustic signals ($t = 0.2$ s in Fig. 1). We assume that the volumes of water and quartz fiber (Fig. 3, *a*) with thicknesses $l_1 = \sqrt{\pi\alpha_1 t}$ and $l_2 = \sqrt{\pi\alpha_2 t}$ ($\alpha_1 = 0.14\,\mathrm{mm^2/s}$ and $\alpha_2 = 1.4\,\mathrm{mm^2/s}$ are the temperature conductivity coefficients for water and quartz, respectively) along the optical axis are already heated by that time. A water volume in the form of a hollow cylinder (with length $l_1 + l_2$ and wall thickness $l_1$), which surrounds the mentioned heated fiber and liquid volumes, is also heated (Fig. 3, *a*). Then,

$$\Delta T = \frac{kPt}{\pi R^2(C_1\rho_1 l_1 + C_2\rho_2 l_2) + \pi(2Rl_1 + l_1^2)(l_1 + l_2)C_1\rho_1} \approx 121^\circ\mathrm{C}, \quad (1)$$

where $k = 0.30 \pm 0.05$ is the absorbed energy fraction; $P = 4\,\mathrm{W}$ is the power; $R = 200\,\mu\mathrm{m}$ is the fiber radius; $C_1 = 4180\,\mathrm{J/(kg \cdot K)}$ and $C_2 = 1050\,\mathrm{J/(kg \cdot K)}$ are the thermal capacities of water and quartz, respectively; and $\rho_1 = 1000\,\mathrm{kg/m^3}$ and $\rho_2 = 2200\,\mathrm{kg/m^3}$ are the densities of water and quartz, respectively.

It should be taken into account that the estimate obtained using formula (1) concerns the average temperature within the designated water volume (Fig. 3, *a*). Since temperature decreases with distance from the fiber tip, its value at the very end of the fiber with the absorbing coating is higher. Such significant superheating relative to the liquid–vapor equilibrium temperature (with the maximum superheating attained in experiments being 210°C; see [18] and references therein) is accompanied by explosive water boiling [19]. The probability of this process increases with the degree of superheating, which is maximized near the optical axis at the surface of the thin absorbing layer on the fiber tip (Fig. 3, *b*). A shock wave (SW in Fig. 3, *b*) produced as a result of initial explosive boiling may initiate [20] the process of explosive boiling along the fiber tip (Fig. 3, *b*). Vapor released within this volume induces the formation of a rapidly expanding ellipsoidal bubble (Fig. 3, *c*). This bubble collapses $\sim 200\,\mu$s after its formation and ejects a submerged jet (Fig. 2). According to the results of numerical calculations [2], such a jet is mushroom-shaped at the initial stages. This is exactly what was observed at $t = 200\,\mu$s (Fig. 2).

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## Conflict of interest

The author declares that he has no conflict of interest.

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