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Photoacoustic shock wave emission and cavitation from structured optical fiber tips

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Photoacoustic waves generated at the tip of an optical fiber consist of a compressive shock wave followed by tensile diffraction waves. These tensile waves overlap along the fiber axis and form a cloud of cavitation bubbles. We demonstrate that shaping the fiber tip through micromachining alters the number and direction of the emitted waves and cavitation clouds. Shock wave emission and cavitation patterns from five distinctively shaped fiber tips have been studied experimentally and compared to a linear wave propagation model. In particular, multiple shock wave emission and generation of strong tension away from the fiber axis have been realized using modified fiber tips. These altered waveforms may be applied for novel microsurgery protocols, such as fiber-based histotripsy, by utilizing bubble-shock wave interaction. © 2016 AIP Publishing LLC.

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The small size and flexibility of optical fibers allow their insertion into the urinary and vascular system to conduct laser-based microsurgeries, for instance, fragmentation of urinary stones,¹ angioplasty,² and laser thrombolysis.³ The mechanism of laser tissue ablation depends on the laser pulse duration and wavelength, as well as the ablation region parameters.⁴ If the pulse duration τ is shorter than the acoustic and thermal relaxation time of the medium, strong photoacoustic waves can be excited from the irradiated volume.⁵ The stress and thermal relaxation times are t_{st} and t_{th} , where $\tau < t_{st} = \delta/c$ and $\tau < t_{th} = \delta^2/4k$. Here, δ is the length scale of the irradiation volume equal to the fiber diameter, c is the speed of sound, and k is the thermal diffusivity of the absorber. Within the limit of linear absorption, the photoacoustic wave emitted can be modeled with a linear wave equation using a delta-type source term.⁶ Above a threshold intensity, the liquid is vaporised due to non-linear absorption which is accompanied by the rapid expansion of a vapor bubble and complex fluid flow.⁷ Here, we focus on pulses at sufficiently low-energy that result in linear absorption, see Ref. 8.

Using pressure measurements and numerical solutions of the wave equation, Paltauf *et al.*⁹ have demonstrated that laser irradiation of a liquid under stress confinement first compresses and then strains the liquid away from the fiber optic tip. The straining is caused by diffraction of the compressive wavefront at the circumference of the fiber tip, which generates a toroidal tensile wave that refocuses along the fiber axis. This tensile stress may rupture the liquid and form a cloud of microscopic cavitation bubbles. For medical applications, it is widely known that bubble-shock wave interaction can lead to intense bio-effects¹⁰ which can be either harmful or utilized for therapy. Histotripsy is a recent successful application of bubble-shock wave interactions, which uses pulse trains of compressive and tensile waves

generated by an extracorporeal acoustic source.¹¹ In this procedure, cavitation bubbles are nucleated by the tensile waves and are collapsed by the subsequent compressive shock fronts. These cycles generate intense shearing flows which liquefy the tissue to scale much smaller than the size of cells.¹² It would be advantageous to have such a shock wave source at the tip of an optical fiber to allow coupling into surgical catheters for highly targeted laser ablation.

In recent years, remarkable progress has been made with laser generated ultrasound. Baac *et al.* focused laser generated shock waves down to 100 μm while achieving 57 MPa of positive pressure for biological applications.^{13,14} Based on a similar light absorbing film of carbon nanotubes, Colchester *et al.*¹⁵ demonstrated laser generated ultrasound at the tip of optical fibers. Existing efforts to generate ultrasound via optical fibers have been focused on using chemical coatings, e.g., gold nanocomposites,¹⁶ or preparing micro-machined attachments for fiber tips.¹⁷ However, the tension achieved via these acoustic emitters is far below the tensile stress needed to induce cavitation.

In this letter, we use laser machining for shaping fiber tips, in order to emit complex waveforms at sufficient amplitude to induce cavitation. We report on direct visualization of the waves, numerical simulations, and localized pressure measurements. The results show that the structured fiber tips are capable of multiple shock wave emission from a single laser pulse, as well as steering and shaping of photoacoustic waves and cavitation clouds. This suggests that shaped fiber tips are able to generate suitable waveforms for cavitation-based microsurgery protocols.

To obtain structured optical fiber tips, multimode silica fibers ($d = 600 \mu\text{m}$, FT600EMT, Thorlabs, USA) are flatly cleaved at both ends, and laser micro-machining is done on one end with a picosecond infra-red laser (Duetto, Time-Bandwidth Products, Switzerland), for details see Ref. 18. In the present study, five tip structures have been tested: flat

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FIG. 1. Schematic of the stroboscopic photography setup.

cleave, oblique cut, step, groove, and ridge, shown in Fig. 2 from right to left. Stress confinement is obtained by submerging the tip in an aqueous red dye solution (Cochineal Red, Bake King, Singapore) and coupling a green nanosecond Nd:YAG laser pulse ($\lambda = 532$ nm, $\tau = 6$ ns, $E \leq 10$ mJ, Orion, New Wave Research, USA) into the cleaved fiber end. Using a spectrometer, the absorption coefficient of the red dye was measured to be $\mu = 355$ cm $^{-1}$ at 532 nm. The scene is illuminated with a red 6 ns pulse, generated through laser induced fluorescence emission from a Rhodamine dye. To achieve this, a second Nd:YAG laser is focused mildly into the fluorescent dye, coupled into a fiber, brought to the scene, expanded, and weakly diffused. By varying the delay between the two laser pulses, one inserted into the structured fibers and the other used for illumination, shadowgraph images of the shock waves and nucleation of cavitation can be recorded with a sensitive CCD camera (Sensicam QE, PCO, Germany). The setup is shown schematically in Fig. 1.

Fig. 2 shows the acoustic waves and cavitation in front of each fiber structure 300 ns after the laser pulse. The top row shows shadowgraph image from the experiments, while

the bottom row presents the solution of the linear wave equation at the same time instant. For the flat and oblique cut, the acoustic field is composed of two main components: a planar compressive wave conforming to the shape of the fiber tip and a toroidal diffraction wave caused by the edge of the tip.^{8,9} For the oblique cut, the minimum pressure and the cavitation cloud are steered away from the fiber axis, i.e., perpendicular to the surface, but not parallel to the axis. The photoacoustic wave fields in front of the step, groove, and ridge structures are more complex: from a single laser pulse, multiple shock waves are generated. A compressive wave is emitted from each liquid layer adjacent to an irradiated surface, i.e., two compressive waves are formed by the step structure, and three by the groove and the ridge. Tensile diffraction waves show an even more complex emission scenario for structured tips, which nevertheless can be easily explained with a linear wave equation in three dimensions.

The photoacoustic waves induced by the laser pulse are modeled by the linear wave equation, which is solved for the acoustic pressure p

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0. \quad (1)$$

The shock wave emitted from the fiber tip is modeled as a high frequency, short pulse Dirichlet boundary condition on the tip surface, i.e., $p = p_a \sin(2\pi f t)$ for $t < \frac{1}{2f}$ and $f = 10$ MHz. The initial amplitude p_a does not affect the quantitative behavior of the solution and it can be calibrated to the experimentally measured pressure, since the governing equation (Eq. (1)) is linear. The glass fiber boundary is modeled as a sound hard boundary condition, i.e., $\hat{n} \cdot \nabla p = 0$, where $\hat{n}$ is the normal vector at the surface. The outer limits of the liquid domain, modeled here as water, are implemented as plane wave radiation boundary condition

$$\hat{n} \cdot \nabla p + \frac{1}{c} \frac{\partial p}{\partial t} = 0. \quad (2)$$

We use a finite element solver (Mathematics Module, COMSOL Multiphysics, Sweden) to solve Eq. (1) in 3D with the boundary conditions specified above. The structured fiber tips are modeled based on their measured dimensions from an optical microscope (VHX-2000, Keyence, Japan).

FIG. 2. Acoustic transients and cavitation induced by tensile stress in front of structured fiber optics after a single laser pulse ($\tau = 6$ ns, $H_0 < 1$ J/cm 2 , and $\mu = 355$ cm $^{-1}$). Top row shows shadowgraph images and bottom row presents numerical solutions of the linear wave equation corresponding to the same instant of time.

Please note that we solve the wave equation only in the liquid domain and do not resolve elastic waves in the fiber to reduce the computational cost.

A time sequence of the shadowgraph images and numerical solutions of the acoustic wave equation are shown for the flat cleaved fiber and compared with one of the tip structures in Figs. 3 and 4. As described in the previous studies^{8,9} on the flat cleaved tip, a shock wave is emitted from the irradiated liquid volume quickly after the laser pulse, see Fig. 3. While this shock wave is compressive, diffraction of this positive pressure wave from the edge of the optical fiber forms a toroidal acoustic wave with the opposite polarity, i.e., negative pressure. After tensile diffraction waves D1 and D2 overlap, the liquid along the fiber axis is ruptured and a cavitation cloud is formed, following the trail of the peak negative pressure. It is notable that this cavitation cloud is growing along the fiber axis and extends deeper than the optical penetration depth. In addition to the planar shock wave and tensile diffraction wave that travel away from the fiber tip, an oblique pressure wave is observed in the liquid traveling in the opposite direction, marked in Fig. 3 with F1. This oblique pressure wave is due to radiation of a flexural wave that travels downward along the body of the fiber. Since the speed of sound in the silica glass fiber c_g is faster than in the liquid c_l , a Mach cone is formed in the liquid with the angle $\beta = \tan^{-1} \frac{c_l}{c_g}$. See video in Fig. 3 for shadowgraph images and numerical simulation of shock wave emission from the flat cleaved tip.

Compared to the flat cleaved fiber, the acoustic transients in front of the structured fiber tip are more complex, shown in Fig. 4. Shortly after the single laser pulse, the liquid adjacent to the two distal fiber surfaces absorbs the pulse energy and two compressive pressure waves are emitted. At 100 ns, in addition to the positive pressure waves, three circles are observed which are tensile diffraction waves

emitted from the tip edges. At 200 ns, two of the diffraction waves, D1 and D2, overlap above the upper step surface, and a cavitation cloud begins to form perpendicular to the upper surface. Additionally, the three tensile waves D3, D4, and D5, which are emitted from the edges on the lower surface, overlap and overcome the yield strength of the dye solution near the vertical step surface, creating a prominent curved cavitation cloud. As shown at 300 and 400 ns, both the smaller and larger cavitation clouds follow the trails of peak negative pressure formed by the tensile waves. This is evident in the bottom row of Fig. 4, which is generated by the time-accumulated pressure isosurfaces at a cavitation threshold $p = -0.5p_a$. The video in Fig. 4 shows the shadowgraph images and numerical simulation of shock wave emission from the stepped tip.

The fiber optic hydrophone (HFO-690, Onda Corp., USA) allows measuring the pressure with a spatial resolution of 100 μm and a temporal resolution of 20 ns. In Fig. 5, we compare the numerical solutions with the measurements from the flat and stepped fiber tip at two locations: probe 1 on the axis of cylindrical symmetry and probe 2 away from the axis, marked in Figs. 3 and 4. Both probes are located on the symmetry plane of the fiber tips, at $x=0$. Comparing Fig. 5(a) with Fig. 5(b) reveals two shock wave emissions by the structured fiber optic, while only one is generated by the flat cleaved fiber. For the flat tip in Fig. 5(c), the tensile stress is highly focused on-axis but rapidly drops off-axis, in agreement with earlier studies.^{8,9} In contrast, the structured fiber tip allows significant tension to be generated off-axis, as shown in Fig. 5(d). Please note that we have conducted the pressure measurements at 1 mJ laser energy, which is below the cavitation threshold, and only normalized pressure is shown in Fig. 5. The maximum measured tensile stresses in Fig. 5 are 43.5, 31.8, 12.3, and 34.1 bars from left to right. Very good agreement could be achieved between the linear

FIG. 3. Shock wave emission and cavitation cloud formation from a flat cleaved fiber. The shadowgraph images from the top row are compared with the numerical solution of the linear wave equation in the middle. The bottom row shows evolution of the cavitation cloud based on the simulation data, generated by accumulation of pressure isosurfaces at the threshold $p = -0.5p_a$. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4939511.1>]

FIG. 4. Shock wave emission and cavitation cloud formation from a stepped fiber tip. Similar to Fig. 3, experimental shadowgraphs are at the top, numerical solution in the middle, and prediction of cavitation clouds based on the simulation at the bottom row. The stepped tip emits multiple shock waves and forms two cavitation clouds. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4939511.2>]

acoustic wave model and the experimentally obtained pressure-time traces.

The pressure measurements in front of structured fiber optics, for instance, the stepped tip in Fig. 5, show that modifying the tip geometry leads to multiple shock wave emissions. This provides the possibility of generating bubble-shock wave interactions using structured fiber optics, which could be utilized for novel, fiber-based tissue ablation protocols. Additionally, structured fiber tips allow for altering the direction of the cavitation cloud, for example, to steer the cloud from vascular lumen into the surrounding tissue. The simple and computationally cheap linear wave model can be run iteratively to obtain an optimum fiber tip shape for a

specific application, while remaining within mechanical and manufacturing constraints.

FIG. 5. Pressure measurements from a fiber optic hydrophone (blue, solid lines) compared with the numerical solution of the linear wave equation (red, dashed lines). The structured fiber tip generates multiple compressive and tensile waves on and off-axis from a single laser pulse.

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