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Study of Micro Shock Waves and Cavitation Generated by Ho:YAG Laser Beam for Medical Application

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Abstract

For medical application of underwater shock waves as a less-invasive approach, a reliable micro shock wave source is required. The present paper reports progress in production of underwater micro shock waves by direct irradiation of laser beam through an optical fiber. Energy source was a Q-switched Ho:YAG laser with 91 mJ/Pulse energy measured at the end of a 0.60 mm diameter glass optical fiber. The generation and propagation of underwater shock waves from the optical fiber were quantitatively visualized by double exposure holographic interferometry. Sequential flow visualizations revealed that plasma generated by the laser beam, drove spherical shock waves in water. Heat induced flow in front of the fiber vanished after 100 ms. Peak overpressures were measured at various stand-off distances by needle hydrophones. Effects of the optical fiber end configuration on the shock waves strength were clarified. The weak shock waves produced by this method have potential to be applied for precise medical procedures such as revascularization in neurosurgery.

Introduction

For applying shock waves to sensitive and precise medical procedures like revascularization therapies and neurosurgery, generation of underwater micro shock waves plays an important role. Such delicate applications make limits on usage of conventional underwater shock wave sources like shock wave reflection and focusing over half-ellipsoidal cavity so-called Extracorporeal Shock Waves ESW [2], micro explosives [4], or electric sparks [1]. In the present study a Q-switched Holmium: Yttrium Aluminum Garnet (Ho:YAG) laser and a 0.60 mm glass optical fiber are used. Advantages of this method over previous shock wave sources are two order of magnitude reductions in focusing area if compared with ESW and elimination of product gases of micro explosives.

From another point of view, Ho:YAG laser has been intensively used in medical therapies [3, 5, and 8]. However, mechanism of its effectiveness has not yet been well clarified.

Nakahara and Nagayama [6] studied underwater shock waves emanated from roughened end surface of an optical fiber by pulse laser input using shadowgraph technique. Their qualitative study limited to visualization of shock waves at its early stage. Shaw et al. [9] and Tong et al. [11] showed production of cavitation bubble after laser beam focusing in water. Schiffers et al. [7] by using high speed Schlieren photography studied the collapse of a laser-generated cavity near a rigid boundary. In their experimental study they focused Nd:YAG laser beam by focusing lenses.

The present research aims to clarify quantitatively: (i) process of the shock wave generation by direct laser beam irradiation through the optical fiber, (ii) effects of the fiber end configuration on the shock wave strength, (iii) growth and behaviour of the generated cavitation bubble, and (iv) structure of heat induced flow in front of the fiber.

Materials and Methods

Energy source was a Q-switched Ho:YAG laser (Nippon Infrared Industries Co., Ltd.,) with 90±10% mJ/Pulse energy measured at the end of a 0.60 mm diameter glass optical fiber, pulse duration of 200 ns, and wavelength of 2.1 μm. The laser beam was transmitted through the optical fiber.

Double exposure holographic interferometry was used for quantitative flow visualization [10]. Figure 1 shows a schematic diagram of the optical set-up. The optical arrangement consists of two paraboloidal schlieren mirrors (P.M.) of 200 mm dia. and 1,000 mm in focal length. A beam splitter transmitted 60% of source light intensity to an object beam and 40 % to a reference beam. Mirrors (M) were used to make the light path lengths of object beam and reference beam identical with each other. Light source was holographic double pulse ruby laser (Apollo Laser Inc. 22HD, 25 ns pulse duration, 1J per pulse). Visualization laser light of object beam was diverged with a lens (L), collimated with the 200 mm dia. paraboloidal mirror, and illuminated the test section. As seen in Fig. 1, the image of phenomenon in the test section was focused with a focusing lens and was collected on the holographic film placed on a film holder. This method is called image holography so that the result is identical with Mach Zehnder interferometry. Reference and object beams were then superimposed on a holographic film. The films were 100 mm x 125 mm AGFA GEVAERT 10E75 sheet films. Double exposure holographic interferometry was used. The first laser exposure was carried out before triggering of the Ho:YAG laser and the second exposure was synchronized with the propagation of the shock wave at the test section with a proper delay time.

The constructed holograms were later reconstructed by illuminating them with an Argon-Ion laser beam (514.5 nm wave length and 1 watt). The reconstructing laser beam was adjusted by diverging and converging lenses as shown in figure 2. Neo Pan SS 100 mm x 125 mm sheet films were used to record

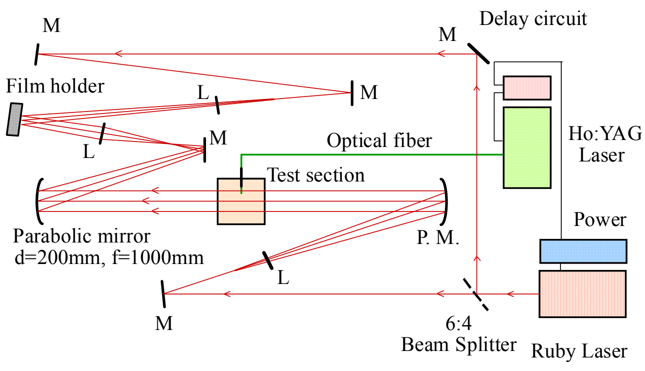


Figure 1. A schematic diagram of holographic interferometric optical arrangement.

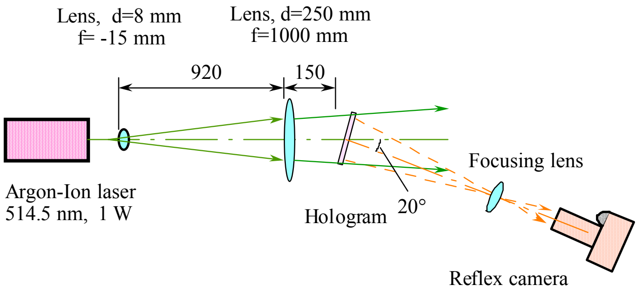


Figure 2. A schematic diagram of optical setup for reconstruction of holograms.

reconstructed images.

Figure 3 shows a schematic of the experimental set up for pressure measurement. A stainless steel container equipped with observation windows was used. The optical fiber and pressure transducers were exactly aligned in lateral, horizontal, and vertical directions. PVDF needle hydrophones with 0.5 mm sensitive dia. and 50 ns rise time (Imotec Messtechnik, Germany) were used for pressure measurements.

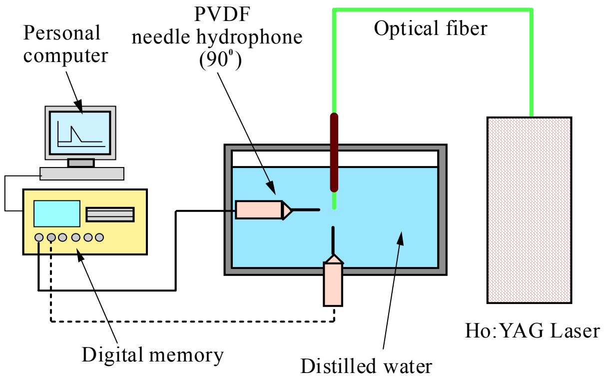
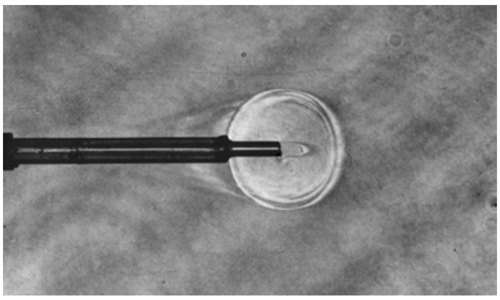
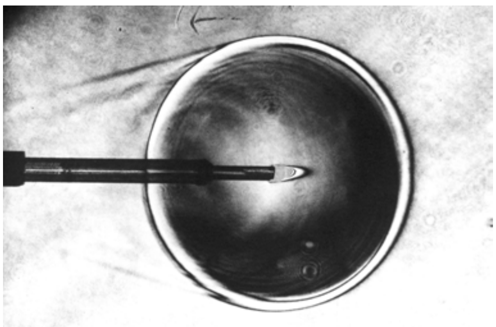


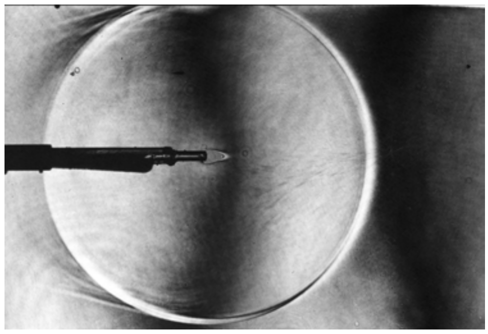
Figure 3. Experimental set up for pressure measurement.



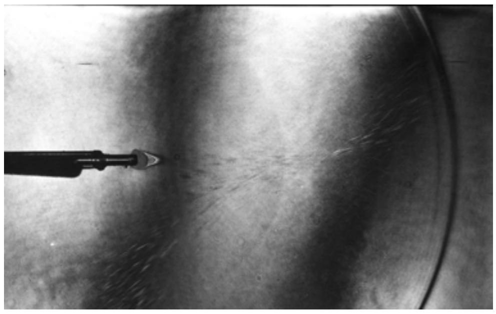
(a) 1.7 μs



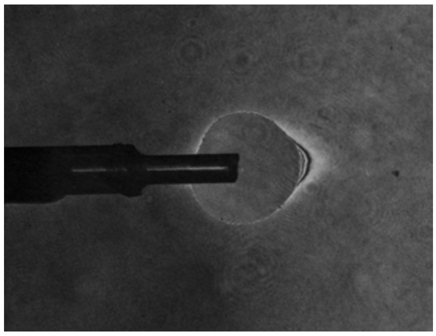
(b) 4 μs



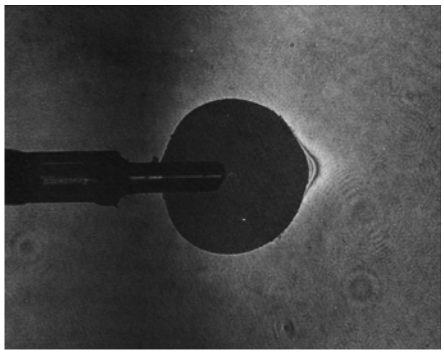
(c) 6.5 μs



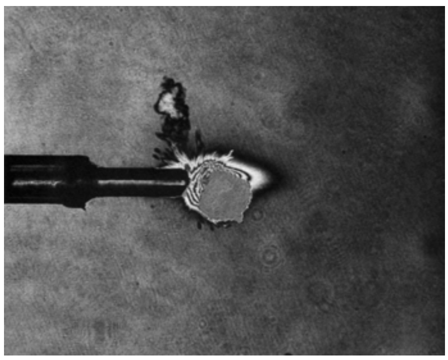
(d) 12.5 μs



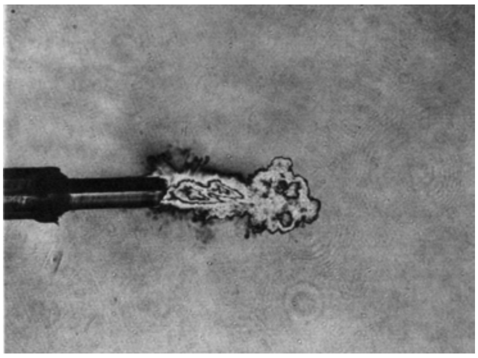
(e) 100 μs



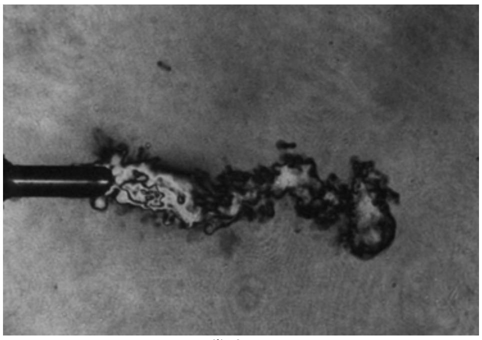
(f) 200 μs



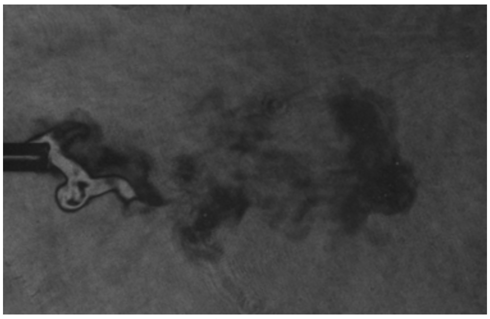
(g) 300 μs



(h) 700 μs



(i) 2 ms



(j) 10 ms

Figure 4. Sequential infinite fringe holograms of the underwater shock waves and the vapor cavities produced by Ho:YAG laser beam irradiation from roughened end 0.60 mm glass optical fiber.

Results and discussion

Flow visualization

Figure 4 shows sequential infinite fringe interferograms of generation and propagation of the underwater shock waves from roughened end of the optical fiber. Figure 4a, 1.7 μs after shock wave production, shows a 2.55 mm radius spherical shock wave in water. The shock wave generation associated with the laser breakdown in the water. The laser interaction produced micro plasma in the water and heated the liquid in front of the fiber. The plasma drove spherical shock wave in water. This process followed by formation of a high temperature vapor cavity. Wave propagation through the optical fiber produced a conical precursor wave which is clearly observable in figure 4a. Figures 4b, c, and d show the sequence of the spherical shock wave propagation at 4, 6.5, and 12.5 μs, respectively. In front of the optical fiber in figure 4b at 4 μs the vapor bubble of about 0.41 mm dia. is observed and fringes next to it indicate the high temperature of that zone. In figures 4b-d first shock wave followed by another shock with about 0.6 mm radial distance and shock front had a fold shape. This process might be related to Ho:YGA laser irradiation from the optical fiber. A random or rough end surface of the fiber can produce diffuse transmission of the laser beam and separate focal areas with different energies. This made a delay for distinct plasma generations and shock waves. Figures 3e-f, at 100 and 200 μs, show cavitation bubble of 1.15 and 1.6 mm radius, respectively. The high temperature in front of the fiber resulted in higher growth of the vapor cavity in that direction. Figure 4g, at 300 μs, shows the cavitation bubble after its first collapse. By that moment secondary cavity is produced which is observable in front of the fiber in figure 4g. By elapse of time heat dissipation in front of the fiber can be seen in figures 4h-j.

Pressure measurement

Pressure histories at various stand-off distances R were measured. In order to determine the strength of the laser generated and cavitation induced shock waves, different kind of surface finished optical fibers were examined. Results are shown in figure 5. By increasing the roughness of the optical fibers end, stronger shock waves were produced. Figure 6 shows enlarged views of the fiber ends referring to figure 5. As can be seen by making the fiber end sharper, higher overpressures were obtained. Figure 7 shows pressure histories for a hyperboloidal end optical fiber at R=4.0 mm. At 280 μs collapse of the cavitation bubble produced a secondary strong pressure pulse. Figure 8 shows a hologram of underwater shock wave for hyperboloidal end optical fiber. An integrated single shock wave in figure 8 refers to effective laser focusing in front of the hyperboloidal fiber, so that production of higher strength shock wave became possible. Variation of laser generated cavitation pressure pulses with stand-off distances in front of the fiber (0º) and perpendicular to the fiber (90º) is shown in figure 9. Good agreement between two measurements with 0º and 90º angles is obtained. Spherical shock waves became more uniform by propagation as can be seen in figure 9.

Conclusions

The obtained results are summarized as follows:
1) A Q-switched Ho:YAG laser and an optical fiber were used for production of underwater spherical micro shock waves.
2) Using double exposure holographic interferometric quantitative flow visualization generation process and propagation of shock waves were observed. Behaviour of the induced cavitation bubbles was clarified.
3) Effects of the optical fiber end configuration on the shock waves strength were studied.
4) The weak shock waves produced by this method have potential to be applied for precise medical procedures such as revascularization in neurosurgery.

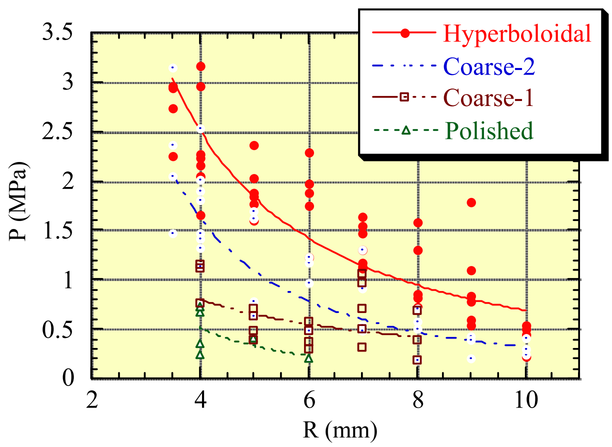


Figure 5. Effects of the optical fiber end configuration on peak overpressure.

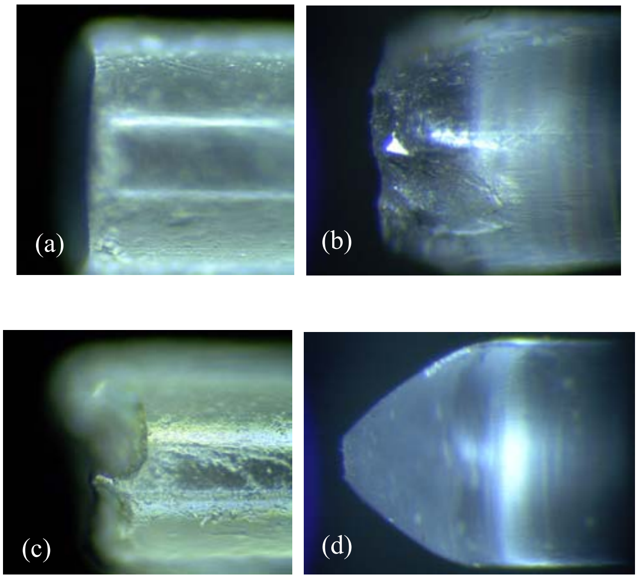


Figure 6. Photographs of the optical fibers referring to figure 5: (a) Polished, (b) Coarse-1, (c) Coarse-2, (d) hyperboloidal.

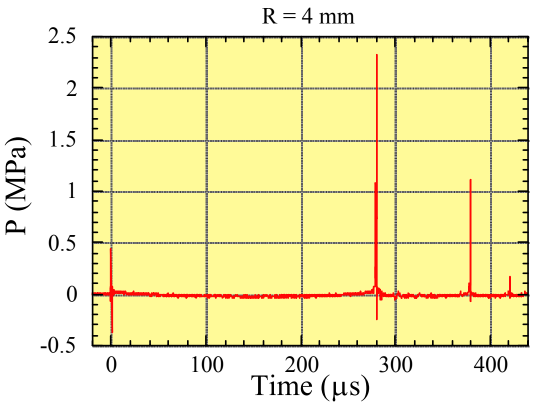


Figure 7. Pressure histories measured in water at R=4.0 mm from the hyperboloidal end optical fiber.

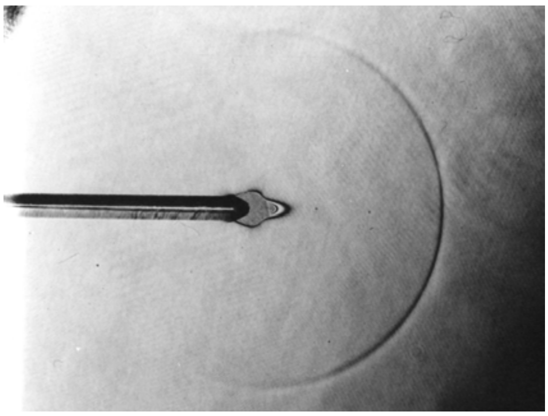


Figure 8. Infinite fringe hologram of the underwater shock wave produced 3.2 μs after Ho:YAG laser beam irradiation from hyperboloidal end optical fiber.

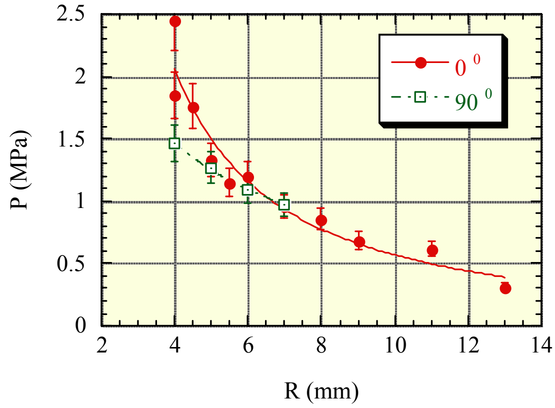


Figure 9. Variation of peak overpressure of the laser induced underwater shock waves with stand-off distance from the optical fiber of figure 4.

References

[1] Fernstroem, I. & Johansson B., Percutaneous pyelolithotomy. A new extraction technique, Scan. *J. Urol. Nephrol.* **10**, 1976, 257-259.

[2] Heustler, E., Destruction of kidney stones by means of auto focused guided shock-waves, 2nd European Congress Ultrasonic and Medicine, 1975.

[3] Johnson, D.E., Cromeens, D.M., Price, R.E., Transurethral incision of the prostate using the Holmium:YAG laser, *Laser in Surg. and Medicine* **12**, 1992, 364-369.

[4] Kodama, T., Takayama, K., Nagayasu, N., Uenohara, H., Yoshida, M., A basic study of shock wave revascularization therapy for cerebral embolism, *Neurosonology* **10**, 1997, 79-83.

[5] Koslin, M.G. & Martin, J.C., The use of the Holmium laser for temporomandibular joint arthroscopic surgery, *J. Oral. Maxillofacial Surg.* **51**, 1993, 122-123.

[6] Nakahara, M. & Nagayama, K., Water shock wave emanated from roughened end surface of an optical fiber by pulse laser input, *J. Material Proc. Tech.* **85**, 1999, 30-33.

[7] Schiffers, W.P., Shaw, S.J., Emmony, D.C., Acoustical and optical tracking of the collapse of a laser-generated cavitation bubble near a solid boundary, *Ultrasonics* **36**, 1998, 559-563.

[8] Shapshay, S.M., Rebeiz, E.E., Bohigian, K., Hybels, R.L., Artez, H.T., Pankratov, M.M., Holmium: Yttrium Aluminum Garnet laser-assisted endoscopic sinus surgery: Laboratory experience, *Laryngoscope* **101**, 1991, 142-149.

[9] Shaw, S.J., Jin, Y.H., Schiffers, W.P., Emmony, D.C., The interaction of a single laser-generated cavity in water with a solid surface. *J. Acoust. Soc. Am.* **99** (5), 1996, 2811-2824.

[10] Takayama, K., Application of holographic interferometry to shock wave research, Proc SPIE **398**, 1983, 174-181.

[11] Tong, R.P., Schiffers, W.P., Shaw, S.J., Blake, J.R., Emmony, D.C., The role of splashing in the collapse of a laser-generated cavity near a rigid boundary, *J. Fluid Mech.* **380**, 1999, 339-361.