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Ultrasound induced by CW laser cavitation bubbles

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Abstract. The generation of ultrasound by a collapsing single cavitation bubble in a strongly absorbing liquid illuminated with a moderate power CW laser is described. The ultrasound shock wave is detected with hydrophone and interferometric device. To obtain a stronger pulse it is necessary to adjust a liquid absorption and a beam diameter. Their influence can be qualitatively understood with a simple model.

1. Theoretical considerations

The cavitation generated by a short and powerful laser pulse is a well known phenomenon[1-3], but the possibility of producing a cavitation bubble with a medium power CW laser in strongly absorbing liquid is less known [4,5]. Cavitation with CW illumination is interesting both from the fundamental point of view and as a cheaper and safer source of ultrasound shock wave. Here we shortly discuss the conditions for obtaining a shock wave from a collapsing cavitation bubble with high amplitude using the CW laser as a light source.

The bubble formation includes following stages. First, the small volume of liquid (typically 0.1-0.3 mm size) is overheated. This lasts from milliseconds to seconds. When the temperature of the overheated water reaches T_N=180-240 *ºC*, an explosive phase transition occurs producing a vapour bubble. The bubble growth starts from a random nucleation event. When the bubble grows to the region of a liquid with lower temperature T_B, the collapse occurs. At the final stage of collapse, a shock wave is generated. The local temperature returns to its initial value, and under CW illumination the process repeats itself, resulting in nearly periodic train of bursts. We are interested to obtain a shock wave with the maximal energy, thus the bubble has to be larger, because the energy transferred into the wave is proportional to the energy stored in the bubble, and this is roughly proportional to its volume. The factors we can control for CW illumination are the laser power, the beam diameter and the absorption length of the liquid. The qualitative understanding of their influence on the resulting bubble size can be obtained with a simple approximate model.

Let us suppose, that the laser beam with a total power U is absorbed inside a liquid with thermal conductivity k in a sphere with a radius a. The steady state temperature distribution in this case depends on the distance from the sphere centre r. It is obtained by solving a steady-state heat conduction equation, and the solution is mathematically equivalent to the potential of a uniformly charged sphere [6]:

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$$T(r) = \frac{3U}{8\pi a k} - \frac{Ur^2}{8\pi a^2 k} \quad , \quad r < a \tag{1}$$

$$T(r) = \frac{U}{4\pi k r} \quad , \quad r > a \tag{2}$$

where T is the temperature excess over the liquid initial temperature T_0.

If cavitation occurs when the temperature distribution is close to the steady state, the temperature in the centre is:

$$T(0) = \frac{3U}{8\pi a k} = T_N - T_0 \tag{3}$$

and the resulting radius of the bubble is close to the $r_0 = a$. The maximal bubble radius for a given laser power can be estimated as $r_0 = \frac{3U}{8\pi k(T_N - T_0)}$, which gives a correct order of magnitude for experimentally observed bubbles.

If the steady state temperature distribution is not reached when the temperature in the centre becomes sufficient for the start of nucleation, the temperature distribution width is smaller, than in a steady state, which is a known property of the heat conduction equation (it follows from the Green function for this equation [6]). This leads to a smaller bubble, and smaller shock wave energy. Thus, making a laser power bigger with a fixed beam diameter results in diminished shock wave (because of smaller bubble size), and higher repetition rate (because of faster heating to the temperature of nucleation). To obtain stronger shock wave with a higher laser power, it is necessary to make a beam diameter bigger, and to adjust the liquid absorption to the final bubble size. For higher laser power the optimal absorption coefficient diminishes. If the laser spot at the input is too big, or absorption is too low, the temperature of nucleation cannot be reached, and no cavitation is observed.

2. Experiment

To investigate the influence of the spot size, light absorption and laser power on the shock wave amplitude we used the cell with a water solution of copper nitrate ($Cu(NO_3)_2$), figure 1. The beam of semiconductor laser with maximal output power 1.5 W was focused inside a cell with a 10X objective. The shock wave was detected with a hydrophone placed at a distance 10 mm from the bubble spot.

In figure 2 we present the results. It is seen, that to obtain bigger signal for higher laser power it is necessary to increase the beam diameter. When the diameter becomes too big, cavitation stops. Note, that for a *fixed* spot diameter raising power generally results in lower signal. If the absorption length is much smaller, than the final bubble diameter, one can expect stronger deviations from the theory above. This situation is clearly seen for 1120 mW laser power and 90 cm^{-1} absorption coefficient. In this case the pressure diminishes when the beam diameter grows from 120 to 220 microns, and grows again for bigger diameters till the disappearance of cavitation. If the absorption becomes smaller, the beam diameter for which the signal maximum is obtained becomes bigger, and the maximal obtainable signal grows.

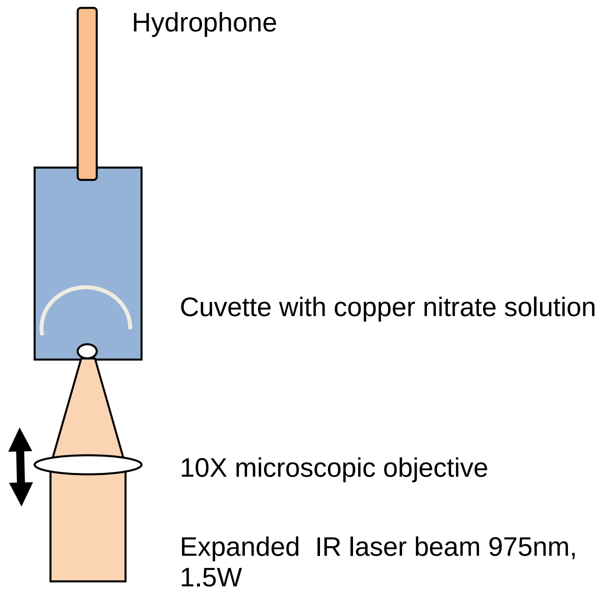


Figure 1. The experimental setup. The focused laser beam illuminates the cuvette from the bottom. The spot size is varied by objective displacement.

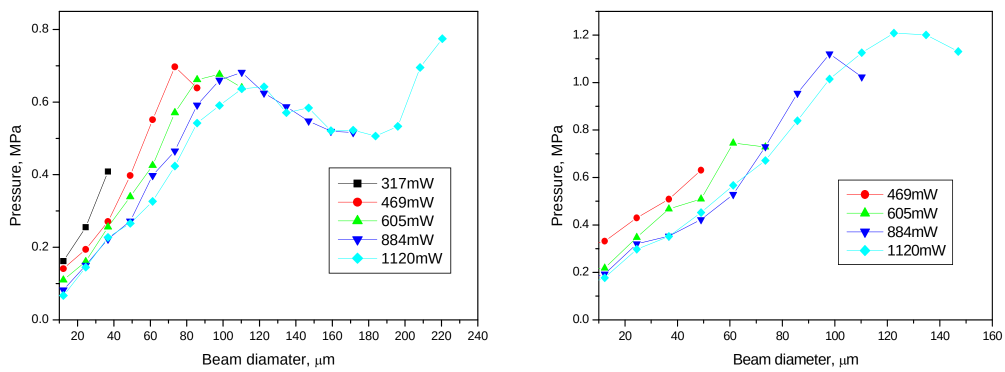
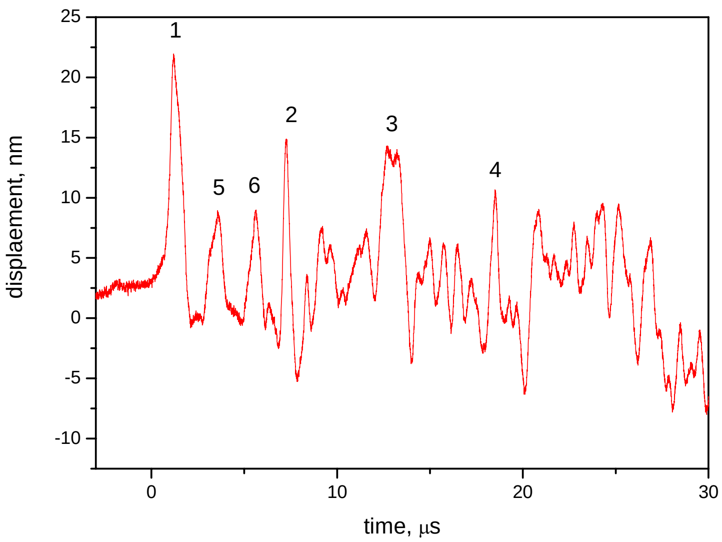


Figure 2. Shock wave pressure as function of the input beam diameter for different incident light power and liquid absorption coefficients 90 cm^{-1} (left) and 45 cm^{-1} (right). Permanent illumination, every point represents an average over 200 collapse events.

For our studies of adaptive optical detection [7] we are interested in a simple method of producing high-frequency ultrasound shock waves in solids. The cavitation cell coupled to a mirror results in a useful device for this purpose (figure 3). The resulting mirror surface displacements are comparable to the displacements, obtained with a traditional method of laser pulse impinging on the mirror from the back side [7]. Thus, potentially, this excitation method can be used for ultrasound inspection with a CW laser instead of the pulsed one. However, the resulting spikes are wider for cavitation, than for a pulsed laser. Additionally, because of a big number of interfaces in the setup, many spikes due to the wave reflections in a cell appear. If the propagation of wave in a solid is of interest, these additional spikes complicate the interpretation. Also the obvious disadvantage is the need for a liquid layer and a window for light. We have tried to obtain cavitation bubbles near the free surface of absorbing liquid, but the resulting shock wave proved to be much weaker, than for bubbles which form close to the water-glass interface.



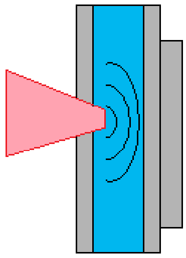


Figure 3. Mirror displacement after the bubble collapse. The cell geometry is depicted to the right. The 5 mm absorbing liquid layer is between two 1.7 mm thick glass walls, the 3 mm thick glass mirror (the last element to the right) is set in contact with a cell wall using a thin oil film. The laser beam with 1.5 W power is chopped with 1Hz frequency, and illumination time is 0.1 s. The single shot measurement.

3. Conclusions

In conclusion, the cavitation induced by a moderate power CW laser produces an ultrasound shock wave which can be potentially useful for sample characterization. This is a relatively cheap and safe method of ultrasound generation with light. To obtain the strong wave with a given laser power, it is necessary to adjust the beam diameter and liquid absorption coefficient. A simple theory permits to understand qualitative influence of parameters involved, but for better description more realistic models are required.

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