Experimental investigations of underwater laser propulsion microspheres based on a tapered fiber propulsion system

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Received: 28 April 2022 / Accepted: 23 September 2022 / Published online: 10 October 2022
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Abstract
An underwater propulsion microsystem is proposed in this work, which employs a nanosecond laser pulse out from the tapered fiber tip. Noteworthily, the system can generate a directional shock wave (or plasma) to propel the polystyrene (PS) microsphere. Through simulation, the shock wave propagation characteristics and the bubble dynamic are investigated. Experimentally, high-speed photography method is employed to obtain the motion image of microsphere. The results show that the propulsion efficiency is dependent on the laser energy. Meanwhile, we explain the role of the bubble dynamic process in propelling microsphere, and find that the bubble diameter increases with the laser energy. In addition, an experiment is performed to separate and remove the PS microsphere clusters in water at fixed point. Compared with conventional technology, this new method has advantages of high controllability, directional and non-contact, and can be used for directional manipulation of underwater microstructures and removal of contaminated microspheres in water environments.

1 Introduction
As a novel area of laser applications, laser propulsion technology has attracted extensive attention of researchers in various countries [1–4]. For example, Myrabo et al. [5] successfully propelled a 11 cm diameter satellite though the laser pulse propulsion system, and the result showed that the propulsion efficiency is related to laser energy. With further development of laser propulsion technology, the research work has gradually shifted from atmospheric and vacuum environments to water environment [6–8]. Recently, Chen et al. [9] reported that the interaction between aluminum target and laser pulse in water environment, and analyzed the pulsation dynamic of the bubble at the target tail. When a target surface is irradiated by a laser pulse, high-power energy is focused in water, and generates the plasma, shock wave, and bubble, which props the target [10]. Underwater laser propulsion has many advantages, for example, it can enhance the interaction time between the shock wave and the target surface because water can act as a confinement layer.

Besides, under the same conditions, the pressure generated by the bubble will increase the laser propulsion efficiency in water environment [11]. Therefore, some researchers have tried to apply the underwater laser propulsion on many occasions, such as underwater cleaning [12], underwater plastic forming [13, 14] and drug delivery [15, 16].

In addition, the investigations in the atmospheric environment show that laser propulsion has already affected the motion of objects ranging from macroscopic materials [2, 17] to microscopic objects and even individual microspheres [18, 19]. Such as in the work of Yu et al. [20, 21], explored the important of the shock wave mechanisms for governing the interaction of SiO2 and polystyrene microspheres (diameters from 20 to 80 μm) with nanosecond laser pulses, and clarified the influence of the laser energy and microsphere size on laser propulsion. For underwater laser propulsion of microspheres, besides the laser energy, it is necessary to consider the influence of the bubble [22]. During the dynamic process of bubble, the shock wave [23] and micro jet [24] will be generated to affect the motion of the microspheres. Moreover, the conventional underwater laser propulsion system usually generates laser with higher energy (approximately at the millijoule order), and may easily damage target. Other than that, the laser spot diameter is large and difficult to control, and the propulsion direction of the microsphere cannot be accurately controlled [25, 26]. Therefore, a laser propulsion system with tapered fiber structure

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needs to proposed, which can effectively control the laser energy and scalable laser spot to realize the microsphere underwater propulsion.

Herein, we propose a microscale laser propulsion system with nanosecond laser pulses out from the tapered fiber tip, and investigate the interaction of microsphere with laser pulses in water environment. Through simulation and experiment, the process of underwater laser propulsion and shock wave propagation characteristics are investigated. Experimental results show that as the laser energy increases, more energy is partitioned to the microsphere and the propulsion efficiency also increases. Meanwhile, we record the dynamic image of the bubble generated from the microsphere, and the influence of laser energy is discussed. In addition, we utilize the laser propulsion system with tapered fiber structure to separate and remove the PS microsphere clusters in water. The laser propulsion system with tapered fiber structure has the characteristics of easier operation and precise positioning. Based on these features, the study of PS microsphere propulsion by using the tapered fiber laser propulsion system has potential applications for the underwater laser cleaning and the underwater manipulation of microstructures.

2 Theoretical analysis of underwater laser propulsion process

To study underwater laser propulsion of microsphere, we consider a physical model as schematically illustrated in Fig. 1a, b. A single laser pulse is guided by the tapered fiber, and the laser is directly focused to induce optical breakdown of the water, resulting in the generation of a high energy plasma. Subsequently, there are two possible physical processes responsible for the propulsion of the microsphere. When plasma expands rapidly outward, the shock wave will be formed, as shown in Fig. 1a. Simultaneously, optical breakdown will be accompanied by bubble phenomenon. Then the bubble experiences a series of expansion and contraction, and produces the high-intensity micro jet and the shock wave indicated in Fig. 1b. The plasma-induced shock wave, the bubble-induced shock wave and the bubble oscillating micro jet are the important sources of the propelling force, which drive the microsphere movement through recoil effect.

2.1 Shock wave propagation characteristics

To qualitatively analyze intensity distribution of the shock wave, we first propose a 2D simulation model of tapered fiber propulsion system. Figure 1c shows that the shock wave propagates outward in a discontinuous spherical. We select the first four shock waves to analyze, there is an obvious intensity gradient was found in the propagation process, and the intensity of the shock wave increased with the laser energy at the same position (Fig. 1d).

In the theoretical analyze, we describe the dependence of the shock wave propagation distance $R$ and time by using the Sedov-Taylor scale [27]:

$$R = \xi \left( \frac{E_0}{\rho_0} \right)^{1/\sigma+2} \frac{t^2}{\sigma+2}$$

(1)

The propagation velocity of the shock wave can be expressed as:

![Fig. 1 Schematic of principle: a the shock wave-induced microsphere movement and b the bubble-induced microsphere movement. c The underwater shock wave propagates along the laser direction. d The intensity of the shock wave as a function of distance. e The propagation distance and velocity of a shock wave as a function of time at different energies, $E=8.83, 13.16, 18.5, 20.05 \mu J$. f The propagation velocity of a shock wave as a function of time at different energies.](image-url)
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where the dimensionless constant $\xi \approx 1$, $E_0$ denotes the shock wave energy, $\rho_0 = 1 \times 10^3$ kg/m$^3$ is the density of water, $t$ is the propulsion time and $n = 3$ for spherical shock wave [27].

The results of propagation characteristics of the shock wave at the laser energy of 8.83, 13.16, 18.5, 20.05 μJ are presented in Fig. 1e, f. It can be seen that the propulsion distance $R$ and velocity show an upward trend with the increase of the laser energy emitted from the propulsion system. Moreover, for the same laser energy, the propagation distance difference ($\Delta R$) decreases gradually at a same time interval ($\Delta t$), which indicates that the propagation velocity ($v = \Delta R / \Delta t$) decreases monotonically with time (Fig. 1f).

To find the mechanisms of the shock wave-induced microsphere movement, we add a microsphere into the 2D simulation model, and simulate the pressure variation when the shock wave propagates to the microsphere surface. Simulation results are shown in Fig. 2, the diameters of microsphere and tapered fiber tip are set to be 50 and 10 μm. A high-pressure shock wave outward from the tapered fiber tip. As soon as the shock wave reaches the point $R$, the microsphere is subjected to strong pressure of the shock wave. Then the shock wave is reflected and gradually diffuses outwards, which is consistent with the results in Ref. [28]. With the increase in the shock wave action time, the pressure-bearing area of the microsphere surface gradually expands, and the shock wave pressure propels the microsphere through recoil effect.

2.2 Single bubble dynamic process

The underlying physical mechanisms of the bubble-induced microsphere movement will be discussed based on the calculations of the single bubble dynamics. In the case of an infinite, incompressible and inviscid liquid, Rayleigh [29] deduced the differential equation of a single spherical bubble motion:

$$R\ddot{R} + \frac{3}{2}R^2 = \frac{P_R - P}{\rho}$$  \hspace{1cm} (3)

where $R$ is the bubble radius (being a function of the time), $\dot{R}$ is the first derivative, $\ddot{R}$ is the second derivative, $P_R$ is the pressure inside the bubble, $P$ is the pressure of the environment, and $\rho$ is the liquid density. When considering the influence of gas content, liquid viscosity, and surface tension on bubble movement, the Eq. (3) can be expressed as:

$$R\ddot{R} + \frac{3}{2}R^2 = \frac{1}{\rho}[P_R - P - 4\mu \dot{R} - \frac{2\sigma}{R} + (kP - P_R + \frac{2\sigma}{R_0})(\frac{R_0}{R})^{3\gamma}]$$  \hspace{1cm} (4)

where $\mu$ is the liquid viscosity coefficient, $\sigma$ is the liquid surface tension coefficient, $R_0$ is the initial radius of the bubble (the maximum of the bubble radius), $\gamma$ is the gas adiabatic index, and $k$ represents the bubble gas content ($0 < k < 1$) [30].

We calculate the dependence of bubble radius variation and time by using Eq. (4). We assume that the environment temperature $T = 20$ °C, Table 1 summarizes the major environment parameters. Figure 3 shows the bubble radius as a function of time at the different maximum bubble radius $R_{\text{max}} = 83, 100, 142, 165$ μm. It can be seen that the larger

Fig. 2  Pressure simulation during propagation of an underwater shock wave to the microsphere. a High-pressure shock wave is outward from the tapered fiber tip. b–d High-pressure shock wave acts on the surface of the microsphere, and then the pressure is reflected and gradually diffuses outwards
bubble maximum radius has a longer pulsation period. The explanation is as below:

As for one single spherical bubble, the energy $E_b$ during each pulsation period can be described as [29]:

$$E_b = \frac{4\pi}{3} (P - P_R) R_{\text{max}}^3$$  \hspace{1cm} (5)

Based on the Eq. (5), we find that the $E_b$ is proportional to the third power of $R_{\text{max}}$. It means that the larger bubble has the more energy, and the time to dissipate energy increases accordingly.

We select a bubble pulsation period to analyze. Firstly, the bubble expands to the maximum radius. During the expansion process of the bubble, the positive pressure is generated to propel the microsphere; With increase of time, the bubble radius gradually decreases, which is considered as the bubble contraction process. At this stage, the generated shock wave and micro jet are outward and propel the microsphere away from the bubble [31].

### 3 Experiments setup

Figure 4 shows the experimental step employed in underwater laser propulsion. The propulsion system is drawn from a multimode fiber by flame-heated taper-drawing technique. The diameter of the system tapered tip is decreased from 125 to 10 μm within 300 μm lengths. A Q-switched Nd: YAG laser emitted the nanosecond laser pulse. Optical objective focused the pulse laser and coupled the laser into the multimode fiber. The energy meter monitored the laser energy. A high-speed CCD collected the plasma expansion and microsphere dynamic motion. Plasma spectra was obtained by the spectrometer. Inset: Side view image of PS microsphere and fiber.
laser (wavelength of 532 nm, pulse duration of 10 ns, repetition rate of 7 Hz) is used as the energy source. The laser beam is split into probe beam and pulse beam by employing a 50:50 beam splitter, then we select a 4× optical objective (NA = 0.10) to couple the pulse beam into a multimode fiber. Probe beam shoots at the energy meter (Field Maxill-Top, resolution is 0.01 μJ) to measure the laser energy. Pulse beam light is launched from the propulsion system tip, which exceeded the water breakdown threshold to produce the plasma and single cavitation bubble. The polystyrene (PS, density: 1.05 g/cm²) microsphere is suspended in water on the surface of the polymethyl methacrylate (PMMA) substrate. The estimate variation in microsphere diameter is less than 5%. To ensure the horizontal alignment of the fiber tip and the microsphere, we select a 3D-translation stage (resolution is 1 μm) to control the propulsion system. The reflected light passes through 532 nm filter and beam splitters into the high-speed CCD (Photron Fastcam-max) [32]. In the process of the underwater laser propulsion, the dynamic motions of the microsphere and the bubble are recorded by high-speed CCD.

4 Results and discussion

4.1 Underwater laser propulsion of PS microsphere

In the experiment, we use the 3D-translation stage to manipulate the tapered fiber to be parallel to the microsphere in water, which directionally propel the microsphere. Figure 5 shows the movement image of PS microsphere collected by the high-speed CCD at the laser energy $E = 25.3 \mu J$, the diameter of the PS microsphere is 50 μm. Firstly, at about $t = 0.25$ ms, the laser breaks down the water at the tip of the tapered fiber to generate the plasma, and generates the shock wave and a single bubble, which is consistent with the results in Fig. 1a, b. As shown in Fig. 1f, the shock wave carries high energy at $t = 0$ ns and expands outward with a velocity of $v \geq 70$ m/s. PS microsphere is propelled forward under the action of the shock wave pressure and the bubble pressure (Fig. 5). It can be seen that approximately the PS microsphere is horizontally recoiled along the $X$ axis direction because the propulsion system has an advantage of outputting dictional shock wave. With the increase of the time, the shock wave velocity approaches 0 m/s (Fig. 1f), and the PS microspheres velocity decreases due to the reduction of the shock wave pressure and the action of the water resistance (Fig. 5III-VI). Furthermore, during the laser propulsion process, the bubble lags the PS microsphere and moves along the

![Fig. 5 Image of PS microsphere recorded by the high-speed CCD during the underwater laser propulsion process. Laser energy $E = 25.3 \mu J$. Diameter of the PS microsphere is 50 μm](image)
We consider that this is caused by the combined effect of the shock wave pressure reflected on the surface of the microsphere (Fig. 2) and the pressure directed to the center of the bubble [31].

A set of similar propulsion experiments were conducted with varying laser pulse energy ($E = 8.83, 13.16, 18.5, 20.05 \mu J$) to investigate the influence on PS microsphere underwater propulsion (20 μm), as shown in Fig. 6a. It can be observed that in the same time, with the increase of the single pulse energy $E$, the distance of PS microsphere increases (Fig. 6b). Moreover, we can obtain the moving distances of the microsphere $\Delta D$ and the time between two frames $\Delta t$ by processing the images, so the velocity $v$ can be calculated by $v = \Delta D/\Delta t \ [2]$. Therefore, the slopes in Fig. 6b can be expressed as the velocity of the PS microsphere, and we find that the velocity is proportional to the laser energy. This can happen due to the plasma density monotonically increases with the laser energy, and the microsphere gains more momentum from the plasma according to the law of conservation of momentum [33].

To further discuss the relationship between the movement of the PS microsphere and the laser energy, the propulsion efficiency is introduced. As shown in Fig. 6c, the propulsion efficiency can be evaluated by the momentum coupling coefficient ($C_m$) and the energy partitioning ($mv^2/R^5$). The momentum coupling coefficient $C_m$, which is defined as the total imparted momentum $mv$ per unit laser energy $E$ [34]:

$$C_m = \frac{mv}{E}$$  \hspace{1cm} (6)

where $m$ is the mass of the PS microsphere, $v$ is the velocity of the PS microsphere. The energy partitioning ($mv^2/R^5$) can be used to describe the relationship between the energy of the shock wave $E_0 = \rho_0 R^5/t^2$ in Eq. (1) and the PS microsphere kinetic energy ($mv^2$) [20]. Figure 6c shows the experimental results of the momentum coupling coefficient $C_m$ and the energy partitioning $mv^2/R^5$ under different laser energy for PS microsphere. In our case, the $C_m$ presents an increase in trend with laser energy $E$, and the ratio $mv^2/R^5$ increases as the energy until reaching a maximum of 76.6 J/cm, which point that more energy is assigned to PS microsphere. Based on the above analysis, we can infer that the laser energy $E$ is a critical parameter to improving the propulsion efficiency of PS microsphere.

4.2 Bubble generated by the underwater laser propulsion

On the basis of theoretical analysis in Sect 2.2, the role of bubble dynamic process in propelling microsphere during...
the underwater laser propulsion and the influences of laser energy are investigated. As illustrated in Fig. 5, we dip a small amount of UV glue on the end of the fiber to fix a single PS target microsphere (50 μm). A single laser pulse \(E = 45.9 \, \mu J\) is launched though the tapered fiber propulsion system tip. Thus, to decrease the effect of the shock wave pressure in propelling microsphere, the gap distance between the propulsion system and microsphere is set to 50 μm.

Figure 7a shows the dynamic image of a single bubble generated in the front of the target microsphere over an 8.33 μs interval. In our experiment, time is set to 0 when pulse laser is focused in water to generate plasma (see Fig. 7a I), and then a quasi-spherical bubble is generated (azimuth angle \(\phi = 60^\circ\)) (Fig. 7a II). From 0 to 24.99 μs is the first dynamic process of bubble. It can be seen that the bubble gradually expands. At \(t = 33.32 \, \mu s\), the bubble expands to the maximum diameter of 166 μm. During the second dynamic process, the bubble shrinks to the minimum diameter at 66.64 μs. This can happen due to the negative pressure generated by the internal pressure of the bubble is lower than the pressure of the water, so that the gas content of the bubble is gradually reduced. As shown in Fig. 7b, the red curve is the curve fitted by the experimental data of the diameter changing with time, and the pink curve is the simulation curve of the bubble diameter changing with time (Fig. 3). It can be found that the two curves have the same trend, both of which are expansion and shrinkage. However, the experimental data are twice as large as the simulation. We speculate this phenomenon is derived from (1) Bubble gas content increases, and (2) Surface tension acting on the bubble decreases, which is caused by the contact between the bubble and the air environment in the experiment.

In addition, it can be found that the PS microsphere disappears from the end face of the fiber at about \(t = 41.65 \, \mu s\). We think that this phenomenon is derived from the pressure generated by the bubble dynamic process. The bubble pressure can be decomposed into the horizontal component \(F_x\) and the vertical component \(F_y\). During the bubble expansion...
process, the horizontal component $F_x$ converts from a positive propulsion force to a negative attractive force, and the vertical component $F_y$ converts from a positive compressive force to a negative lift force. During the initial bubble contraction process, the pressure can be composed of a lift force and an attractive force. As a result, the PS microsphere overcomes resistance force under the action of the lift force and the horizontal component $F_x$, and then disappears from the field of view, which is consistent with the results in Ref. [35]. Meanwhile, we believe that the microsphere is only propelled by horizontal component $F_x$ in general cases (azimuth angle $\phi = 90^\circ$). With the acceleration of the bubble–liquid interface, the microsphere is propelled away from the bubble in the horizontal direction. During the growth of bubble, unsteady pressure changes around the microsphere are caused [35].

By combining experiment and theory, we propose three dominant regimes to accelerate the movement of the PS microsphere, namely, (1) high pressure caused by the plasma shock wave (in Sect. 4.1), (2) the expansion and contraction of the bubble, (3) the power generated by the contact between the bubble and the microsphere.

Furthermore, the influence of laser energy on the single bubble diameter is shown and discussion [36]. According to the experimental results of the underwater laser propulsion (referring to Fig. 6a), we obtain the function of the bubble diameter and the laser energy (Fig. 7c). The bubble diameter increases with the laser energy, which is explained that in the process of generating bubble, the water absorbs more heat from the laser and plasma, thus producing more water vapor. When the laser energy reaches 20.05 $\mu$J, the growth rate of the bubble diameter gradually slows down. This behavior can be well understood by the plasma shielding effect, where the laser energy absorbed by the plasma does not reach the microsphere [37]. The experimental results illustrate that the diameter of bubble is dependent on the laser energy.
4.3 Underwater laser propulsion separates and removes PS microsphere clusters

This section is devoted to the feasibility of separating and removing PS microsphere cluster in water environment by tapered laser propulsion system. As shown in Fig. 8, we add 50 μm PS microspheres in water environment, and it can be found that microsphere clusters are generated under the van der Waals force. Currently, conventional methods are largely associated with ultrasonic and higher energy laser [38–41]. However, the energy of the two methods is not easy to control, and the PS microspheres cannot be manipulated at fixed points. We demonstrate a simple, but intriguing method of effectively locating, separating and removing the microsphere clusters by using the tapered underwater laser propulsion system (Fig. 8a, b I). A localized and directional shock wave and bubble are generated at the end of the tapered laser propulsion system owing to the breakdown of water by a single laser. The shock wave pressure and bubble pressure precisely propel the PS microsphere clusters (Fig. 8a, b II). For the bimolecular target microsphere cluster, through manipulating the system tip to point toward the middle of the cluster, the microsphere cluster can be accurately separated into two single microspheres, as shown in Fig. 8a VI. For the multi-molecular target microsphere cluster, under the action of the shock wave and the pressure of the bubbles, the microsphere cluster is separated into single microspheres. Then the microspheres move along the direction of the shock wave, as shown in Fig. 8b III-VI. We observe that the PS microspheres in water are completely removed (Fig. 8d VII). As a result, the tapered laser propulsion system method shows the unique advantages such as fixed point, directional, fast and non-contact in the microsphere separation and underwater cleaning field.

5 Conclusion

In conclusion, we present a tapered fiber laser propulsion system, and investigate the interaction of PS microsphere with nanosecond laser pulses in water environment. This propulsion method has many advantages over those available, such as low cost, simple structure, directional and easy to adjust. Based on the simulation, we discuss and analyze the shock wave propagation characteristic and the single bubble dynamics process. It indicates that PS microsphere is acted upon by the laser-induced shock wave pressure and the pressure induced by bubble. Experimentally, the underwater laser propulsion of PS microsphere is observed by the tapered fiber system. The propulsion efficiency increases with the laser energy, which means that PS microsphere can be propelled efficiently based on this feature. Furthermore, through the underwater propulsion experiment on the PS microsphere fixed on the end face of the fiber, we propose that the microsphere is moved under the action of bubble pressure. In addition, PS microsphere clusters in water are separated and removed at fixed point during the experiment, which indicate that the tapered fiber laser propulsion system can be applied in the microsphere separation and underwater cleaning field. We believe that the results of this paper can lay some theoretical and experimental basis for the underwater laser propulsion research.

Author contributions Yichen He wrote the main manuscript text. Yichen He prepared figures 1-8. All authors reviewed the manuscript.

Funding National Natural Science Foundation of China (52271344); National Key R and D plan of the Ministry of science and technology (2018YFC0310102); Joint fund for weapons and equipment (6141B020702); Natural Science Foundation of Heilongjiang Province of China (LH2021E032).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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