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Liquid heating based on interaction between evanescent light and Au nanoparticles

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1. Introduction

In recent years, inkjet technology has expanded its applications beyond printing and is now widely used in areas such as 3D printing and regenerative medicine [1]. In the thermal method, ink is heated by Joule heating of the resistive wires, generating bubbles to eject liquid droplets. However, the energy density of the resistive wires is not very high, limiting the size reduction of the heater unit [2]. Therefore, we are focusing on evanescent light as a technique for ejecting liquid droplet. **Fig. 1(a)** shows the evanescent light formed at the interface between the prism and the water when the laser is irradiated at more than the critical angle. The electric field of evanescent light in the water decays exponentially out of the surface of the prism along z-axis. It is believed that by using high-energy pulsed lasers, the energy of light can be confined to extremely small regions, thereby enabling the achievement of high energy density [3,4]. according to our experiments, the prism tended to break with a high probability before atomizing the water. Through our analysis of an electromagnetic field simulator, it was determined that this was due to a 1.75-fold increase in electric field intensity at the point where the total internal reflection of the laser was occurred, as shown in **Fig. 1(b)**. The researchers in Kyushu Univ. reported the similar cases [5]. Therefore, it was found that because the point of total internal reflection is located inside prism, the point is the first to break, making it difficult to vaporize the water using the evanescent light. Consequently, we consider a method to increase the intensity of evanescent light by more than twofold by utilizing plasmon resonance of Au nanoparticles. Au nanoparticles are placed on the interface between prism and water and the evanescent light is irradiated as shown in **Fig. 1(c)**. In this paper, the magnification of electric field intensity due to the interaction between evanescent light and Au nanoparticles is investigated. Both the simulation and the water jet experiment are demonstrated to show its feasibility.

2. Evanescent light

According to Snell's law, the critical angle is determined to be 61.7° where the incident light shows the total internal reflection at the interface between prism and water. The optical wavelength of Nd:YAG laser is 1064 nm, therefore the 1/e-penetration depth Λ of the evanescent light is 834 nm in the water [6].

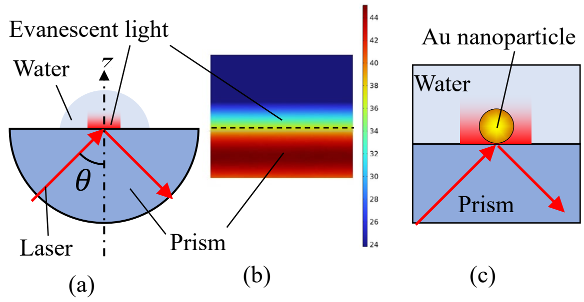


Fig. 1. (a) Depiction of evanescent light irradiated to water droplet on prism surface. (b) Intensity of electric field around interface between prism and water expressed by electro-magnetic simulation. (c) Concept of the interaction between Au nanoparticle and evanescent light.

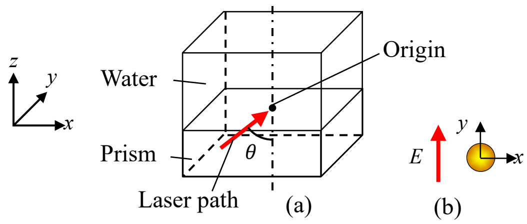


Fig. 2. Schematic diagram of simulation model. (a) 3-dimentional simulated space. Arrangement of (b) a single Au nanoparticle.

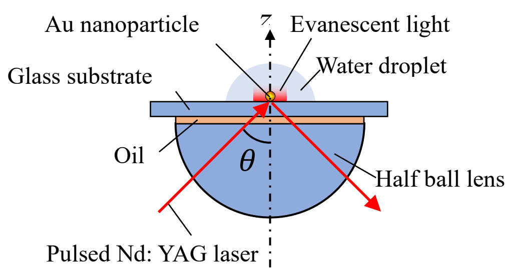


Fig. 3. Experimental setup for liquid jet generated by enhanced evanescent light.

3. Experimental setup

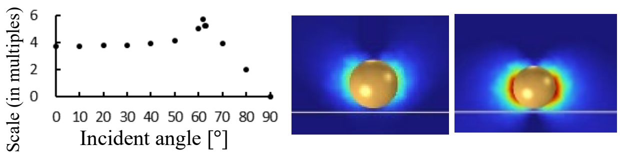
The electro-magnetic simulator (COMSOL) was conducted to investigate the intensity of the electric field of the evanescent light enhanced by Au nanoparticle around the point where the total internal reflection was occurred between prism and water. The magnification factor of evanescent light intensity was aimed at a minimum of two times greater than its original electric field intensity in particular. **Fig. 2(a)** shows the simulated space consisting of the prism region (n_h = 1.51) and the water region (n_w = 1.33). The width of the xy-plane, which means the interface between the water and the prism, is 750 nm a side and the heights along *z*-axis are 250 nm, and 400 nm for the prism and the water region. The origin was placed on the center of the xy-place, which was also the target for laser irradiation. The laser path was arranged on the xz-plane with the incident angle θ between the *z*-axis. The electric field of the incident laser was 23.8 V/m in amplitude and was oriented to the y-axis. **Fig. 2(b)** depict the Au nanoparticles on the origin of the *xy*-plane. Although the best wavelength for the plasmon resonance of the Au nanoparticle was approximately 600 nm, the wavelength of the laser in the simulation was 1064 nm that we actually had. The effect of using a wavelength of 1064 nm instead of using 600 nm is that the magnitude of the electric field becomes approximately three times smaller.

Fig. 3 shows the experimental setup. The Au nanoparticles were fixed on the glass substrate and it was placed on the half ball lens with the oil between them. The droplet of water was placed over the Au nanoparticles. The pulsed Nd:YAG laser (1064 nm wavelength, 6 ns pulse width) was irradiated from a downward with the angle θ. The angle of 63° is more than the value of the critical angle, which creates the evanescent light on the glass substrate. The electric field intensity increased through the plasmon resonance between the Au nanoparticles and the evanescent light, leading to a rapid rise in water temperature, followed by vaporization, plasma formation (ablation), and the water jet was occurred. The phenomenon was observed by the high-speed camera every 100 μs after the launch.

4. Results

Fig. 4(a) shows the magnified electric field of evanescent light according to the incident angle of the laser as shown in Fig. 3(b). The vertical axis represents the scale in multiples. When the incident angle of the pulsed laser was 0° (direct laser irradiation) and 63° (evanescent light irradiation), the scaling factors were 3.75 and 5.26 along y-axis, as shown in **Fig. 4(b) and Fig. 4(c)**. Note that the maximum value of the intensity of electric field was not observed the bottom of the particle but observed in the middle of it. If the peak value of the electric field intensity is placed at the bottom of the particle, it is possible that the breakage of the glass substrate is triggered by over heat. It has been revealed that the magnification of the evanescent light is enhanced by the existence of Au nanoparticles, which is greater than the case of the direct laser irradiation.

Fig. 5 depicts the water jet phenomenon. Upon the power of 3.8 MW laser irradiation at time zero, the luminescence occurred at the interface between water and glass after 100 μs, followed by water ejection in the next moment. In this experiment, no prism damage was generated. It was possible to perform this experiment without any breakage inside the prism at least for ten repetitions. When the prism had been broken the laser power was required 5 MW for water jet. It is considered that the significant enhancement of the electric field intensity outside the prism (in the water droplet) is achieved due to the interaction between the Au nanoparticles and the evanescent light, which enabled an effective energy irradiation onto the water droplet.



(a) (b) (c)

Fig. 4 (a) Scaling factors of electric field according to the incident angle of the laser. Distribution of electric field intensity along y-axis around Au nanoparticle when the incident angles are (b) 0° and (c) 63°.

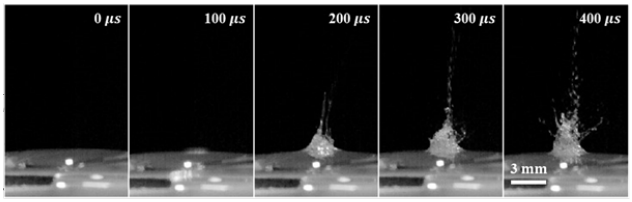


Fig. 5 Liquid jet generated by enhanced evanescent light taken by high-speed camera every 100 μs after the launch.

Acknowledgment

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