Laser-induced Breakdown Probability in Water at 0.532 μm and 1.06 μm

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1. Introduction

Recently, lasers have found numerous applications in medicine(1) in which the presence of water or liquid is essential for application. This increased the necessity of the studies on the interaction of laser radiation with liquids.(2)

In this paper, probabilistic behavior of optical breakdown in water is investigated as a function of the laser intensity using Q-switched 0.532 μm and 1.06 μm lasers with 5nsec duration and is compared with the breakdown probability of air in which a avalanche mechanism is believed to govern the breakdown process.

2. Experimental Procedure

A Q-switched Nd:YAG laser of 1.06 μm and its second harmonics of 0.532 μm with a pulse duration of 5nsec were used in the breakdown experiment. The laser beam was attenuated by neutral glass filters and focused into distilled water in a quartz cell by a lens with short focal length. The occurrence of breakdown was confirmed by the observation of a visible plasma emission and audible acoustic signature. The breakdown field was estimated from the measured laser power by joulemeter ED-100(Gentec Inc.) and the transmission rate of filters. Breakdown experiments were repeated 100 times every 5 seconds at each laser field near breakdown.

3. Experimental Results

The laser field is in proportion to the root of the laser energy W divided by the laser wavelength λ, where the beam diameter of the laser is constant. So the $\sqrt{W}$ is used as the laser field, when the laser wavelength is constant. In the experiment of the wavelength dependence of breakdown, the $\sqrt{W}/\lambda$ is used as the laser field.

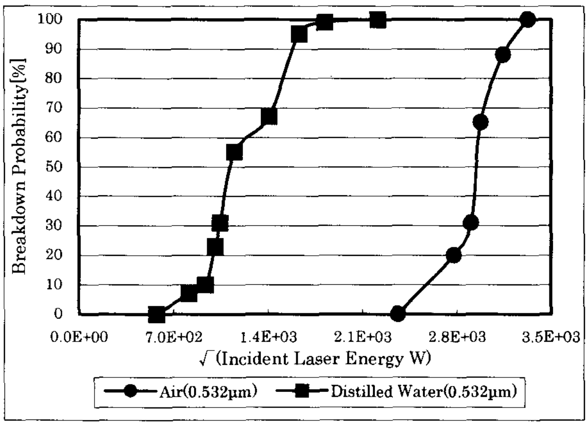

Fig.1. Breakdown probability vs. laser field in air and distilled water at 0.532 μm.

Figure 1 shows plots of the breakdown probability versus the incident laser field $\sqrt{W}$ at 0.532 μm in air and distilled water. The

50% probability breakdown field increases and the plots of the data lie in a narrower field region with decreasing the density of the sample (water→air).

Typical behavior of the breakdown probability, on logarithmic scale, versus the reciprocal laser field 1/√W is shown in Fig.2, which is read from Fig.1.

The breakdown probability P depends on the laser field E(√W), through the simple relation[(3),(4)]

$$P \propto \exp(-K/E) \qquad (1)$$

for values of P ranging from a few percents to more than 60~70% in distilled water.

This dependence has been considered suggestive for an avalanche breakdown mechanism because the dc ionization coefficient that governs avalanche breakdown in gases and semiconductors depends on the electric field in the same manner.

In air the linearity of P vs. 1/E (1/√W) keeps in the whole region of the breakdown probability. In air, initial electrons are produced by natural causes (cosmic radiation, etc.) and these electrons produce avalanche ionization. Therefore, the whole laser energy is used to produce avalanche ionization.

In distilled water, initial electrons are supplied by multiphoton ionization of impurities in water. Since more laser energy is used to cause multiphoton ionization of impurities in the higher electric field region, the probability data deviate from the linear curve in the region of the breakdown probability 60~100%.

The same experiment as Fig.1 and Fig.2 was done at 1.06 μm. Figure 3 shows the breakdown probability as a function of the incident laser field √W at 1.06 μm. From this

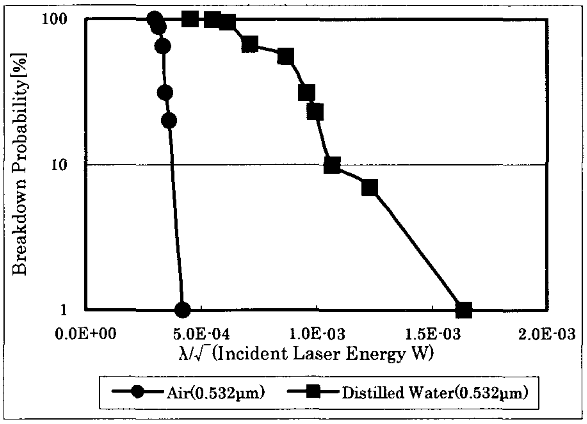

Fig.2. Breakdown probability on a logarithmic scale vs. reciprocal laser field at 0.532 μm.

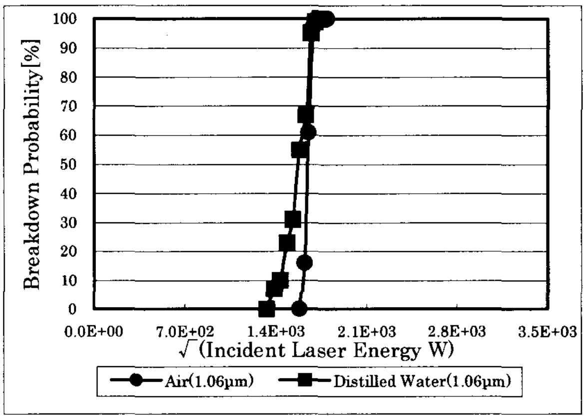

Fig.3. Breakdown probability vs. laser field in air and distilled water at 1.06 μm.

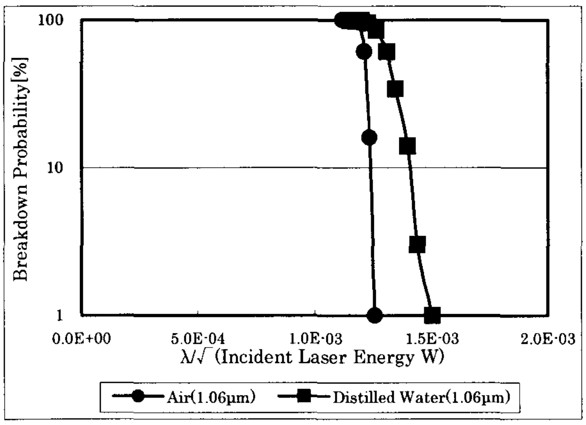

Fig.4. Breakdown probability on a logarithmic scale vs. reciprocal laser field at 1.06 μm.

figure the dependence of the logarithmic P versus the reciprocal laser field $1/\sqrt{W}$ was shown in Fig.4. This figure shows the similar dependence of the breakdown probability to the Fig.4. In air the linearity of P vs. $1/E(1/\sqrt{W})$ keeps in the whole region of the breakdown probability. Therefore the whole laser energy is used to produce avalanche ionization.

In distilled water, in the higher electric region, the probability data deviates from the linear curve in the region of the breakdown probability 70~80%. This means that in distilled water the multiphoton ionization from impurities plays an important role in the breakdown process in the higher electric field region. The difference in the probability curve between 0.532 μm and 1.06 μm is discussed in the next section.

4. Discussion

In the following the difference of the breakdown process in distilled water between at 0.532 μm and 1.06 μm is discussed using Fig.5 , which are replotted from Fig.2 and Fig.4. At 1.06 μm the slope of the curve is sharper and the linear region ranges in the higher electric field than those at 0.532 μm.

Since the photon energy of 1.06 μm radiation is a half of 0.532 μm radiation, at 1.06 μm the effect of multiphoton ionization from impurities on breakdown is less likely to occur compared with the case of 0.532 μm. Furthermore, the lower the optical frequency avalanche ionization is likely to occur. Then, at 1.06 μm the linear region of ln P vs. 1/E curve ranges to the higher electric field.

Figure 6 shows the 50 % probability breakdown field in distilled water and air at 0.532 μm and 1.06 μm. The difference of the breakdown field between at 0.532 μm and 1.06 μm decreases increasing the density of the sample. Simple microwave breakdown theory in which the energy loss is neglected predicts the breakdown field as follows

$$E \propto \sqrt{\frac{\nu_m^2 + \omega^2}{\nu_m}} \qquad (2)$$

,where e, m and ν_m are the electron charge, electron mass and the collision frequency of

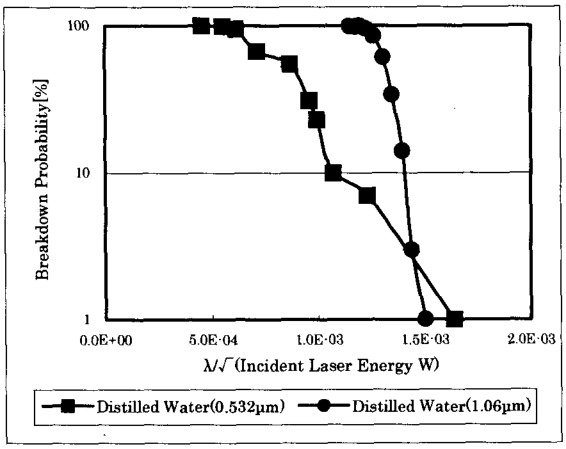

Fig.5. Breakdown probability on a logarithmic scale vs. reciprocal laser field in distilled water at 0.532 μm and 1.06 μm.

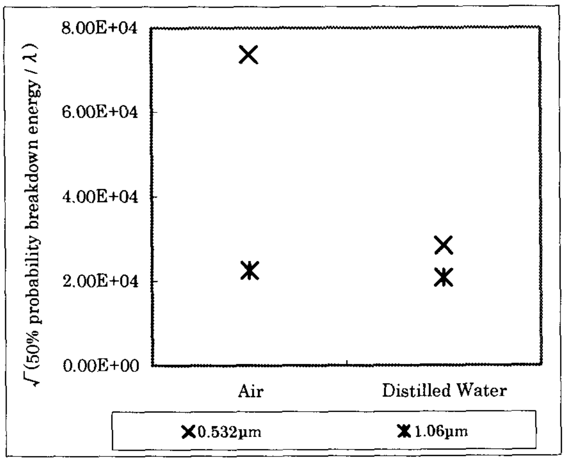

Fig.6. Wavelength dependence of breakdown field ($\sqrt{W}/\lambda$) in air and distilled water.

electrons with liquid molecules. The higher laser frequency means the higher breakdown field. In air , since the ionization energy is so high, the multiphoton ionization process is not the main mechanism of breakdown. In distilled water, however, since the ionization energy (including ionization from impurities) is lower than in air, the multiphoton ionization process plays an important role in the breakdown process. Then the breakdown field in distilled water at 0.532 μ m decreases resulting in the small difference of the breakdown field between at 0.532 μ m and 1.06 μ m.

5. Conclusion

(1) The breakdown probability P of distilled water depends on the laser field E through the simple relation $P \propto \exp(-K/E)$. This suggests that the mechanism of laser-induced breakdown in distilled water is governed by the electron avalanche process.

(2) In air initial electrons are produced by natural causes and these electrons produce avalanche ionization. The linearity of P vs. 1/E(1/√W) keeps in the whole region of the breakdown probability.

(3) In distilled water multiphoton ionization from impurities plays an important role in breakdown in addition to avalanche ionization process. At 0.532 μ m multiphoton ionization process is more important in breakdown than at 1.06 μ m.

(4) The difference of the breakdown field between at 0.532 μ m and 1.06 μ m decreases increasing the density of the sample(air→water).

References

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