Laser Interaction with Grass Tissues

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Jaesung Jang: Thesis Committee Member # 2

ABSTRACT

This thesis has three chapters as first chapter: UV, Visible and IR light interaction with grass-tissues, second chapter: IR light with different water absorption coefficient interaction with grass-tissues and third chapter: laser lawn mowing system.

Fist chapter, we investigated how UV, Visible and IR light affect grass tissues. Grass tissues are composed mainly of pigments and water. Chlorophyll plays the role of the photosynthesis and it is not only the green pigment but it also absorbs visible light (blue and red) well. The water content of grass tissues helps the photosynthesis with carbon dioxide and it can react well with absorbed IR light. UV light can break the chemical bonding of materials more easily than longer wavelengths (i.e. Visible and IR regimes), since the shorter wavelengths have higher electrical potential than longer wavelengths. 355nm (UV), 532nm (Visible) and 1064nm (NIR) wavelengths generated by a picosecond pulsed laser were used in the experiment. Thus, we made a process map of each wavelength and we analyzed the difference between the three wavelength regimes by using a scanning electron microscope and an optical microscope. From a process map of each wavelength, we found that the 355nm is most effective energy transfer to grass-tissues than 532nm and 1064nm wavelength and 1064nm (IR) light can reduce the damage of grass-tissues because of water absorption coefficient dominant. Therefore, we believed that chlorophyll dominant case and water dominant case have difference interaction mechanism. The chlorophyll dominant case makes directly energy of light transfer to grass-tissues then grass-tissues ablated directly. However, the water dominant case makes responses (carbonization, through-cut, partial-cut and decoloration) by heat of around absorbed area from water evaporation in grass-tissue or on surface of grass.

In chapter II, Er:YAG (2.94μm) and CO2 (10.6μm) laser interaction with grass tissues had investigated. 2.94μm and 10.6μm light, Infrared (IR) regimes, laser have high water absorption coefficient as 12000 and 860 cm^{-1} respectively. The sample thickness (grass thickness) is around 110μm. Since we can believe that the water content can reduce damage to grass-tissues from results previous Chapter I, the effect of water content in grass tissues had investigated in this chapter as how differently affect grass tissues as different water absorption coefficient at 2.94μm and 10.6μm wavelength cases. Plus, we investigated beam size effect and how seasonally affect grass-tissues (water concentration). Therefore, some results were found. Even though same intensity and interaction time, response is different as large beam size makes only carbonization response. 2.94μm with high water absorption coefficient light made faster response change than 10.6μm light at using same beam size (1mm).

Chapter III, Typical lawn mower is cut the lawn by contact method such as rotate blade and its equipment used foil fuel engine. From these reason, typical lawn mower can make noise seriously and dangerous and some pollution. However, laser lawn mower is using non-contact method and electrical power. Thus, it can be more quite, safety and little pollution. Furthermore, from previous results Chapter I and II, developed process maps of each laser can be used to manufacturing laser lawn mowing system. In this chapter, we will introduce concept of laser lawn mowing system and suggest optical-setups to cut-well and advantage and disadvantage of each wavelengths.

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I. UV, VISIBLE AND IR LIGHT INTERACTION WITH GRASSTISSUES

1.1.INTRODUCTION

Investigation of laser interaction with tissues were conducted very well that their mechanism also found well by the power density and the exposure time of the laser [1]. If the laser exposure time is longer, the input energy is piled up, and the heat affected zone (HAZ) is larger [2]. The interaction mechanisms are different depending on the energy density [1]. Ultrafast short pulsed laser (from picosecond to femtosecond laser) can minimize the HAZ, and its energy intensity is very high. Thus, these lasers are that photo-disruption and plasma induced ablation mechanism is dominant. However, the general short pulsed lasers (from microsecond to nanosecond laser) have larger HAZ and weaker energy density than ultrafast short pulsed laser. Therefore, the mechanisms of short pulsed laser are photo-ablation and thermal interaction. Except of above kinds of lasers, other lasers (CW or long pulsed laser) conduct the photochemical interaction with tissues [1].

The studies of UV, Visible and IR regimes laser interaction have been investigated variously. For instance, the interaction between laser and various materials such as cellulose, gelatin, ceramic and metal had been founded that characteristic of each wavelengths[3-5]. The grass plants are well known as green plant with photosynthesis that means the chlorophyll is important factor in the role of photosynthesis. The photosynthesis is the process of organic matter (glucose) synthesis from water and carbon-dioxide, using the energy of sunlight. The chlorophyll can absorb well the visible regimes of light, especially blue and red lights, however, green light is reflected. This means that many plant leaves are green color [6]. Water content is help to photosynthesis of grass and constitute of structure approximately over 60 % [6-8]. The detailed information for structure of grass tissues will be explained next introduction.The photosynthesis of leave is using energy of light transfer though the chlorophyll a and b, carotenoid, pigments and so on. In other words, the photon of lights is collected in the antenna complexes of photosystemthrough the above contents. Nevertheless, if the small excess light energy radiatesplant, the energy transfer path (i.e. antenna photosystem) will be closed and the contents of plant will generate the heat to prevent defect[1, 6]. The huge amount of excess light energy can damage plants as carbonization and decoloration[6].The amount of absorbed light energy of matter is decided by reflectance and absorbance of its matters and wavelengths. The reflectance is fraction of incident light reflected by a surface of matter. Thus, the light is transmitted into the matters except the reflected light. To comparedifference of wavelengths effect to grass tissues, we founded that the reflectance and absorption coefficient of main contents which are chlorophyll and water in grass tissues.Furthermore, we investigated how UV, Visible and IR light with a picosecond pulsed laseraffect the grass tissues. As a result of experiment, UV light affects higher grass-tissues than the others probably since its short wavelength has much high photon energy and high absorption coefficient as chlorophyll in grass tissues. Visible light showed more carbonization area in result than the others because of chlorophyll contents. However, IR light (1064nm) has smaller carbonization than the others since its low absorption coefficient of chlorophyll and higher water absorption coefficient than the others.

1.2. THE STRUCTURE OF GRASS TISSUES AND OPTICAL PROPERTIES

We experimented using 'Kentucky bluegrass'. The central stem of grass is thicker than the both edges of the grass. Thus, we assumed thickness of grass using averaging values from both side wing of grass.The structure and composition of grass are remarkably similar to the leaves of green plants. Generally, the composition ratio of a photosynthesizing plant can be changed by the amount of absorbed sunlight or the concentration of chloroplasts [6, 9]. However, since we want to know the composition of water and chlorophyll in grass tissue, we found lots of references and normalized the data from references such as absorption coefficient, volume and mass percentage of tissue and reflectance.

The composition of various leaves has been investigated from Jaquemoud et al [10]. In their results, the amount of water contained in various leaves averages 66.4%, the largest constituent. Chlorophyll a and b are 36.9 and $11.7\, cm^2 \mu g^{-1}$ respectively. Sometimes, light matter as feather is expressed as weight per area. This way is commonly used in plant-biochemistry [6]. Thus, we used this unit for the amount of water and chlorophyll contents. The average thickness of leaves is 194.5μm [10]. Heike Winter investigated the subcellular volume and metabolite concentrations in barley and spinach leaves [7, 8]. Suplick had found the volume fraction of water for 'Kentucky bluegrass' to be around 65% to 72% volume of water in 'Kentucky bluegrass' depending on the status of the grass [11]. D. Buter had found the mass fraction of chlorophyll as 2.6 μg/mg [12]. Actually, water in fresh grass tissues is permeated throughout, but we neglected the permeated water in tissues which means the volume fraction of water in grass is only considered the volume fraction of vacuoles. Therefore, we could assume the volume ratio of water and chlorophyll from the numerous references. Thus, the volume fractions of water and chlorophyll are assumed to be 65 and 25 % respectively.

To compare chlorophyll and water, we researched reflectance and absorption coefficients for them. Richard Willstatter and his coworker had found the chlorophyll absorption spectrum from 1905 to 1913[6]. From their results, the chlorophyll can absorb primarily visible regimes specially, from 550nm to 700nm and below the 480nm [6]. The reflectance and scattering absorption coefficients of various leaves had been found by Barry D. Ganapol and his coworker by means of the leaf experimental absorptivity feasibility model (LEAFMOD). As shown in their result, the empirical reflectance values are found by spectrophotometer with stack variable leaves. However, the scattering absorption coefficient is a feasibility model. Thus, the reflectance (R) of leaves at 532nm is 0.1, Rat1064nm is 0.5. Therefore, the transmittance (T) including absorbed light at 532nm and 1064nm is 0.9 and 0.5 respectively [13]. The water also and chlorophyll absorption coefficient (α_c) had been found as the leaf construct PROSPECT model from experimental data (Jacquemoud et al) [10]. Also the water absorption coefficient (α_w) had been found by Querry et al in 1973 [14]. Lichtenthaler had also found also chlorophyll absorbance [9]. However, since the water absorption coefficient and the chlorophyll absorption coefficient have different unit such as $cm^{-1}$and $cm^2\mu g^{-1}$, we synchronized these units as cm^{-1}. The synchronization method is to multiply the specific absorption coefficient ($cm^2\mu g^{-1}$) by the density (μgcm^{-3}). Therefore, we can assume the reflectance and the absorption coefficients of water and chlorophyll contents in grass tissues. We calculated the effective absorption coefficient (α_e) and absorbance of grass from the assumed values. In the case of the effective absorption coefficient we only considered the main contents which are chlorophyll and water (See, Figure 1 and Table 1).

Wavelength (nm)	1-Reflectance (Percentage)	Absorption coefficient (cm^{-1})		Effective Absorption coefficient (cm^{-1})
		Water	Chlorophyll	
355	~0.9	0.002	~318	~318
532	0.9	0.017	75	75
1064	0.5	0.61	0	0.38

Table 1. Grass tissue optical properties

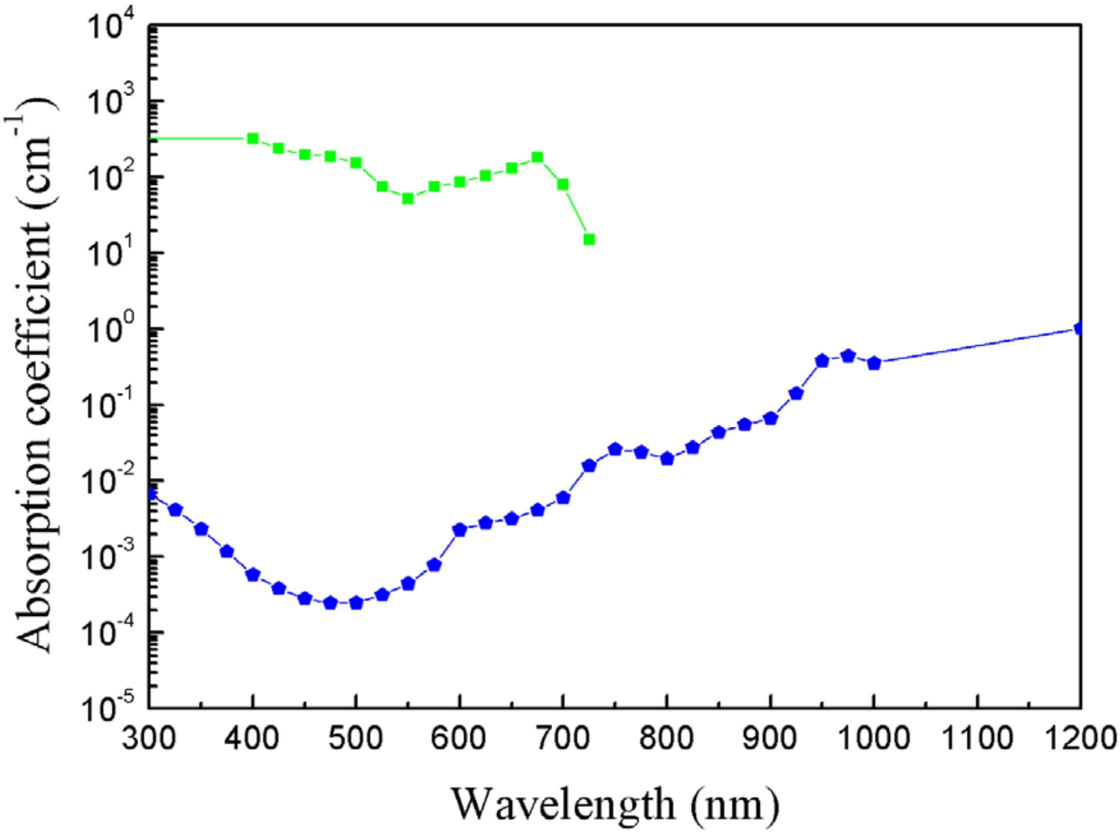


Figure 1.Chlorophyll (green)and Water (Blue) absorption coefficient. Chlorophyll absorption coefficient were calculated using specific absorption coefficient times density of chlorophyll. The water absorption coefficient was taken from reference [14].

As shown in Table 1, the optical properties of grass tissue were estimated. In the case of 355nm, we can assume the over the 400nm because absorbance of chlorophyll at 355nm is over at 400nm in Hartment's absorption spectra [9]. Moreover, we calculated the absorption coefficient of water and chlorophyll in 'Kentucky blue grass' the thickness of which is measured as 110μm from the experimental samples.

Also we calculated the energy efficiency of the three wavelengths (i.e. 355nm, 532nm and 1064nm) using the Beer-Lambert law.

$$I = I_0 e^{-\alpha l} \tag{1.1}$$

Here I is the intensity after transmit through thickness of matter l, I_0 is the intensity of incident light. Once considering the effective absorption coefficient and transmittance, the intensity of light after transmit through the grass I_t is expressed by the following equation.

$$I_t = TI_0(1-e^{-\alpha l}) \tag{1.2}$$

From the equation 1.2, Absorptivity (A) can be calculated by the following equation.

$$A = T(1-e^{-\alpha l}) \tag{1.3}$$

Therefore penetration depth and absorptivity can be estimated from equation 1.1, 1.3 and Table 1 (See, Table 1). So, we can expect the result that each wavelength irradiates the grass tissues. In case of 355 nm, its penetration depth is 31.4 μm which is shorter than the others. It means the UV is can transfer energy faster to grass tissue than other wavelengths. So, we expected the energy transfer sequence to be 355nm, 532nm and 1064nm. The average thickness of grass or leaves is around a hundred micrometers. So, an energy absorption efficiency of 355nm is reasonable but other wavelengths are inefficient. Furthermore, absorptivity is also presented such that 355nm is the largest value. It is also shown that grass tissue can absorb more energy by interacting with 355nm and then the energy order is 532nm and 1064nm.

As shown in Figure 2, Penetration of 355nm, 532nm and 1064nm were calculated using effective absorption coefficient. Thus, we assumed that the 355nm wave is most effective energy transfer to grass-tissues than 532nm and 1064nm. Experimental sample, grass, has 110um thickness. Thus, grass-tissues will fully absorb energy of 355nm through three times. However 532nm and 1064nm can't fully absorb energy of light since their penetration depth is longer than 355nm. Therefore, we assumed that 355nm energy transfer into grass-tissues is highly proportional. However, 532nm and 1064nm energy transfer into grass-tissues does not proportionally. So, we expected that 355nm interaction with grass tissues is the crucial effect. But 532nm and 1064nm have different dominant contents which are chlorophyll and water. Therefore, we had experimented and analyzed to compare the empirical results with our expectations and also morphologically observed the surface and cross-section of grass tissues by optical microscope and scanning electron microscope and optical microscope.

Wavelength (nm)	Penetration depth (cm)	Absorptivity (Percentage)
355	0.003	0.87
532	0.013	0.71
1064	2.631	0.002

Table 2. Expected penetration depth and absorptivity for three wavelengths (355, 532 and 1064nm)

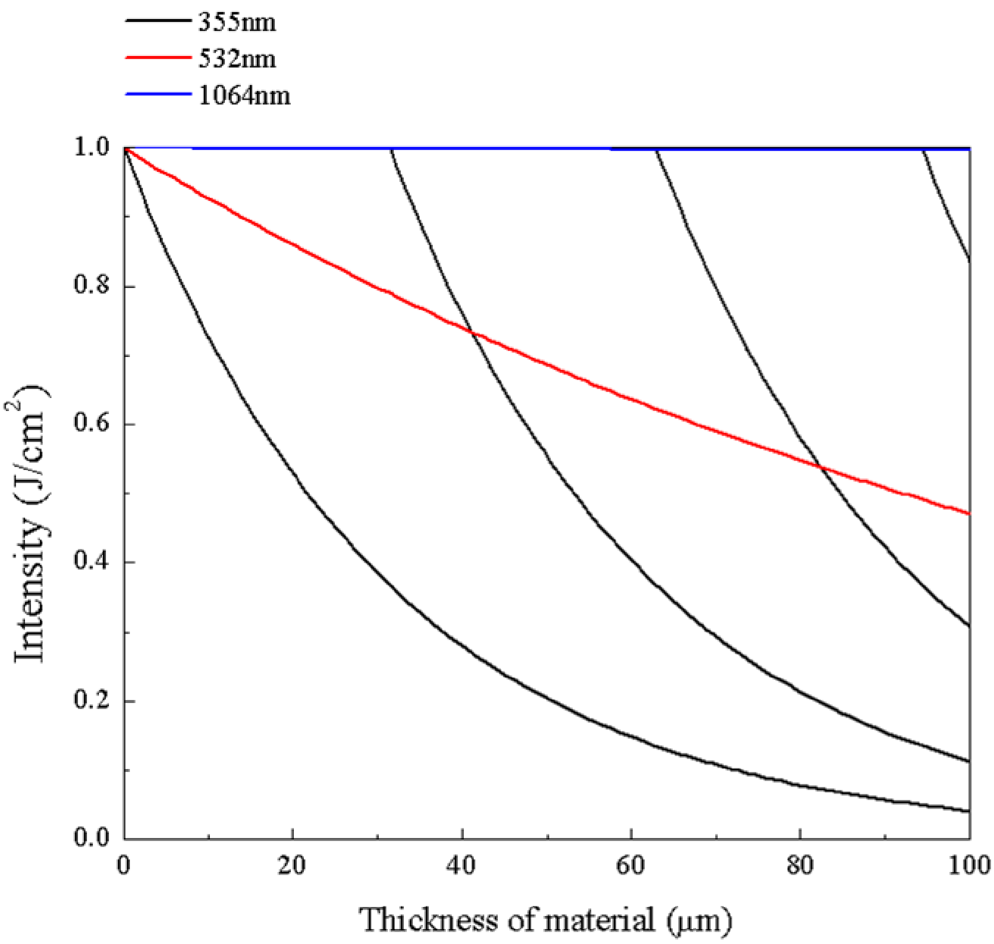


Figure 2. Penetration of 355nm, 532nm and 1064nm. Penetration values were calculated by beer-lambert law using effective absorption coefficient.

1.3.EXPERIMENTAL SETUP

A picosecond laser (Talisker 355-4, Coherent Co.) was used in this experiment. Its cavity is Nd:YVO4 that generates 532nm and 355nm harmonically from 1064nm. The samples of grass are 'Kentucky bluegrass'. The thickness of the collected grass was around 110μm within ± 5μm to fix the experimental condition. Since the grass is flexible, focusing the beam on the surface of grass was difficult thus we made a PMMA standard jig and all samples were fixed on the jig as shown inFigure 3. The experimental conditions use the maxima and minima output of power and stage speed, thus we can observe the full range of instrumental conditions (described in Table 3). And the experimental system is shown inFigure 4. The experiment was conducted with the same beam size at three wavelengths (1064nm, 532nm and 355nm) using a beam expander to adjust the beam size. Therefore, the factor of different beam sizes is neglected. Thus, the same experimental conditions were implemented.

Wavelength (nm)	Power (W)	Speed (mm/s)	Pulse duration (s)	Repetition rate (KHz)	Beam size (μm)	Average Thickness (μm)
355	0.01~5	1~500	12 picoseconds	200	20	110
532	0.01~6.25	1~500				
1064	0.01~13.8	1~500				

Table 3. Experimental condition

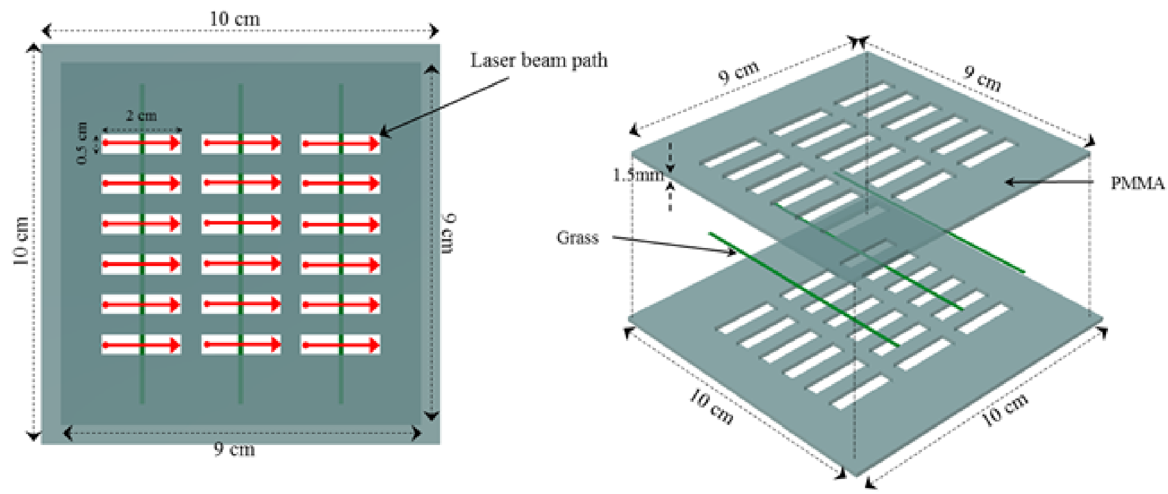


Figure 3.Schematic of standard experimental fixture.Red line showed laser beam path and green shape is grass leaves. Gray colored fixture is PMMA experimental fixture.

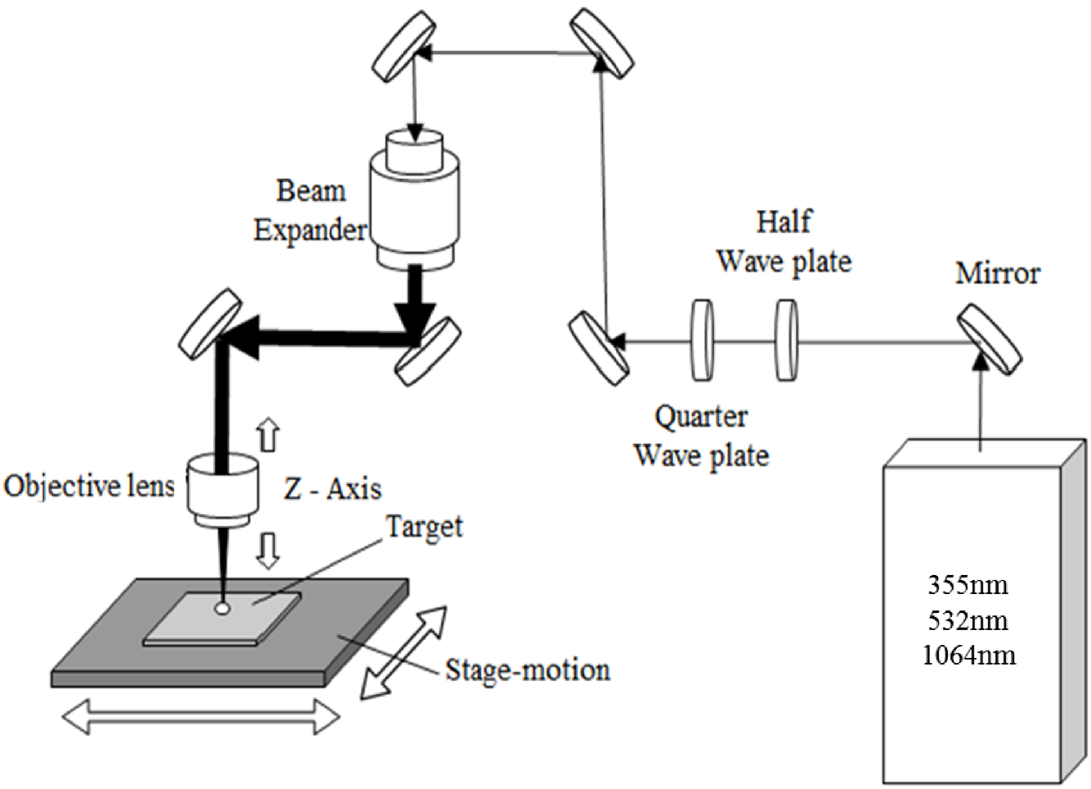


Figure 4.Schematic of experimental system is showed. Repetition rate is 200KHz. pulse duration is 10~15 picoseconds. And these laser cavity is Nd:YVO4 and it has harmonic generation using 1064nm.

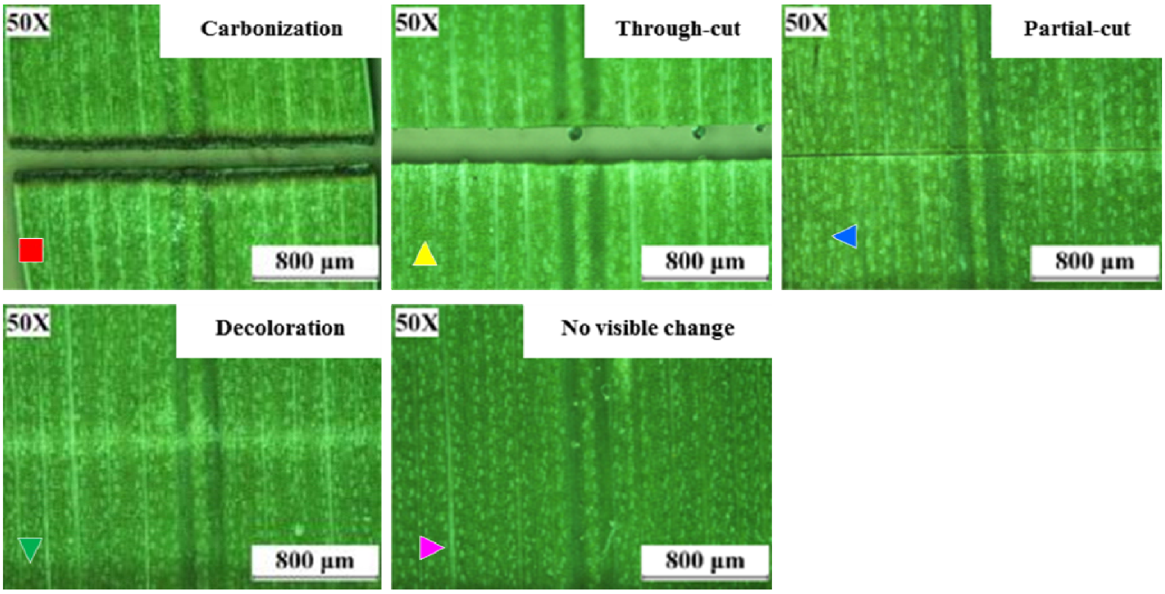


Figure 5. The criteria for classification of results, carbonization was decided as red square, through-cut was decided as yellow triangle (up), partial-cut was decided as blue triangle (left), Decoloration was decided as green triangle (down), No visible change was decided as violet triangle (right). Thus, we used those criteria name, shape and color in this study.

To analyze experimental results, imaging surface and cross-section of grass tissues were measured classification (as shown inFigure 5). There are 5 types of classification which are named by us such as carbonization, through-cut, partial-cut, decoloration and no visible change. Carbonization is proof of defected grass-tissues which made by high-temperature from the high amount of heat energy. Moreover, carbonization is the conversion of an organic material (i.e. grass-tissues) into carbon-containing residue or carbon through the pyrolysis or destructive distillation. For instance, if the grass-tissue receives excessive energy of light, temperature of absorbed grass-surface will increase over 100ºC then the carbonization will begins make grass-tissues blackly. Second, Through-cut and partial-cut express well-cut without damage. That were made by two type of mechanism which cases are grass-tissues received energy directly and heat of around absorbed area makes breakdown for grass-tissues combinations. Decoloration means whitening surface of grass. Decoloration made by vaporization of water in tissues or cell ablation. No-visible change is no response and invisible to the naked eye. Although cross-sectional image will be introduced to analyze what occurs in the grass tissues and it will be regarded results and discussion section.

1.4. RESULTS AND DISCUSSION

1.4.1. Threshold of three wavelengths

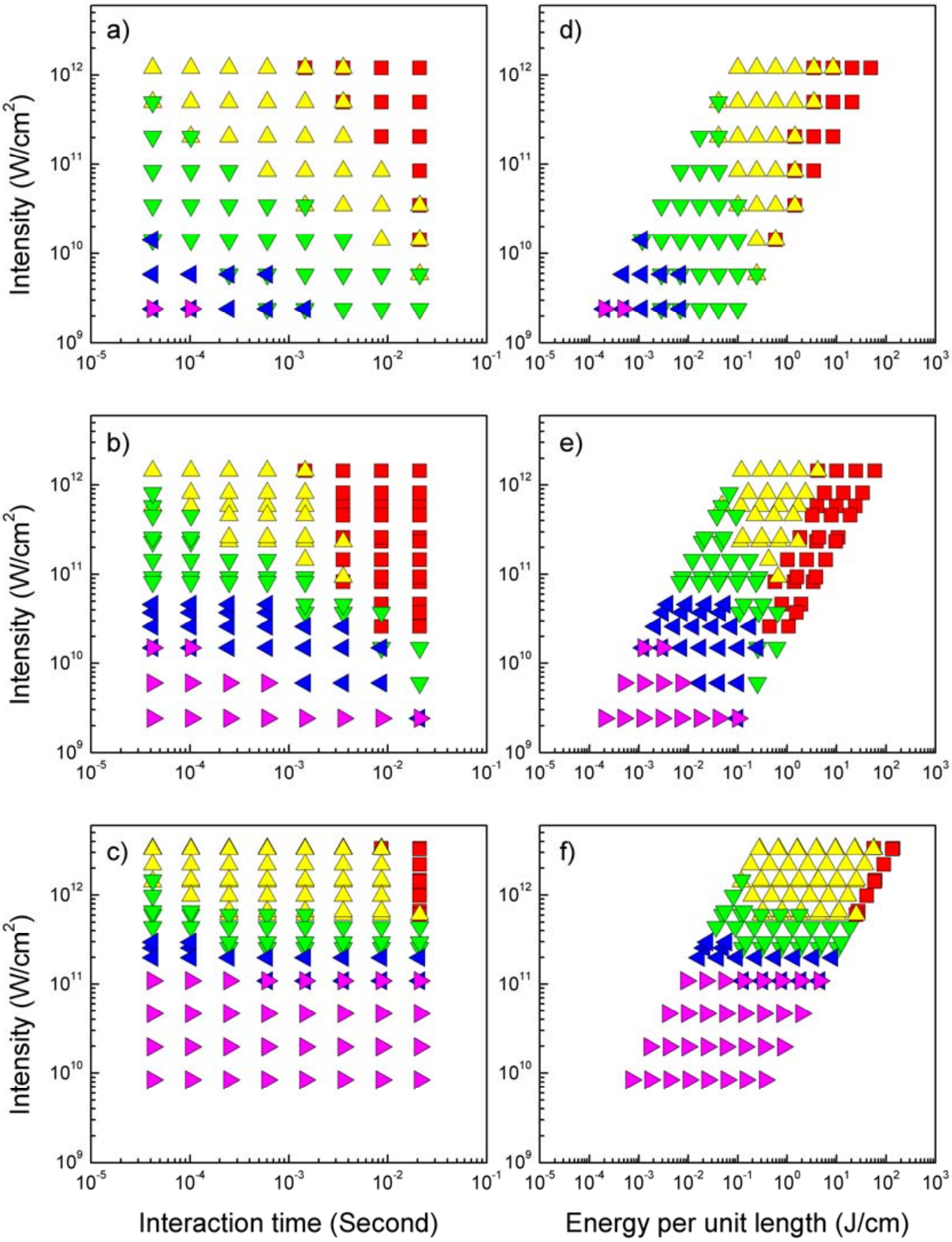


Figure 6. Results for incident intensity of three wavelengths; a) and d) are result of 355nm, b) and e) are result of 532nm, c) and f) are result of 1064nm. Each data point is presenteddifferent colors as explained the criteria for classification (Red: Carbonization, Yellow : Through-cut, Green : Partial-cut, Blue : Decoloration, Violet : No-visible change).

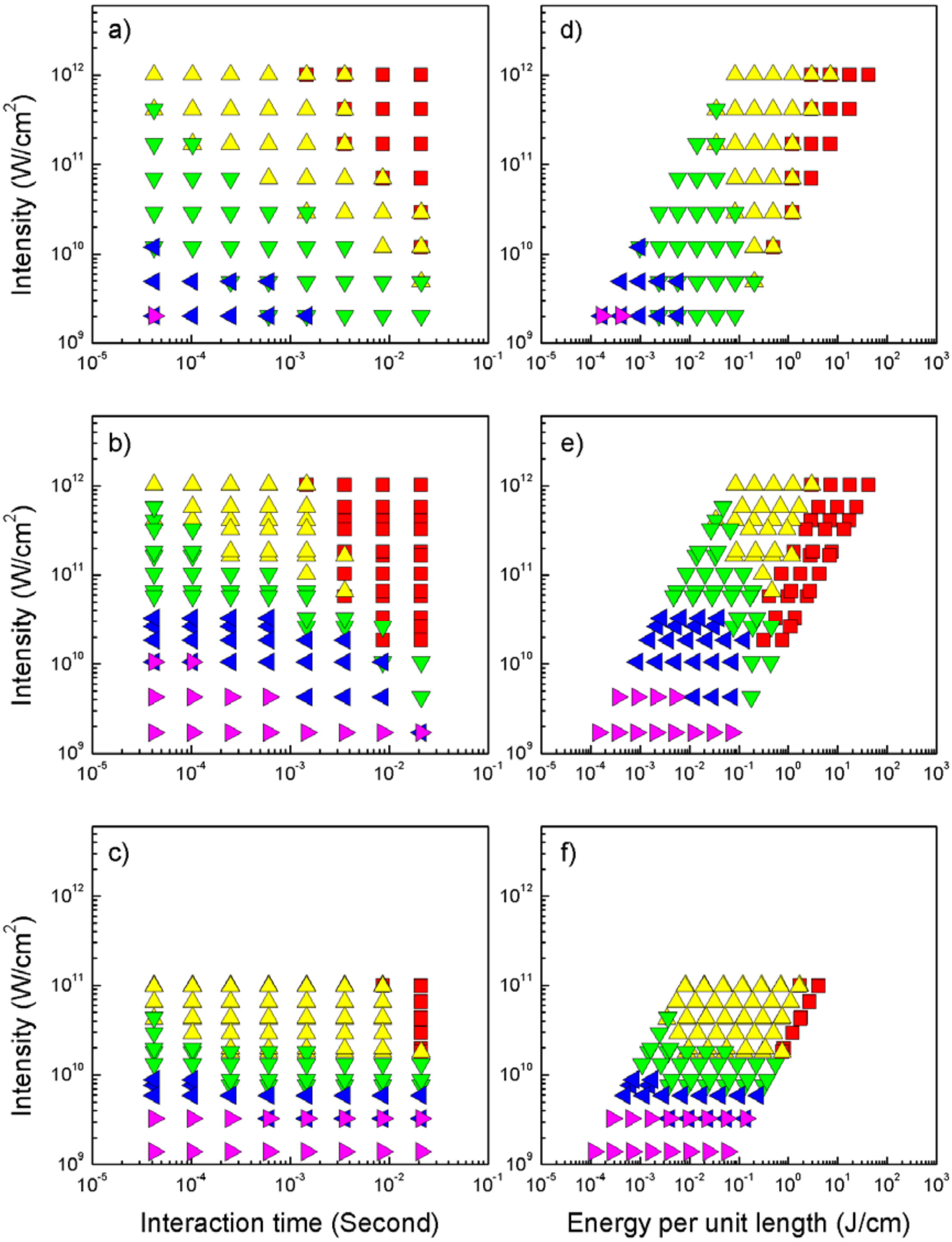


Figure 7.Results for absorbed intensity of three wavelengths; a) and d) are 355nm, b) and e) are 532nm, c) and f) are 1064nm. Each data point is presented as different colors (Red: Carbonization, Yellow : Through-cut, Green : Partial-cut, Blue : Decoloration, Violet : No-visible)

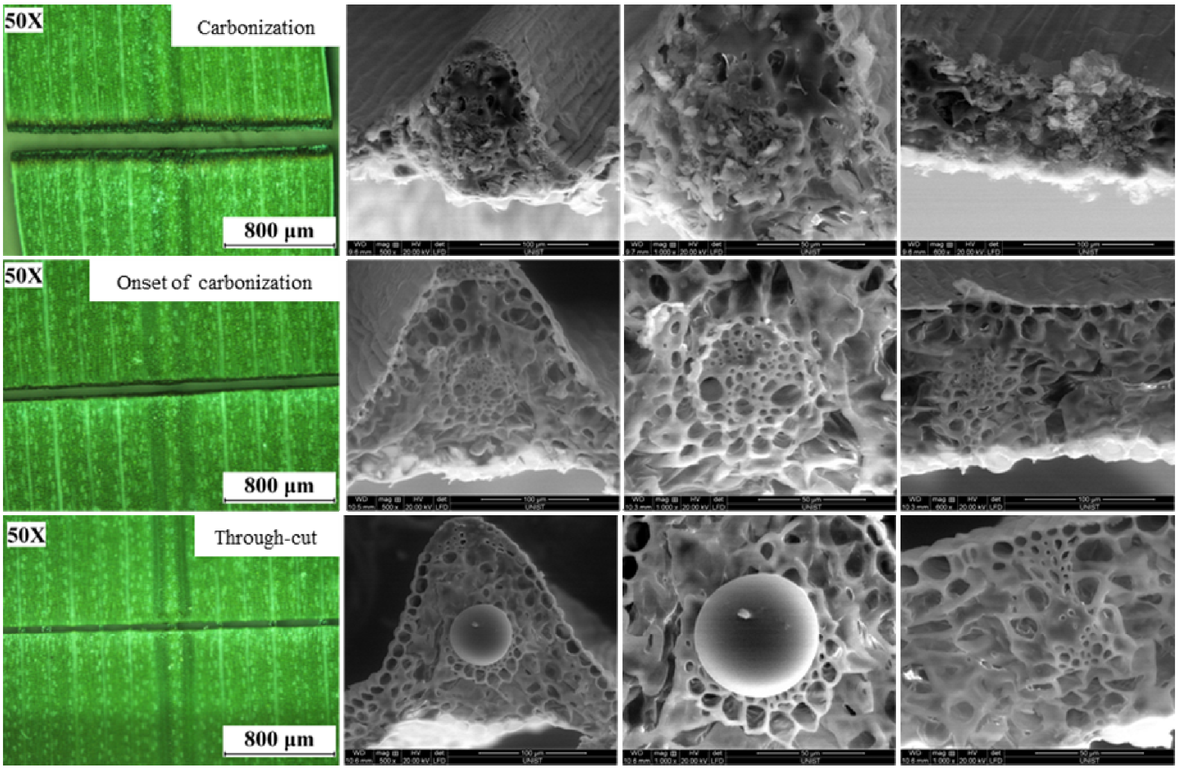
In the case of 355nm a) and d) , the experiments had been conducted a total of 4 times, 2 times on 22 and 27 December 2011 separately, 2 times on 11 January 2012. The experiments of 532nm b) and e) were conducted 4 times on 22, 28 December, 12 and 16 January. And the experiments for 1064nm c) and f) were conducted on 23, 28 December, 2 and 16 January.

From the Figure 6 and Figure 7left side results, as the interaction time becomes longer, the amount of energy of light increases. Once grass tissues absorb a huge amount of energy, the grass tissues could be damaged by carbonization since energy could be transformed to heat. Otherwise, the grass tissues absorbed an appropriate amount of energy then through-cut or partial-cut occurred without damage to the grass tissues. For the same reason, a small amount of energy caused decoloration or no visible change in grass tissues. The amount of light intensity also affected the grass tissues proportionally to interaction time. The intensity of light related to the interaction mechanism.

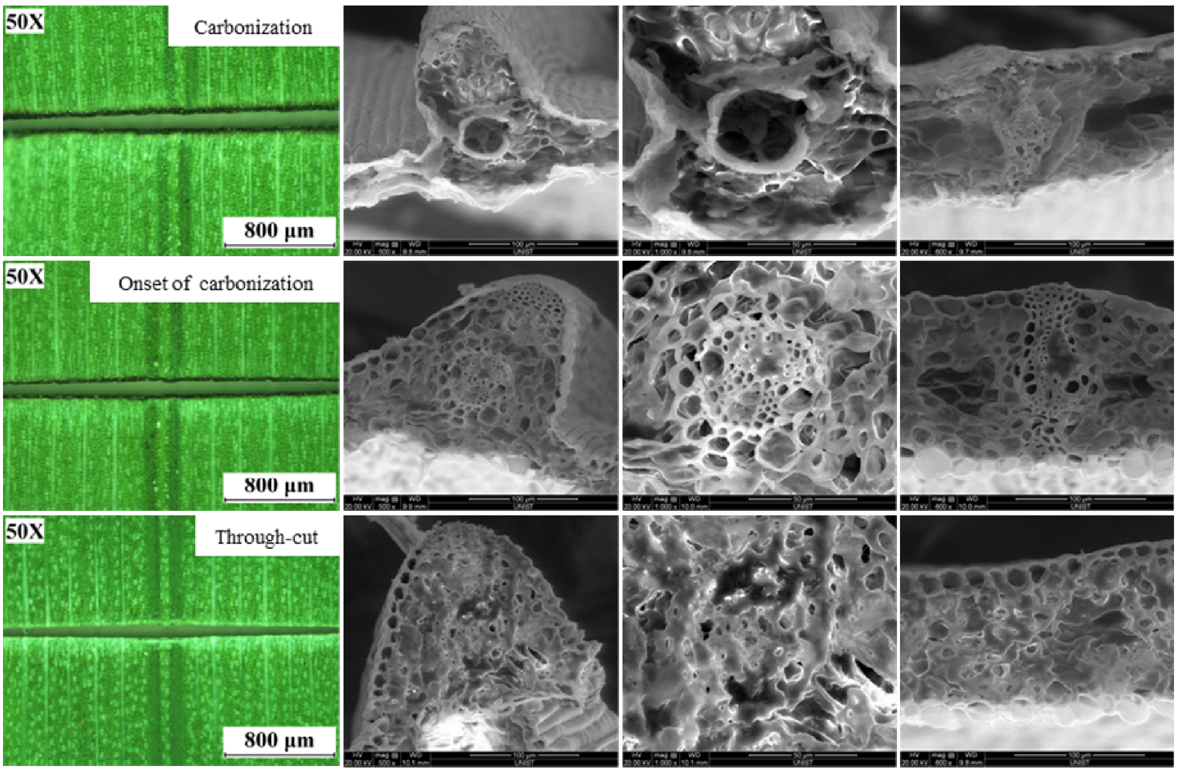
The energy threshold could be estimated by means that interaction time multiply intensity of light. However, the grass tissues responded differently to the three wavelengths interaction since the wavelengths have different reflectance and absorptivity. The distinction of each threshold is difficult for that reason. While UV light (355nm) had more affected on energy per unit length than interaction time, IR light (1064nm) had more affected on interaction time. These findings assume that their energy transfer target is difficult. We believe that UV and visible light intensively interact with chlorophyll but, IR light interacts with water. For these reasons, the responses of chlorophyll and water are different in that chlorophyll absorption can generate response since the chlorophyll covered the surface and cell wall. However, water content is in the grass-tissue. Thus, water dominant case generates interaction with light in tissue then around absorbed area will received heat from water evaporation. Furthermore UV, visible and IR light have a huge gap of absorption coefficient (See, Table 1). IR light has a smaller effective absorption coefficient than UV and Visible light. That means UV and visible light cases can generate heat faster than IR light case. Thus, IR light interaction with grass tissues presented a smaller carbonization zone and larger through-cut zone. Absorptivity (Table 2) and penetration depth are also hugely different. At IR light interaction with grass tissues, grass tissue response begins at a high intensity of light as shown in Figure **6**. It is higher than the others. Visible light also needs higher intensity to make any response on grass tissues than compared to UV light, since visible light also has a smaller absorption coefficient than UV light. However the results of 355nm light interaction with grass-tissue showed response at almost every area because, the efficiency of energy transfer depends on penetration depth and target thickness, while the average thickness of grass-tissues are close to the penetration depth of 355nm light (As shown in Table 2 and Table 3). Therefore, we can believe that our expectations were reasonable. UV light can affect grass-tissues intensively. Visible light has less effect and IR light the least, with each type of light causing different responses.

1.4.2. Morphological experimental results of three wavelengths

a) 355nm



b) 532nm



c) 1064nm

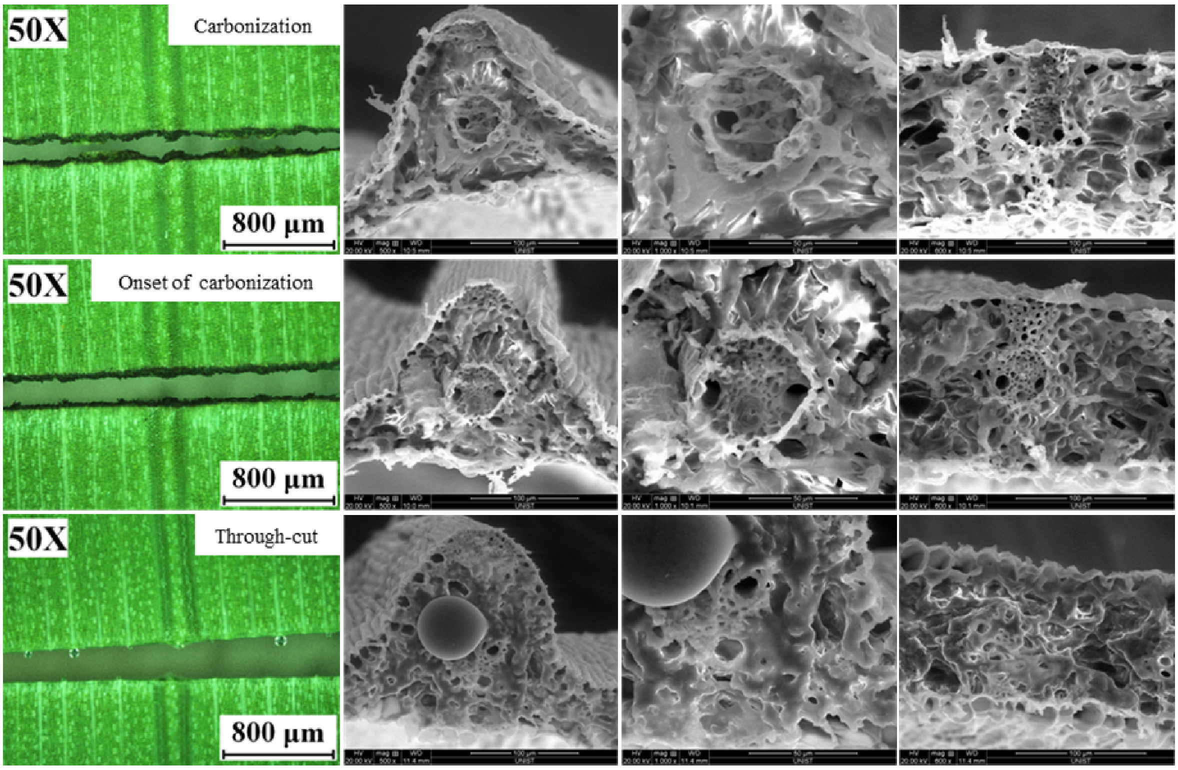


Figure 8.a) 355nm results, Top view image of microscope and Cross-section image of SEM. Carbonization: 5W, 1mm/s, Partial carbonization : 2.058W, 2.4mm/s, Penetration : 0.349W, 5.9mm/s. beam spot size : 20um

b) 532nm results, Top view image of microscope and Cross-section image of SEM. Carbonization: 6W, 1mm/s, Partial carbonization : 2.406W, 5.9mm/s, Penetration : 0.965W, 14.3mm/s. beam spot size : 20um

c) 1064nm results, Top view image of microscope and Cross-section image of SEM. Carbonization(from top to bottom) : 13.8W, 1mm/s and 13.8W, 2.4mm/s, Penetration : 2.502W, 5.9mm/s. beam spot size : 20 um

The results in Figure 8are the surface and cross-sectional image of each case when carbonization, onset of carbonization and through-cut responses had been occurred. As shown in Figure 8 Carbonization of each case, the grass tissues have been damaged and distorted. However, Figure 8 Onset of carbonization showed less damaged grass-tissues than the Carbonization case. We can provide that its proof is less distortion of damaged grass-tissues. Moreover, the through-cut case didn't show any distortion and also we can believe this case has no damage without carbonization. Since the surface and cross-section image of grass-tissues showed that grass-tissues has wet and droplet and heat generation of through-cut case is less than the other cases such as Carbonization and

Onset of carbonization. Furthermore we can believe that between the grass-tissues inside pressure and outside pressure are different. Thus, no-evaporated water in grass tissue went out of grass-tissue. And also in the case of carbonization phenomena it can be assumed that a huge amount of energy can generate a huge amount of heat thus it can remove the remaining of water in grass-tissues and close to path of grass tissues. However there was no difference of wavelength effect.

1.5. CONCLUSION

The main contents of grass are chlorophyll and water. There are different absorption coefficients at three wavelengths (355nm, 532nm and 1064nm). 355nm and 532nm are dominant at chlorophyll contents. 1064nm is dominant at water contents but it is a much smaller absorption coefficient than the chlorophyll contents. The magnitude unit order of estimated effective absorption coefficient at 355nm and 532nm light are around 100, 10 times 1064nm light. For this reason, grass tissues interaction with light begins following order 355nm, 532nm and 1064nm. The energy transfer efficiency of 355nm is the best of the three wavelengths, because a penetration depth of 355nm light is close to the sample thickness and then following order efficiently 532nm and 1064nm. And also the 355nm light response threshold is sensitive on energy per unit length but the 1064nm light response threshold depends on the magnitude order of intensity. We can believe the reason is that 355nm light is more efficient than 1064nm, thus 355nm light can cause a response change faster than 1064nm. But 1064nm light has a relative small amount of absorption coefficient compared to the others. Thus, it can cause a slow response change. The differences of the main energy transfer target haveoccurred in different areas of each response such as carbonization, through-cut, anddecoloration. Actually in the case of 1064nm, the water absorption coefficient is much higher than the chlorophyll contents and also water can evaporate without causing damage, thus, 1064nm can cause less damage to grasstissues less than the others which are 355nm and 532nm. However its water absorption coefficient is very small, thus compare with the water and chlorophyll interaction effects are difficult. But we can believe that the water content of grass tissues can reduce damage. Therefore, we will investigate the water effect on grass-tissues by high water absorption coefficient lasers such as Er:YAG and CO2 lasers.

II. INFRARED INTERACTION WITH GRASS TISSUES

2.1. INTRODUCTION

Water optical properties had been investigated by George M. Hale and Marvin R. Querry as explained at Chapter I. (see, Figure 1 in Chapter I). From their results, absorptivity and absorption coefficient of water had been calculated by following equation.

$$A = 4n/[(n+1)^2 + k^2] \quad (1.4)$$

Here, 'A' is absorptivity, 'n' is refractive index and 'k' is extinction coefficient. Refractive index and extinction coefficient can be changed by materials. For example, air is n = 1.

$$\alpha = \frac{4\pi k}{\lambda} \quad (1.5)$$

'α' is absorption coefficient and also it is as known as Lambert absorption coefficient, 'λ' is wavelength. As shown in Table 4, penetration depth and efficiency of energy transfer had been found.

Wavelength (μm)	Absorptivity (Percentage)	Absorption coefficient (cm^{-1})	Penetration depth (μm)
10.6	0.98	860	11.6
2.94	0.98	12000	0.8

Table 4.The absorptivity and penetration depth for each wavelengths (2.94 and 10.6 um).

Water absorbs 2.94µm and 10.6µm wavelength around 90%, but amount of absorption coefficient of 2.94µm wavelength is 14 times 10.6µm wavelength. Because of gap between absorption coefficient of 2.94µm and 10.6µm, light of 2.94µm wavelength transfer energy to grass-tissues faster than 10.6µm. However, penetration depths of 2.94µm and 10.6µm wavelength are 0.8µm and 11.6µm respectively, average thickness of grass leaves is 110µm. Since these reason, we can expect that efficiency of energy transfer about two wavelengths has little gap. However, light of 10.6µm wavelength is longer than light of 2.94µm as 3.6 times. We knew already that water content's absorption of IR light can reduce the damage of grass tissues from conclusion of 'Chapter I'. Therefore, to compare with between IR regimes, effect of absorption coefficient difference had been investigated between these two wavelengths.

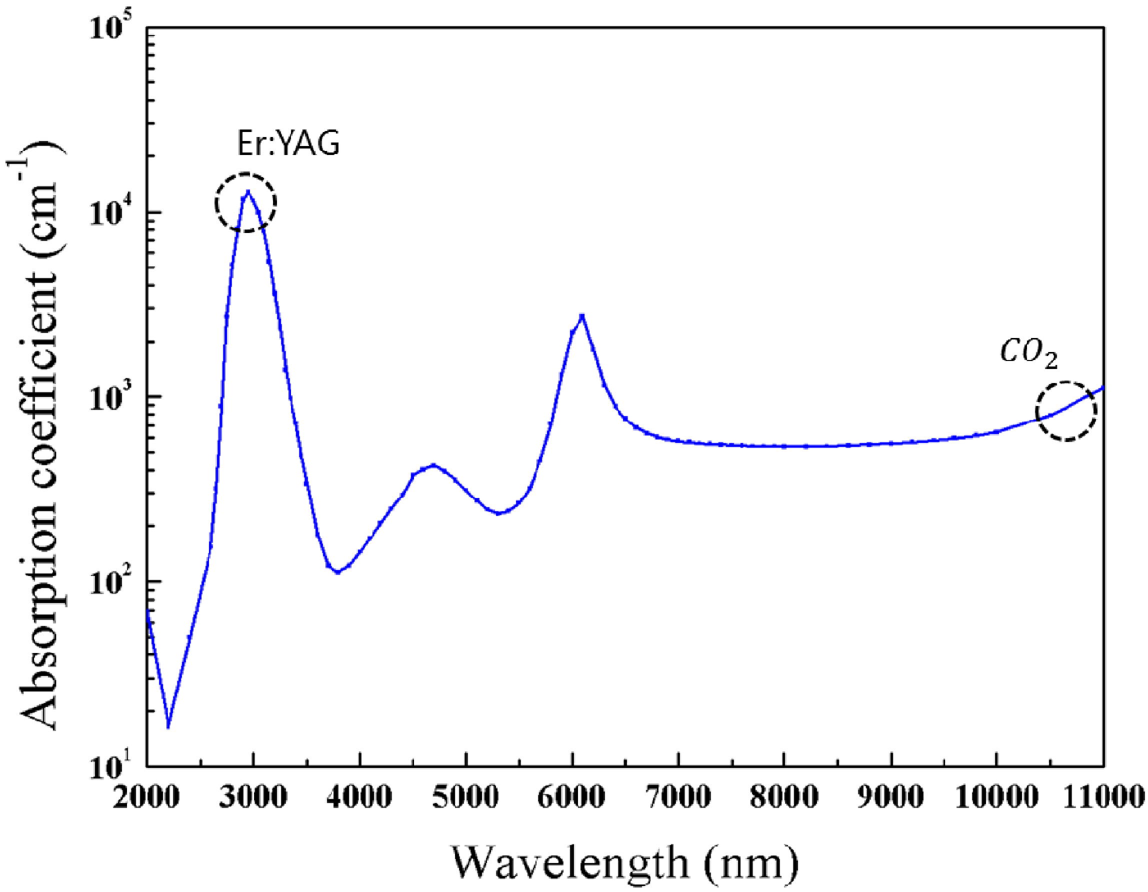


Figure 9. Water absorption coefficient for 2.94um and 10.6um [14]

2.2. EXPERIMENTAL SETUP

Experiments of CO_2 laser and Er:YAG laser were conducted by control the stage speed and power in minima and maxima ranges. Data acquisition is 10 points in speed and power as log scales. Experiments were conducted a total of 3 times and as same conditionrepeatedly. Experimental condition is as followTable 5. And also experiments were conducted by using standard jig as in 'Chapter I'. Average thickness of grass leaves are 110μm. And also the samples were classified as show inFigure 10. There are 4 classifications named by us carbonization, onset of carbonization, through-cut, partial-cut. As explained before in 'Chapter I', 4 classifications are such as proof of defective grass tissues and well-cut without damage.

Wavelength (μm)	Power (W)	Speed (mm/s)	Pulse duration (ms)	Repetition rate (Hz)	Beam size (mm)
10.6	0.01~5	1~500	120	5000	0.18
2.94	0.01~6.25	1~500	350	10	1

Table 5.Experimental condition.

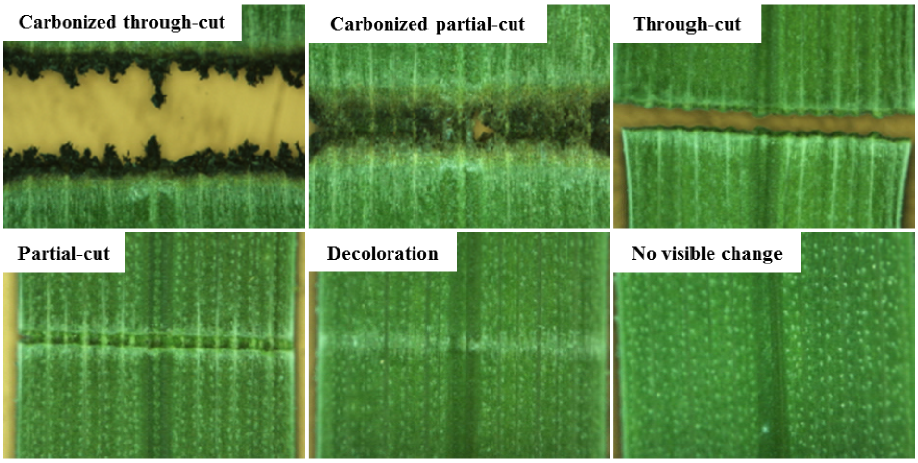


Figure 10. Sample classification

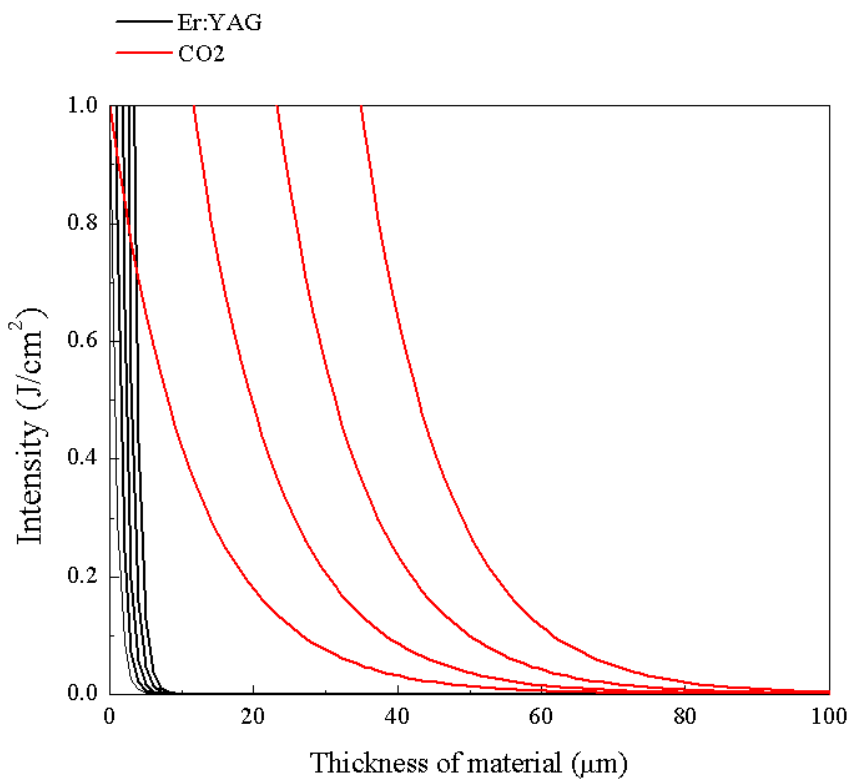


Figure 11.Water penetration depth for the 2.94um (black lines, Er:YAG) and 10.6μm(Red lines, CO_2 laser) wavelengths. The thickness of grass is 110μm.

As shown in Fig.10, the criteria of sample classification was defined as Chapter I, however, its classification method is quite different since the CO_2 and Er:YAG laser made different response which is carbonized partial-cut. Thus, we can separate each response such as carbonized through-cut, carbonized partial-cut, through-cut, partial-cut, decoloration and no visible change. Those responses named by us as chapter I criteria method.The carbonized through-cut showed the defected grass-tissues which case indicate that grass-tissues received excess amount of energy and it believed that excess amount heat made by water evaporation in grass-tissues. Carbonized partial-cut is defined partial-cut with carbonization.And other responses without carbonization is same as criteria of sample classification of Chapter I. Thus, we analyzed each experimental result using by this criteria.

Water penetration depth of Er:YAG laser is different from CO_2 laser, since their amount of water absorption coefficient is different. Penetration depth means when weak intensity of incident light as 30%. Figure.11 showed that penetration depth for Er:YAG and CO_2 along the grass thickness (110μm). This plot explained that, energy of two lights (Er:YAG and CO_2) can be consumed within thickness of grass. However, Er:YAG laser energy consumption is more faster than CO_2 laser.But this means uncertain that Er:YAG is more efficient than CO_2. Therefore, we investigated effect of absorption coefficient. And we expected that Er:YAG is more efficient to energy transfer to grass tissues than CO_2 laser.

2.3. RESULTS AND DISCUSSION

2.3.1. Seasonal effect on grass-tissues

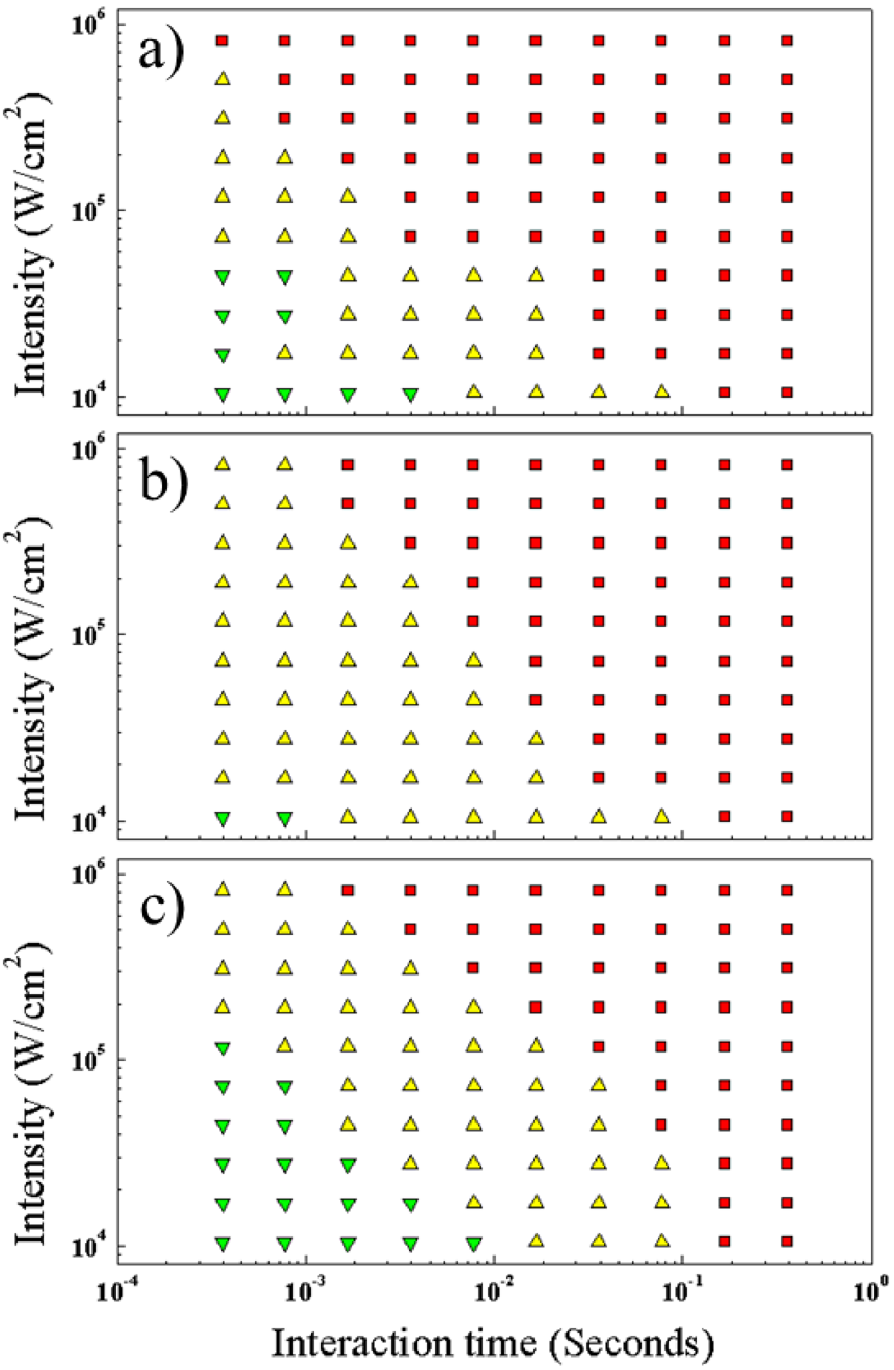


Figure 12.Intensity (W/cm^2) and interaction time (seconds), these results are conducted to compare with season. We want to know the water status effect. (red square: carbonization, yellow upper triangle: through-cut and green lower triangle: partial cut). Experiments were conducted by CO_2 laser.Experimental dates : a) 12 October 2011, b) 22 December 2011, c) 31 May 2012.

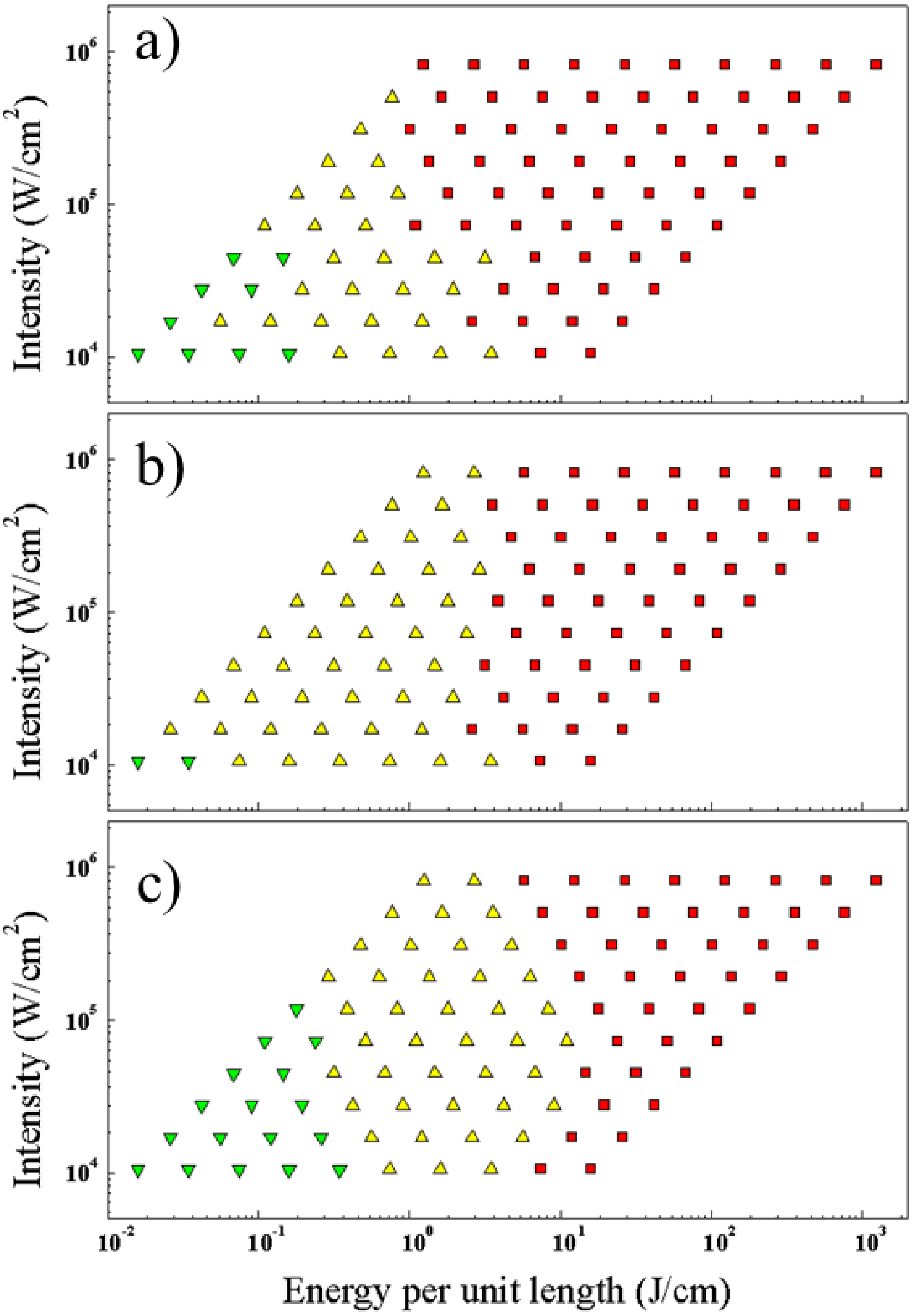


Figure 13. Intensity (W/cm^2) and energy per unit length (J/cm), these results shown the CO_2 laser's energy transfer is quite proportional to each response. (red square: carbonization, yellow upper triangle: through-cut and green lower triangle: partial cut).CO_2laser conducted in this experiment. Experimental dates : a) 12 October 2011, b) 22 December 2011, c) 31 May 2012.

Wavelength (μm)	Repetition rate (Hz)	Pulse duration (us)	Beam size (um)	Thickness of grass (um)	Absorption coefficient of water (cm^{-1})
10.6 (CO2)	5000	120	180	110	860

Table 6. Experimental condition of season effect (CO_2 laser)

	12Oct.	22Dec.	31May
Max temperature (°C)	24.8	3.5	23.9
Min temperate (°C)	11.6	-4.5	16.2
Mean temperature (°C)	18.3	0.7	19.2
Cloud cover	5.4	1.8	4.4

Table 7. Environmental condition

Water content in grass-tissues is varying dependent environmental condition. Also water is IR light dominant. Thus, we investigated the season effect of grass-tissues, only fresh matters, however, were used in this study. The experimental condition is as shown in Table. 6. And environmental condition of each case is as shown in Table 7.

From results, threshold of through-cut and carbonization were found. The 12 October experiment has ~17J/cm^2 through cut threshold and ~190J/cm^2 carbonization threshold. And the 22 December experiment has ~6J/cm^2 through cut threshold and ~ 205J/cm^2 carbonization threshold. 31 May experiment has ~30J/cm^2 and ~630J/cm^2. Therefore, we knew that 22 December, a winter day, has the smallest amount of through cut threshold. It is less 1/3 an 1/5 less than fall (12 October) and spring (31 May). Its reason believed that the winter season, water content on surface of grass-tissues is larger than other seasons. However, carbonization threshold at winter (22 December) and fall (12 October) is quite similar. Also this finding believed that once penetrate surface of grass, through-cut threshold is almost same as each condition of grass. In particular, carbonization threshold at spring (31 May) is 3 times larger than other seasons. It means that spring season needs more energy absorption to make carbonization response, since the water content in grass-tissues, spring season is the largest quantity of season. It means that water content in grass-tissues is varying and dependent on the weather. It can be common sense but we want to investigate how many influence of seasonal effect on the water content in grass-tissues. As shown in Figure 13, we can know that energy transfer to grass-tissues by CO_2 laser is quite proportional to amount of energy. And also its finding is some different for Chapter I's result which is 1064nm result, even 1064nm IR light is water domain receptor, but, it has too small amount of water absorption coefficient. So, 1064nm IR light is not quite proportional to amount of energy, 1064nm IR light is just sensitive on amount of intensity of incident light. Therefore, we found that high amount of water absorption coefficient made easily and proportionally energy transfer to grass-tissues. Furthermore, it believed that fresh matter (grass) has quite similar threshold magnitude order. Thus, we used this finding in manufacturing of laser lawn mower.

2.3.2.Beam size effect on laser interaction with grass-tissues

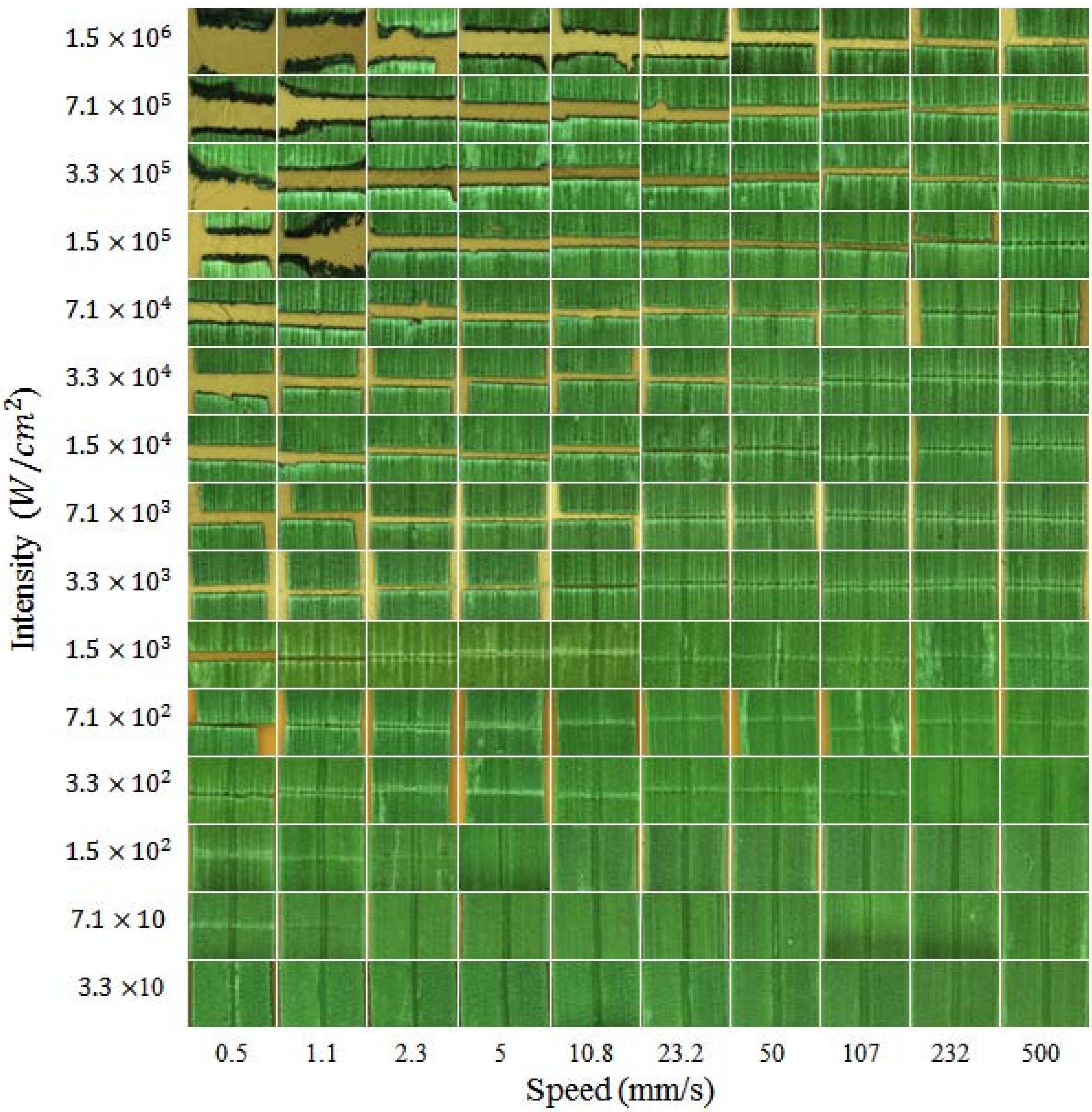


Figure 14. Intensity and speed (mm/s), these result that threshold of each response. and we used analysis method in criteria of classification method. And also above result used as beam size is 180μm.

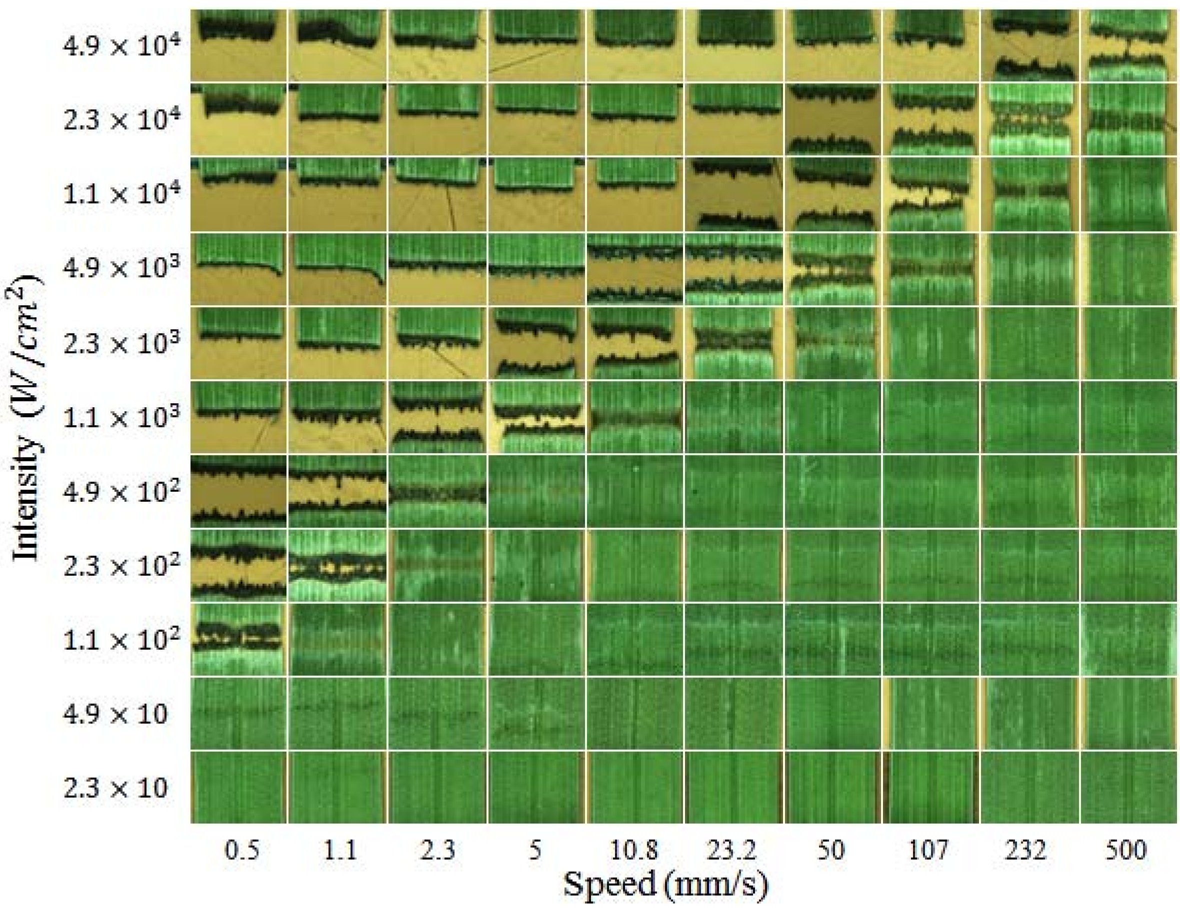


Figure 15.1mm beam size was used in above result to compare with 180μm.And also it showed threshold of each responses.

Wavelength (μm)	Repetition rate (Hz)	Pulse duration (us)	Beam size (um)	Thickness of grass (um)	Absorption coefficient of water (cm^{-1})
10.6 (CO2)	5000	120	180, 1000	110	860

Table 8. Experimental condition of different beam size effect (CO_2 laser)

As shown in Figure 14 and Figure 15, the microscope image of grass-surface with each data point has been arranged. And Figure 14 and Figure 15 experiment were conducted using as described in Table 8.And also, this experimented conducted on the same days to avoid varying water content in grass-tissues. Result of these experiments showed that experiment using 180μm and 1mm beam size. One of findings shows easily us that 180μm experiment showed through-cut and partial-cut without carbonization but, 1mm experiment showed even through-cut and partial-cut always with carbonization at same experimental condition. To compare with 180μm and 1mm beam size effect, we plotted the each response and measured threshold of each responses (See, Figure.16 and Figure.17).

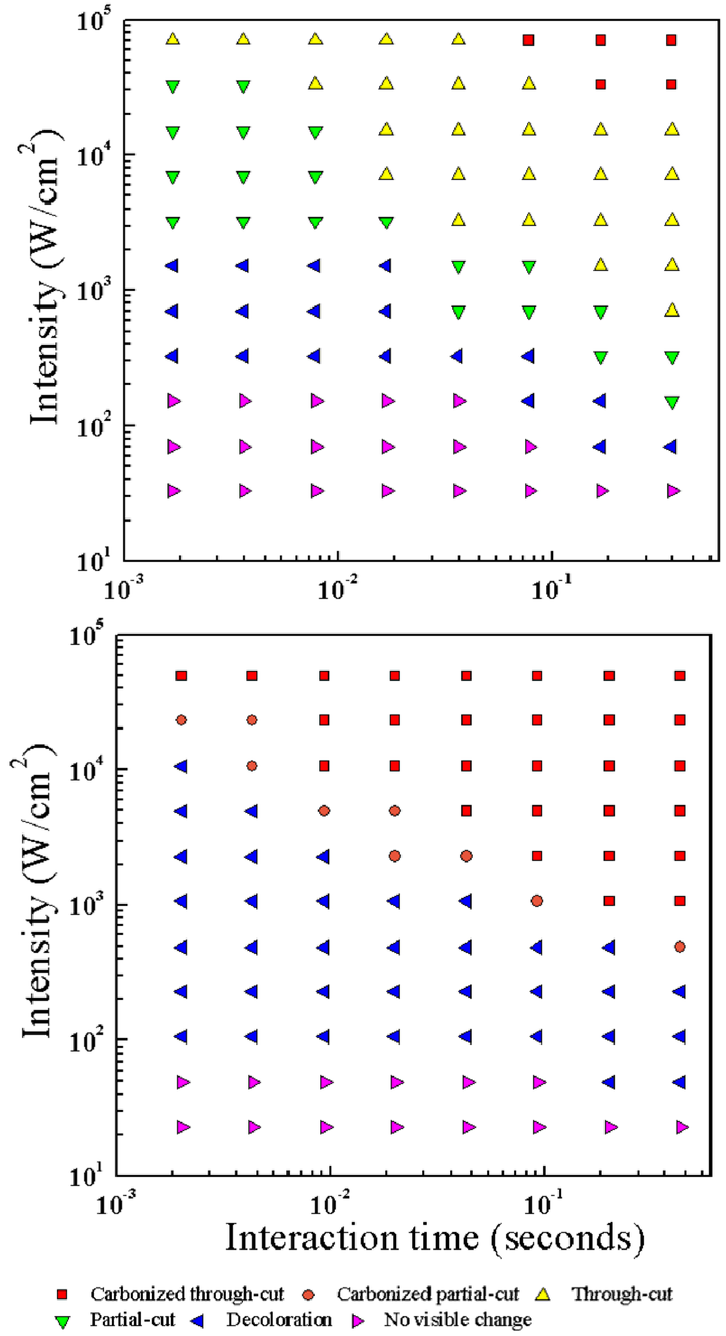


Figure 16. Results of CO_2 laser experiment using 180um (up) and 1mm (down) beam size, each response were named as legend. These results also showed threshold of each responses.

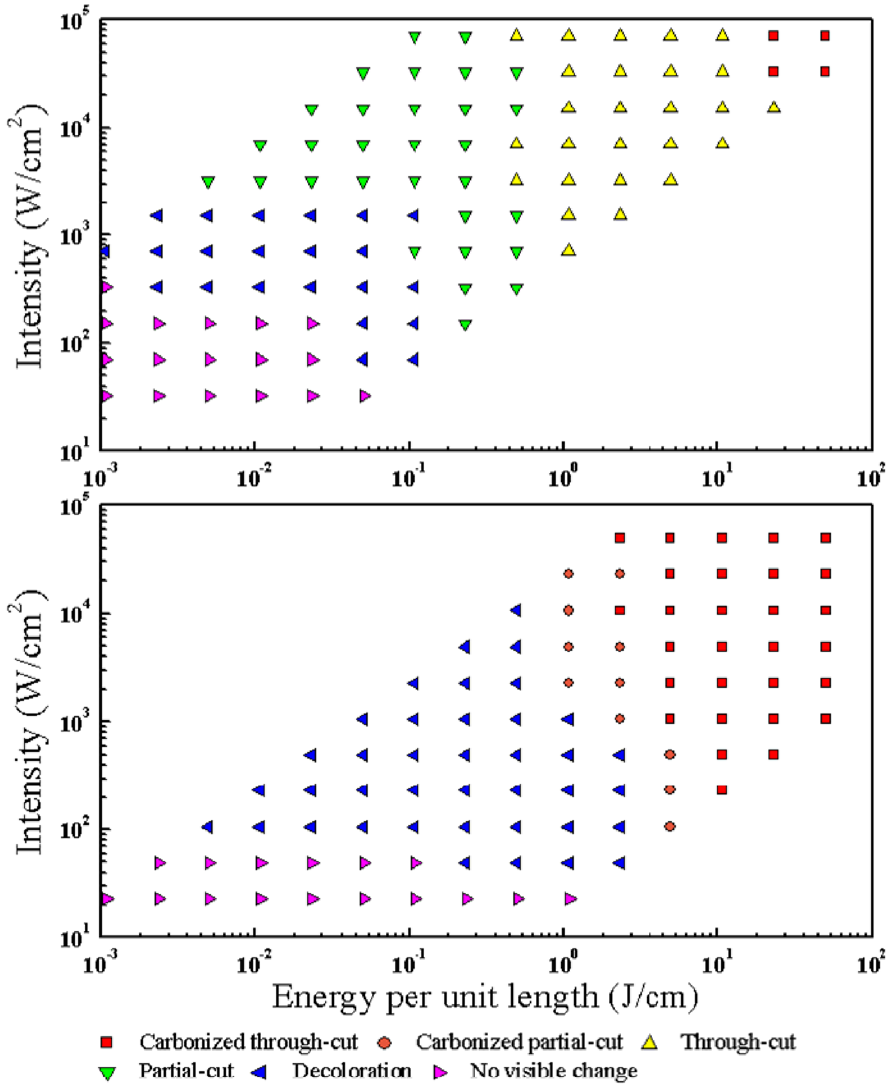


Figure 17. Intensity vs. energy per unit length about 180μm and 1mm beam size. The range of intensity and energy per unit length are same to compare with different beam size. And also it showed that threshold of each response were received energy of incident light

As shown in Figure 16 and Figure 17, we can know that even though beam size is different but involved in same experimental condition, small beam size made through-cut and partial-cut without damage. Large beam size, however, made through-cut and partial-cut with damage. Its finding is believed that the heat affect zone area. Since the heat affect zone area is larger, the amount of water evaporation is also increase. Thus, grass-tissues were received more damage large heat affect zone than small heat affect zone. However, if we neglect the carbonization effect, threshold of each response of 180μm and 1mm beam size experiments is almost same. It means that amount of energy decide to make carbonization as shown in Figure 17. From the Figure 16, we can measure the threshold of each response. And from the Figure 17, we can know that their energy per unit length is different.

Other findings are the slope of results. As shown in Figure 16, 180μm and 1mm beam size has proportional energy transfer to grass-tissues that intensity is quite proportional interaction time. Thus, Figure 16 has almost 45 degree slope and Figure 17 has almost perpendicular slope except of decoloration and no visible change. We believed this reasons that the IR light energy transfer to inside of grass-tissues more than surface of grass since the surface reflectance is smaller than inside reflectance since the water content in grass-tissues. However, this phenomenon is complicated to express, because the grass leaf is not flat and their content position is not homogeneous. Therefore, we know that water dominant case received more energy at once penetrated surface than covered surface of grass leaf. And also its finding can be shown the mechanism of water dominant cases.

2.3.3.Morphological results of CO_2 laser experiment using 180μm and 1mm beam size

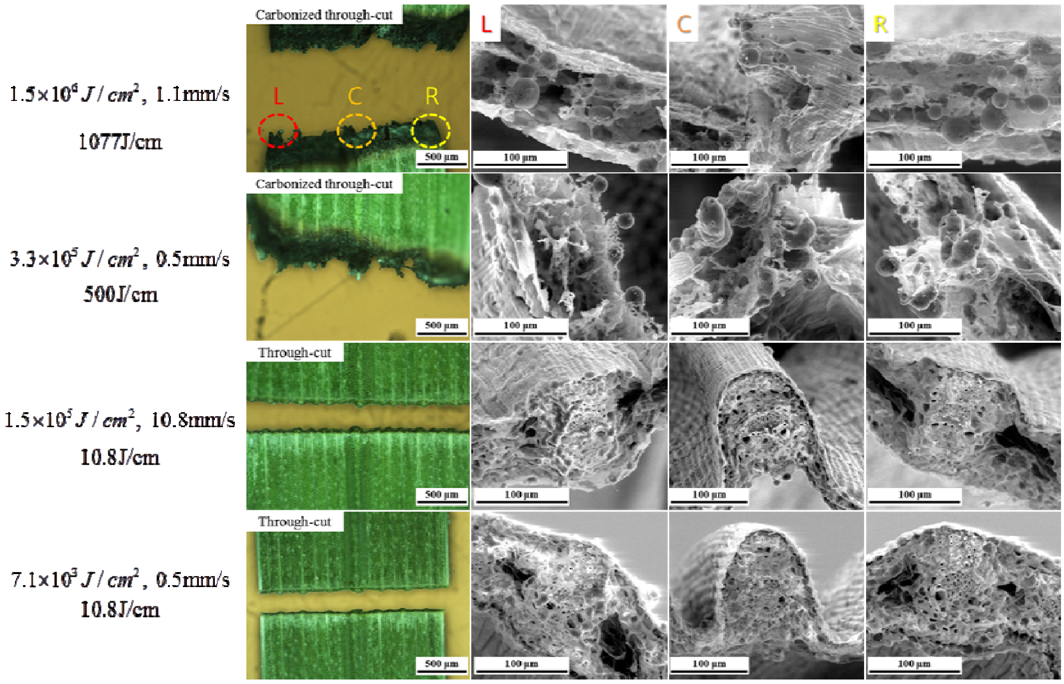


Figure 18. The result of 180um beam size (CO_2 laser). It showed that difference of each response. L is left side blade of grass-leaf , C is center of grass leaf and R is right blade of grass leaf.

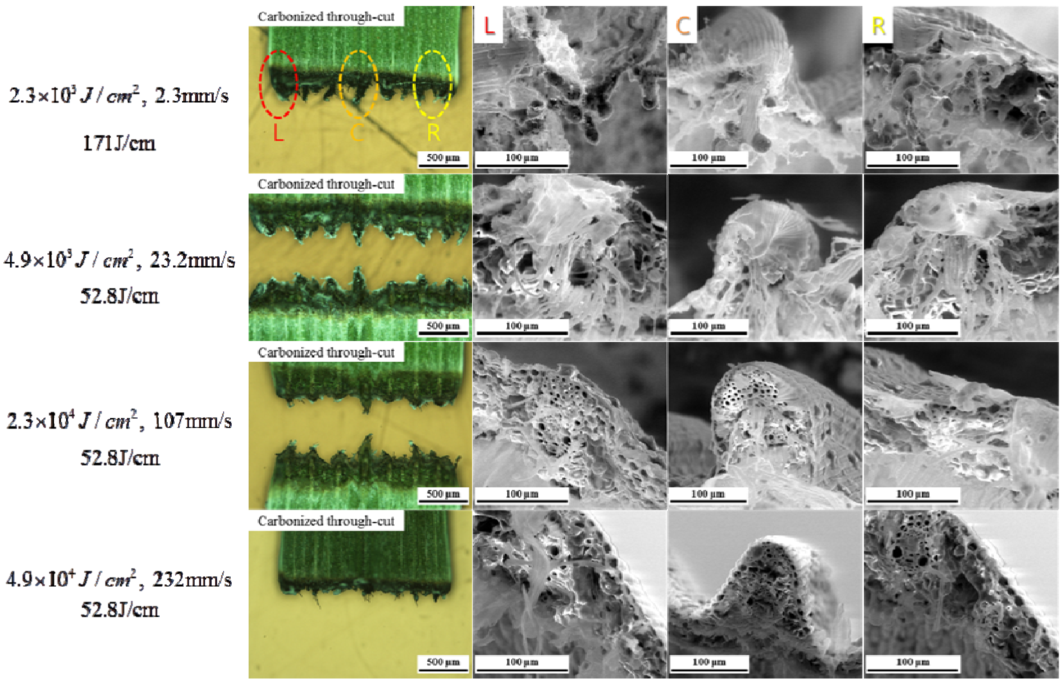


Figure 19. The result of 1mm beam size experiment(CO_2 laser), these results showed that only carbonized responses were occurred even through-cut. It is quite different to 180μm case.

From the morphological results, we can easily understand and distinguish between through-cut without damage and carbonized through-cut. In 180μm case, carbonization and through-cut cross-sectional images are quite different. The carbonization showed some burn mark and has some ashes. As shown in Figure 18, some grain is on the edge of carbonized grass-tissues. Its grain is assumed ashes from huge amount of thermal interaction. And also, ashes grain is also occurred in Figure 19, carbonization images. However, small amount of intensity and interaction time made no ashes grain and its carbonized images (Figure 19. Third row) showed little defected tissues. Therefore, # of grain and grain size depends on the energy per unit length.

Through-cut images in 180μm case indicate no damaged tissues since grass-tissue is porous and no distortion (See Figure 18. through-cut images). However, 1mm case only showed carbonized through-cut which is quite or little damaged grass-tissues as shown in Figure 19. From the results, during carbonized through-cut occurred on grass-tissues, the amount of damage is defined by the amount of energy per unit length. Therefore, the optimum amount of energy per unit length, in other words, optimized intensity of light and interaction-time decide to avoid damage generation.

2.3.4. Er:YAG experimental result (1mm beam size)

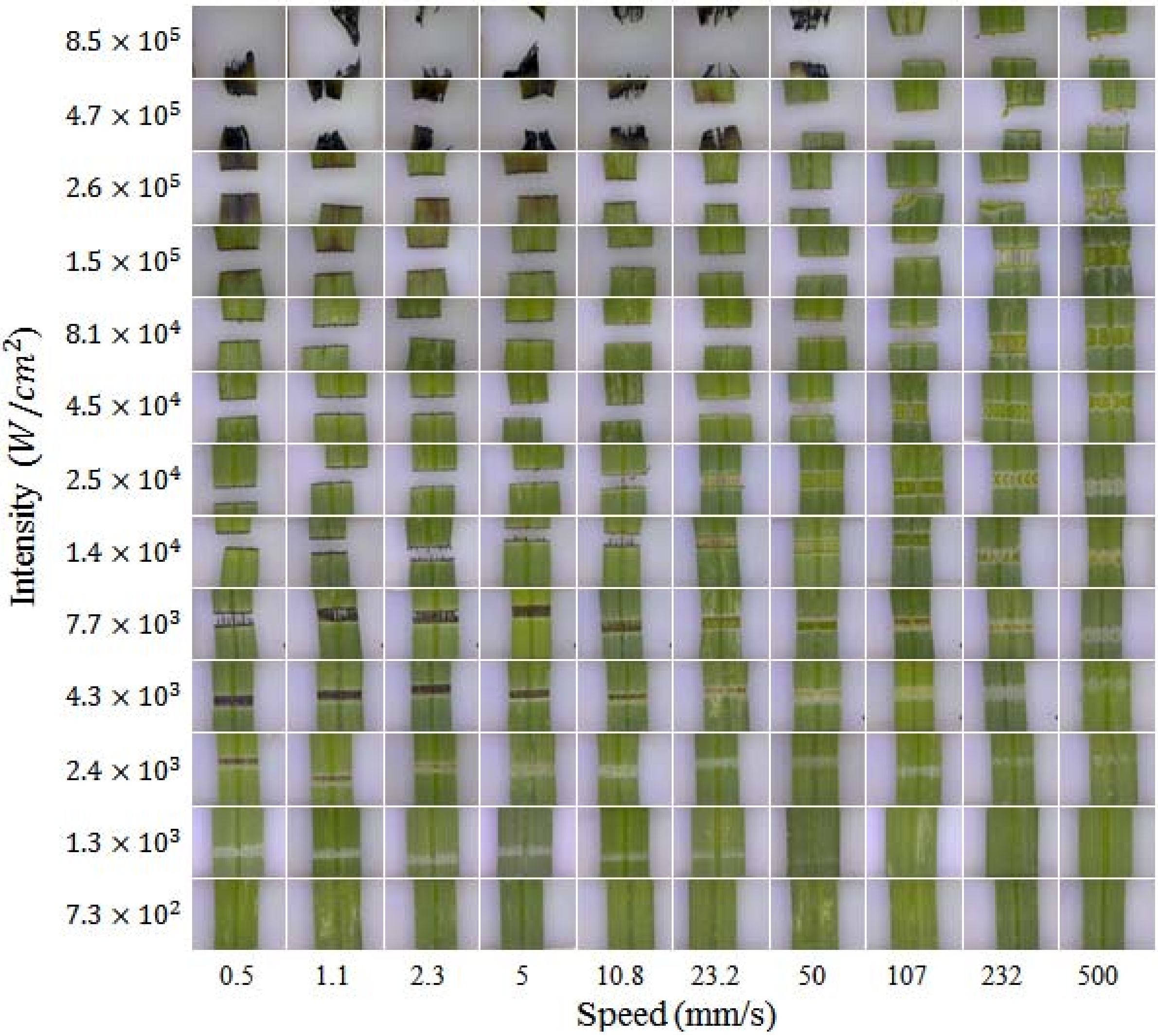
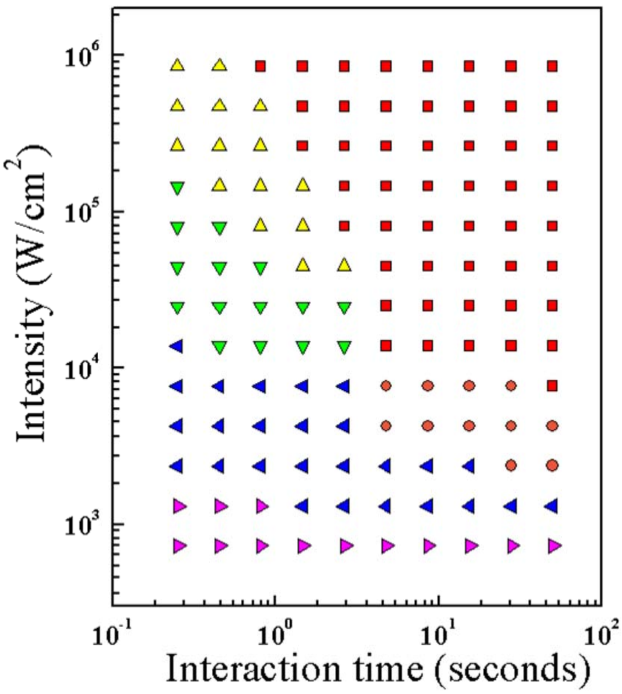


Figure 20. The result of Er:YAG laser, 1mm beam size was conducted this experiment. The image measurement is different from CO_2 laser experimental case, since this experiment conducted other place.

Wavelength (μm)	Repetition rate (Hz)	Pulse duration (us)	Beam size (mm)	Thickness of grass (um)	Absorption coefficient of water (cm^{-1})
2.94 (Er:YAG)	10	300	1	110	12000

Table 9. Er:YAG laser experimental condition



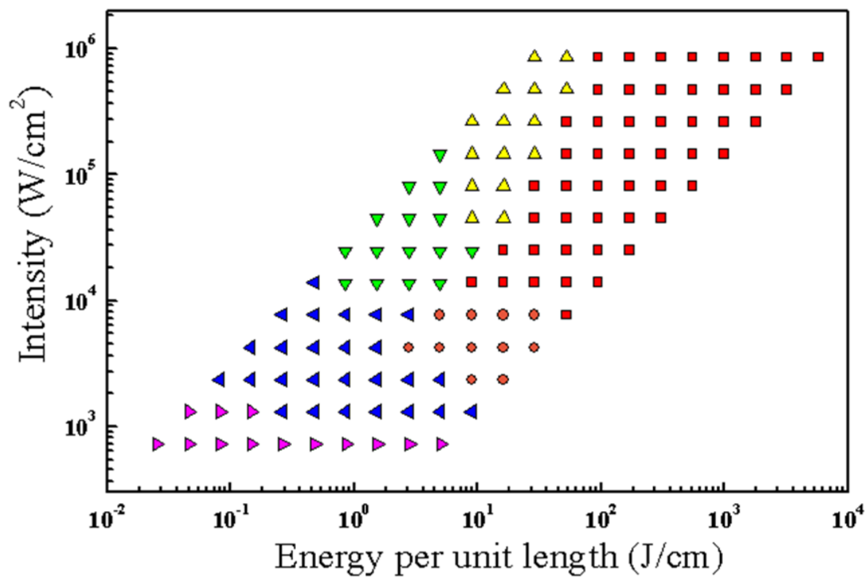


Figure 21. The results of Er:YAG laser, Top plot showed that the intensity with interaction time. Beneath plot showed energy per unit length with intensity of light.Red square: Carbonized through cut, Orange square: Carbonized partial cut, Yellow upper triangle: Through-cut, Green lower triangle: Partial-cut, Blue triangle (left direction): Decoloration and Violet triangle (Right direction): No visible change.

Er:YAG laser 1mm beam size experimental results (Figure 20, 21) are little different from CO_2 laser 1mm beam size experimental results. Experimental condition of Er:YAG laser is described in Table 9. As explained CO_2 laser experiment (beam size 1mm), this results showed only carbonized response except for decoloration and no visible change responses, while Er:YAG laser experiment showed not only carbonized through cut and carbonized partial cut but also through cut and partial cut without damage. Its finding believed that high water absorption coefficient can reduce the damage of grass-tissues. However, Er:YAG laser result showed also carbonized through-cut and carbonized partial cut, its reasons are assumed that the heat affect zone is also large, 1mm beam size, same asCO_2 laser experiment. And also repetition rates of Er:YAG has too low, 10Hz, comparing repetition rates 5000Hz of CO_2 laser. Er:YAG interaction times is too longer than CO_2 laser. Thus results of Er:YAG laser (Figure 21. Top plot) showed that relative long interaction occur only carbonized through-cut and carbonized partial-cut.

Energy per unit length with intensity of light showed same trend of CO_2 laser that partial-cut, through-cut and carbonization is quite perpendicular, decoloration and no visible change is quite horizontal. Reasons are assumed as same that CO_2 laser case since the Er:YAG and CO_2 laser are water dominant cases.

2.3.5. The comparison with Er:YAG and CO_2 laser with same beam size (1mm)

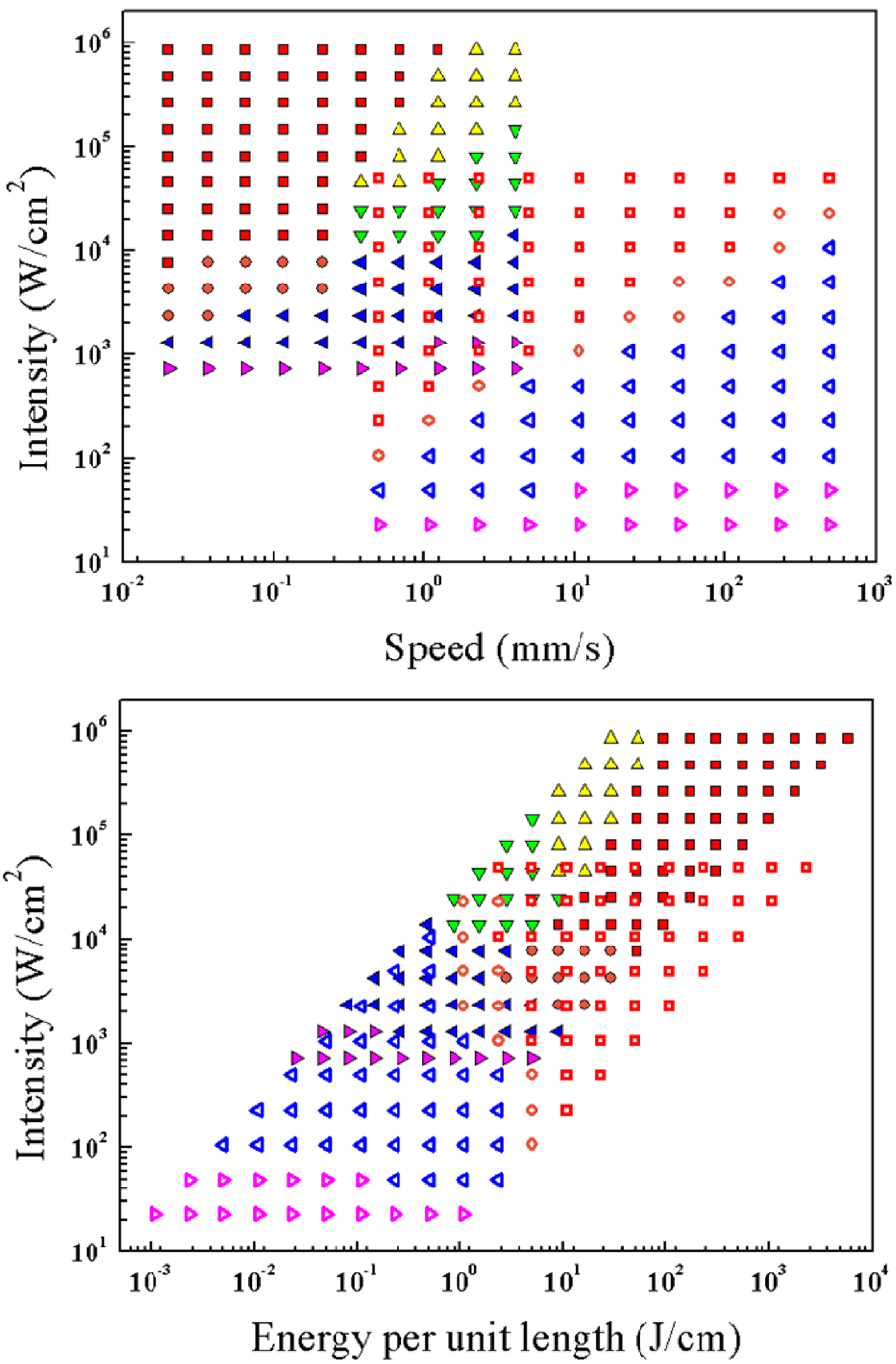


Figure 22. These results were overlapped Er:YAG and CO_2 laser experimental results. It showed the water absorption coefficient effect. As explained before, The Er:YAG laser has more 14 times larger water absorption coefficient than CO_2 laser. (Solid shapes: Er:YAG laser, Squre lines: CO_2 laser)

To compare with Er:YAG and CO_2 laser, each result were overlapped on a plot as shown in Figure 22. Top plot indicated intensity of light with speed. Same intensity and same speed region showed Er:YAG and CO_2 laser responses overlapped. In particular, Er:YAG occurred carbonized partial-cut, decoloration and no visible change, however, CO_2 laser occurred carbonized through-cut and carbonized partial-cut at same region (same experimental condition: intensity of light, speed). At introduction, we expected that Er:YAG laser is more easily energy transfer than CO_2 laser. However, overlapped region showed opposite results. Its reasons assumed that their pulse duration and repetition rate are different. Thus, actual absorbed amount and number of pulses became differently. Therefore, we used energy per unit length (Figure 22). As shown in Figure 22. Energy per unit length with intensity of light showed that Er:YAG laser make less damage than CO_2 laser. However, each response is quite similar. And also Er:YAG laser needs more intensity of light to occur the decoloration and through-cut. Its finding believed that Er:YAG penetration depth is too short.

2.4. CONCLUSION

IR light is water dominant. Water content in grass influences threshold of partial-cut and carbonized through-cut since the water content in grass-changes reflectance of grass surface and carbonization. However, In case of fresh grass-leaf, through-cut threshold is almost same and unaffected seasonal effect. Even though same conditions (intensity and speed), small beam size occur less damage of grass-tissues than large beam size. Therefore carbonization is more affected amount of energy than intensity of light. High water absorption coefficient affect to reduce amount of damage, however, too much high absorption coefficient may makes unnecessary energy consumption. Therefore, optimized input intensity and speed is more dominant factors to avoid amount of damage. And also different water absorption coefficient of IR lights (2.94μm and 10.6μm) has similar threshold. However, response change rate of each wavelength is quite different between 2.94μm and 10.6μm.

Process map of CO_2 and Er:YAG laser had been developed by several experiment, it can be applied manufacturing lawn mowing system. We believed that Er:YAG(2.94μm) laser is suitable for manufacturing lawn mowing system since its energy efficiency is better than CO_2 laser.Therefore, we will develop the laser lawn mowing system. At next Chapter III, we will introduce the concept of laser lawn mowing system and optical system and compare with several lasers.

III. LASER LAWN MOWING SYSTEM

3.1.INTRODUCTION

Laser lawnmower system is control the intensity of light and speed of mower to through-cut grass leaves without carbonization. Through-cut zone is expected from previous results of several wavelength experiments such as 355nm, 532nm, 1064nm, 2.94µm and 10.6µm wavelengths. Because process map for each wavelength is different, its solution can be various. The optimized intensity of light and speed of lawn mower is calculated to conduct through-cut without damage. So, intensity of light and mower speed can be adjustable to keep within cut-well range (from no-cutting edge to onset of carbonization edge). Thus, the control unit will be manufactured by using each process map. The process map of 355nm, 532nm, 1064nm and 10µm wavelength had been found by means separate experiments. For instance, Figure 23is shown schematic of cut-well zone which is estimated from the results of experiments. In Figure 23, linear lines are used as boundary but it will be linear or not. Mower speed is used as x-axis that can be easily changed as interaction time or energy per unit length. In this chapter III, the principle of cutting mechanism and optical-setup will be introduced. Also the prototype of CO_2 laser lawn mower will be manufactured then evaluation of performance will be implemented.

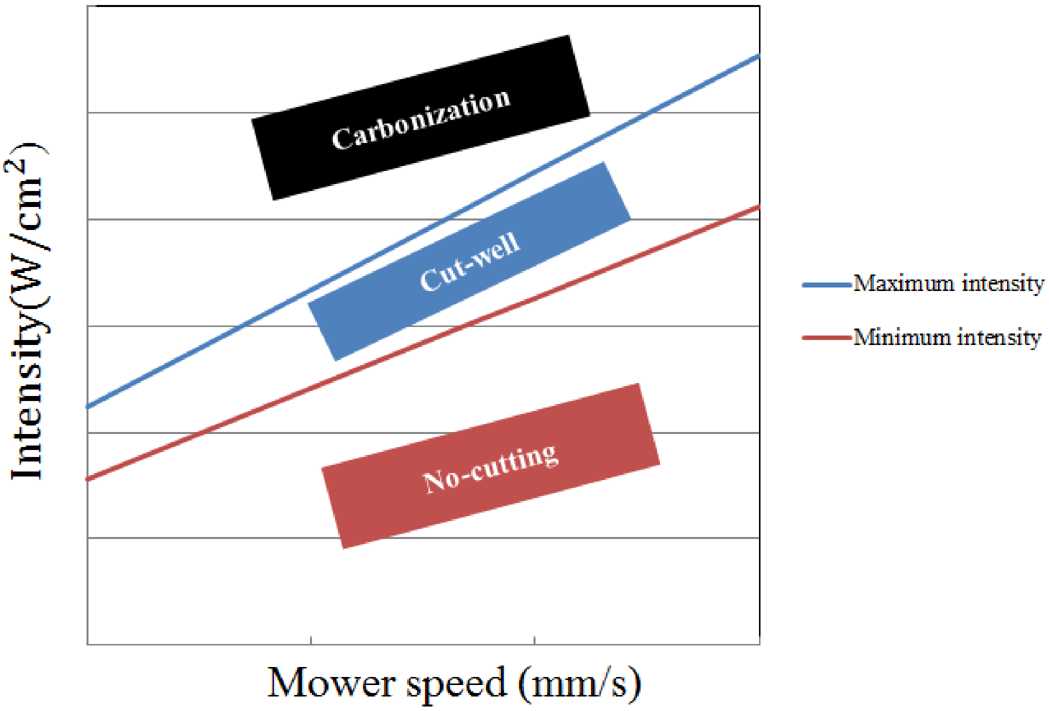


Figure 23. These showed that carbonization, cut-well and no-cutting area. These area can be used in laser lawn mower manufacturing.

3.2. THE CONCEPT OF LASER LAWNMOWING SYSTEM

Laser interaction with grass-tissues will be found by using intensity of laser beam and speed. (Here, intensity of laser beam is power (P) divided by unit area then multiply double in Gaussian beam case.) Thus, process map of optimized range (cut-well) also will be developed. And process map can be changed by type of laser (pulse duration, wavelength), type of grass and environmental condition (temperature, humidity, season, state of grass and so on). Speed of laser mower is calculated by wheel speed sensor. Since lasers interact well with water and chlorophyll in grass,manufacturing of laser lawn mower is considered that absorptivity of water and chlorophyll changes dramatically depending on wavelengths. Particularly, laser in Infrared (IR) wavelength regime can almost amount of energy transfer towater. 2.94μm wavelength has advantage for manufacturing laser lawnmower since the 2.94μm is the high water absorption coefficient in IR ranges. Moreover, 10.6μm is also favorable because it has also high water absorption coefficient but it is smaller than 2.94μm wavelength.The water composition in grass will be considered that is normally 70%, but composition can be changed depending on season. Depending on type of laser, characteristic of beam divergence is different during beam radiation. So, intensity of beam has to keep within optimized through-cut zone (cut-well range). And also focusing lens or favorable optics can be used to make suitable cutting-length. To secure the safety, dump can be installed at end of beam path to block leaking beam. Finally, control unit will be installed as following functions to utilize optimized process depending on type of laser, speed of lawnmower and optical-setup.

▪ Calculate optimized intensity of beam and lawnmower speed to keep within through-cut zone.

▪ Adjust optical system and beam size to keep the optimized process on the beam path during changing the process condition.

▪ Find through-cut zone depending on type of laser, type of grass and environmental condition (temperature, humidity, season and state of grass).

Expected advantages using laser lawn mower are below.

▪ Laser lawn mower is quiet, safety and little pollution since laser lawn mower has no rotate blade and no engine.

▪ As shown in Figure 24andFigure 25, laser lawn mowing systems can be manufactured as two types of electrical system such as plug and battery types. And also small electrical capacity can be used to utilize laser lawn mower since the energy consumption of laser lawn mower is much smaller than mechanical mower (using engine and rotate blade).

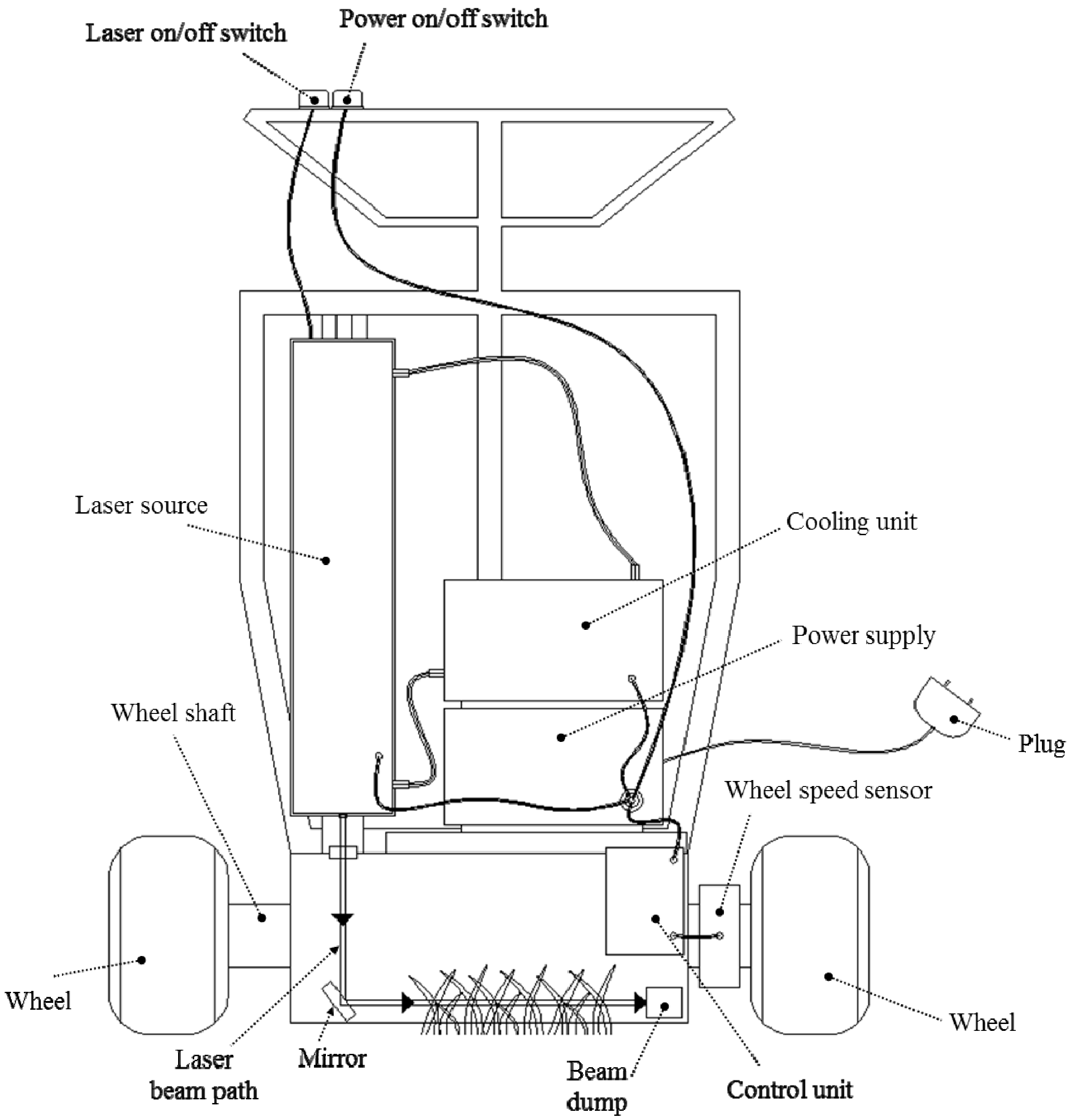


Figure 24. Schematic of laser lawn mowing system (using electrical plug)

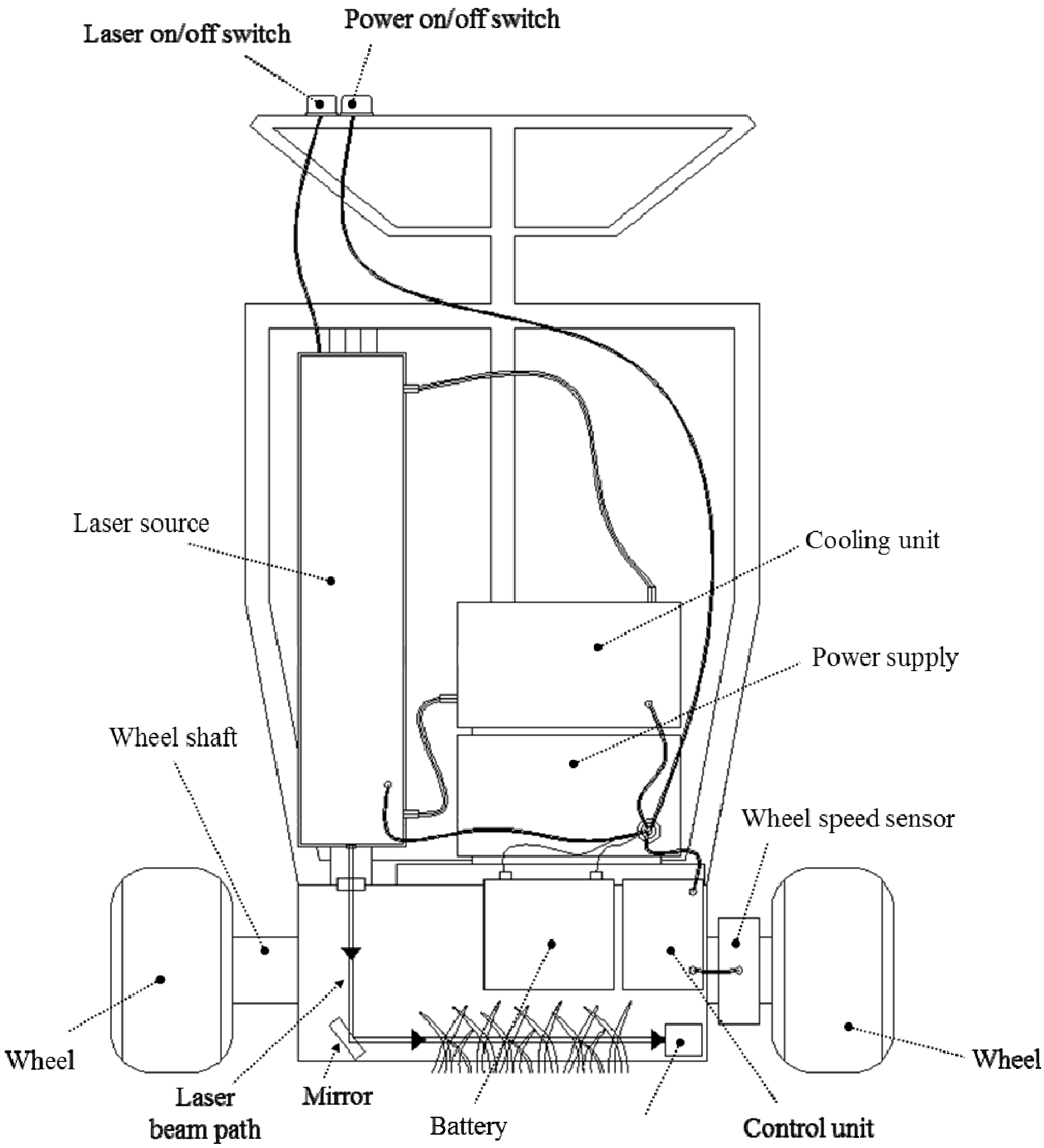


Figure 25. Schematic of laser lawn mowing system (using battery)

3.3. DESIGN FOR OPTICS

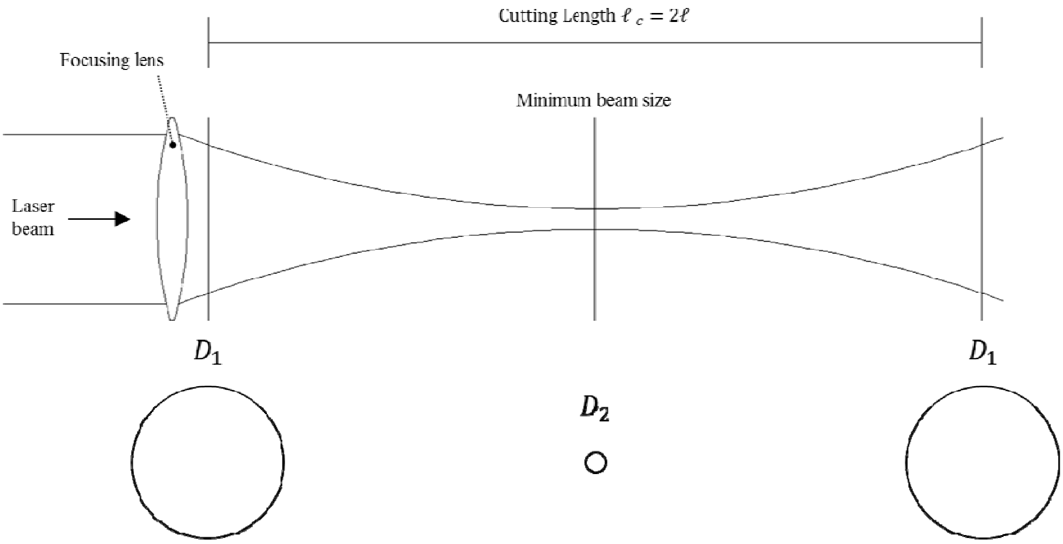


Figure 26.Schematic of variation in beam size during laser beam irradiation.

A laser beam progress is no parallel and its cross-sectional diameter of a laser beam is changed as shown in Figure 26(D1 to D2). Therefore, once the output power of a laser is consistent then intensity of a laser beam, power per unit area, will increase (D1 to D2) and decrease (D2 to D1). Even same output power of a laser, too small beam size can cause much high intensity, thus carbonization can be caused on grass-tissues, however, too larger beam size can make much low intensity, thus grass-cut can't be generated. Therefore, to manufacture the laser lawn mower, the intensity of a laser beam has to within through-cut zone during changing the beam size. And also as shown in Figure 26, if a laser beam is progressing and possible cutting length is 2ℓ, maxima beam size D1 and minima beam size D2 must be adjustable to cut well properly the grass in range of possible cutting length. Furthermore, these values (beam size, focal length, wavelength and so on.) are changed depending on the wavelengths of laser. If the laser beam profile is Gaussian and focal length is 2ℓ, a below equation must be satisfied.

$$\ell = \frac{D_1 D_2}{4}\frac{\pi}{\lambda} \qquad (1.6)$$

And also, output power of a laser beam is related the intensity and beam size (D) of a laser as following equation.

$$P = \frac{\pi}{8} D^2 I \qquad (1.7)$$

From equation 1.7 and 1.8, abelow equation can be obtained.

$$\ell = \frac{2P}{\lambda\sqrt{I_1 I_2}} \tag{1.8}$$

Therefore, the output power of a laser and optical setup are calculated to keepthe cut-well zone by using equation 1.7, 1.8 and 1.9. And also its functions are charged of control unit. Optimized solutions are not only one that can be various.

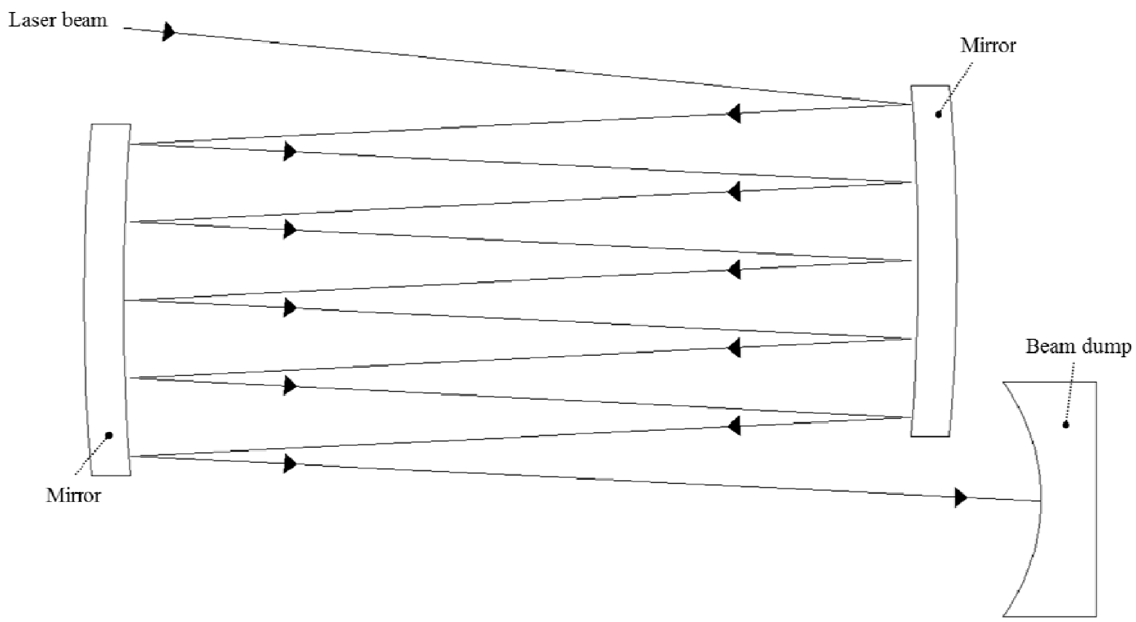


Figure 27. Schematic of basic optical setup

Optical setup can be various types depending on characteristics of a laser (wavelength and output power). Ifthe beam divergence angle is very small and possible cutting length is long, a one exposed beam can be used several times by using both side mirrors as show inFigure 27. Furthermore, beam dump can be installed to prevent leaking beam caused by beam divergence. However, if possible cutting length is shorter than 2ℓ in Figure 26, focusing lens can be installed in beam path to expand cutting length as drawn inFigure 28.In this case, beam size should be changed between D1 and D2 to progress in range of cutting length.

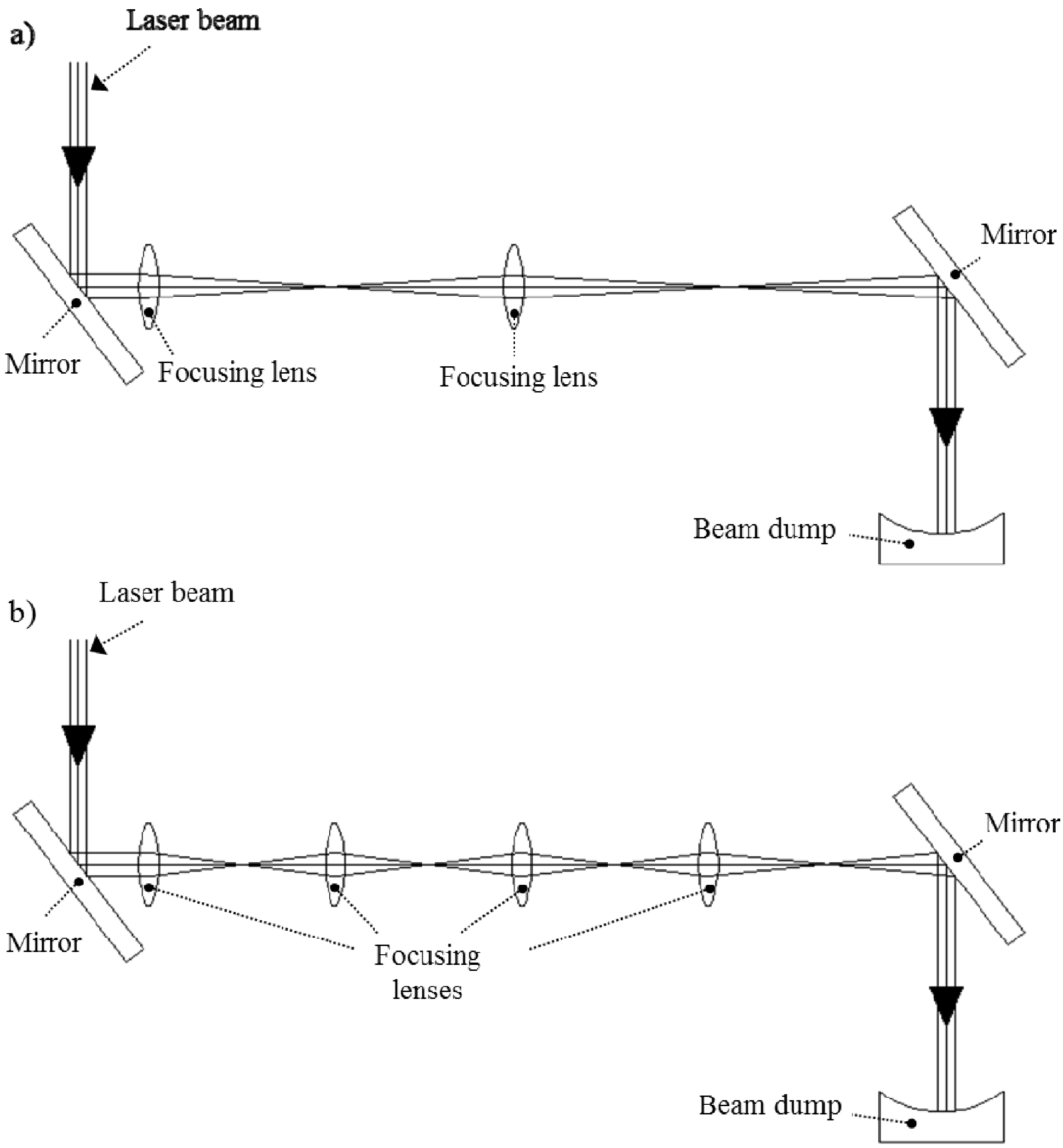


Figure 28.Schematic of method for cutting length expansion (a long wavelength laser as CO_2 laser can use this way.).

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