# Longitudinally Excited $CO_2$ Laser

Kazuyuki Uno

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## 1. Introduction

In the mid-infrared region (3 – 30 μm), there are only several kinds of commercial laser as shown in Fig. 1. A $CO_2$ laser is very important because the $CO_2$ laser emits high output energy and various pulse shapes at the wavelength region between 9.2 μm and 11.4 μm with a high absorptivity in many substances. The first $CO_2$ laser was developed by C. K. N. Patel in 1964 and had a continuous output power of a few milliwatts (Patel, 1964). In 1968, the pulsed $CO_2$ laser was developed by A. E. Hill and had a few joules (Hill, 1968). Nowadays, various types of $CO_2$ lasers have been developed. The characteristics of $CO_2$ laser pulses are determined by the discharge tube structure (a longitudinal excitation scheme like Fig. 2 (a) or a transversal excitation scheme like Fig. 2 (b)), the discharge types (DC discharge, RF discharge, or pulsed discharge) and the oscillation system (CW oscillation, Q-switched oscillation, or pulsed oscillation).

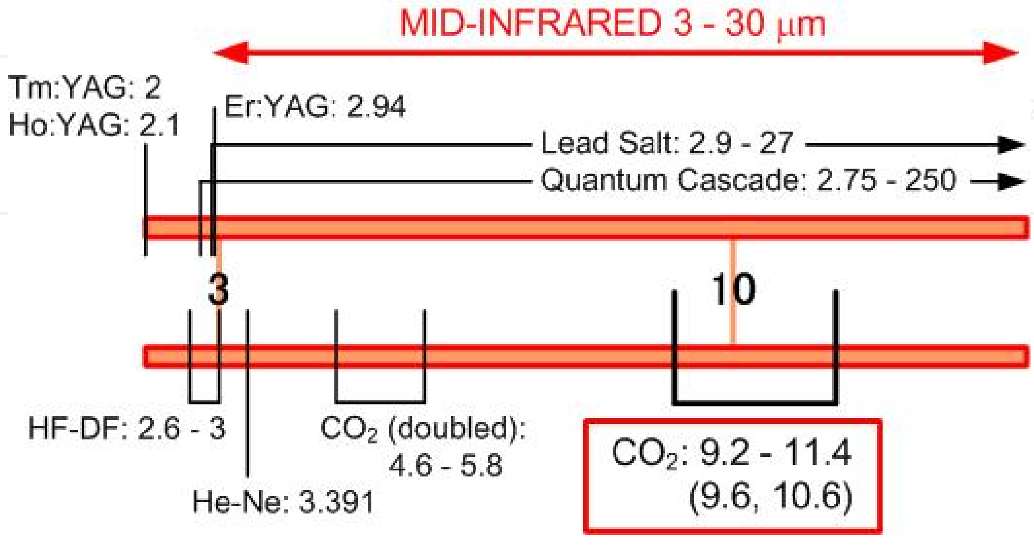
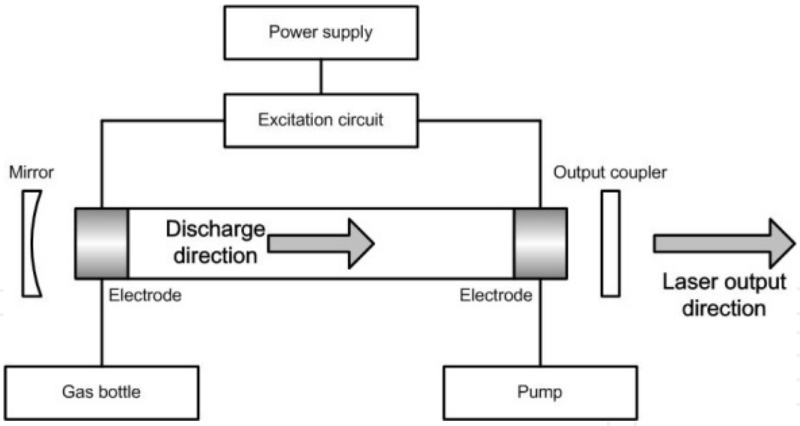
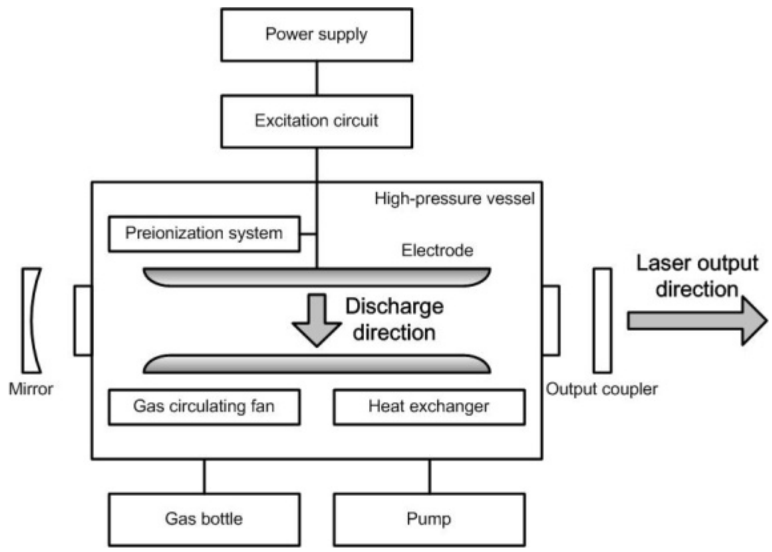



**Figure 1.** Mid-infrared commercial lasers (Photonics.com). Unit is μm.




(a)




(b)

**Figure 2.** Excitation system. (a) Longitudinal excitation system. (b) Transversal excitation system.

In the CW oscillation and the long pulse oscillation (a pulse width of 10 μs – 10 ms), a low power $CO_2$ laser (< 10W) is used as a medical laser like tooth and skin treatments. A $CO_2$ laser emitted 20 – 100 W is used for cutting a nonmetallic substance like a film, cloth, leather, paper, rubber, a plastic, acrylics, etc. A high power laser emitted 100 – 400 W is used for cutting metal, glass, and ceramics. A short pulse $CO_2$ laser that emits an output energy of a few joules and a pulse width of about 100 ns is used for puncturing and patterning of a nonmetallic substance, removal of surface polymer material which does not give a damage to a metal board, and etc. Specially, a large and high output $CO_2$ laser called "Lekko VIII" that emitted an output energy of 10 kJ and a pulse width of 1 ns was developed in Institute of Laser Engineering, Osaka University, Japan, 1981 (Yamanaka et al, 1981). Recently, the $CO_2$ laser attracts attention as a driver laser for a Laser-Produced-Plasma Sn-EUV source (13.5 nm) and a excitation laser for a Terahertz laser ($CH_3F$, $C_2H_2Cl$, $CH_3OH$, $D_2O$, and etc., 30 – 300 μm) (Ueno et al, 2007; He et al, 2010).

## 2. Principle of $CO_2$ laser

The $CO_2$ laser oscillates in the vibrational level of $CO_2$ molecular. The $CO_2$ laser has about 100 oscillation lines at the center of 9.6 µm and 10.6 µm between 9.2 µm and 11.4 µm. Fig. 3 shows the energy diagram of $CO_2$ laser. Generally, the $CO_2$ laser is pumped by glow discharge in the low mixed gas ($CO_2$, $N_2$, He, and etc.) pressure. The $N_2$ serves to improve the output energy and the efficiency due to the energy transfer from the vibrational level of $N_2$ to the upper laser level of $CO_2$. However, in the short pulse oscillation, $N_2$ causes a laser pulse tail because of the long lifetime of the vibrational level of $N_2$. The He serves to make the discharge uniform. The $CO_2$ molecular is efficiently pumped by very low electron temperature because the energy of the laser upper level 001 is 2349.2 $cm^{-1}$ and the energy required for excitation of $CO_2$ molecule is about 0.28 eV. However, generally, the $CO_2$ molecular pumped by the higher electron temperature than 0.28 eV because of an electrical gradient to sustain the discharge. The $CO_2$ laser oscillates at 10.6 µm band (001 – 100 transition) and 9.6 µm band (001 – 020 transition) and has about 100 oscillation lines because of the P branch and the R branch related to the rotational level. The laser lower levels of 100 and 020 are relaxed by the collision with the $CO_2$ molecule of ground state. The 010 level serves as a bottleneck. But the thermal relaxation of the 010 level is accelerated by the collision with other molecular, He atom and the laser tube wall. Then, the 010 level returns to the ground state. Therefore, in the efficiently laser oscillation, the $N_2$ molecular that supplies the upper laser level of $CO_2$ and media like He that eases the lower laser level of $CO_2$ are essential. However, in the low-pressure pulse-discharge at the low repetitive operation, He may be unnecessary.

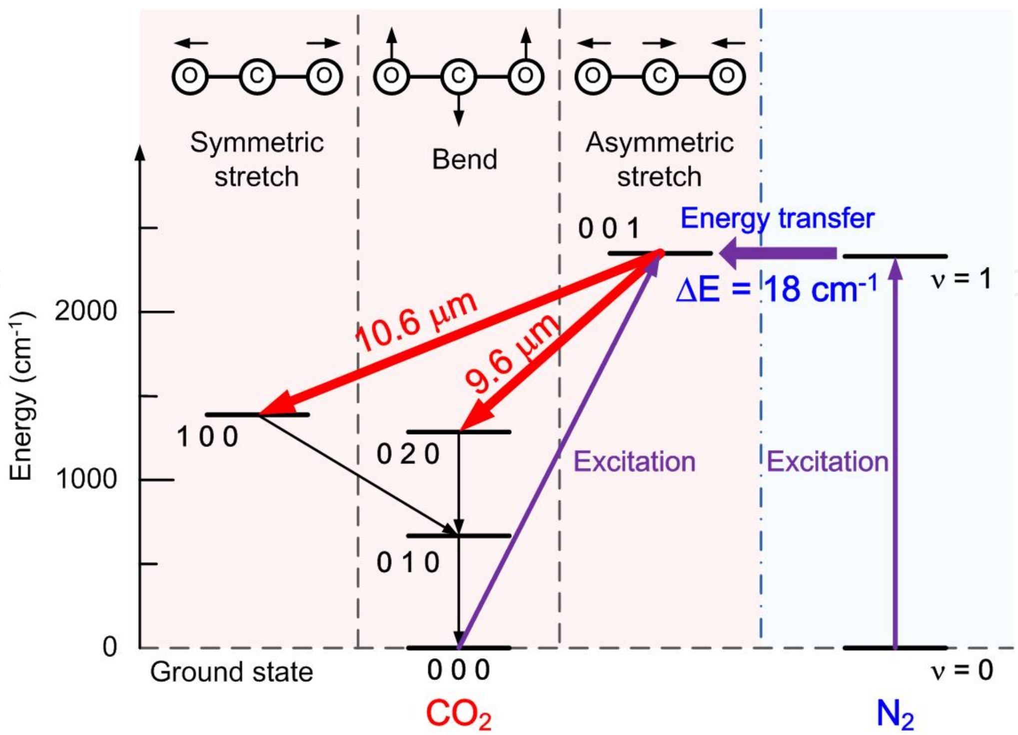



**Figure 3.** Energy diagram of $CO_2$ laser.

## 3. Longitudinal excitation scheme

In the longitudinal excitation scheme, the excitation discharge is in the direction of the laser axis. This system was used in the early stage of development of lasers such He-Ne lasers (633 nm), $N_2$ lasers (337 nm) and $CO_2$ laser (9.2 – 11.4 µm). In this system, a dielectric tube with the small inner diameter (1 – 2 cm in $CO_2$ lasers) and the long length (> 30 cm in $CO_2$ laser) is used as a discharge tube. Metallic electrodes are attached to each end of the tube. The long discharge length provides a high breakdown voltage (> 20 kV) at a low gas pressure (< 10 kPa). Therefore, this system does not require a high gas-pressure vessel. Moreover, this laser may oscillate at narrow spectral width because the low-pressure operation produces the small pressure broadening. A uniform discharge can be obtained easily because of the fast electron drift velocity (the long mean free path) of the low pressure operation; additionally, the discharge uniformity is not affected by residual charges in the longitudinal excitation because a discharge takes place in a discharge tube with a long length and small inner diameter. In a RF discharge, an electronic trapping occurs. A uniform discharge takes place because electrons vibrate by the high-frequency electric field and are trapped between the discharge gaps. In a pulsed discharge, a uniform discharge takes place by a diffuse streamer discharge is formed by diffusing uniformly and progressing the minute spark discharge with which an avalanche and optical ionization are combined (Fig. 4).

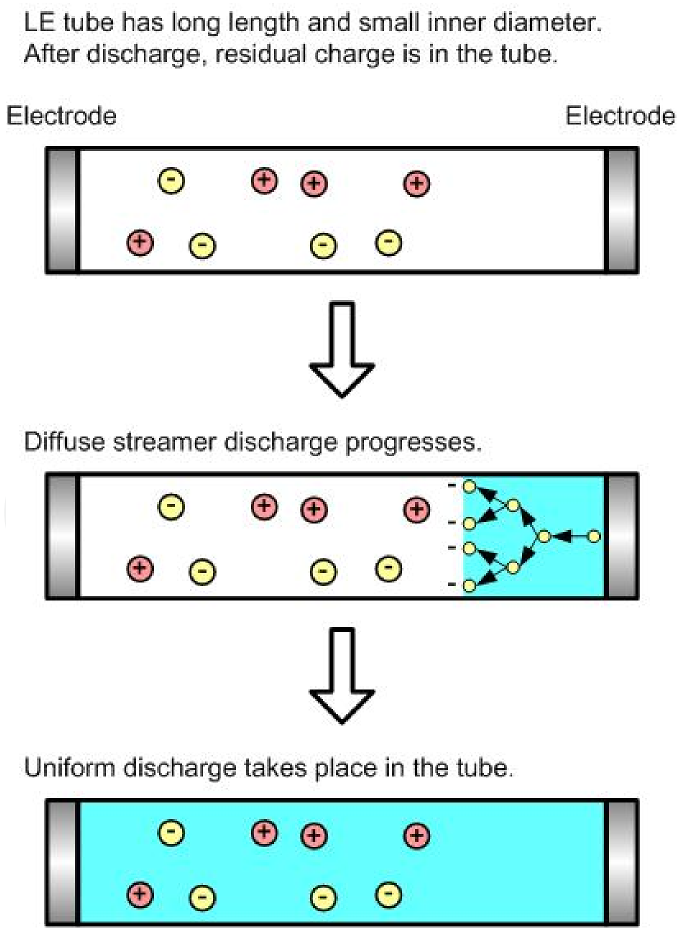



**Figure 4.** Longitudinally pulsed discharge.

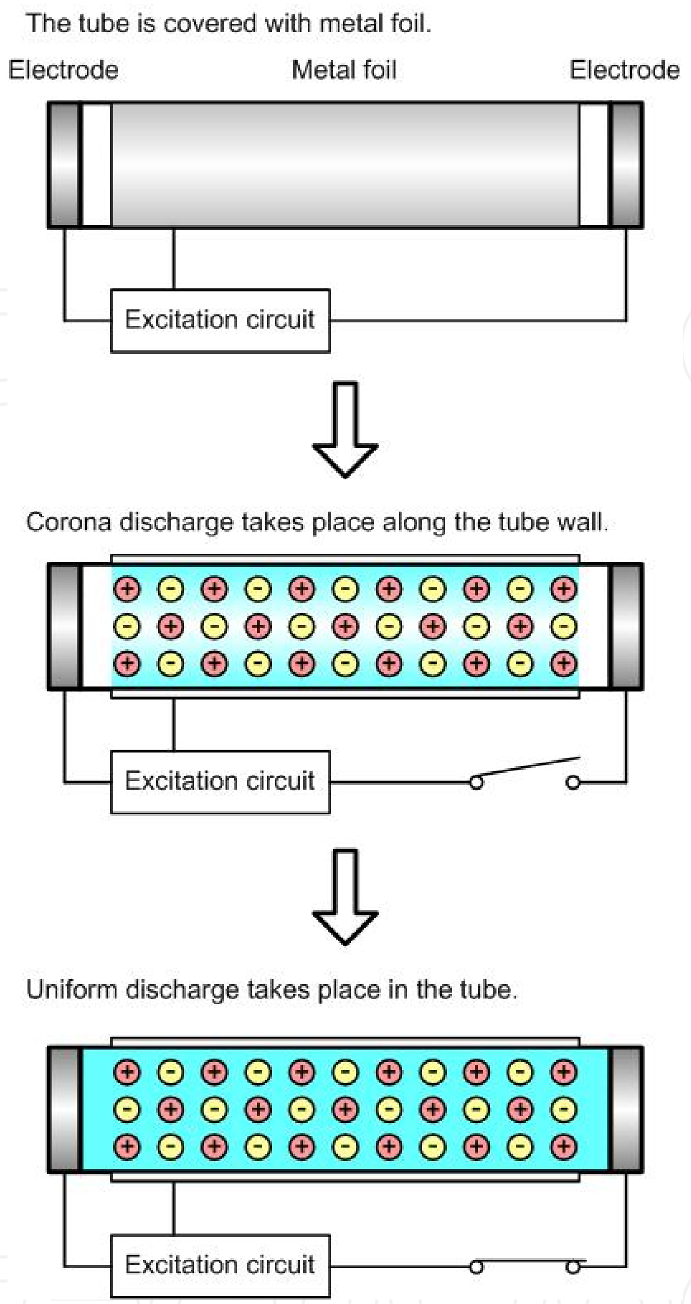



**Figure 5.** Longitudinally pulsed discharge with strong preionization.

Therefore, the longitudinal excitation scheme does not require a pre-ionization device like UV and X-ray source. On the other hand, when the pre-ionization is required in the high-pressure operation (> 1 atm), the discharge tube is covered with Al foil (Fig. 5, 6) (El-Osealy et al, 2002b; Uno et al, 2009; Uno et al, 2012a). A corona discharge occurs along the tube wall before the main discharge to serve as pre-ionization. Therefore, nothing is put in the discharge tube. In the longitudinal excitation scheme without pre-ionization, a gas lifetime is long. The gas lifetime is a phenomenon in which the laser output energy decreases with operation time in a sealed-off operation. Impurities increases with time in the discharge tube, UV and X-ray for the pre-ionization cannot reach the center part of the discharge space, the uniform discharge cannot take place, the localization of the discharge occurs, and

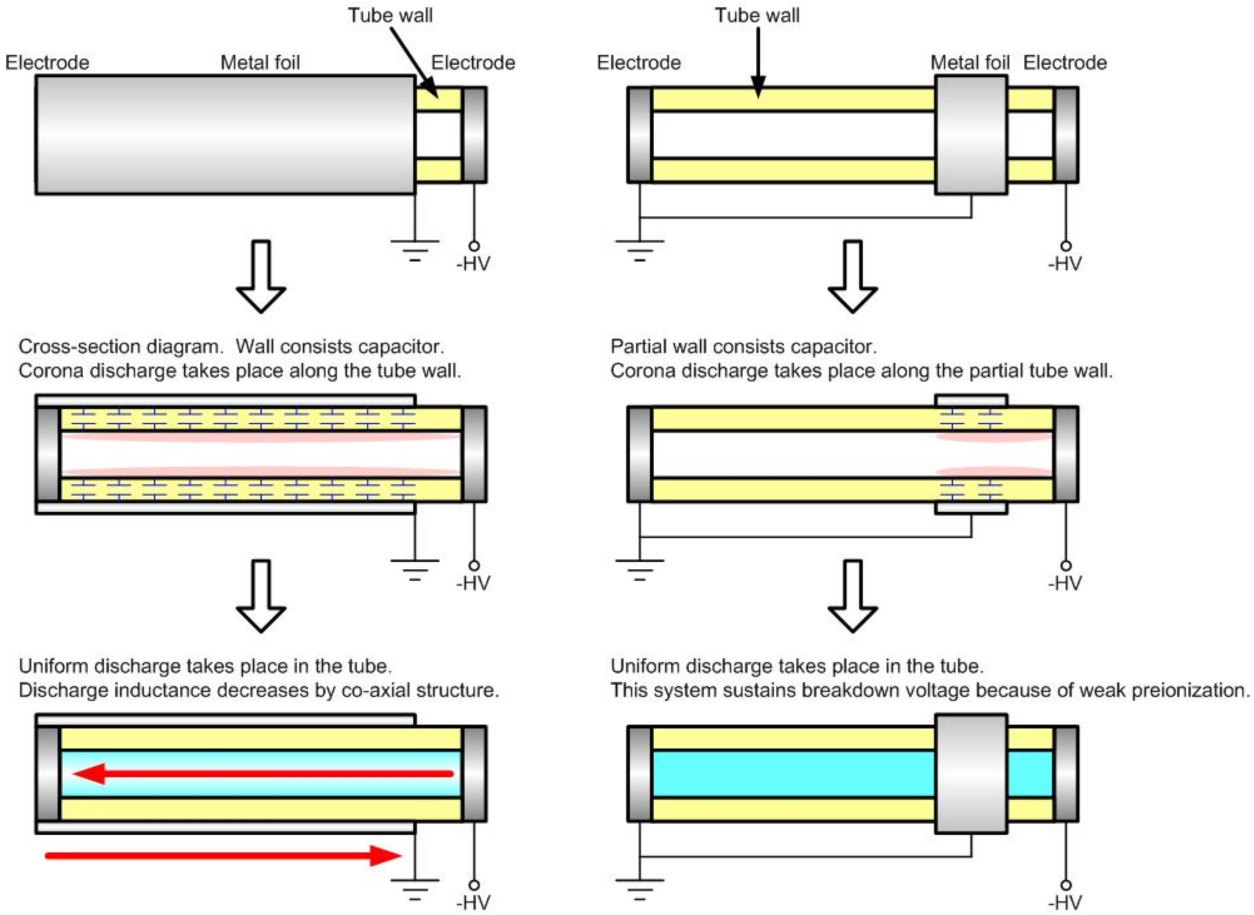



**Figure 6.** Longitudinally pulsed discharge with simple preionization.

the laser output energy decreases. Therefore, this scheme without the pre-ionization is suitable for the long lifetime operation. Additionally, in this scheme, the perfect hard-sealed discharge tube without a gasket packing like a rubber O-ring is producible because the structure of the discharge tube is simple. Therefore, this scheme is suitable for the long lifetime gas laser. In fact, a low-output sealed-off $CO_2$ laser has a CW oscillation or a high repetition oscillation without a gas-flowing system and water-cooling system effectively. Additionally, in this scheme, the beam section of the laser is circular because the discharge tube is used a dielectric tube like a glass tube and a ceramics tube. All the optical elements may be circular. This scheme produces laser beam with good beam quality because the length of optical cavity is long enough to the diameter of aperture (the inner diameter of the discharge tube). Therefore, in the longitudinal excitation scheme, a high performance laser can be developed with a simple, portable, and low-cost device.

In the longitudinal excitation scheme, as shown in Table 1, various laser oscillation from mid-infrared to vacuum ultraviolet has been reported. In recent years, especially, new gas lasers, for example, a longitudinally excited $CO_2$ laser with short laser pulse like TEA and Q-switched $CO_2$ laser (Uno et al, 2009), a longitudinally excited $N_2$ laser with the same excitation system as an excimer lamp (Uno et al, 2006), and a longitudinally excited $F_2$ laser at low-pressure (total pressure of 40 Torr) (El-Osealy et al, 2002b) have been developed.

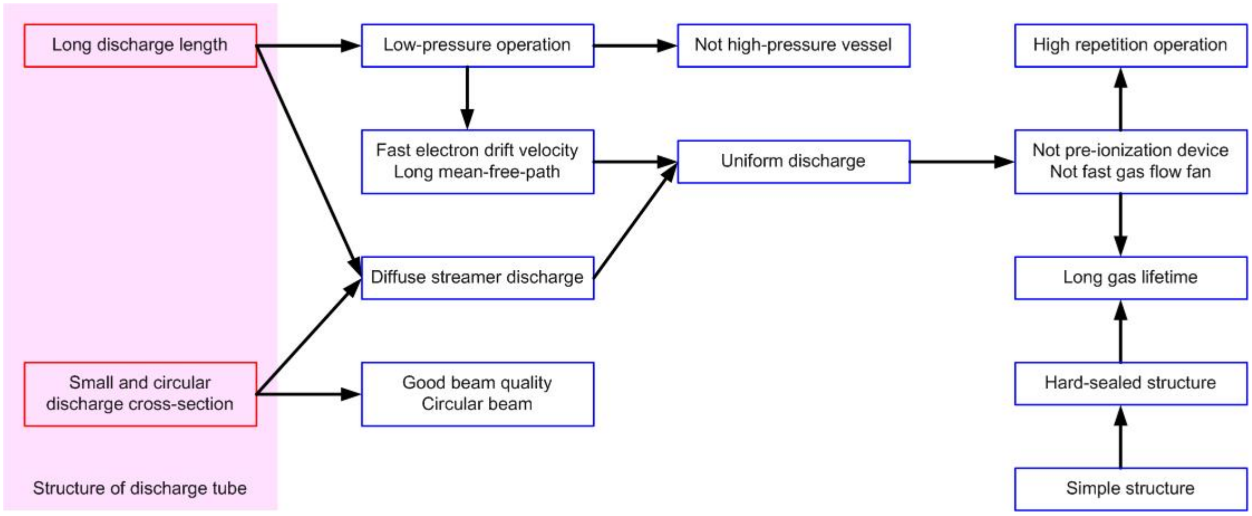



**Figure 7.** Characteristics of longitudinal excitation system.

| Laser | Wavelength | | Example of reference |
|---|---|---|---|
| $CO_2$ laser | Mid-infrared | 9.2 – 11.4 μm | Patel, 1964; Hill, 1968; Chung et al, 2002; Uno et al, 2009 |
| Xe laser | Near-infrared | 1.73 – 3.51 μm | Komatsu et al, 1991 |
| F laser | Visible | 630 – 780 nm | Hocker & Phi, 1976; Uno et al, 2008 |
| He-Ne laser | | 544, 594, 612, 633 nm | Javan et al, 1961 |
| XeF laser | Ultraviolet | 351 nm | Burkhard et al, 1981; Cleeschinsky et al, 1981 |
| $N_2$ laser | | 337 nm | El-Osealy et al, 2001; Uno et al, 2006; Uno et al, 2008 |
| XeCl laser | | 308 nm | Zhou et al, 1983; Furuhashi et al, 1987 |
| KrF laser | | 248 nm | Newman, 1978; Eichler et al, 1985 |
| ArF laser | Vacuum-ultraviolet | 193 nm | Rosa et al, 1986 |
| $F_2$ laser | | 157 nm | El-Osealy et al, 2002a El-Osealy et al, 2002b |

**Table 1.** Longitudinally excited gas lasers.

## 4. Excitation system

The shape of laser pulse depends on the discharge and oscillation types. The discharge type can be divided into the DC (direct current) discharge, the RF (radio frequency) discharge and the pulsed discharge. The oscillation type can be grouped into the CW (continuous wave) oscillation and the pulsed oscillation including Q-switched oscillation. The DC and RF discharge provides the CW oscillation basically and can provide the long-pulsed oscillation (the pulse width from several μs to several ms) by switching of excitation discharge and the short-pulsed (giant-pulsed) oscillation (the pulse width of about 100 ns) by using Q switch. Although it is well known the pulsed discharge provides the long-pulsed oscillation, the pulsed discharge can provide the short-pulsed oscillation (the pulse width of about 100 ns and the pulse tail of several tens μs) like the Q-switched $CO_2$ laser and a TEA-$CO_2$ laser.

### 4.1. DC discharge

Figure 8 shows a general longitudinally excited $CO_2$ laser pumped by DC discharge. The DC-$CO_2$ laser commonly is used a high-voltage (a few tens kV) DC power supply and emits the CW power of several tens kW. The output power can control delicately by adjustment of DC voltage.

A discharge tube is made of a heat-resistant hard glass pipe with an inner diameter of several mm and is the co-axial dual structure for cooling by water. Cooling improves the efficiency and output power of the laser oscillation by decreasing the plasma temperature. Additionally, high output power can be provided by a multi-path system folding back the optical path in the resonator and a multi-beam system which uses multi-tubes. High power DC-$CO_2$ laser emitting CW power of 1 kW using 20 discharge tubes with the inner diameter of 9 mm and the length of 195 cm has been reported (Deshmukh & Rajagopalan, 2003).

A low power $CO_2$ laser can operate in a sealed-off mode. In a long-life sealed-off $CO_2$ laser, a gold catalyst is used to regenerate $CO_2$ from the dissociation products formed during discharge (Tripathi et al, 1994). In the sealed-off $CO_2$ laser, the laser beam (output power and beam quality) is stable because discharge and the distribution of particles are uniform. In a high power $CO_2$ laser, a gas-flowing system circulating fresh gas is used for preventing the decrease of the oscillation efficiency by the deterioration of gas. The longitudinal excitation system has only an axially flowing type.

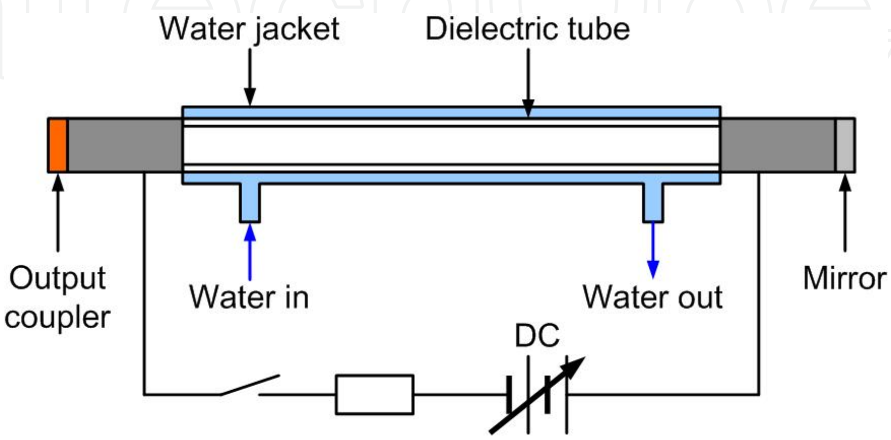



**Figure 8.** Discharge tube with water jacket.

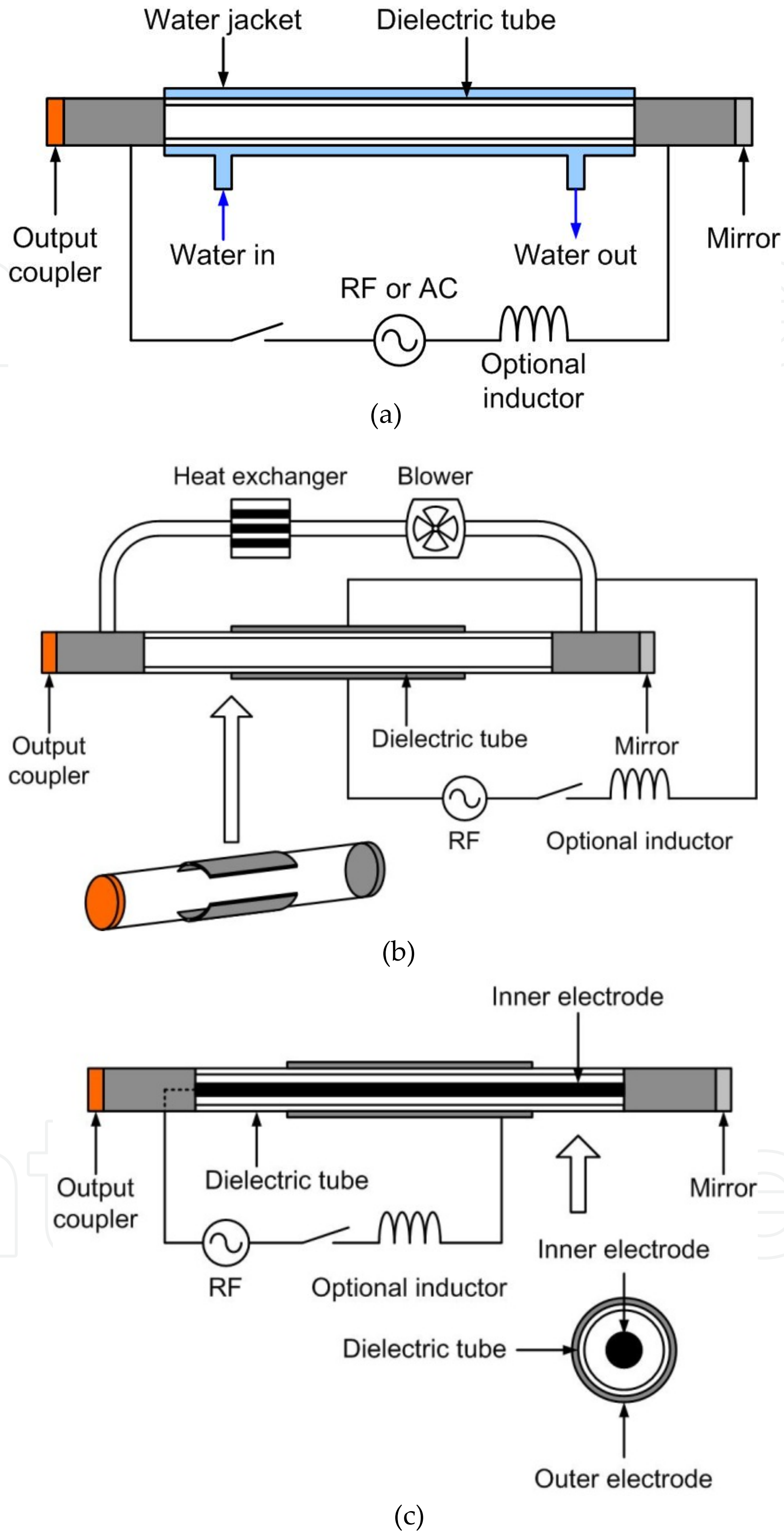



**Figure 9.** RF discharge tube. (a) Longitudinal excitation (Lee et al, 2000). (b) Transverse excitation (Terai et al, 1993). (c) Coaxial RF-$CO_2$ laser (Bethel, 1998).

## 4.2. RF discharge

The first $CO_2$ laser by C. K. N. Patel used the RF discharge excitation, 27 MC/s (Patel, 1964). In the RF discharge excitation, the medium gas is pumped by a high-frequency voltage (typically 13.56 MHz). In this system, electrodes are able to be put on the outer wall of discharge tube. Thus, the electrodes are not sputtered and there are little degradation of gas and contamination of optical components. A compact high-output $CO_2$ laser can be developed by high discharge input-energy per unit volume. An electronic trapping provides good pulse characteristics.

However, generally, the RF discharge excitation scheme uses the discharge tube like Fig. 9. Fig. 9 (b) looks like the longitudinal excitation scheme, but is the transversal excitation scheme because the direction of discharge is perpendicular to the direction of a laser axis.

In the low pressure region less than 10 kPa, the laser pumped by RF wave more than 0.1 MHz emits CW and the laser pumped by RF wave less than 10 kHz emits pulse shapes. Generally, the pulse oscillation of RF-$CO_2$ lasers is realized by switching of excitation discharge and the duty ratio of ON and OFF (Nagai, 2000). Fig. 10 (a) is a example of normal pulses by chopping the CW output. In the axial flowing system, the gas existence time in the discharge tube is long and the rise of gas temperature is large. It is difficult to keep the peak value of a pulse constant for a long time. Therefore, a narrow pulse shape called an enhanced pulse like Fig. 10 (b) or a super pulse like Fig. 10 (c) takes place.

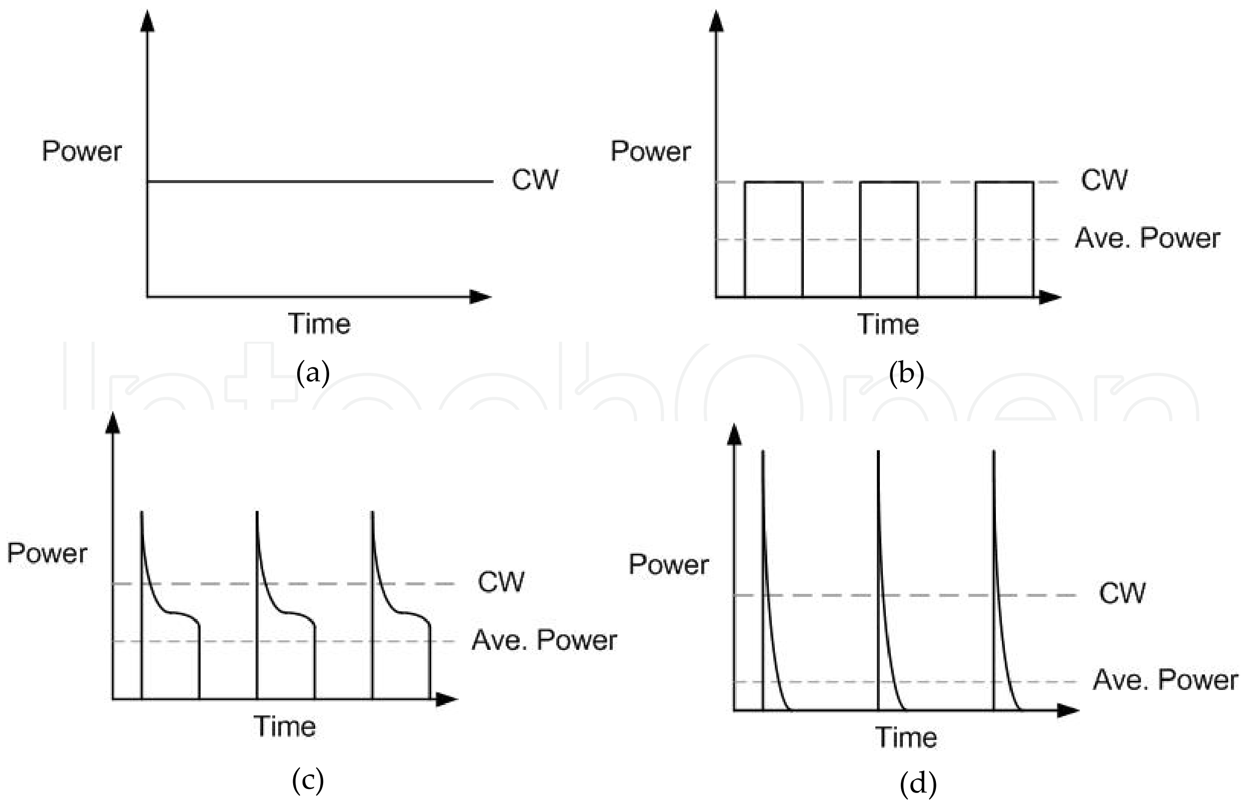



**Figure 10.** Images of RF-$CO_2$ laser output (Nagai, 2000). (a) CW. (b) Normal pulses. (c) Enhanced pulses. (d) Super pulses.

In the slab RF-$CO_2$ laser, commercial sealed-off $CO_2$ lasers produces the broad output range from CW 20 W to CW 1 kW and the high peak pulse oscillation of 2.5 kW at the pulse width 50 μs at 1 kHz (Coherent, Inc., DIAMOND E-1000). In a compact fast axial flow $CO_2$ laser, the output power of CW 2.1 kW has been reported (Biswas et al, 2010). Additionally, a low-power $CO_2$ laser pumped by AC discharge of 60 Hz whose frequency is lower than RF discharge has also been reported (Lee et al, 2000).

### 4.3. Q-switch

A Q switch is a system to produce a giant pulse with a short pulse and a high peak power. A Q value is a standard of the resonator performance and is a ratio of a loss energy to a storage energy in the cavity. It is hard to carry out a laser oscillation when a Q value is low, and it is easy when a Q value is high. The Q switch rapidly decreases the high resonator losses, that is, rapidly increases the Q value.

A CW-$CO_2$ laser using a Q switch produces a giant pulse with a pulse width from a few tens ns to a few μs and a peak power of several kW. In a $CO_2$ laser, the use of a mechanical chopper, rotating mirror (Battou et al, 2008), electrooptical (CdTe) (Tian et al, 2005) or acoustooptical modulators (Xie et al, 2010), or saturable absorber ($SF_6$) (Soukieh et al, 1999) has been reported.

### 4.4. Pulsed discharge

A $CO_2$ laser is easily oscillated by applying a high voltage pulse of about 20 kV to a longitudinal discharge tube filled by $CO_2$ gas. Fig. 11 shows a longitudinally excited pulsed $CO_2$ laser with a general and easy excitation circuit (Chung et al, 2002; Loy & Roland, 1977). A voltage pulse of several hundreds V is generated by a power supply and is fed to a step-up transformer. The high-voltage pulse of about 20 kV is directly applied to the discharge tube. The high-voltage pulse has a long rise time of about a few hundred μs because the transformer with a large inductance is directly connected to the discharge tube. When the applied voltage reaches the breakdown threshold, a discharge starts and the laser oscillates. The laser output energy depends on the discharge volume and the input energy. The laser pulse has a long width from several tens μs to several ms because the excitation circuit produces a long and high voltage pulse and the discharge formation time is long. For example, the discharge tube with the length of 80 cm applied the high voltage pulse of 25 kV and produced the output power of 35 W and the width of 3 ms at 60 Hz (Chung et al, 2002).

The longitudinally excited $CO_2$ laser produces a short laser pulse like TEA-$CO_2$ laser and Q-switched $CO_2$ laser by a fast discharge. Fig. 12 shows a $CO_2$ laser with a capacitor transfer circuit that is used for transversal excited excimer lasers and is known as a fast discharge circuit (Miyazaki et al, 1986). A low-inductance storage capacitor $C_s$ was charged up to DC voltage of about 20 kV. A spark gap was switched by a trigger pulse from a trigger circuit, and the high voltage was transferred to a buffer capacitance $C_b$. When the voltage reached

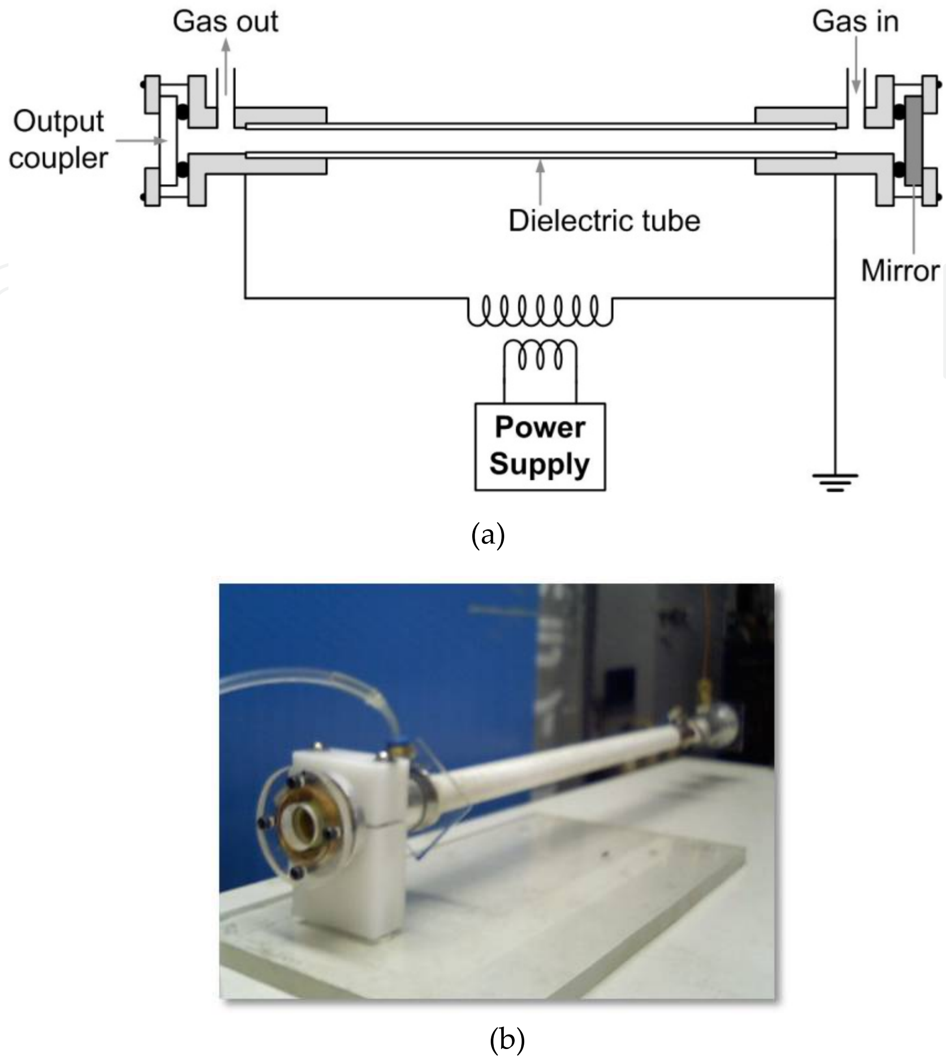



**Figure 11.** Image of longitudinally excited long-pulse $CO_2$ laser. (a) Schematic diagram. (b) Photograph.

the breakdown threshold, a rapid main discharge took place in the discharge tube. The high-voltage pulse of a rise time less than 100 ns is applied to the discharge tube. Additionally, a high-voltage resistor is connected in parallel with the discharge tube. A low resistance acts as a shunt resistance and provides a rapid discharge.

For example, in our study (Uno et al, 2009), the discharge tube was a ceramic pipe made of alumina, with an inner diameter of 13 mm, an outer diameter of 17 mm, and a length of 45 cm. The discharge tube was covered with an Al sheet. Therefore, the laser tube had a coaxial structure for reducing the discharge impedance. An optical cavity was formed by a ZnSe output coupler with a reflectivity of 80% and a high-reflection mirror with a radius of curvature of 20 m. The distance between the output coupler and the mirror (i.e., the cavity length) was 54 cm. In the excitation circuit, the storage capacitance $C_s$ was 5.4 nF and charged up to DC 20 kV, and the buffer capacitance $C_b$ was 2.8 nF. The fall time of the discharge voltage decreased from 32.8 μs (10 MΩ) to 0.97 μs (100 Ω). In the fast discharge, the gain increases gradually from the start of discharge. When the gain becomes enough

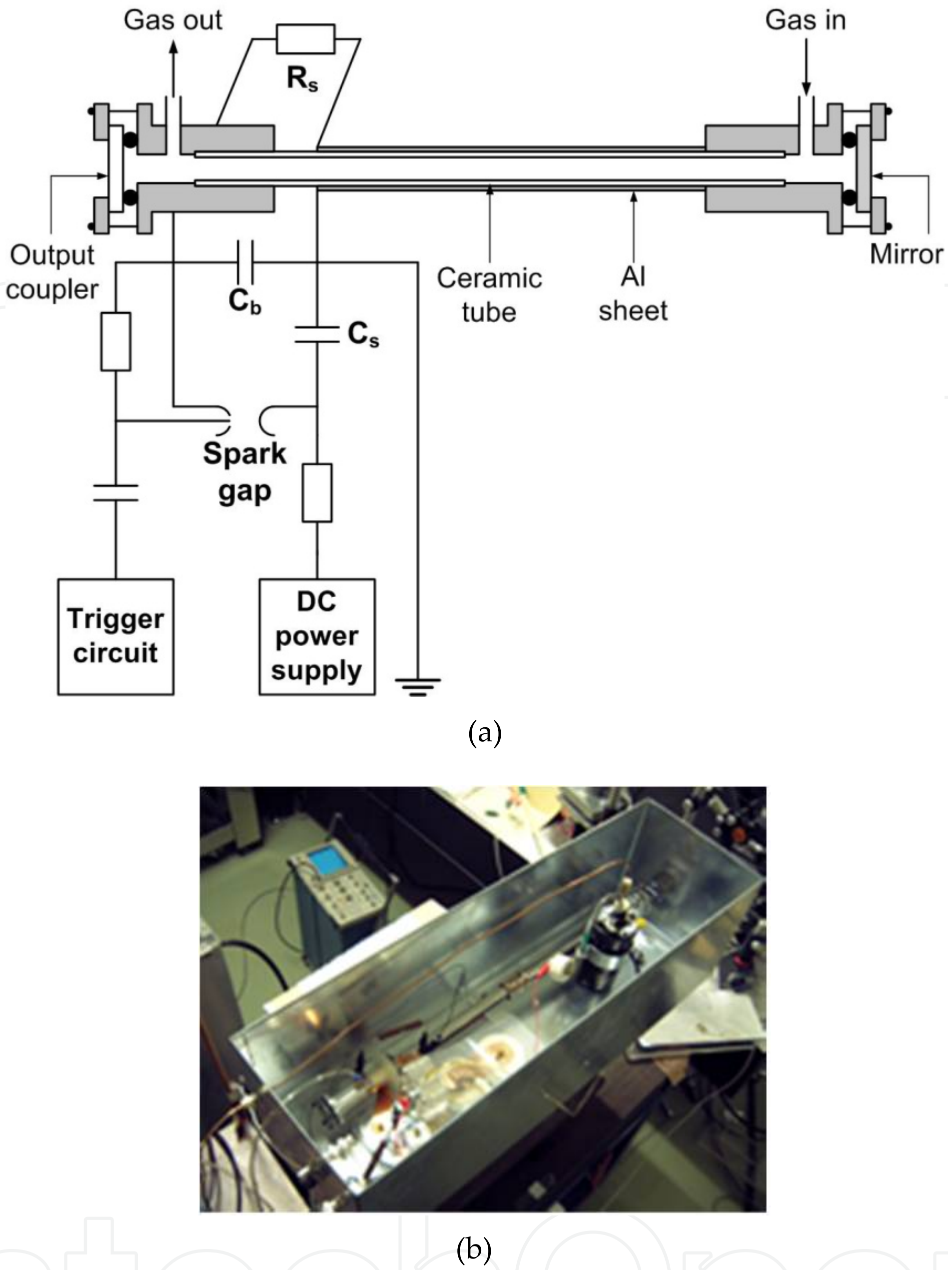



**Figure 12.** Longitudinally excited short-pulse $CO_2$ laser with capacitor-transfer circuit (Uno et al, 2009). (a) Schematic diagram. (b) Photograph.

after several μs from the start of discharge, the laser oscillates by a gain Q switch and a spike laser pulse is formed. At that time, the main discharge finishes mostly. Low current after the main discharge and the energy transfer of the upper-level $N_2$ with the long lifetime causes the laser pulse tail of several tens μs. The pulse tail can be eliminated by eliminating the after current or using of pure $CO_2$ gas to eliminate the long $N_2$ tail. Fig. 13 and 14 shows the laser pulse in the discharge formation time of 32.8 μs and 0.97 μs, respectively, at the same discharge tube with the inner diameter of 13 mm and the length of 45 cm and the same gas pressure of 2.9 kPa ($CO_2$: $N_2$: He= 1: 1: 2) (Uno et al, 2009). Fig. 13 shows the laser pulse with the spike pulse width of 103.3 ns, the pulse tail length of 61.9 μs, and the output energy of 50 mJ by the discharge formation time of 32.8 μs. The pulse tail length was defined from the end of the spike pulse to the end of the pulse tail. Fig. 14 shows the laser pulse with the spike pulse width of 96.3 ns, the pulse tail length of 17.2 μs, and the output energy of 30 mJ by the discharge formation time of 0.97 μs. These results showed the fast discharge caused the decrease of the pulse tail.

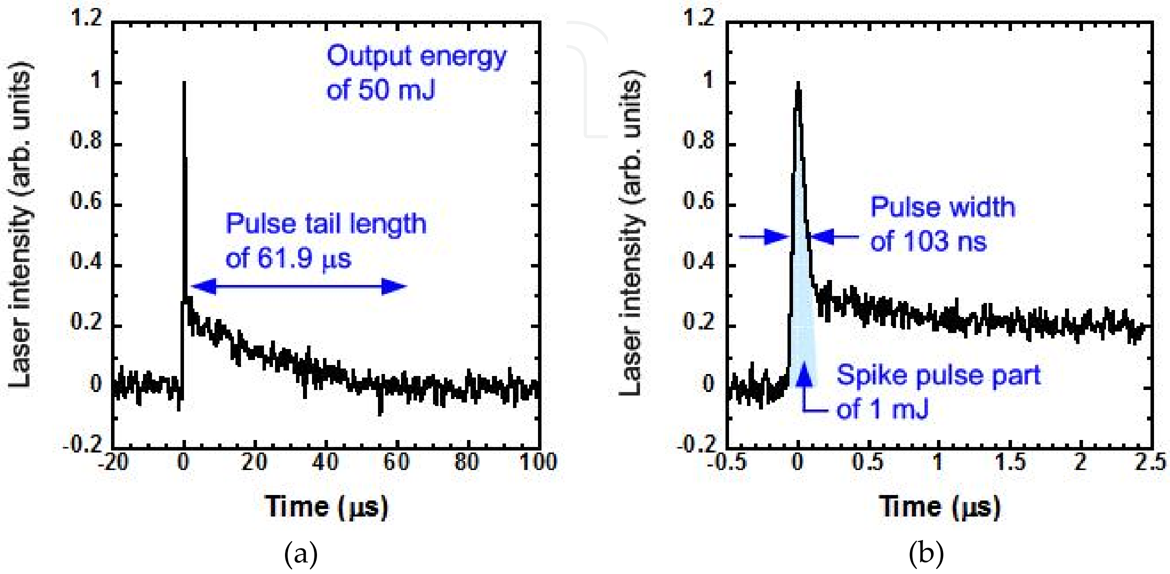



**Figure 13.** Laser pulse waveforms at slow discharge (discharge formation time of 32.8 μs and gas pressure of 2.9 kPa ($CO_2$: $N_2$: He= 1: 1: 2)) (Uno et al, 2009). Intensity of vertical axis is normalized by peak strength. (a) Overall waveform. (b) Magnified time scale view of spike pulse.

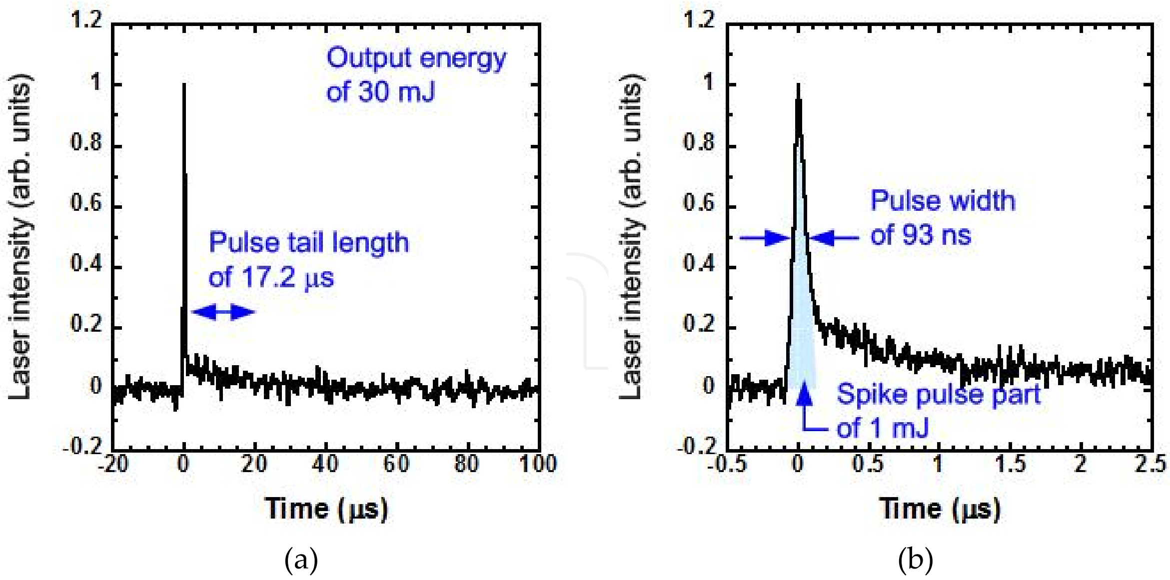
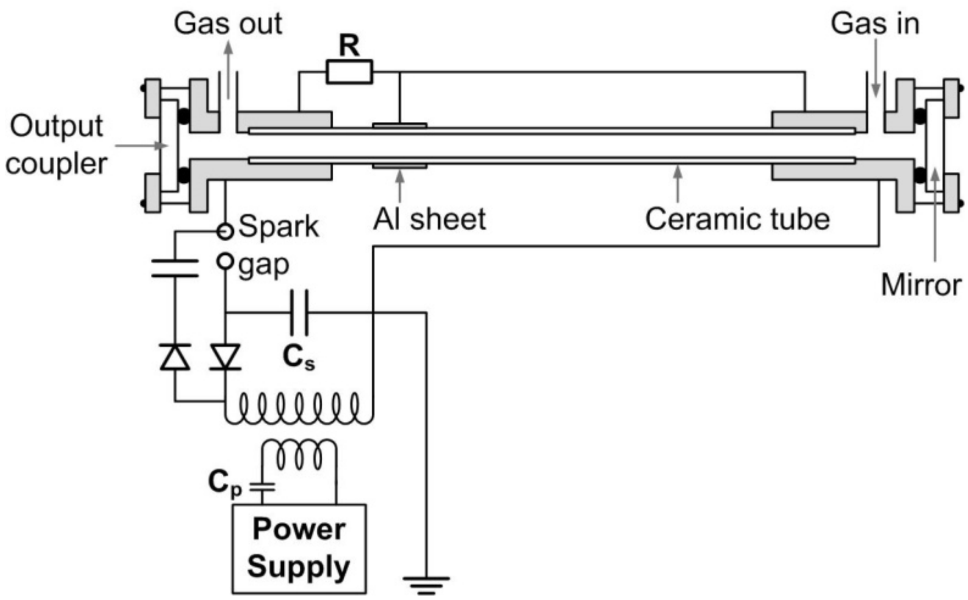
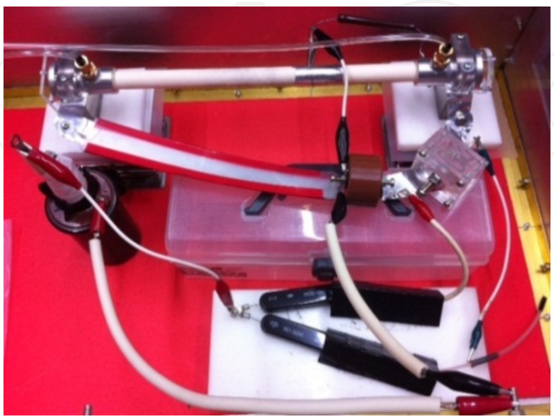



**Figure 14.** Laser pulse waveforms at fast discharge (discharge formation time of 0.97 μs and gas pressure of 2.9 kPa ($CO_2$: $N_2$: He= 1: 1: 2)) (Uno et al, 2009). Intensity of vertical axis is normalized by peak strength. (a) Overall waveform. (b) Magnified time scale view of spike pulse.

The capacitor-transfer circuit like Fig. 12 developed for the transversely excited excimer laser (Miyazaki et al, 1986). The capacitor-transfer circuit has a buffer capacitance in parallel with the laser tube. The buffer capacitance functions to increase the applied voltage due to the storage capacitance. However, because the transverse excitation scheme has a narrow electrode gap and a small discharge impedance, a buffer capacitance is required to sustain the discharge. On the other hand, the longitudinal excitation scheme has a wide electrode gap and a large discharge impedance and does not require a buffer capacitance to sustain the discharge. Therefore, a circuit without a buffer capacitance, called a direct-drive circuit like Fig. 15, has been developed (Uno et al, 2012a). Fig. 15 shows a longitudinally excited $CO_2$ laser with a direct-drive circuit (Uno et al, 2012a). A negative several hundreds V pulse was generated by the power supply with a silicon-controlled rectifier and was fed to a




(a)



(b)

**Figure 15.** Longitudinally excited short-pulse $CO_2$ laser with direct-drive circuit (Uno et al, 2012a). (a) Schematic diagram. (b) Photograph.

transformer, which had a primary capacitance. First, a negative voltage pulse was generated and was used to charge a storage capacitor through a rectifier. Then, a positive voltage pulse generated by the overshoot of the transformer was applied to the trigger electrode of the spark gap through a rectifier and a small capacitor. The storage capacitor was charged, the spark gap was switched, and the high voltage was applied to the laser tube. When the voltage reached the breakdown threshold, a rapid discharge took place in the laser tube. This system produces a short pulse $CO_2$ laser with a spike pulse.

For example, in our study (Uno et al, 2012a), the laser tube was the almost same as the above longitudinally excited $CO_2$ laser with the capacitor-transfer circuit. A different point was a partially preionization. Part of the discharge tube was covered with an Al sheet for a high discharge starting voltage. In the excitation circuit, the primary capacitance $C_p$ was 10.2 µF and the storage capacitance was 700 pF.

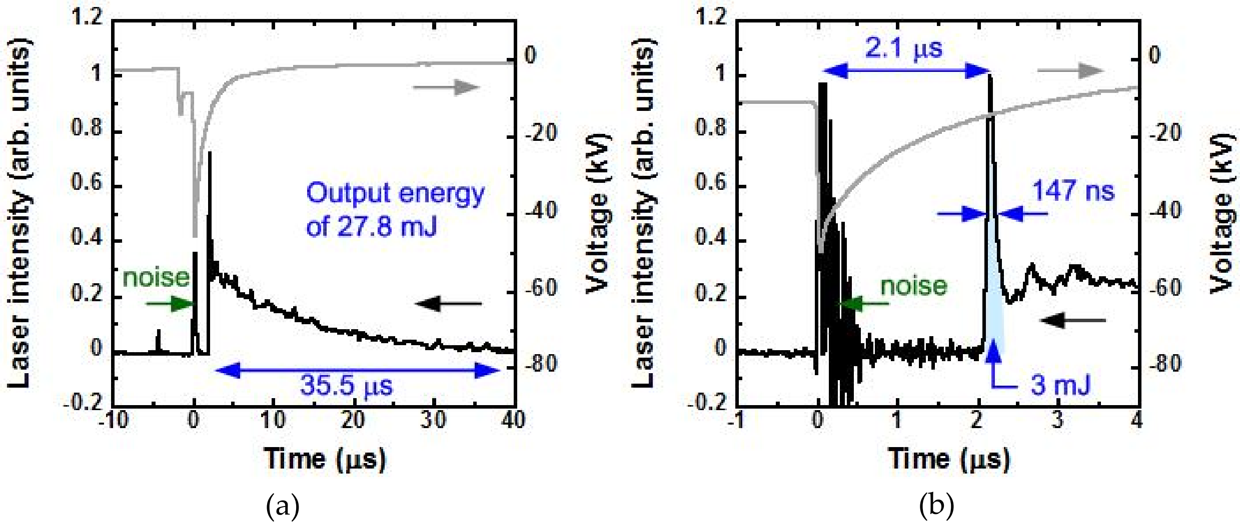



**Figure 16.** Discharge voltage and $CO_2$ laser pulse waveforms at 3.4 kPa (mixed gas, $CO_2 : N_2 : He = 1 : 1 : 2$) (Uno et al, 2012a). Black and gray lines represent laser pulse and discharge voltage, respectively. (a) Overall waveform. (b) Magnified time scale view of spike pulse.

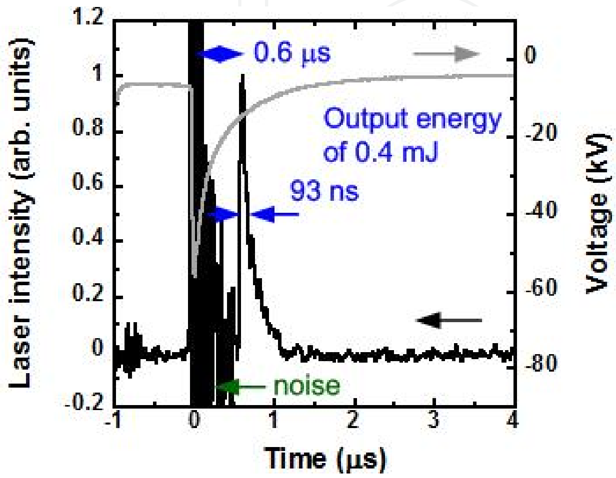
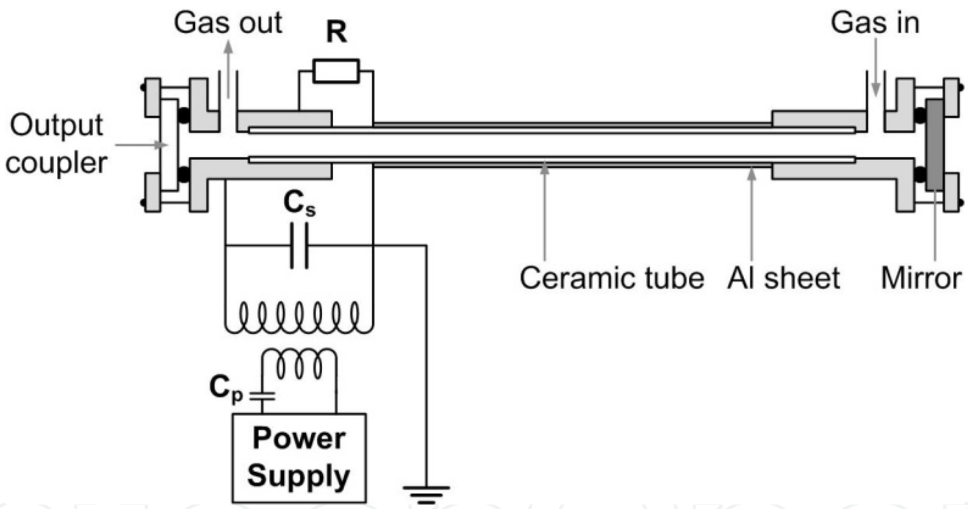


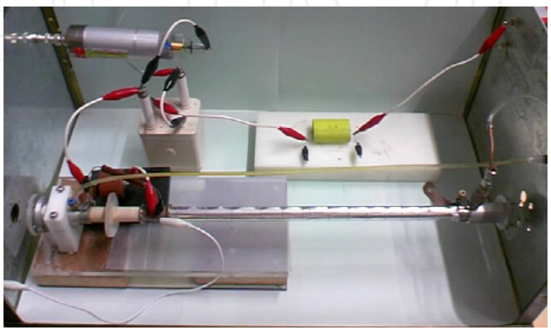

**Figure 17.** Discharge voltage and $CO_2$ laser pulse waveforms at 2.2 kPa (pure $CO_2$) (Uno et al, 2012a). Black and gray lines represent laser pulse and discharge voltage, respectively.

Fig. 16 shows the discharge voltage and laser pulse waveforms at the mixed gas ($CO_2$: $N_2$: He= 1: 1: 2) pressure of 3.4 kPa. The discharge starting voltage was –60.2 kV, and the fall time of the discharge was 4.4 μs. The laser oscillation began 2.1 μs after the start of discharge. The laser pulse had a sharp spike, like that from TEA and Q-switched $CO_2$ lasers. The spike pulse width was 147 ns (FWHM), and the pulse tail length was 35.5 μs. The laser output energy was 27.8 mJ, and the energy of the spike pulse part was estimated to be 3.1 mJ. Fig. 17 shows the discharge voltage and laser pulse waveform at the pure $CO_2$ gas pressure of 2.2 kPa. The discharge starting voltage was –60.8 kV, and the fall time of the discharge was 1.9 μs. Laser oscillation began 0.6 μs after the start of discharge. The laser output energy was 0.4 mJ. The laser pulse contained a spike pulse only, and the width was 93 ns (FWHM). Pulse-tail-free oscillation was realized by the use of pure $CO_2$ gas.

Figure 18 shows the simplest short-pulse longitudinally excited $CO_2$ laser (Uno et al, 2012b). This system has a laser tube, a capacitor, a resister, and a pulse power supply with a low-voltage silicon-controlled rectifier, and a set-up transformer only. The excitation circuit does not have a high-voltage switch; instead, the laser tube plays the role of the switch. Therefore, this system is almost same as the above long-pulse longitudinally excited $CO_2$ laser. However, the step-up transformer has the fast rise time of about 3 μs. The fast transformer produces the fast discharge which causes the short laser pulse.




(a)



(b)

**Figure 18.** Short-pulse longitudinally excited $CO_2$ laser with switchless circuit (Uno et al, 2012b). (a) Schematic diagram. (b) Photograph.

For example, in our study (Uno et al, 2012b), the laser tube was the same as the above longitudinally excited $CO_2$ laser with the capacitor-transfer circuit (Uno et al, 2009). In the excitation circuit, the primary capacitance $C_P$ was 4.7 μF, the storage capacitance $C_s$ was 700 pF, and the resistor R was 10 MΩ.

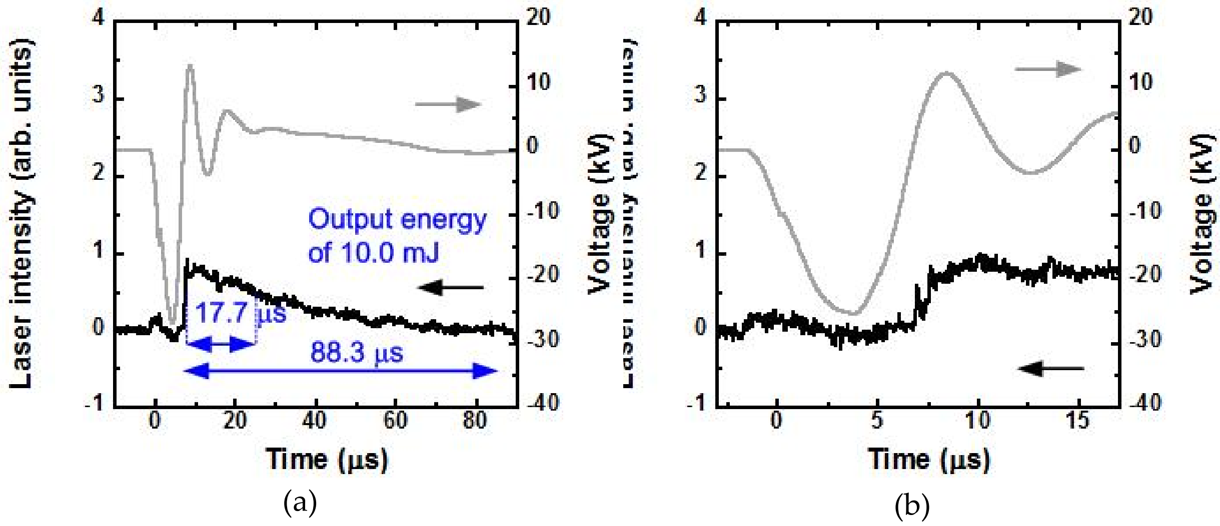



**Figure 19.** Discharge voltage and $CO_2$ laser pulse waveforms at 3.8 kPa ($CO_2$: $N_2$: He= 1: 1: 2) (Uno et al, 2012b). Black and gray lines represent laser pulse and discharge voltage. (a) Overall waveform. (b) Magnified time scale view of the start of discharge.

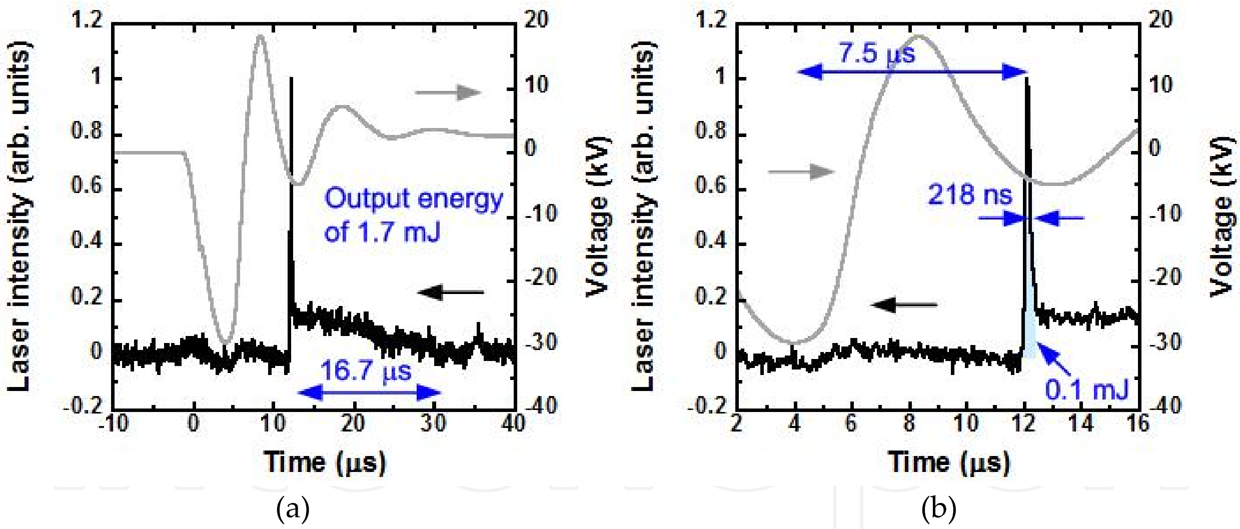



**Figure 20.** Discharge voltage and $CO_2$ laser pulse waveforms at 9.0 kPa ($CO_2$: $N_2$: He= 1: 1: 2) (Uno et al, 2012b). Black and gray lines represent laser pulse and discharge voltage, respectively. (a) Overall waveform. (b) Magnified time scale view of the start of discharge.

The long pulse oscillation takes place at gas pressure less than 3.8 kPa ($CO_2$: $N_2$: He= 1: 1: 2) and the short pulse oscillation takes place at gas pressure more than 4.2 kPa. Fig. 19 shows the discharge voltage and laser pulse waveforms at 3.8 kPa. The discharge voltage reached -25.8 kV at a raise time of 3.4 μs. In the low pressure, the breakdown voltage is low. The discharge starts when the applied voltage reaches the breakdown voltage. The fall time of the main discharge was 2.8 μs. Laser oscillation took place 3.5 μs after the start of discharge. At this time, the discharge continues. The laser pulse did not have a spike pulse and is a conventional long pulse oscillation. The laser output energy was 10.0 mJ. The laser pulse width was the full width at half maximum (FWHM) of 17.7 μs and the pulse length of 88.3 μs. Fig. 20 shows the discharge voltage and laser pulse waveforms at 9.0 kPa. The discharge voltage reached -29 kV at a raise time of 3.1 μs. In the high pressure, the breakdown voltage is high and the applied voltage reaches maximum. The fast discharge is influenced by the impedance matching of the excitation circuit and the discharge space. The fall time of main discharge was 2.2 μs. The laser oscillation took place 7.5 μs after the start of discharge. The laser pulse had a spike pulse width of 218 ns and a pulse tail length of 16.7 μs. The laser output energy was 1.7 mJ. The energy of the spike pulse part was estimated to be 0.1 mJ. It may be necessary to improve the output energy for various supplications.

## 5. Application

### 5.1. CW and long pulse

#### *5.1.1. Medical applications*

80 wt% of soft biological tissue is water. Evaporation of water is a factor important for soft tissue excision (Awazu, 2008). In laser irradiation, evaporation of water takes place at the critical temperature of 101 K (Auerhammer et al, 1999). The evaporation of water causes the soft tissue excision around the laser irradiation part. The tensile strength of soft tissue is about 10 MPa on skin and several MPa on corneas, blood vessel, and muscle (Duck, 1990). The laser excision of soft tissue is carried out by a high mechanical power which causes a phase transition because 1 atm is about 0.1 MPa.

A $CO_2$ laser is effectively absorbed in water. In 9.2 – 11.4 μm of the $CO_2$ laser wavelength band, the absorption coefficient is $10^3$ $cm^{-1}$ (Zarrabi & Gross, 2011). Therefore, in the $CO_2$ laser, the penetration depth to soft biological tissue is short and about 50 μm. The $CO_2$ laser evaporates only surface of soft tissue. Heat influence of deeper tissue is small and the damage to normal tissue is minimally suppressed. Edema and sharp pain after an operation are little because the heat influence is restrictive. In the $CO_2$ laser irradiation, shrink, dehydration, and carbonization of surface tissue take place. They cause water evaporation and vaporization of inner tissue. In this process, a protein denaturation layer of residual tissue is certainly generated. The denaturation layer functions as a solidification layer for an arrest of hemorrhage.

At present, a $CO_2$ laser of about 3 W a pulsed CW of (10 – 1000 ms and a super pulse of 0.1 – 1 ms) is used for the skin treatment such as eliminating a mole, a wart, macule (Gotkin et al, 2009) and wrinkle the aurinasal treatment such as hay fever and allergic rhinitis (Takeno et al, 2009), the eye treatment such as blepharochalasis and droopy eyelid (Rokhsar et al, 2008), and the dental treatment such as section and evaporation of soft tissue, hemostasis, and stomatitis (Zand et al, 2009). The advantages of $CO_2$ laser surgery are alleviation of bleeding, pain and edema, and shortening of operation and recovery time.

### *5.1.2. Industrial applications*

When laser is irradiated to a material surface, a part is reflected by the reflectance of the material to the laser wavelength at the material surface, and the remainder is absorbed at the material surface. Then, the temperature of the material surface increases. A part of the heat is radiated by the heat radiation rate of the material, and the remainder conducts to inside by the heat conductivity of the material and makes the internal temperature increase. The surface temperature is fixed by the balance between the thermal energy lost by heat conduction and radiation and the thermal energy given by the laser. If the surface temperature does not reach the melting point of the material, a surface treatment takes place. If the surface temperature reaches the melting point, the melting takes place. When the heat input stops by movement or a stop of the laser beam, the material is cooled. Solidification causes welding. Eliminating the molten material (e.g. gas blowing) causes cutting. When the surface temperature exceeds the boiling point of the material by increasing the thermal energy given by the laser beam, a hole called keyhole begins to be formed. The laser reaches the inside of the material through the keyhole. The penetration causes deep melting process called keyhole welding.

The laser cutting is a specialty application of $CO_2$ lasers. In the laser cutting, a beam control is important. In space, the beam with $TEM_{00}$ mode or the beam with low order mode of axial symmetry like $TEM_{00}$ mode is required. In time, the control of the beam power (W/cm$^2$) is required. In the laser cutting of metals like steel, a fine cutting without heat influence, strain, and dross is required. It is very important to optimally control heat input by control of the peak power, the repetition rate, the duty ratio, and so on. These factors must be optimally controlled according to the kind of material, the thickness, and the cutting speed. A metal with a few mm of thickness can be cut by the $CO_2$ laser with the peak power of 100 – 200 W, the repetition rate of about 300 Hz, the cutting speed of about 30 cm/min, and the duty ratio of about 30%. In non-metallic materials such as woods, cloth, paper, ceramics, glass, gum, plastics, polyimide, epoxy, polycarbonate, vinyl and so on, the absorption of $CO_2$ laser light is very large. Most of these non-metallic materials can be processed (cutting, hole making, marking, etc.) by a low output CW-$CO_2$ laser emitted less than 300 W. The laser processing is used for the cutting of automobile instrument panels and clothes, the hole making of the material (e.g. ceramics), which the mechanical processing is difficult for, and so on.

## 5.2. Short pulse

### *5.2.1. Applications by commercial TEA-$CO_2$ lasers*

An ablation process by irradiation of a short-pulse $CO_2$ laser is used for hole-making a printed board, marking to a resin board, and cleaning a metal part. In the hole-making of a printed board, improving density of trace is the purpose. Making a via-hole with a diameter of 50 mm or less requires several tens kW of the peak power, a few μs of the pulse width and a few kHz of repetition rate. Thus, TEA-$CO_2$ lasers are used for the-hole making. The laser marking stamps the model number and name of a product, the date of manufacture, a lot number, etc. In a TEA-$CO_2$ laser, image transfer with mask is used because the TEA-$CO_2$

laser produces high output power. $CO_2$ lasers are used for marking to resin boards, such as glass epoxy. In the laser cleaning, TEA-$CO_2$ lasers are used for dirt and coat removal on metal material. Dirt and a coat are removed by laser ablation because they tend to absorb the $CO_2$ laser light than metal. This process does not give the damage by heat to a surface of metal, because the laser light is reflected when the metal material appears. The laser cleaning does not use a medical fluid and blast material, and is a dry process.

### *5.2.2. Future applications*

At present, drilling of hard tissue (enamel and dentine) uses an Er:YAG laser with the wavelength of 2.94 μm that is well correspond with the absorption wavelength of water. In 2.94 μm of the Er:YAG laser wavelength, the absorption coefficient is $10^4$ $cm^{-1}$ (Zarrabi & Gross, 2011). The laser light is focused on water and micro-explosion of water drills hard tissue. $CO_2$ laser can also drill hard tissue because the $CO_2$ laser (9.2 – 11.4 μm) is well absorbed in water. However, a long-pulsed $CO_2$ laser which is used in the present dental clinic causes carbonization of hard tissue. Fig. 21 (a) and (b) shows the human tooth surface irradiated by a long-pulsed longitudinally excited $CO_2$ laser with the pulse width of 30 μs and the output energy of 80 mJ. The dentin which contains heat-sensitive protein was carbonized by thermal influence because of the long-pulsed $CO_2$ laser. On the other hand, Fig. 21 (c) and (d) shows the human tooth surface irradiated by a short-pulsed longitudinally excited $CO_2$ laser with the spike pulse width of about 100 ns, the pulse tail length of about 60 μs, and the output energy of 80 mJ (Uno et al, 2009). The short-pulsed $CO_2$ laser resulted in almost no carbonization not only for the enamel but also for the dentine.

Additionally, $CO_2$ lasers are also absorbed in the human tooth (Heya et al, 2003). The dentine has a weak acid resistance and becomes a saprodontia easily. The dentine is reformed to a hydroxyapatite that has a strong acid resistance by the laser with the wavelength of 8.8 – 10.6 μm (Heya et al, 2003). $CO_2$ lasers can change the dentine to the hydroxyapatite because the wavelength corresponds to the wavelength of the $CO_2$ laser. Moreover, the dentin covers dental pulp and is porous. Exposure of the dentine causes dentinal hypersensitivity. The irradiation of the $CO_2$ laser melts and blocked the dentine surface. Thus, by the $CO_2$ laser, the medical treatment of dentinal hypersensitivity is also possible. The longitudinally excited $CO_2$ laser is expected as a complex dental care machine because the laser can produce the long pulse for the soft tissue treatment and the short pulse for the hard tissue treatment with a low-cost and portable device.

Glass marking can be effectively performed by a low-power $CO_2$ laser because glass absorbs infrared light well. Additionally, the glass marking is energy saving because a $CO_2$ laser has high electro-optical conversion efficiency. However, a long-pulsed $CO_2$ laser produces cracks on the surface of glass by heat influence. Fig. 22 (a) shows the glass surface irradiated by a long-pulsed longitudinally excited $CO_2$ laser with the pulse width of about 30 μs and the output energy of about 45 mJ. The processing part looks white by cracking. On the other hand, a short-pulsed $CO_2$ laser produces crackless marking. Fig. 22 (b) shows the glass

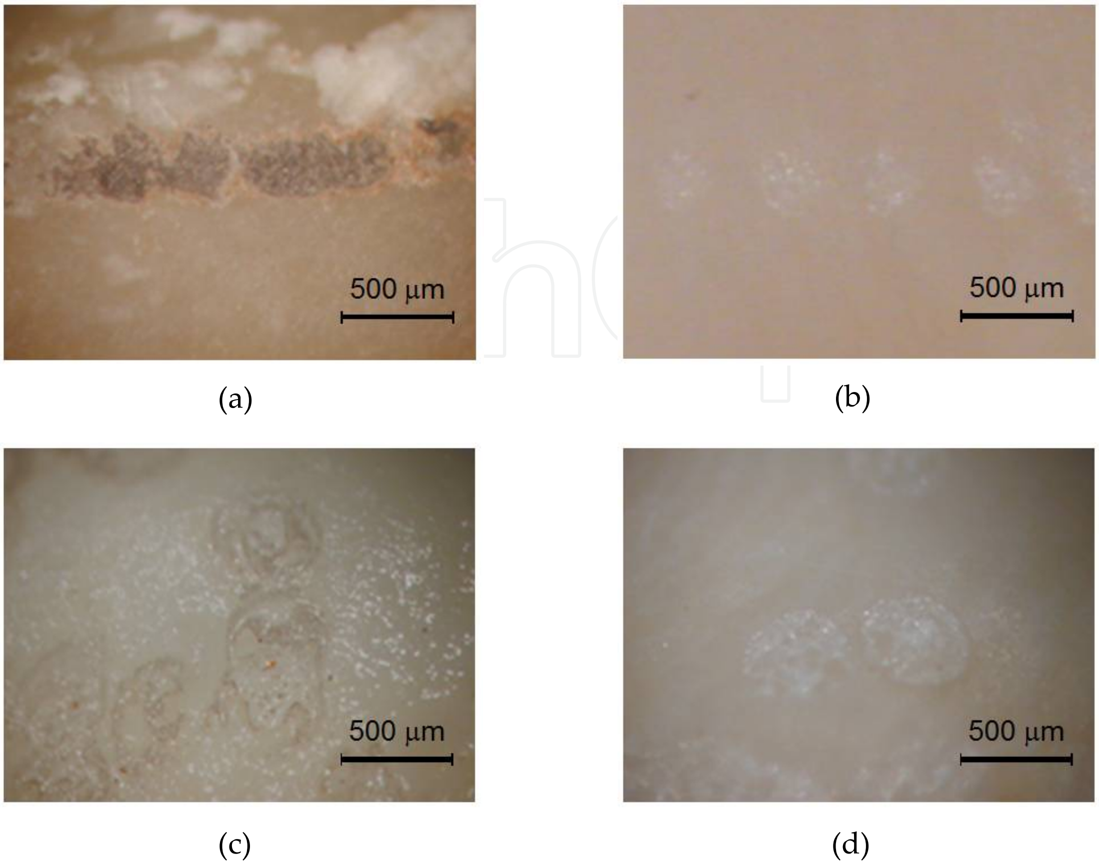



**Figure 21.** Tooth surface irradiated longitudinally excited $CO_2$ laser (Uno et al, 2009). (a) Dentine surface by long-pulsed $CO_2$ laser irradiation. (b) Enamel surface by long-pulsed $CO_2$ laser irradiation. (c) Dentine surface by short- pulsed $CO_2$ laser irradiation. (d) Enamel surface by short- pulsed $CO_2$ laser irradiation.

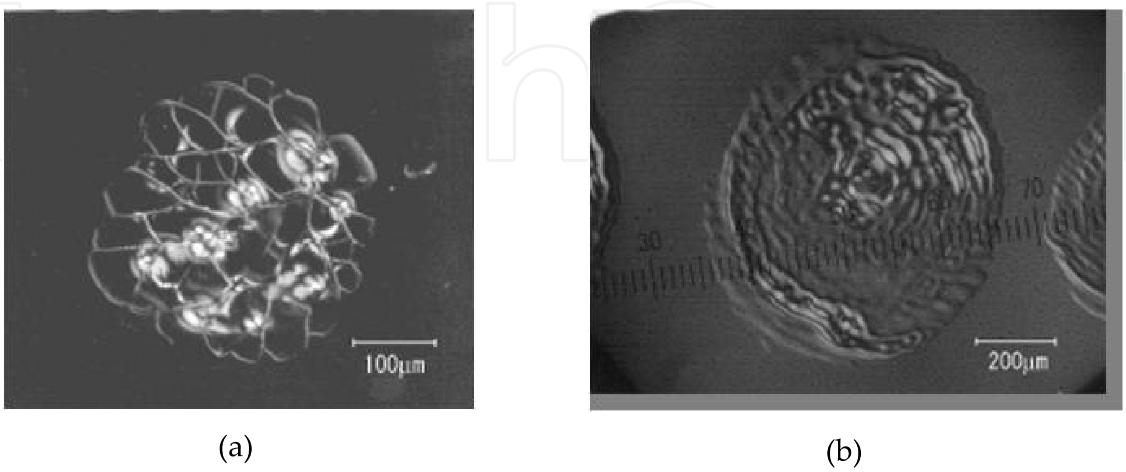



**Figure 22.** Glass surface irradiated longitudinally excited $CO_2$ laser (Uno et al, 2009). (a) Long-pulse $CO_2$ laser irradiation. (b) Short-pulse $CO_2$ laser irradiation.

surface irradiated by a short-pulsed longitudinally excited $CO_2$ laser with the spike pulse width of about 100 ns, the pulse tail length of about 60 μs and the output energy of about 45 mJ (Uno et al, 2009). The processing part is not visible with the naked eye because the part does not have a crack. In fact, the short-pulsed $CO_2$ laser produces stealth marking. However, the irradiation fluence is limited by the heat influence of the pulse tail. Therefore, the development of a short-pulsed $CO_2$ laser without pulse tail is desired. The short-pulsed longitudinally excited $CO_2$ laser with a low-cost and portable device will produce a device for product identification and traceability by marking for every process in a factory, and management of a sample by marking in a research institution.

## 6. Conclusion

In this chapter, the longitudinally excited $CO_2$ laser has been described. The excitation system and mechanism of the $CO_2$ laser, the feature of longitudinal excitation system and the excitation discharge, and the application of the CO2 laser have been explained. Especially, in the longitudinally excited $CO_2$ laser pumped by pulse discharge, new excitation circuits have been introduced and the relation between the discharge and the laser pulse has been explained. The longitudinally excited $CO_2$ laser can produce CW oscillation, long pulse oscillation, or short pulse oscillation with a compact, simple, and low-cost device. The development of a maintenance-free and warm-up-free device can be expected by the simple structure. Therefore, a user-friendly $CO_2$ laser which anyone can use easily always anywhere will contribute to various fields.

## Author details

Kazuyuki Uno
*University of Yamanashi, Japan*

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