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ARC-DISCHARGE MONITORING SYSTEM OF A HIGH-POWER REPETITIVELY-PULSED TEA CO_2 LASER

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Abstract

High-power repetitively-pulsed TEA CO_2 lasers are excited by a glow discharge, and it turns out to be the arc discharge under some conditions. The arc-discharge is a disadvantageous condition and must be avoided. According to the Faraday electromagnetism induction principle, the arc-discharge monitoring system with a magnetic-field probe is designed for high-power repetitively-pulsed TEA CO_2 lasers. The magnetic-field variation induced by the discharge current can be tested, and the discharge state can be distinguished according to the output induction voltage. Experimental results show that the magnetic-field induction voltages generated by a glow discharge and an arc discharge are very different ones. The maximum induction voltage of the glow discharge is 2.0 V, while the minimum induction voltage of the arc discharge is 2.5–4 V. Three alarm levels are set by measuring the arc-discharge intensities. At the first level, automatic filling–exhausting equipment starts to refresh the gas media, at the second level, the laser repetition rate is reduced, and at the third level the laser operation stops immediately. As a result, the working reliability of a high-power repetitively-pulsed TEA CO_2 laser system can be improved significantly by using the arc-discharge monitoring system.

Keywords: TEA CO_2 laser, glow discharge, arc discharge, discharge monitoring system.

1. Introduction

High-power repetitively-pulsed TEA CO_2 lasers (transversely excited atmospheric CO_2 laser) are electrically-excited gas laser, the average power of which usually exceeds 10^4 W, with peak power higher than 10^{12} W and pulse energy beyond 10^3 J [1–3]. After decades of development, they became the most promising gas laser for realizing high-power and high-energy outputs with good beam quality. High-power

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repetitively-pulsed TEA CO_2 lasers are widely used in many applications, such as laser nuclear fusion, isotope separation, laser ranging, and so on [4–8]. In addition, they are in demand for the research on laser propulsion [9, 10].

All these applications require a laser system with long-time and high-reliability operations, which are affected by several problems, such as arc discharge, insulation puncture, and bugs of electrical and electronic components. Among these problems, the transition from the glow discharge to the arc discharge happens most frequently and obviously influences the operating reliability of TEA CO_2 lasers. At the beginning stage of an arc discharge, the discharge currents between the two main electrodes in the discharge chamber concentrate at some area. After being generated, the arc discharge is located at a small fixed area on the electrodes, leading to a highly uneven distribution of the discharge-current intensity.

Many unfavorable effects on TEA CO_2 lasers are caused by the arc discharge. First of all, the local current is too high in order to excite the medium enough, which leads to instability in the output-pulse energy. Second, the gain media are excited unevenly, resulting in the uneven distribution of the refractive index and the deterioration of the laser-beam quality. Third, the high-current discharge at a fixed area between the discharge electrodes may lead to irreversible damage in the electrode surfaces. Finally, the plasma impedance at the arc-discharge area abruptly becomes smaller when the glow discharge is converted into the arc discharge; then the current density at a local area increases rapidly, and the total impedance between the electrodes decreases instantly, leading to an unstable discharge or even its end. The large current variations will introduce significant electromagnetic interference (EMI), causing working bugs or damage to the laser electronic system.

Therefore, the discharge state of the main electrodes is the core of the whole laser system, which must be monitored at all times. Few methods for detecting the arc discharge are reported, besides the detection of the UV-light intensity or the visible-light intensity combined with the measurements of the discharge current [11, 12]. However, background light, such as UV spark pre-ionization discharge, interferes with these methods, so the detection is not accurate enough. Because there is a large difference in the current intensities between the glow discharge and the arc discharge, the method employing the detection of the magnetic-field intensity can be used for evaluating the arc discharge. Background light does not interfer with this method, and the detection is very accurate.

Based on the principle of electromagnetism, i.e., variations in the current intensity always generate variations in the magnetic intensity, an arc-discharge monitoring system for high-power TEA CO_2 lasers containing a magnetic field probe is developed in this paper. The output signal of the magnetic-field probe is transmitted to the signal processing circuit, and the arc discharge is divided into a weak arc discharge and a strong arc discharge according to the induced voltage in the signal-processing circuit. The signal of the arc discharge is extracted to be counted or added up according to the counted or statistical result.

The arc discharge is divided into three alarm levels — on the first level, there are ten weak arc-discharge pulses counted in 100 continuous discharge pulses, on the second level there are five continuous weak arc-discharge pulses, and on the third there is a strong arc discharge. On the first or the second alarm level, refreshment of gas media and reduction of discharging repetition rate are adopted. On the third level, the laser is shut down immediately for protection.

2. System Design

2.1. Magnetic-Field Probe

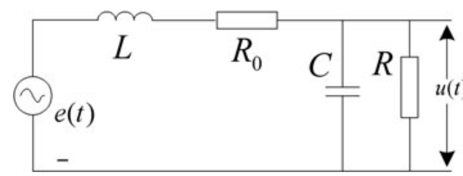

Fig. 1. Equivalent circuit of the magnetic-field probe.

Many methods are used for measuring the pulsed magnetic field. The widely used magnetic–optical effect is applicable for measuring strong pulsed magnetic fields, but the accuracy is not sufficient for weak transient magnetic field measurements [13]. The electromagnetic-induction method based on the Faraday electromagnetic induction principle has not only a wide range of measurements and a wide bandwidth but is also simple and sensitive. Therefore, the electromagnetic-induction method is chosen to develop a magnetic-field detecting coil that satisfies the measuring requirements. The equivalent circuit of the magnetic-field coil is shown in Fig. 1.

According to the Faraday electromagnetic induction principle, when a detecting coil with N turns and cross-sectional area S is inserted into the measured magnetic field varying with time, the induced electromotive force e is generated in the coil [14], and it can be written as follows:

$$e(t) = -N\frac{d\phi}{dt} = -\frac{dB(t)}{dt}\cdot NS, \tag{1}$$

$$e(t) = LC\frac{d^2u(t)}{dt^2} + (R_0C + L/R)\frac{du(t)}{dt} + (1 + R_0/R)u(t). \tag{2}$$

Here B is the axial magnetic induction intensity of the coil, N is the turn number, S is the coil cross-sectional area, L is the inductance, R_0 is the internal resistance, and R is the external self-integral resistance.

At the initial conditions, Eqs. (1) and (2) are transformed by the Laplace transform and simplified. For the sinusoidal stable-state signal ($s = j\omega$), the sensor bandwidth W is calculated as

$$W = f_H - f_L = \frac{1}{2\pi RC} - \frac{R_0 + R}{2\pi L}, \tag{3}$$

where f_H and f_L are the upper- and lower-limit critical frequencies of the sensor, respectively. In order to get a larger bandwidth, the difference between f_H and f_L should be as large as possible, R should be reduced, and L should be increased. The inductance of a single-turn magnetic detecting coil can be expressed as

$$L = a\mu_0\left[\ln(8a/b) - 1.75\right], \tag{4}$$

where a is the radius of the detecting coil, b is the radius of the conducting wire for coiling, and $\mu_0 = 4\pi\times10^{-7}$ H/m is the magnetic permeability of free space. According to Eq. (4), the bandwidth of the magnetic-field detecting coil increases with increase in a or decrease in b.

According to the above analysis, we designed a single-turn magnetic-field probe in which the magnetic-field detecting coil is a single-turn ring 6 cm in diameter coiled by coaxial cables with a wave impedance of 50 Ω. It is connected to the integral resistance R without putting voltage through a 50 Ω SMA-cable connector. The whole magnetic-field detecting coil is fixed in the copper shield. In order to shield the electric-field effect, gaps are made on the shield and outside the conductor of coaxial cables, respectively. Figure 2 shows the magnetic-field probe.

The radius of a single-turn detecting coil a and the maximum frequency of a measurable signal $f_{\max}$ can be expressed as [15]

$$f_{\max} = 0.2c/2\pi a, \tag{5}$$

and the frequency measured by the designed magnetic-field detecting coil is 319 MHz. The external integral resistance affects the frequency characteristics of the magnetic-field probe, which is estimated to be 0.2 Ω from both theoretical analysis and experiments, and it satisfies the requirement of arc-discharge detection [11].

2.2. Arc-Discharge Monitoring System

The arc-discharge monitoring system for high-power repetitively-pulsed TEA CO_2 lasers comprises mainly the magnetic-field probe and some control units, which are composed of a high-speed voltage comparator, shaping circuit with 74121 circuit chips, a light transmitter with HFBR1521 and 75451 circuit chips, fiber, an HFBR2521 light receiver, and a DSP controller with TMS320F2812 core. The high-power TEA CO_2 laser used in the experiments comprises a capacitor-charging power supply (CCPS), a high-voltage pulse generator (HVPG), discharging units, a laser trigger, and an automatic filling–exhausting equipment. The HVPG contains a discharging switch, storage capacitance C_0, and charging inductance L_0. The repetition rate of the laser is up to 260 Hz. The magnetic-field probe is fixed at the discharge-observing window made of Plexiglas. The magnetic-field detecting coil is parallel to the direction of the main discharging current and perpendicular to the direction of the magnetic field generated by the discharge. The magnetic field passes through the discharge-observing window and gets through the detecting coil, resulting in an induced voltage. The installation sketch map of the magnetic-field probe is shown in Fig. 3, and a schematic diagram of the monitoring system is shown in Fig. 4.

Fig. 2. Magnetic-field probe.

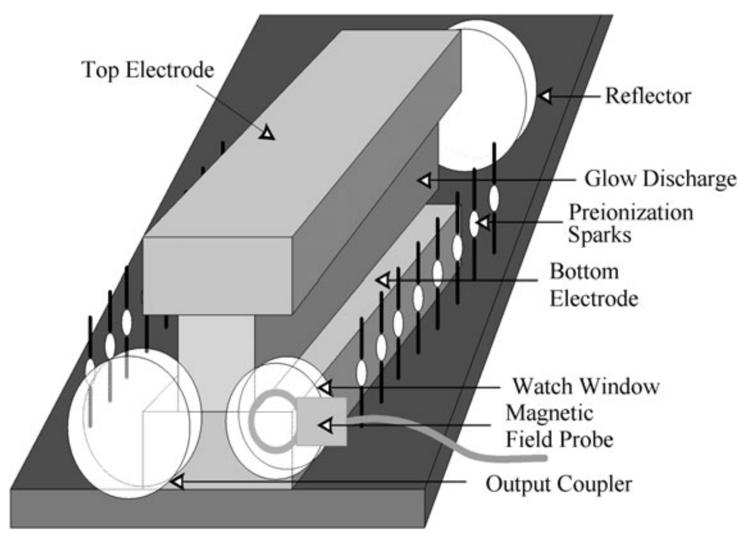

Fig. 3. Installation sketch map of the magnetic-field probe.

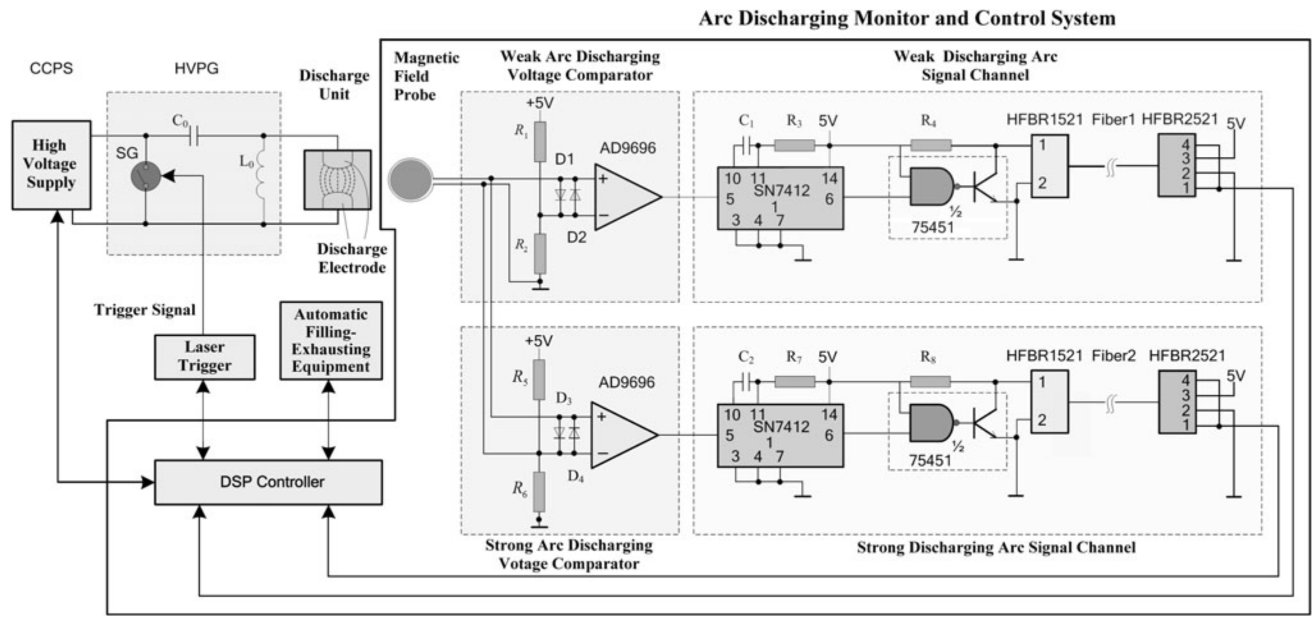

Fig. 4. Schematic diagram of the arc-discharge monitoring system.

3. Results and Discussion

When the laser is operating, the output voltage signal of the magnetic-field probe is sent to a digital oscilloscope (TDS3032B). The measured induced voltages of the glow discharge and the arc discharge are shown in Fig. 5.

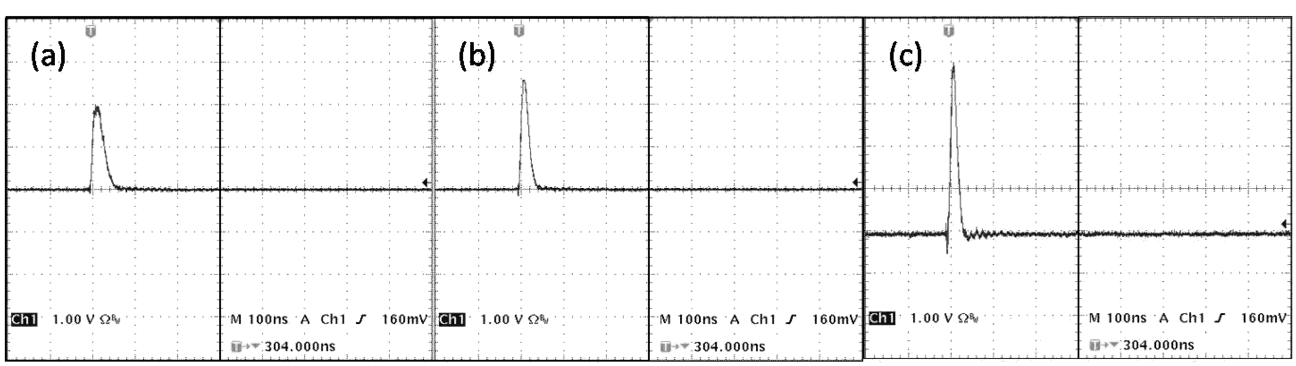

Fig. 5. Glow discharge (a), weak arc discharge (b), and strong arc discharge.

Experimental results show that the maximum output-voltage signal of the magnetic-field probe for the glow discharge is 2.0 V. For the arc discharge, the minimum voltage signal of the weak arc discharge and the strong arc discharge are 2.6 and 4.0 V, respectively. Therefore, the discharge state is estimated to be the weak arc discharge when the voltage >2.6 and <4.0 V, and one has the strong arc discharge when the voltage >4.0 V. The output voltage of the magnetic-field probe is sent to two circuits of the high-speed AD9696 voltage comparators. One circuit is used to discriminate the weak arc discharge with the threshold-voltage set at 2.6 V, and the other is used to discriminate the strong arc-discharge set at 4.0 V in the threshold voltage. The output signals of two circuits are sent to the shaping circuit. The shaping signals are sent to a light transmitter, in which the electric signals are transformed into light signals. Then, the light signals are sent to a light receiver through an optical fiber, by which they are transformed to electric signals, and sent to the DSP controller. Finally, the input signals are processed by the software in the DSP controller.

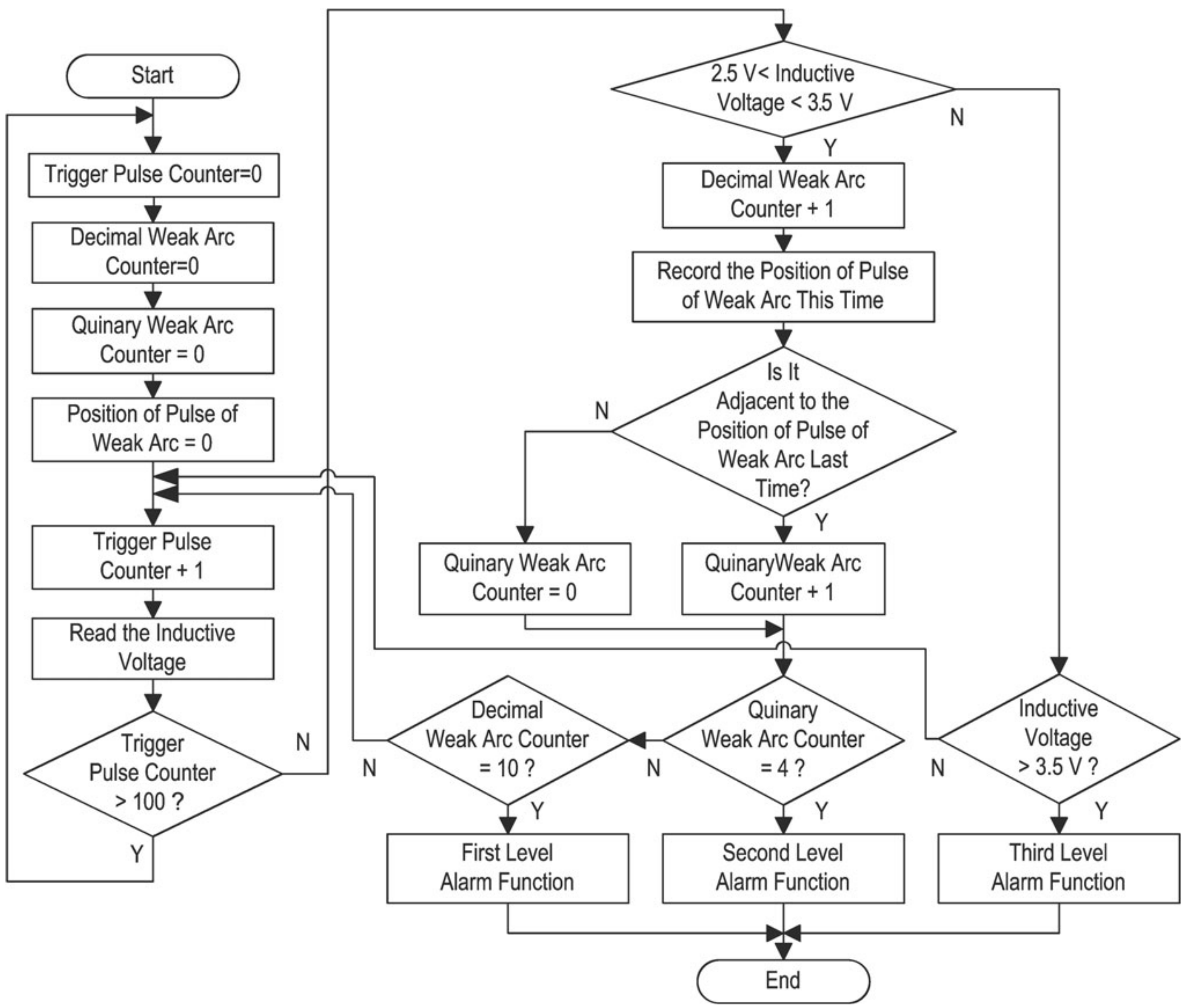

Fig. 6. Flow diagram of the arc-discharge alarm proceeding software.

If there are ten weak arc-discharge pulses counted in 100 continuous discharge pulses, it is a first-level alarm. If there are five continuous weak arc-discharge pulses, it is a second-level alarm. The strong arc discharge is the third level. On the first level, the automatic filling–exhausting equipment is set off by the DSP controller to refresh the gases in the laser discharge cavity to solve the problem of pollution.

When the first level disappears, this means that the gas media are refreshed completely, and the automatic filling–exhausting equipment should be shut down. On the second level, the DSP controller should reduce the discharging frequency appropriately, and the laser should be used on a lower level because the arc discharge was important. On the third level, the laser was broken down, and the DSP controller should be shut down immediately to avoid serious accidents in the high-power repetitively-pulsed TEA CO_2 laser system. The flow diagram of the arc-discharge alarm proceeding software is shown in Fig. 6.

4. Conclusions

The transition from a glow discharge to an arc discharge happens most frequently and affects the reliability and output quality of high-power repetitively-pulsed TEA CO_2 lasers. We designed a magnetic-field probe based on the Faraday electromagnetic induction principle, where an arc-discharge monitoring system is used in a high-power repetitively-pulsed TEA CO_2 laser system. Our experimental results showed that the magnetic-field probe is very sensitive and accurate in distinguishing between the glow discharge and the arc discharge. When arc discharge occurs, the arc-discharge-monitoring system is effective in protecting the high-power repetitively-pulsed TEA CO_2 laser system.

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