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High-power excimer and CO_2 TEA laser technology

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This article reviews the physical background and design of high-power excimer and CO_2 TEA lasers, including a detailed discussion of electrode structures and pre-ionization, gas circulation and acoustic wave management as well as high-voltage switching and magnetic pulse compression technology. Chemical problems associated with the operation of excimer and CO_2 lasers, the lifetimes of various laser components, and operating costs are also discussed.

Introduction

Lasers have established themselves firmly as indispensable general tools in a large number of production processes, such as cutting, welding and surface treatment. In the multi-kilowatt range, the continuous CO_2 laser is mainly employed, while for lower powers and for special applications cw and pulsed Nd: YAG lasers are increasingly used.

Because of their unique properties, which set them apart from conventional lasers, high-power, high-repetition-rate excimer and CO_2 TEA (from transverse excitation atmospheric) lasers have become increasingly important in several specialized industrial applications such as photolithography, paint removal, laser-ultrasonic testing of aircraft and isotope separation.[1,2]

The acceptance of these lasers has been relatively slow, mainly because they employ comparatively complex technology, their output has been relatively low and in particular the excimer laser had the reputation of being expensive and unreliable. However, this has changed in recent years; laser outputs have increased and today excimer and CO_2 TEA lasers with several hundred watts of average power are commercially available and outputs in the kilowatt range have already been demonstrated. In addition, reliability has increased dramatically to the stage where these lasers are now ready to be incorporated into production processes.

This paper gives a short introduction to the basic physics of excimer and CO_2 TEA lasers and summarizes typical output parameters. In the second part, the most important laser engineering aspects will be discussed, including a discussion of electrode structures and pre-ionization, gas circulation and acoustic wave management as well as high-voltage switching and magnetic pulse compression technology. Chemical problems associated with the operation of excimer and CO_2 lasers, and the lifetime of the various laser components will also be discussed.

Background

Spectroscopy

The CO_2 laser operates on vibrational-rotational transitions between low-lying vibrational levels in the ground electronic $^1\Sigma$ state of the CO_2 molecule. There are two main lasing bands originating from the (00^01) (asymmetric stretch) level going to the (10^00) (symmetric stretch) level at 10.6 μm and to the (02^00) (bending) level at 9.4 μm. Bands consist of P-branches ($\Delta J = -1$) and R-branches ($\Delta J = +1$), with lines according to the J number of the lower level and designated as, for example,

9R16 = 9.4 μm band, R-branch, (00^01 $J = 17$) → (02^00 J = 16)

10P20 = 10.4 μm band, P-branch, (00^01 $J = 19$) → (00^00 $J = 20$).

The quantum efficiencies of the 10.6 μm and 9.4 μm transitions are 41% and 52%, respectively, resulting in relatively high achievable overall laser efficiencies. The CO_2 laser can be made to lase on a large number of transitions in the ranges of 9.35 –9.85 μm and 10.3–10.85 μm for the 9.4 and 10.6 μm bands, respectively. The population of the rotational levels is governed by the Boltzmann distribution, resulting in the P20 line at 10.6 μm being dominant at room temperature. By introducing grating wavelength selection in the laser cavity, the laser can be tuned to a large number of individual lines of the emission bands.

Excimer lasers derive their name from the class of molecule employed as the active lasing species. An excimer is a molecule which possesses a bound electronically excited state and an unstable repulsive ground state. A large number of excimer systems have been made to lase, covering the spectral range from 126 nm in the vacuum ultraviolet to 557 nm in the visible; however, only a few of these are of commercial importance. These are the monohalides ArF (193 nm), KrF (248 nm), XeF (351 nm) and XeCl (308 nm) and, because of its extremely short wavelength of 158 nm, the inter-halogen molecule F_2.

The excimer molecule may be formed in an electrical discharge from the constituent laser gases. The laser transition then occurs between the bound upper state and a repulsive or only weakly bound ground state. Because of this unstable ground state, excimer lasers are four-level lasers, which do not suffer from 'bottlenecking' and have therefore an inherently high efficiency.

The excimer formation between the inert rare gas and the halogen atoms can be explained by the change in chemical reactivity of the rare gas atom after electronic excitation. While the rare gas atom possesses a closed electron shell in the ground state, its electron shell structure in the excited state closely resembles that of the neighbouring alkaline atom, which is highly reactive and readily forms a stable molecule with halogens. By analogy, the excited rare gas atoms form stable rare gas halides.

Excitation mechanism

In a gas discharge the direct electron impact excitation of the (001) level of the CO_2 molecule is very small, resulting in poor laser performance. However, adding nitrogen to the gas mixture leads to resonant energy transfer from the $\nu = 1$ vibrational energy level of N_2 to the (001) level of CO_2. This transfer is highly efficient, since the energy difference between the levels is only 18 cm^{-1} and the $\nu = 1$ level of N_2 is metastable with a very long lifetime. N_2 is readily vibrationally excited by electron impact and

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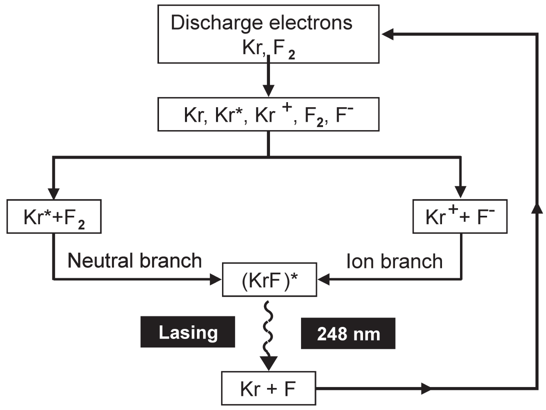

Fig. 1. Dominant formation kinetics of (KrF)*.

higher excited vibrational levels decay rapidly, ending up in the $\nu = 1$ level, resulting in good laser excitation efficiency. CO_2 lasers can be operated cw at low gas pressures or pulsed at pressures close to and exceeding atmospheric pressure.

The rare gas halide laser is excited in a gas mixture, which typically contains a few millibars of the halogen donors F_2 or HCl, a few tens of millibars of the active rare gas and several bars of helium or neon acting as a buffer gas. The production of the excited excimer molecules in an electrical discharge relies on complex plasma reaction processes. As an example, a simplified reaction scheme for KrF is shown in Fig. 1. The formation of the rare gas halogen molecule is dominated by two reaction channels: the ion channel, where ion pair recombination of a positive rare gas ion and a negative halide ion takes place in the presence of a third body (a buffer gas), and by the neutral channel, where a rare gas atom in an excited state reacts with a halogen molecule in the so-called 'harpooning' reaction. These reactions take place on a nanosecond time scale and can be very efficient, with upper laser level production efficiencies of several tens of a per cent. The short spontaneous lifetime of the upper laser level, together with its large bandwidth and short wavelength, lead to a small stimulated emission cross section. The excitation rate has to compete with fast loss processes, collisions and spontaneous decay, leading to the deactivation of (KrF)* with a combined time constant of a few nanoseconds. As a result, pump power densities exceeding 1 MW/cm^{-3} are required for the excitation of excimer lasers, which can be reached only in pulsed systems. Excimer lasers are therefore intrinsically limited to the pulsed mode of operation.

Pumping techniques

Pulsed CO_2 and excimer lasers generally employ electric discharge excitation by fast transverse glow discharges generated between two elongated discharge electrodes. CO_2 lasers operated under these conditions at atmospheric pressure are called CO_2 TEA lasers. A schematic diagram of a discharge excited pulsed gas laser employing a double-discharge excitation scheme is shown in Fig. 2. Electrical volume discharges in a high-pressure gas are inherently unstable and, unless precautions are taken, always degrade into streamer and arc discharges after a short interval. These are inefficient in exciting the laser gas and can severely damage the electrode structure.

Generation of a stable glow discharge requires, first, preionization of the gas volume in the discharge gap, prior to the triggering of the main discharge. This provides a uniformly distributed starting electron density of approximately 10^6 to 10^8 cm^{-3}. Pre-ionization is generally accomplished by UV radiation, generated by auxiliary spark or corona discharges in close proximity to the main discharge electrodes. Second, the laser electrodes have to be carefully profiled in order to provide a highly uniform electric field distribution between the discharge electrodes and avoid field concentrations near the electrode edges. Electrode profiles are generally calculated analytically[2] and are manufactured to a tolerance of a few micrometres using numerically controlled milling machines. Using this technology, outputs of up to several joules and repetition rates in the kHz range can be achieved.

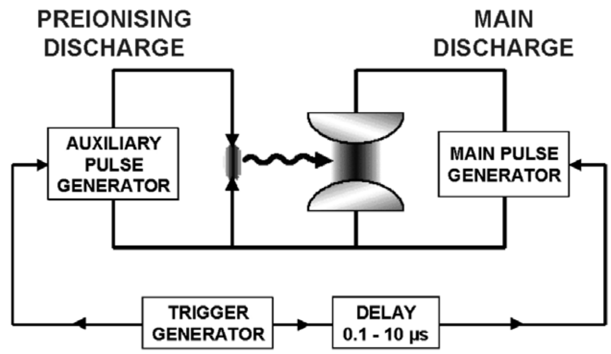

Fig. 2. Schematic diagram of double-discharge excited CO_2 TEA and excimer laser.

Beam properties

CO_2 TEA lasers with average outputs of up to 750 W and repetition rates in excess of 1000 Hz are commercially available.[4] Pulse durations depend on gas mixture and discharge excitation parameters and range from 50 to several hundred nanoseconds.

Representative average output powers of commercial excimer lasers[5] are shown in Fig. 3. The highest outputs of between 180 and 300 W are available from the KrF and XeCl lasers, whereas those of ArF and XeF lasers are about 70 W. F_2 lasers at 157 nm in the vacuum ultraviolet (VUV) are available with up to 20 W. These average powers are achieved with output energies of a few hundred millijoules and repetition rates in the range of 100–300 Hz. Maximum values for pulse energies and repetition rates of up to 3 J and several kHz, respectively, are available. Commercial excimer lasers can in general be operated with a variety of gas mixtures generating outputs on the various emission lines in the same laser system. However, lasers, optimized for a particular wavelength, are also available. The pulse duration of excimer lasers is determined by the duration of the stable glow discharge and pulses are terminated by discharge instabilities towards the end of the excitation pulse. Pulses are generally in the range of 10–50 ns and can be varied over a limited range by the operating conditions of the laser.

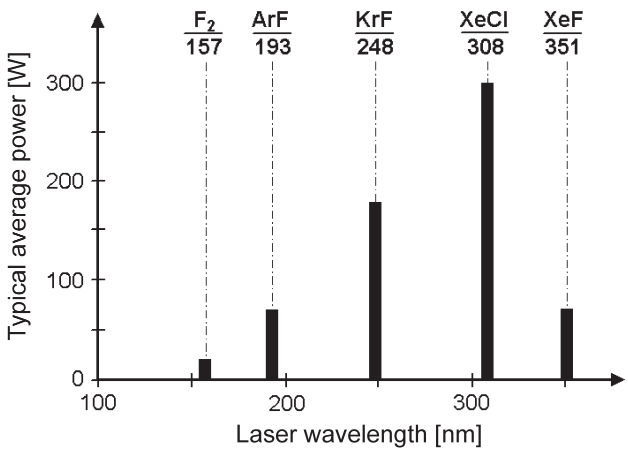

Fig. 3. Average output power of commercial excimer laser systems.

The output beam of CO_2 TEA lasers is generally multi-mode, with a rectangular cross section determined by the discharge dimensions. By introducing mode selection apertures or beam profilers,[6,7] single mode output, at reduced output energies, can be achieved. The beam properties of the excimer laser are a result of its high gain of several % cm^{-1}. The high gain does not allow the formation of stable cavity modes, but leads to a laser beam, which is formed in only 1–3 passes through the laser medium, and consequently possesses a beam divergence governed by the plasma dimensions of the laser. The normally rectangular discharge cross section results in a rectangular beam with a top-hat intensity profile and a typical beam divergence of 3 mrad in the discharge direction and an approximate Gaussian profile with a divergence of 6 mrad transverse to the discharge. A significantly improved intensity distribution of the beam can be obtained by the use of external beam homogenizers,[2] which make use of multi-faceted optics to provide a uniform intensity distribution in the target plane. A near-diffraction-limited laser beam can be generated with unstable resonator optics[8] and by more complex oscillator–amplifier systems.[9]

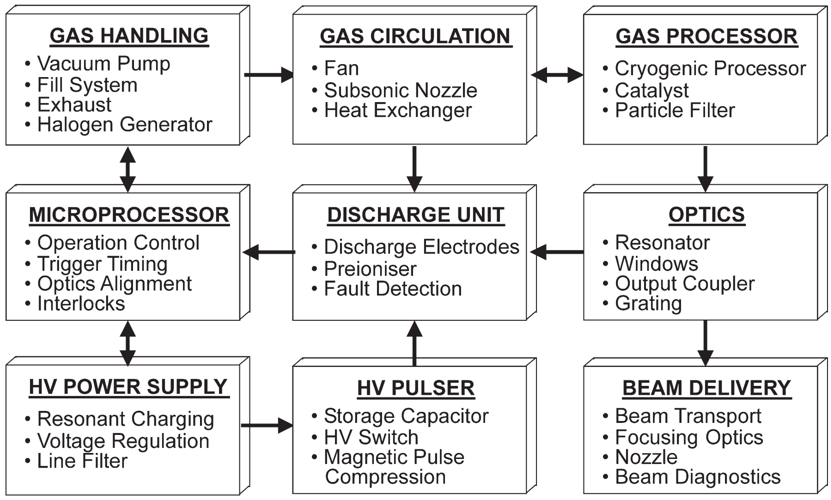

Fig. 4. Block diagram of a high average power industrial excimer laser.

Design of high-power industrial CO_2 TEA and excimer lasers

The typical layout of an industrial high-power pulsed laser system is shown schematically in the block diagram of Fig. 4. The central discharge unit contains the discharge electrodes and the pre-ionizer. The laser optics consist of IR or UV-grade windows and dielectrically coated mirrors. A custom-made beam delivery system, tailored for each particular application, has to be provided. The power conditioning system consists of a high-voltage power supply and a fast high-voltage pulsing circuit to excite the laser. A gas circulation and cooling system, to which the discharge unit is attached, is required to replace the laser gas in the discharge region between successive laser pulses and to remove waste heat. The laser gas is cleaned continuously using either cryogenic processing and particle filters in the case of excimer lasers or catalytic conversion for the CO_2 laser. Cleaned gas is then injected into the window areas to avoid degradation of the laser optics. Peripheral units are responsible for the gas handling and microprocessor control of the system.

The design of lasers to be used in industry is more demanding than that for scientific and laboratory applications. In contrast to scientific applications, where performance is the single most important consideration, issues such as low operating cost, long-term reliability, ease of operation and safety are of overriding importance. As a consequence, designers prefer simple and proven technology, being cautious of possibly more efficient, but more complex and therefore higher risk approaches.

The design of pulsed gas lasers is complicated by several factors. Voltages of more than 40 kV are used for the excitation, requiring efficient, high-dielectric-strength insulators. Radicals and ozone generated in the discharge of CO_2 TEA lasers and the halogens fluorine and chlorine used in excimer lasers are highly corrosive. Excimer lasers are operated at gas pressures of up to 5 bar and contain gas volumes of up to several hundred litres, making high-strength mechanical construction necessary. These factors severely limit the choice of materials that can be employed for the construction of the lasers.

In principle, there are two design options for power scaling of pulsed lasers into the kilowatt regime: they can either be operated at relatively low repetition rates with associated increased pulse energies of more than 1 J, or they can be run at increased repetition rates of several kHz, where the pulse energies then can be kept low. While the electrical power conditioning system generally favours small pulse energies at high repetition rates, the gas circulation unit becomes increasingly bulky and costly at high repetition rates. These two conflicting requirements have to be carefully weighed and traded off against each other in order to arrive at an optimized system.

The key technological problems associated with the high-repetition-rate, high-average-power operation of pulsed lasers are related to discharge stabilization, the pulsed power conditioning system and the gas circulation system.

Discharge system

There are several electrode structures and pre-ionization techniques that can be employed for the excitation of the laser. These determine the discharge cross section and quality and with it the laser energy output and efficiency, which in turn have a strong influence on the design of laser and power conditioning system. The electrode systems commonly used for the excitation of high-repetition-rate, high-power pulsed lasers consists of solid discharge electrodes using side pre-ionization, generally by spark discharge arrays or corona pre-ionizers.

The mechanical design and schematic circuit diagram of an electrode arrangement in use is shown in Fig. 5. It employs

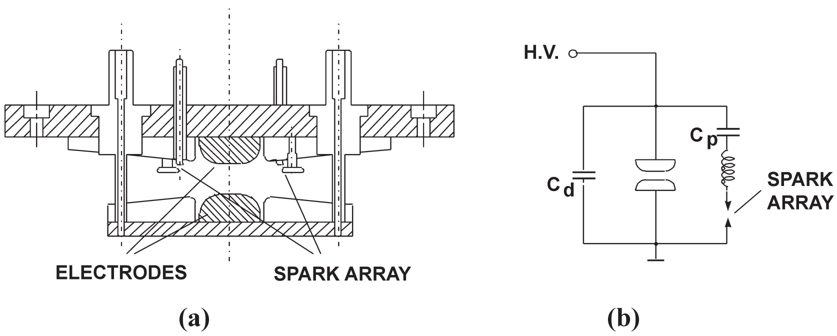

Fig. 5. Electrode structure and pre-ionization arrangement. **a**, Cross-sectional view; **b**, circuit diagram.

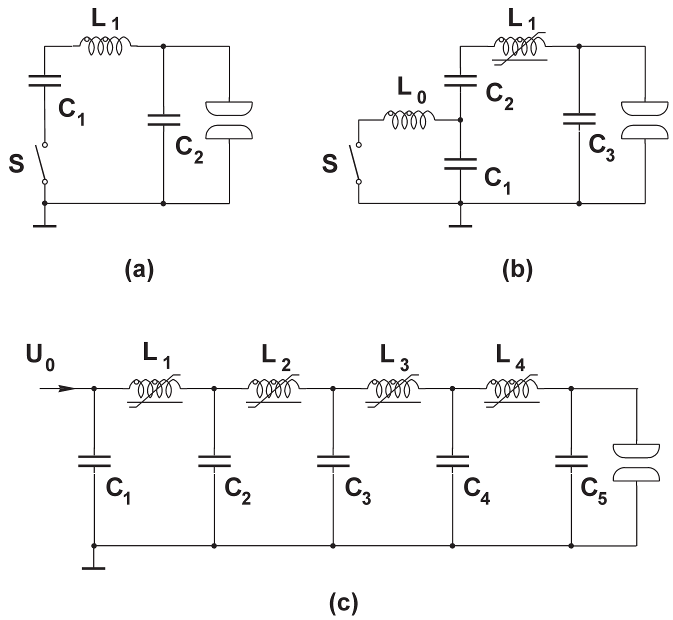

Fig. 6. Excitation circuits for high-power excimer laser. **a**, C–C transfer; **b**, L–C inversion with single-stage pulse compression; **c**, multi-stage pulse compression. S, switch; C, capacitor; L, inductor.

a grounded electrode mounting plate, supporting a pair of stainless steel or nickel-plated uniform field discharge electrodes. Pre-ionization is effected by two spark arrays located adjacent to the electrodes. The electrode length is 800 mm with a separation of 20 mm. The spark arrays are electrically connected in parallel with the electrodes and are individually and inductively ballasted. Their energy is limited by capacitor C_p, which allows for fine-tuning of the amount of energy channelled into the pre-ionization. This energy has to be minimized in order to avoid excessive spark electrode burn-off at the high repetition rates. The electrode assembly incorporates flow profiles which are part of the gas flow nozzle design.

Pulsed power conditioning

Pulsing circuits used for the excitation of high-power, high-repetition-rate pulsed lasers have to be capable of delivering peak currents of several tens of kiloamps at voltages of 30–50 kV. Commonly employed circuits are shown in Fig. 6. The basic C–C transfer circuit in Fig. 6(a) employs simple matched energy transfer from storage capacitor C_1 to the discharge peaking capacitor C_2 and is limited by available switching elements to medium power levels. Thyratrons are the only switches available for this task. They are expensive, however, and their lifetime is limited in high-power applications. Higher power levels can be obtained with circuits using magnetic pulse compression[10] [Fig. 6 (b), (c)]. These circuits employ an intermediate energy store to which the primary energy is initially transferred at a slow rate, thereby reducing the load on the primary switch. This can lead to a marked increase in thyratron life. The energy is then transferred rapidly to the laser by a magnetic switch, which is realized by a saturable inductor employing ferrite or amorphous metal as core material. Since saturable inductors are passive switching elements, they can be designed for very high peak currents and hold-off voltages and have a practically unlimited lifetime.

Thyratrons can be eliminated entirely by the use of multistage pulse compression techniques [Fig. 6(c)] and all-solid-state switching by semiconductor switches.[11] This technology is a major advance towards highly reliable industrial systems, since solid-state switches can have a practically unlimited lifetime.

A compressor has been designed to deliver output pulses of 20–25 J with a peak output voltage of 37.5 kV and 120 ns rise time (10–90%) to the electrodes. Input voltage pulses of 42 kV are supplied by a thyristor or IGBT switched resonant power supply,[12] which charges capacitor C_1 through a voltage step-up transformer with a transfer time of 40 μs. The compressor has been used to drive the high-repetition-rate laser at repetition rates of up to 2000 Hz.

Gas flow system

Repetitive operation of pulsed gas lasers requires gas exchange in the discharge volume between successive excitation pulses of the laser. This is necessary to remove waste heat and discharge products which otherwise would lead to a degradation of the discharge quality and arcing for subsequent excitation pulses. A clearing ratio can be defined as the volume of gas passing through the discharge region between successive laser pulses divided by the discharge volume. Clearing ratios of 2–3 are needed,[13] necessitating gas flow velocities of 50–100 m s^{-1} at repetition rates of 1–2 kHz. Clearing can be complicated by the pre-ionization discharge, which effectively increases the discharge width, and by insufficient flow clearing of boundary layers in the vicinity of the electrodes, causing downstream arcing.

The flow loop design is complicated by mechanical distortions of the system at the high operating pressures of up to 5 bar for excimer lasers. Using finite element structural analysis, an optimized flow system configuration has been devised which is illustrated in Fig. 7. The cylindrical flow system employs a pressure vessel with an outer diameter of 1850 mm and a total gas volume of approximately 1300 l. It uses a magnetically coupled, two-stage axial fan, driven by a 15-kW variable-speed induction motor which provides flow velocities of 90 m s^{-1} at fan speeds of 3900 rpm.

High-repetition-rate operation is further complicated by the disturbance of the discharge medium by acoustic waves and shock waves, which are caused by the rapid energy deposition into the discharge volume. Acoustic and shock waves lead to gas density perturbations which are detrimental to the discharge quality and adversely effect the far field beam quality of the laser output. Density non-uniformities have to be maintained at less than 1% to avoid discharge instabilities and at less than 0.1–0.01% to ensure adequate beam quality.

Several measures can be employed to reduce the effect of acoustic waves. Longitudinal waves travelling in the up- and downstream directions can be reduced by avoiding obstacles in

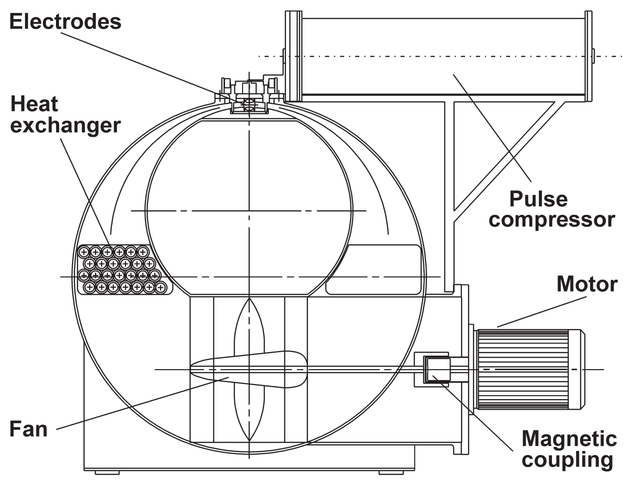

Fig. 7. Cross section of a gas flow system.

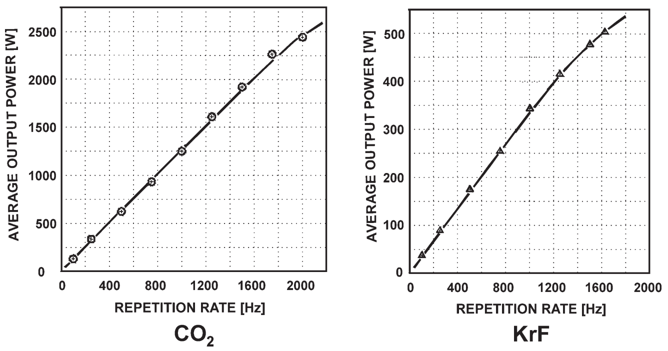

Fig. 8. Average output power of CO_2 TEA laser and KrF laser versus repetition rate.

the flow loop, such as current feed-throughs, flow loop corners and cross-section discontinuities. They can be dissipated and dampened to acceptable levels using flow grids, side wall dampers and mufflers. Transverse waves, travelling in the direction of the optical axis, can be 'walked' out of the cavity by employing tilted side walls. These waves, reflected between the electrode surfaces, can be diffracted and dissipated by the use of suitable electrode contours and damping structures, incorporated with or placed in the vicinity of the electrodes.

Experimental results

A simple optical Schlieren technique[14] employing an expanded HeNe laser beam has been used to study the recovery time for optical density perturbations in the laser medium following the electrical discharge. Results obtained for the CO_2 TEA laser indicate that gas density fluctuations are reduced to the background level after approximately 250 μs, which is considerably shorter than the inter-pulse time at a repetition rate of 2 kHz.

The repetition rate of the laser is limited by downstream arcing to 2 kHz for CO_2 TEA and 1.6 kHz for excimer laser operation. The average output power of the laser versus repetition rate is shown in Fig. 8. The average output power increases approximately linearly with repetition rate, reaching maximum values of 2000 W for CO_2 TEA and 520 W for KrF laser operations at repetition rates of 2.0 and 1.6 kHz, respectively. Single-shot and low-repetition-rate pulse energies of 1 J and 350 mJ, with corresponding overall efficiencies of 5% and1.45%, have been measured for CO_2 TEA and KrF excimer laser operations, respectively. At higher repetition rates, the output falls sharply as a result of degrading discharge quality.

Laser reliability and operating costs

CO_2 TEA and excimer lasers in the industrial environment have to meet more stringent design standards than those in the scientific laboratory. In industrial applications operating costs and system reliability are of primary importance. To minimize costly system down-time, preventative maintenance has to be carried out at scheduled intervals. This requires accurate figures for component lifetimes. Extensive lifetime testing, undertaken by laser manufacturers in recent years, has resulted in improved component MTBF figures approaching the 10^{10} shots level.[2,5] The main problem areas are the laser discharge unit, the electrical switching circuitry, and gas and optics lifetimes.

The discharge unit, consisting of discharge electrodes and pre-ionization pin electrodes, has an inherently limited life because of discharge sputtering. Lifetimes of the discharge electrodes can be extended by the use of special alloys, improved discharge homogeneity and reduced specific energy loading. Burn-off of pre-ionization pin electrodes tends to be rapid at high repetition rates, but can be kept at an acceptable level by minimizing the energy fed into the pre-ionization. Electrode lifetimes for high average power systems approach the 5×10^9 shots level.

The components in the electrical excitation circuit are subject to considerable stress because of the high operating voltages and short current rise times required. Thyratrons, employed as high-voltage switching elements, are still the main life-limiting components, with lifetimes of approximately 10^9 shots, using magnetic pulse compression. All-solid-state switched designs have eliminated the need for high-voltage switching elements entirely and the lifetimes of solid-state switches should effectively be unlimited.

Gas lifetimes are currently the most important operating cost factor, especially for excimer lasers. Gas lifetime is limited mainly by halogen depletion and by the formation of impurities generated by the electrical discharge. Lifetimes have been extended by careful selection of construction materials as well as by the use of on-line gas processing systems, which in the case of the excimer laser cryogenically remove gas impurities and replenish the halogen gas component. Gas lifetimes in excess of 10^8 shots have been achieved for the KrF laser. In CO_2 TEA lasers carbon dioxide is lost by electron impact dissociation, resulting in a build-up of O_2 and CO, which are both detrimental to laser operation. On-line catalytic converters are employed to maintain the gas balance. The use of microprocessor-controlled gas renewal systems permits continuous operation of the laser at stabilized power levels.

Optical materials employed for CO_2 TEA and excimer lasers have to be transmissive in the 10.6 μm and 150–400 nm wave length ranges, respectively, and be resistant to chemical degradation and radiation-induced defects. ZnSe is most commonly used for CO_2 lasers and MgF_2 and CaF_2 for excimer lasers, because of their low absorption and relatively high damage thresholds. In excimer lasers optics deteriorate mainly because of particulate deposits resulting from electrode sputtering and by carbon deposits due to photolysation of halogenated-carbon gas impurities. Laser windows therefore have to be cleaned at regular intervals. Cleaning intervals have been extended by the incorporation of electrostatic particle filters and by window purging to 10^9 shots. The mirror mounts are furnished with facilities for purging of the laser windows with cleaned gas and gate valves, preventing gas loss during optics cleaning.

State of the art component and gas lifetimes in terms of number of shots are listed for CO_2 TEA and KrF lasers in Fig. 9.

Conclusions

Over the past 20 years, CO_2 TEA and excimer lasers have evolved from low-power, unreliable laboratory devices to industrialized systems with average output powers of several

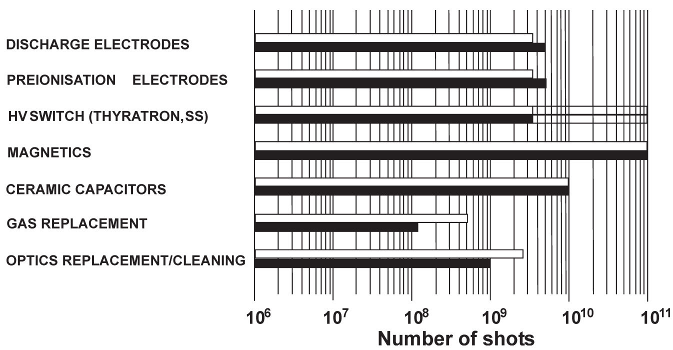

Fig. 9. State of the art component and gas lifetimes CO_2 TEA (white bars) and KrF (black bars) lasers.

hundred watts and MTBF figures in excess of 1000 hours. Commercially available lasers today cover a wide range of output parameters from small waveguide systems with pulse energies of 50 μJ and corresponding average powers of 100 mW to large, transversely excited systems delivering pulses of several joules and average powers approaching 1000 W.

The main thrust in CO_2 TEA and excimer laser development at present is in the direction of high average power, high-repetition-rate systems. Related issues are magnetic pulse compression and solid-state switching technologies to reduce the requirements for high-voltage switches, double and long pulse excitation for improved laser efficiency and X-ray pre-ionization to generate plasmas of large cross section and high pulse energies.

CO_2 TEA and excimer lasers can be adapted to a wide range of established and potential industrial applications, ranging from micro-technology and photolithography to the modification of large surface areas, materials testing and isotope separation. Many of these applications are already in full-scale operation, proving that they can provide viable alternatives to often more costly conventional technology. With new, higher power and more reliable industrial lasers reaching the market, applications can be expected to grow significantly.

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