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Review Article

Applications of CO_2 Laser in Medicine

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ABSTRACT

Since its invention in 1960, the laser has found diverse application in engineering and industry because of its ability to produce high power beams. In the field of metal processing, laser applications include welding, drilling, cutting, scribing, machining, heat treatment, cladding and alloying. In other fields, such as medical surgery, lasers are also used extensively. Lasers are used in a wide range of applications such as, laser surgery, heat treatment, welding and drilling. The much higher reflectivity of CO_2 laser from liquid, vapor and plasma of a tin target results in the production of optically thinner plumes with higher velocity and in a better formation of plasma properties towards more efficient extreme ultraviolet lithography source. However, the spikes in the temporal profiles of current CO_2 laser will additionally affect the properties of the produced plasma. The CO_2 laser also offers more comfort to patients by reducing intraoperative bleeding and postoperative edema, facilitating the process of wound healing after surgery. The boundaries between the tissues receiving heat damage and the surrounding intact tissue are very well defined.

Keywords: Laser, CO_2 laser and Applications.

1. INTRODUCTION

The carbon dioxide (CO_2) laser was first introduced in 1964 by Patel and has been extensively used in the next two decades as an incision tool in increasingly wide areas, such as neurosurgery, dermatology and plastic surgery, otorhinolaryngology, ophthalmology, gynecology and general surgery. In 1984, its reliability resulted in its approval by the U.S. Food and Drug Administration, and thus, medical use of lasers became more prevalent. Currently, the CO_2 laser is considered an indispensable piece of diagnostic and therapeutic equipment. The CO_2 laser produces a beam of infrared light with the principal wavelength bands centering at 10,600 nanometers. Collisional energy transfer between the nitrogen and the carbon dioxide molecule causes vibrational excitation of the carbon dioxide, with sufficient efficiency to lead to the desired population inversion necessary for laser operation. It is easy to actively Q-switch a CO_2 laser by means of a rotating mirror or an electro-optic switch, giving rise to Q-switched peak powers up to gigawatts (GW) of peak power.

Over the last 40 years, lasers have been used extensively in various fields of medicine. The CO_2 laser is a good example, being widely used in ENT and gynecology. It emits infrared radiation, which is readily absorbed by water. During irradiation with CO_2 laser, the tissue temperature begins to rise and when it reaches 100°C water begins to evaporate. This increases the pressure within the organic matrix leading to so called micro explosions. Further irradiation with subsequent tissue desiccation produces a temperature rise of up to a 1000°C, which causes thermal decomposition. Most of the oxygen in the reaction zone is used up, so that tissue disintegration proceeds under low O_2 concentration. As a result of this, not only the typical products of complete oxidation, CO_2 and H_2O, are produced but also products characteristically arising under oxygen deficiency. These include aldehydes, ketones, aromatic alkyles, polycyclic aromatic compounds, pyrroles, pyridines and thioles. It is well known that the degree of carbonization is directly proportional to the concentration of the products of incomplete oxidation and inversely proportional to the concentration of CO_2 and H_2O of combustion[1]. The incomplete thermal oxidation also causes carbonization of the irradiated tissue, which reduces the depth and quality of the laser incisions. Thus, improvements in quality and precision of laser incisions can be achieved by optimizing the oxidation process.

2. APPLICATIONS

Because of the high power levels available, CO_2 lasers are frequently used in industrial applications for cutting and welding, while lower power level lasers are used for engraving. They are also very useful in surgical procedures because water absorbs this frequency of light very well. Some examples of medical uses are laser surgery, skin resurfacing and dermabrasion. Researchers in Israel are experimenting with using CO_2 lasers to weld human tissue, as an alternative to traditional sutures. The common plastic absorbs IR light in 2.8-25 µm wavelength bands, so CO_2 lasers have been used in recent years for fabricating micro fluidic devices from it with channel widths of a few hundred micrometers. Because the atmosphere is quite transparent to infrared light, CO_2 lasers are also used for military range finding using LIDAR techniques. The CO_2 laser is an integral instrument in all aspects of otolaryngology. The numerous types of uses vary from endoscopic resection of malignant laryngeal tumors to the precision of laser stapedotomy as well as to cosmetic skin treatment, but its most effective use is in laryngology and bronchoesophagology[2]. Sheet-metal cutting is the single largest in terms of sales, global industrial laser application. CO_2 lasers dominate this application due to their good-quality beam combined to high output power. It is estimated that more than 40,000 cutting machines using CO_2 lasers have been installed worldwide.

CO_2 laser mostly interacts with a polymer, photo-thermally. When a CO_2 laser is irradiated on a polymer surface, it is strongly absorbed and raises the temperature of the polymer. The polymer is then melted, decomposed and leaving a void in a work piece. Different kinds of polymers can be used for micro fluidic applications by taking a choice care that the fluids in the device do not interact chemically with the device. However just some of the polymers can be machined with CO_2 laser. Most of the polymers leave contamination and soot when exposed to CO_2 laser irradiation. For example, polycarbonate (PC) leaves a brownish residue after exposing to the CO_2 laser. Among different kind of polymers, poly methyl methacrylate (PMMA) is the most suitable polymer for CO_2 laser machining. When PMMA heats up by the CO_2 laser, after passing the glass temperature, the material turns into a rubbery material and by increasing the temperature; the chains are broken by depropagation process and decompose with a non-charring process to its MMA monomer which is volatile[3].

Because of its affinity for water-based tissues, the CO_2 laser has become a favorite instrument of oral surgeons for treatment of pathologic conditions of the oral mucosa. The CO_2 laser has been recommended to treat benign oral lesions, such as fibromas, papillomas, hemangiomas, gingival hyperplasias with different causes, aphthous ulcers, mucosal frenula or tongue ties, as well as premalignant lesions such as oral leukoplakias. Some reports on the use of the CO_2 laser also support the possibility of treating malignant oral diseases in early stages with excisional biopsies. A study demonstrated dissemination of cancer cells into the blood circulation upon incisional biopsies with the scalpel, resulting in an increased risk of metastasis. Here the CO_2 laser, with its sealing effect on vessels smaller than 500 µm in diameter, could be an advantage and therefore even prevent occult micro metastasis. More recent reports have also mentioned the diode laser with wavelengths ranging from 810 to 980 nm in a continuous or pulsed mode as a possible instrument for soft tissue surgery in the oral cavity. Based on the photo thermal effect of the CO_2 and diode lasers, lesions of the oral mucosa are removed with an excision technique or vaporization procedures[4]. The major advantages mentioned in the literature for the use of CO_2 and diode lasers are minimal postoperative swelling and scarring, improved wound healing and decreased postoperative pain. Additionally, both lasers are reported to have some advantages over a scalpel in soft tissue surgery. Unlike the scalpel, the laser instantly disinfects the surgical wound and due to its hemostatic effect affords largely bloodless surgery, allowing a noncontact type of operative procedure and therefore no mechanical trauma to the tissue.

Use of CO_2 laser resurfacing is a powerful tool for the treatment of several skin conditions, such as fine and coarse wrinkles, scars of various origins, uneven pigmentation and dilated pores. Some major drawbacks have progressively limited its use: the need for effective anesthesia, the downtime associated with treatment, the risk of hyper pigmentation and scarring, the need for intensive postoperative care, the long-lasting erythema and the need to avoid sun exposure for extended periods of time. It was developed to overcome the aforementioned drawbacks in the treatment of photo damaged skin. Fractional laser resurfacing with the mid-infrared lasers uses an invisible laser beam, which is strongly absorbed by water in order to reverse the effects of skin aging and scarring. Near infrared wavelengths cause significant pain and require some form of anesthesia. They are also time-consuming and costly. Another disadvantage is that most of these devices are only capable of performing one kind of treatment. The use of ablative lasers in a fractional mode was introduced in 2006. The lesser depth of immediate tissue necrosis, in comparison with the mid-infrared wavelengths, together with the possibility of further heat deposition in the dermis, significantly reduces the pain caused by the procedure without decreasing its efficacy. A new CO_2 laser with less penetration was shown to be more tolerable, but the 1.3 mm spot still makes some local anesthesia and cooling necessary. The spot distribution is uniform as with the mid-infrared devices. A more recent CO_2 laser system with a micro spot system fractional modality has been developed with a new scanning algorithm that keeps the longest possible interval between two adjacent spots, in order to minimize the heat accumulation around the treated areas. This is supposed to significantly reduce the pain during the procedure[5].

Since the CO_2 laser was introduced in 1964, the available beam power has increased from a few mill watts to values above 100 kW continuous-wave. In the field of industrial applications, however, only powers up to approximately 20 kW are being used although industrial lasers of more than twice this power are in principle available. When considering the distribution of lasers with respect to output power and field of application, it can be concluded that most of the lasers are used for cutting at beam powers of up to about 2.5 kW. The number of applications of beam powers up to approximately 6 kW, e.g., in welding or surface treatment, is significantly lower; however, it is increasing steadily. Applications up to 12 kW can only be found for a very small number of examples such as in heavy-section welding. Finally, industrial lasers with powers above 12 kW are presently mostly used for research and development means, where almost no industrial users can be found. Due to this situation it must be looked for the reasons for the existing gap between the availability of very high power lasers and the acceptance by industrial users. Surely, the main reason for this discrepancy is the high expenses connected with laser applications, which are composed of investment, operating and maintenance costs. As the most important criterion for applying lasers is the economical aspect, it must be tried to reduce the cost of the laser source as far as possible, however, without losing the advantages of the laser radiation for materials processing. Studies of the cost of beam energy have shown that CO_2 lasers are by far the cheapest beam sources, followed by Nd: YAG lasers at twice the cost and chemical oxygen iodine lasers (COILs) at four times the cost[6]. Also, from the technical point of view, the CO_2 laser is the best candidate for a 100-kW source, since no principal limitations for scaling CO_2 lasers up to very high beam powers are obvious at present. As a consequence, the most important problem which must be considered is not the implementation of the beam power itself, but the identification of a concept which can be realized at reasonable costs.

Compact transversely excited atmospheric (TEA) CO_2 lasers find numerous scientific and technical applications. These include pulsed laser deposition (PLD), photo-chemistry, optical pumping of molecular lasers etc. These lasers can produce high energy and high average output power with high efficiency. Furthermore, these can be operated at high repetition rates. A fast high voltage and high current switch is required to initiate a volumetric discharge for pumping TEA gas lasers. Conventional exciters employ thyratrons or sparkgaps as discharge switches. However, the aforesaid thyratrons which are expensive have lifetime problems. At the same time, the sparkgaps that often require maintenance have limitations at high repetition rates. The use of all solid-state exciter (ASSE) offers several advantages over conventional excitation circuits[7]. ASSE employs solid-state switches which are combinations of high power semiconductor switches and magnetic switches. These are less expensive and more reliable, and are able to operate at high repetition rates. These do not have lifetime limitations also. Moreover, there is no warming-up time as in the case of thyratron[8].

Surgical lasers form a mainstay of treatment in many disciplines, including ophthalmology, dermatology, dentistry, plastic surgery, otolaryngology and head and neck surgery. In contrast, lasers tend to be used infrequently in most neurosurgical operating rooms, despite early optimism regarding the application of this technology shortly after its development. Unfortunately, cumbersome ergonomics of the CO_2 laser have limited its widespread use. Its long wavelength prevents its transmission using standard fiber optic cables, and bulky articulating arms with mirrors are required to transmit sufficient energy to the surgical site in direct line of sight, restricting freedom of movement. Moreover, resecting a tumor requires constant refocusing of the CO_2 beam if it is coupled to a microscope. Without fiber optic delivery, use of a CO_2 laser through an endoscope is impossible. These shortcomings have kept most neurosurgeons from adopting the CO_2 laser as a regular surgical tool, despite its many potential benefits. Dielectric mirrors are able to efficiently reflect light through a narrow range of incident angles with low absorption losses. The existence of an omnidirectional reflection band allows a dielectric surface to reflect light of any incident angle, known as omnidirectional reflectance. A hollow optical fiber has been created that is lined with an interior omnidirectional dielectric mirror that has a photonic band gap for the transmission of CO_2 laser light with low absorptive losses[9]. This PBF assembly allows for the flexible delivery of CO_2 laser energy in a range of power settings similar to those used for surgical applications with rigid delivery systems, but with the advantage of using a laser delivery apparatus that is on a small scale and does not use a large, inconvenient assembly.

Several different methods of implant decontamination have been proposed. Neither subgingival irrigation with local disinfectants nor local antibiotic therapy with tetracycline fibers provided conclusive therapeutic effects. Systemic administration of antibiotics has also been used in the treatment of peri-implantitis; however, the success was limited due to resistant strains of bacteria and ineffective drug dosages. Citric acid application with sandblasting, sandblasting alone or chlorhexidine irrigation has also been recommended. However, implant decontamination using sandblasting units has been associated with risks such as emphysema. In contrast, encouraging results in dogs have been reported using the CO_2 laser for decontamination to improve reosseointegration. Findings of this animal study suggested that the laser may be an effective therapeutic modality in the treatment of peri-implantitis[10].

The use of laser cutting has become widespread in non-metallic materials such as polymers, composites or ceramics. There are, however few data regarding high strength steel cutting. It is difficult to predict the quality of the cut, due to the coupling of thermal effect of the laser and the oxidation of the material by the oxygen used as assisting gas. The exothermal reactions of iron and other alloy elements are complex and AHSS steels have a high content of alloy elements, which can lead to differences with regard to the cutting of common steels. Laser cutting is a process in which the material is heated to its melting or vaporization temperature. Heating is achieved by concentrating the energy in a very small spot. This allows the cutting of almost all types of materials with thickness of up to 20 mm in the case of steel sheets without the need for very high levels of energy. There are different laser generators depending on the type of the laser-active material they use. Each type of laser creates a laser beam at a given wavelength. The CO_2 generators are the most used for steel cutting with a wavelength 10.6 mm, whilst the Nd: YAG lasers generate a beam with a wavelength of 1.06 mm. In general, the Nd: YAG lasers wavelength is better absorbed by most of materials. Steel, however, has acceptable absorption levels for the beam generated by CO_2. This added to the fact that these CO_2 generators are more powerful and cheaper, explains why their use in industry is much more widespread[11].

Zinc Sulphide is an important II-VI group semiconductor with a large direct energy gap of 3.50-3.70 eV in the UV range, direct energy gap Eg = 3.68 eV for bulk ZnS[12]. It is used as a key material for light emitting diodes and other optoelectronic devices such as electroluminescent displays, Cathodoluminescent displays and multilayer dielectric filters. ZnS is highly suitable as a window layer in heterojunction photovoltaic solar cells; because the wide band decreases the window absorption loses and improves the short circuit current of the cell. In the area of optics, ZnS can be used as a reflector, because of its high refractive index (2.35) and a dielectric filter because of its high transmittance, in the visible range. Among molecular lasers, the CO_2 laser is of greatest practical importance. The high level of efficiency with laser in which laser radiation can be generated in CW and pulse operation is its most fascinating feature. In atom and ion lasers, laser radiation is the result of the electron transitions close to the limit for single or double ionization. The infrared radiation of the CO_2 laser on the other hands is the result of the energy exchange between rotational vibrational levels within the electron ground level[13].

As laser welding of plastics becomes more widely used it becomes correspondingly important to know what is happening or what should be happening in the weld. Laser welding of thermoplastic offers distinct advantages and performance capabilities such us speed, localized heat and fine spot size over the traditional plastics welding methods. Laser welding is popular in industrial applications that require rapid processes, good aesthetics and fine weld lines. To transmit the laser beam to the weld region, the top polymer layer needs to be transparent or translucent to the wavelength of the laser beam used. Heating the interface is further localized by designing the lower layer material to be laser absorbing. The fine laser beam size localizes the heat at the weld interface without altering the material surfaces or damaging the adjacent materials. These unique characteristics make laser welding especially suitable for medical, automotive and electronic applications. Laser welding can be applied to a wide range of thermoplastic polymers. It is also possible to weld materials with different melting temperatures, when there is molecular compatibility between two polymers. The welding of thermoplastics using CO_2 laser achieved, two different types of thermoplastic materials used which are PMMA which is the abbreviation of polymethyl methacrylate and HDPE which is the abbreviation of high density polyethylene[14]. Fig.1 shows the schematic representation of laser welding process.

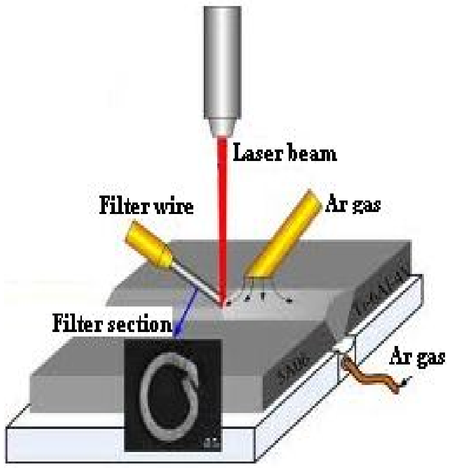

Fig. 1: Schematic representation of laser welding process

For the dielectric coated metallic hollow optical fiber, silver is normally used as the metallic layer, because silver has a high reflection rate in the infrared wavelength region. Cyclic olefin polymer (COP) is one of the normally used dielectric materials[15]. COP-coated silver hollow optical fibers obtained low-loss property not only in the infrared region but also in the visible region. Simultaneous delivery for infrared and pilot laser beam is possible by using this kind of hollow fiber. In medical laser treatment through hollow optical fiber, CO_2 laser irradiated the diseased tissue with the distal end of the fiber contacting the target. Therefore durability of the hollow fiber is important. Hollow optical fiber tip is often sterilized by an autoclave treatment for medical applications after irradiation. COP-coated hollow optical fiber has an obvious deterioration after the sterilization streatment. This can be cause by the somewhat weak adhesion between COP and silver layer[16].

The nature of a polymer surface strongly influences its properties, such as water absorption, reflection of light or dyeing. Surface treatments for polymer modification can be classified as chemical and physical methods. Chemical treatments are frequently used but new technologies are now accessible, considered environmentally friendly processes. Laser technologies can produce morphological modifications on the surface of polymers, resulting in changes in its physical and chemical properties. Induced modifications on polymer surface by laser radiation are now a significantly well known subject, as the treatment of polyamide fibres with pulsed UV-laser and different commercial lasers are available for surface modifications[17]. Adequate power levels for a specific application are very important in surface modification processes because an excessive amount of energy can be supplied, with the consequent damage of the polymer. For instance, infrared lasers like CO_2 are the most powerful lasers and, with no suitable power level, severe thermal damage can result. However, this shortcoming can be overcome by the use of pulsed-mode CO_2 lasers, easier to control than lasers operating in continuous wave mode.

CONCLUSIONS

The wavelength of laser light is extremely pure when compared to other sources of light and all of the photons that make up the laser beam have a fixed phase relationship with respect to one another. Because of its affinity for water-based tissues, the CO_2 laser has become a favorite instrument of oral surgeons for treatment of pathologic conditions of the oral mucosa. Over the last 40 years, lasers have been used extensively in various fields of medicine. The CO_2 laser is a good example, being widely used in ENT and gynecology. It emits infrared radiation, which is readily absorbed by water. During irradiation with CO_2 laser, the tissue temperature begins to rise and when it reaches 100°C water begins to evaporate. This increases the pressure within the organic matrix leading to so called micro explosions. Surgical lasers form a mainstay of treatment in many disciplines, including ophthalmology, dermatology, dentistry, plastic surgery, otolaryngology and head and neck surgery. In contrast, lasers tend to be used infrequently in most neurosurgical operating rooms, despite early optimism regarding the application of this technology shortly after its development. Unfortunately, cumbersome ergonomics of the CO_2 laser have limited its widespread use.

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