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A Study On The Carbon Dioxide Laser

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Abstract: One of the first gas lasers to be created was the carbon-dioxide laser (CO2 laser). One of the most practical kinds of lasers, it was created in 1964 by Bell Labs' Kumar Patel [22]. The most powerful continuous-wave lasers on the market right now are carbon-dioxide lasers. Additionally, they are quite efficient; the output power to pump power ratio can reach 20%. The primary wavelength bands of the infrared light beam produced by the CO2 laser are 9.6 and 10.6 micrometers (μm). [22] In order to improve its performance, a carbon dioxide laser uses carbon dioxide as its main gain medium. Nitrogen (N2), helium (He), and occasionally hydrogen (H2), water vapor, oxygen, or xenon (Xe) are added. This laser works by energizing the gas mixture to produce laser light by promoting the emission of radiation by an electrical gas discharge. In carbon dioxide lasers, the electrical gas discharge can be powered by radio frequency (RF), direct current (DC), or alternating current (AC). The wavelength of the light emitted by these lasers is 10.6 micrometers. In dermatology, they are frequently used for operations like wrinkle reduction, scar removal, and sun damage treatment. Furthermore, for accurate cutting and tissue removal, carbon dioxide lasers are employed as surgical instruments in specialties such as neurosurgery and gynecology.[24]
Keywords: LASER, Energy Source, Gain Medium, Absorption, Spontaneous Emission, Stimulated Emission, Carbon Dioxide Laser.

I. INTRODUCTION

A laser is a device that uses optical amplification, which is based on the stimulated emission of electromagnetic radiation, to emit light. Originally intended to stand for light amplification by stimulated emission of radiation, the name "laser" is an anacronym.[1][2] Theodore Maiman at Hughes Research Laboratories constructed the first laser in 1960 based on theoretical research by Charles H. Townes and Arthur Leonard Schawlow.[3] Coherent light is emitted by lasers, setting them apart from other light sources. Applications such as laser cutting and lithography are made possible by spatial coherence, which enables a laser to be focused to a small area. Additionally, it enables collimation, which keeps a laser beam narrow over long distances and is useful in lidar (light detection and ranging) and laser pointer applications. A highly narrow frequency spectrum can be emitted by lasers due to their excellent temporal coherence. As an alternative, temporal coherence can be utilized to create ultrashort light pulses of femtosecond durations that have a broad spectrum.

Lasers find application in cutting and welding materials, laser disc drives, laser printers, barcode scanners, DNA sequencing instruments, fiber-optic and free-space optical communication, semiconducting chip manufacturing (photolithography), laser surgery and skin t reatments, and cutting and welding supplies. They are also used in laser lighting displays for entertainment purposes and in military and law enforcement devices for marking targets and measuring speed and range. In order to excite fluorescence as a white light source, semiconductor lasers operating in the blue to near-UV range have also been used in place of light-emitting diodes (LEDs). This allows for a much smaller emitting area because of the laser's much greater radiance and eliminates the droop that LEDs experience. Some automobile headlamps already use such devices.[4][5][6][7] The term "microwave amplification by stimulated emission of radiation" (maser) refers to the first device that used amplification by stimulated emission, and it worked at microwave frequencies.[8] Initially called optical masers, these identical optical devices were later abbreviated as lasers after the word "light" was substituted for the word "microwave" in the acronym.[9] These days, all of these devices—such as infrared, ultraviolet, X-ray, and gamma-ray lasers—that operate at frequencies higher than microwaves (about 300 GHz and beyond) are referred to as lasers, while those that operate at microwave or lower radio frequencies are referred to as masers.[10][11] In the field, "to lase" is a back-formed verb that means "to give off coherent light," notably when referring to a laser's gain medium. [12] A laser is said to be "lasing" when it is in operation.[13] Naturally occurring coherent emissions are also referred to as masers or lasers, as in atom laser and astrophysical maser.[14][15] Despite what the term suggests, a laser that generates light on its own is actually an optical oscillator rather than an optical amplifier.[16] One funny observation is that it would have been more accurate to refer to the phenomenon as "light amplification by stimulated emission of radiation" abbreviated LASER.[15] Due to the original acronym's extensive usage as a common noun, optical amplifiers are now also known as laser amplifiers.[17]

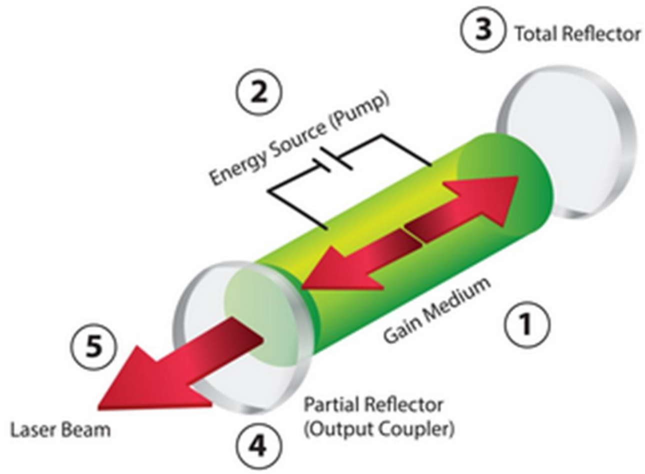


Figure 1: The components of a typical laser system [18]

II. LITERATURE REVIEW

Albert Einstein proposed in 1916 that, in the right conditions, atoms may spontaneously release excess energy as light or when stimulated by light. This idea eventually led to the development of the laser. In 1928, German physicist Rudolf Walther Ladenburg made the first observation of stimulated emission, however it didn't seem to have any applications at the time. [21] In 1951, while attending Columbia University in New York City, Charles H. Townes devised a method for producing stimulated emission at microwave frequencies. He showed off a functional apparatus that concentrated "excited" ammonia molecules in a resonant microwave cavity, causing them to emit a pure microwave frequency, at the end of 1953. For "microwave amplification by the stimulated emission of radiation," Townes gave the gadget the name maser. The theory of maser operation was separately described by two scientists from the P.N. Lebedev Physical Institute in Moscow: Nikolay Gennadiyevich Basov and Alexander Mikhaylovich Prokhorov. All three received a share of the 1964 Nobel Prize in Physics for their contributions. [21]

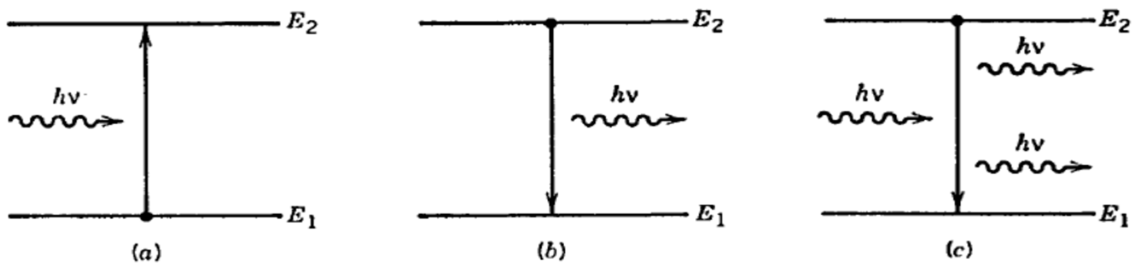
The mid-1950s saw a sharp increase in maser research, but atomic clocks and low-noise microwave amplifiers were the sole uses for masers. In 1957, Townes suggested that they attempt to expand the use of maser action to the considerably shorter wavelengths of visible or infrared light to his brother-in-law, Arthur L. Schawlow, a former postdoctoral student at Columbia University who was working at Bell Laboratories. Townes also spoke with Gordon Gould, a Columbia University graduate student who immediately came up with his own laser concepts. In a groundbreaking study published in the Physical Review on December 15, 1958, Townes and Schawlow presented their concepts for a "optical maser." In the interim, Gould produced a patent application and created the word "laser." The question of who should be acknowledged as the "inventor" of the laser Townes or Gould became very contentious and resulted in years of legal disputes. In the end, Gould was awarded four patents beginning in 1977, which brought in millions of dollars in royalties. [21] The Townes-Schawlow proposal inspired other groups to attempt laser construction. The secret military contract was based on the Gould proposal. Theodore H. Maiman was the first to succeed at Hughes Research Laboratories in Malibu, California, by using an alternative strategy. He used a photographer's flash lamp to produce intense pulses that excited the chromium atoms within a synthetic ruby crystal. He selected this material after carefully examining its light-absorbing and light-emitting properties and determining that it should function as a laser. He created red pulses with a ruby rod the size of a fingertip on May 16, 1960. The first gas laser was created at Bell Labs in December 1960 by Ali Javan, William Bennett, Jr., and Donald Herriott. It used a helium and neon mixture to continuously produce an infrared beam. The first semiconductor laser was created in 1962 by Robert N. Hall and colleagues at the General Electric Research and Development Center in Schenectady, New York.[21]

Though practical uses took years to develop, lasers soon captured the public's attention, partly because of their resemblance to the "heat rays" of science fiction. While working with Maiman on the ruby laser, a young physicist by the name of Irnee D'Haenens made a long-lasting joke in the laser community when she said that the device was "a solution looking for a problem." Townes and Schawlow had anticipated using laser beams for airborne or spaceborne signal transmission as well as basic research. Gould imagined more potent beams that could drill and cut through a variety of materials. A significant early achievement occurred in late 1963 when Emmett Leith and Juris Upatnieks, two researchers at the University of Michigan, created the first three-dimensional holograms using lasers.[21]The first widely used lasers in commerce were helium-neon lasers.

Straight lines could be projected for alignment, surveying, construction, and irrigation right away since they could be set to produce a visible red beam rather than an infrared one. Ruby laser pulses were soon being used by eye surgeons to fuse detached retinas back together without making incisions in the eye. The laser scanner used for automated checkout in supermarkets was the first widespread use of lasers; it was created in the middle of the 1970s and gained popularity a few years later. Personal computer laser printers and compact disc music players quickly followed.[21] Lasers are becoming commonplace instruments in many fields. In lecture halls, laser pointers draw attention to presentation points, and laser target designators direct smart bombs to their intended targets. Razor blades are welded, undesired hair is removed, tattoos are bleached, and patterns are written on manufacturing line products without ever touching them using lasers. The surfaces of Mars and the asteroid Eros were profiled in unprecedented detail by laser rangefinders aboard space spacecraft. Physicists have used lasers in the lab to chill atoms to within a very small degree of absolute zero.[21]

III. THE PRINCIPLE OF LASER OPERATION

The laws of quantum physics, which restrict atoms and molecules to possessing finite amounts of stored energy that vary depending on the nature of the atom or molecule, shape laser emission. When all of an atom's electrons are in the closest orbits to its nucleus, the atom has the lowest energy attainable (see electronic configuration). We refer to this stage as the ground state. An atom is said to be "excited" when one or more of its electrons have taken in energy and are able to travel to outer orbits. In general, excited states are unstable because light is released as electrons transition from higher to lower energy levels.[21]



(a) Absorption (b) Spontaneous emission and (c) stimulated emission

Figure 2: The three fundamental processes occurring between the two energy states of an atom [19]

Einstein realized there were two possible ways to produce this emission. Discrete light packets, or photons, are typically released spontaneously and without the help of an external source. Alternatively, if the energy of the passing photon precisely matched the energy that an electron would release spontaneously upon descending to a lower-energy configuration, it may cause an atom or molecule to emit light. The proportion of lower-energy to higher-energy combinations determines whether process is dominant. Lower-energy setups are typically more common. Accordingly, it is more likely for a photon that spontaneously emits to be absorbed and raise an electron from a lower-energy configuration to a higher-energy configuration than it is for a second photon to be released in order to cause a higher-energy configuration to descend to a lower-energy configuration. Stimulated emission will cease as long as lower-energy states are more prevalent.[21]Nonetheless, spontaneously released photons are more likely to trigger more emissions, creating a cascade of photons, if higher-energy configurations predominate (a situation referred to as population inversion). A population inversion cannot be produced by heat alone; an additional technique is needed to specifically excite the atoms or molecules. This is usually accomplished by either shining a strong light on the laser material or by running an electric current through it.[21]

There are just two energy levels in the most basic system that can be imagined, like Townes' ammonia maser. Three or four energy levels are involved in more practical laser systems. The material in a three-level laser is initially stimulated to a high-energy, brief state that then spontaneously transitions to a relatively lower-energy state known as a metastable state, which has an exceptionally long lifespan. The reason the metastable state matters is that it retains and traps excitation energy, causing a population inversion that can be further induced to release radiation and return the species to its ground state. A three-level laser is the ruby laser created by Theodore Maiman.[21] Unfortunately, the three-level laser can only function in the event that the ground state is empty. Most three-level lasers are limited to producing pulses because when atoms or molecules produce light, they build up in the ground state, where they can absorb the stimulated emission and stop the laser action. The four-level laser solves this problem by having an additional transition state situated between the ground and metastable levels. As a result, numerous four-level lasers can provide a continuous beam for several days.[21]

IV. THE ELEMENTS AND CHARACTERISTICS OF LASER BEAM

Although population inversions can occur in liquids or solids, gasses and solids make up the majority of laser media. Usually, an electric current or external light source is used to excite laser gasses inside the cylindrical tubes, a process known as "pumping" the laser. Likewise, transparent crystals or semiconductors with trace amounts of light-emitting atoms can be used in solid-state lasers. [21] To increase the amount of light energy in the beam, an optical resonator is required. A pair of mirrors placed facing each other such that light emitted along the line between the mirrors is reflected back and forth creates the resonator. Light that is reflected back and forth across the laser medium becomes more intense with each pass when a population inversion occurs in the medium. Unamplified light seeps in from the mirrors' surroundings. Only a portion of the incident light is transmitted by one or both mirrors in a real laser cavity.[0] The type of laser determines the fraction of light transmitted, or the laser beam. The amount of light added by stimulated emission on each round trip between the mirrors, if the laser produces a continuous beam, equals the light appearing in the beam plus losses within the optical resonator.[21] Technically , a laser oscillator is created when a resonant cavity and laser medium are combined to create what is often referred to as a laser. Many laser characteristics are determined by oscillation, which indicates internal light generation in the apparatus. A laser would be nothing more than an optical amplifier in the absence of mirrors and a resonant cavity; it could only amplify light coming from an external source and not produce an internal beam. The first optical amplifier was demonstrated in 1961 by American Optical researcher Elias Snitzer, but applications for these devices were limited until the rise of fiber optic-based communications. [21]

Generally , laser light is distinct from other types of light because it is concentrated into a narrow beam, restricted to a small range of wavelengths (commonly referred to as "monochromatic"), and composed of waves that are phase-locked to one another. These characteristics result from interactions between the laser medium, the resonant cavity, and the stimulated emission process.[21]A photon that is stimulated will produce another photon that is identical to the original, with the same phase, wavelength, and direction. As a result, the two photons are coherent, with phase peaks and valleys, with respect to one another. Then, other identical photons can be stimulated to emit by both the original and the new photon. This uniformity is increased by alternating the light through a resonant cavity; the laser design determines the beam's narrowness and coherence. Even if a visible laser appears to be pointing at a location on the wall across from you in a room, the beam's collimation is not always perfect. The distance between the laser mirrors and diffraction, which scatters light at an aperture's edge, determine how much the beam spreads. The amount of diffraction is directly related to the laser wavelength divided by the emitting aperture size; the beam spreads more slowly through larger apertures.[21] At a wavelength of 0.633 micrometers, a red helium-neon laser emits light from a one-millimeter aperture. The resulting beam diverges at an angle of around 0.057 degree, or one milliradian. At a distance of one kilometer, a one-meter spot will result from such a modest angle of divergence. On the other hand, a standard flashlight beam creates a comparable one-meter spot in a matter of meters. Still, not every laser produces a tight beam. Semiconductor lasers require external optics to concentrate their beams since they emit light with a wavelength of close to one micrometer from an aperture of similar size, meaning that their divergence is at least 20 degrees.The laser material, the stimulated emission process, and the laser resonator's optics all affect the output wavelength. A material can support stimulated emission throughout a specific range of wavelengths for each energy level transition; the range's extent depends on the nature of the material and the transition. The mechanism concentrates emission at wavelengths where the chance of stimulated emission is largest. The probability of stimulated emission changes with wavelength.[21]

Laser oscillation is supported by resonant cavities at wavelengths that satisfy a resonant requirement, which is that the integral number N of wavelengths λ must match the round trip distance of light between the mirrors. The round-trip distance 2L must equal $N\lambda/n$, or $2L = N\lambda/n$, if the cavity length is L and the material's refractive index is n in the laser cavity. We refer to each resonance as a longitudinal mode. The wavelengths of neighboring modes are closely separated, with the exception of semiconductor lasers, and the laser often generates light concurrently on two or more wavelengths that are within 0.1 percent of one another. For most practical purposes, these beams are monochromatic; additional optics can be added to restrict laser oscillation to an even narrower wavelength range and to a single longitudinal mode.[21] A beam is more coherent when its wavelength range is less, indicating that all of the light waves inside it are exactly synchronized with each other. The coherence length is a metric used to measure this. This coherence length = $\lambda 2/2\Delta\lambda$ if the center of the wavelength range that is emitted is λ and the wavelength range that is emitted is $\Delta\lambda$. Coherence lengths typically vary from millimeters to meters. For example, recording three-dimensional object holograms requires such lengthy coherence durations.

The typical power of a laser can range from microwatts to over a million watts in the case of the most powerful experimental lasers. Lasers can produce pulsed or continuous beams. When a laser produces an output that is essentially constant over a period of seconds or more, it is referred to be continuous-wave; the steady red beam produced by a laser pointer is one example.

The output energy of pulsed lasers is concentrated into short, high-power bursts. One or more pulses can be fired by these lasers at regular intervals. At the peak of an incredibly brief pulse, instantaneous power might be very high. Peak power output from laboratory lasers has surpassed 10^{15} watts for durations of roughly 10^{-12} seconds.[21] In laboratory investigations, pulses can be compressed to a very short period of approximately 5 femtoseconds ($5 \times 10{-}15$ seconds) to "freeze" the activity during incredibly rapid occurrences, including steps in chemical processes. Similar to how a magnifier concentrates sunlight onto a small spot to ignite paper, laser pulses may likewise be focused to concentrate high strengths on small spots.[21]

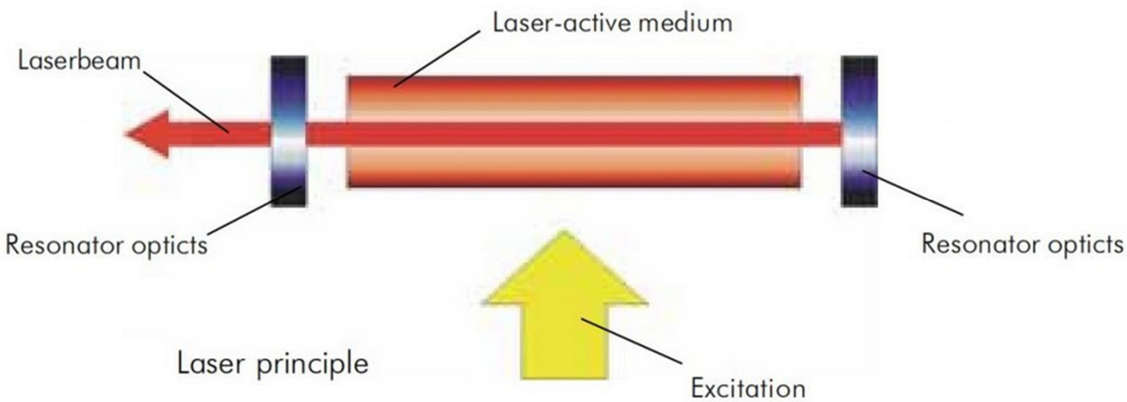


Figure 3: The basic principle of laser physics [20]

V. CARBON-DIOXIDE LASER

The carbon dioxide laser, or CO2 laser, is a type of molecular gas laser that emits light in the long-wavelength infrared spectrum. A gas mixture of carbon dioxide (CO2), helium (He), nitrogen (N2), and maybe some hydrogen (H2), oxygen (O2), water vapor, and/or xenon (Xe) serves as the gain medium. An electrical gas discharge, which can be run with DC current, AC current around 20 kHz to 50 kHz, or in the radio frequency (RF) domain, is used to electrically pump such a laser.The most effective method has been found to be a resonant energy transfer from nitrogen molecules, even if direct excitation of CO2 molecules into the upper laser level is feasible. In this case, the electric discharge excites the nitrogen molecules into a metastable vibrational state, whereupon they impart their excitation energy to the CO2 molecules upon collision. After that, the CO2 molecules that have left play a significant role in the laser transition. Helium is used to eliminate heat and depopulate the lower laser level. Carbon monoxide CO, created in the discharge can be reoxidized to carbon dioxide with the aid of other components like hydrogen or water vapor, especially in sealed-tube lasers. [23]

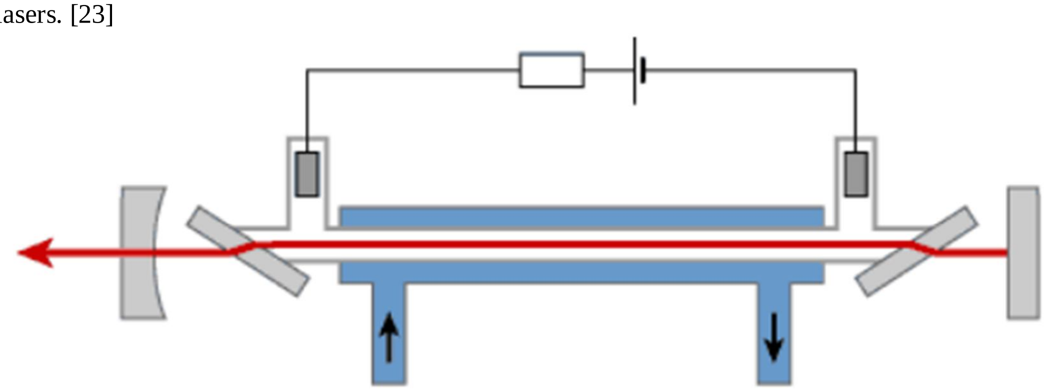


Figure 4: Schematic setup of a sealed-tube carbon dioxide laser.[23]

CO2 lasers typically emit at a wavelength of 10.6 µm, but there are dozens of other laser lines in the region of 9 to 11 µm particularly at 9.6 µm. This is because two different vibrational states of the CO2 molecules can be used as the lower level, and for each vibrational state, there is a substantial number of rotational states, leading to many sub-levels. Dipole transitions (the only ones with a relatively high strength) are possible with J = ±1, where R branch leads to higher photon energies (shorter wavelengths) and P branch to lower energies.

The P and R branches of the stronger band transitions, which include one of the two probable final vibrational levels, are located about 10.6 µm and 10.2 µm, respectively, with P20 being the dominant transition. In contrast, the P and R branches of the other band transition at approximately 9.6 and 9.3 µm, respectively.[23] A CO2 laser can be made to laser on one of over a dozen transitions with relatively closely spaced wavelengths in each branch with the help of an appropriate wavelength tuning element in the laser resonator. However, because of the discrete rotational states of the molecules, continuous wavelength tuning is not feasible. Occasional jumps to other transitions during operation or simultaneous lasing on a few transitions are possible if the resonator lacks a wavelength-selective device. There are devices that are specifically optimized for other wavelengths, like 10.25 µm or 9.3 µm, which are far better suited for certain applications, like laser material processing, because that radiation is much more absorbed in certain materials (e.g. polymers). However, the majority of commercially available CO2 lasers emit at the standard wavelength of 10.6 µm. Special infrared optics may be needed to create such lasers and use their radiation because typical transmissive 10.6-µm lenses may, for example, show excessive reflections.[23] Average output powers typically range from a few tens of watts to several kilowatts. Because of a particularly advantageous excitation pathway, the power conversion efficiency can range from 10% to 20%, which is higher than that of most gas lasers, higher than that of lamp-pumped solid-state lasers, and lower than that of many diode-pumped lasers. The large-quality infrared optics, frequently composed of materials like zinc selenide (ZnSe) or zinc sulfide (ZnS), are necessary for CO2 lasers because of their large output powers and lengthy emission wavelengths. The safety of CO2 lasers is seriously threatened by their high drive voltages and high powers. At low levels, however, they are reasonably harmless for the eyes due to their lengthy operating wavelength.[23]

VI. TYPES OF CARBON-DIOXIDE LASER

Although the CO2 laser family is highly diverse, sealed-tube or no-flow lasers which have the gas supply and laser bore enclosed in a sealed tube are frequently used for laser powers ranging from a few watts to several hundred watts. Either a slow gas flow or diffusion—with the helium's very beneficial effect—transport waste heat to the tube walls. These lasers are small and strong, and they can readily operate for thousands of hours or more. In this case, techniques for continually replenishing the gas must be used, namely for catalytic re-oxidization of CO to offset the dissociation of CO2. The quality of the beams might be very good.[23] High-power diffusion-cooled slab lasers, which are distinct from solid-state slab lasers, feature a gas gap between two planar water-cooled radiofrequency electrodes. If the electrode spacing is modest in relation to the electrode width, the extra heat is effectively transferred to the electrodes by diffusion. An unstable resonator with output coupling at the side of a highly reflecting mirror is frequently used for effective energy extraction. When the beam quality is reasonable, an output of several kilowatts can be achieved.[23] The high beam quality and multi-kilowatt continuous-wave output powers are also appropriate for fast axial flow and fast transverse flow lasers. The fast-moving gas combination removes surplus heat by passing through an external cooler, also known as a heat exchanger, before being used once more in the discharge. The gas can be periodically refilled and continually regenerated. Although transverse flow lasers have the largest output powers, their beam quality is usually inferior.[23] The gas pressure of transverse excited atmosphere (TEA) lasers is extremely high, roughly atmospheric. Transverse excitation is carried out via a sequence of electrodes along the tube because the voltage needed for a longitudinal discharge would be too great. Because the gas discharge would not be stable at high pressures, TEA lasers are only used in pulsed mode. They can be constructed for outputs of tens of kilowatts when paired with high pulse repetition rates, however they typically yield average output powers below 100 W.[23] For multi-megawatt powers (such as those used in anti-missile weapons), there are gas dynamic CO2 lasers (a type of chemical laser) where the energy is produced by a chemical reaction in a manner similar to a rocket engine rather than by a gas discharge.These ideas result in very various laser topologies, each with unique advantages and disadvantages in terms of gas consumption, beam quality, output power potential, and device lifetime. [23]

VII. CONCLUSION

Solid-state lasers, especially YAG and fiber lasers, that operate in the 1-µm wavelength range compete with CO2 lasers used for laser material processing (such as metal welding and cutting or laser marking). The benefits of these shorter wavelengths include the possibility of beam distribution via fiber cables and more effective absorption in a metallic workpiece. (Optical fibers for high-power 10-µm laser beams are nonexistent since the area lacks appropriate materials with extremely high transparency.) Furthermore, if the beam quality is high, 1-µm beams can be more closely focused. However, diode-pumped lasers are typically more costly, while high-power lamp-pumped lasers typically cannot reach the latter potential. For some materials, such as polymers and ceramics, CO2 laser beams are actually very advantageous in terms of absorption. A CO2 laser may be used as a comparatively inexpensive and reliable option even in situations where absorption is less advantageous than for a solid-state laser.

However, the lack of high-power fiber cables for CO2 laser radiation is a significant drawback.The cutting and welding industry continues to utilize CO2 lasers extensively, especially for items thicker than a few millimeters, and their sales continue to account for a sizable portion of total laser sales worldwide. The development of high-power thin-disk lasers and sophisticated fiber cables, along with methods that take use of the high beam quality of these lasers, may cause this to change to some extent in the future.[23]

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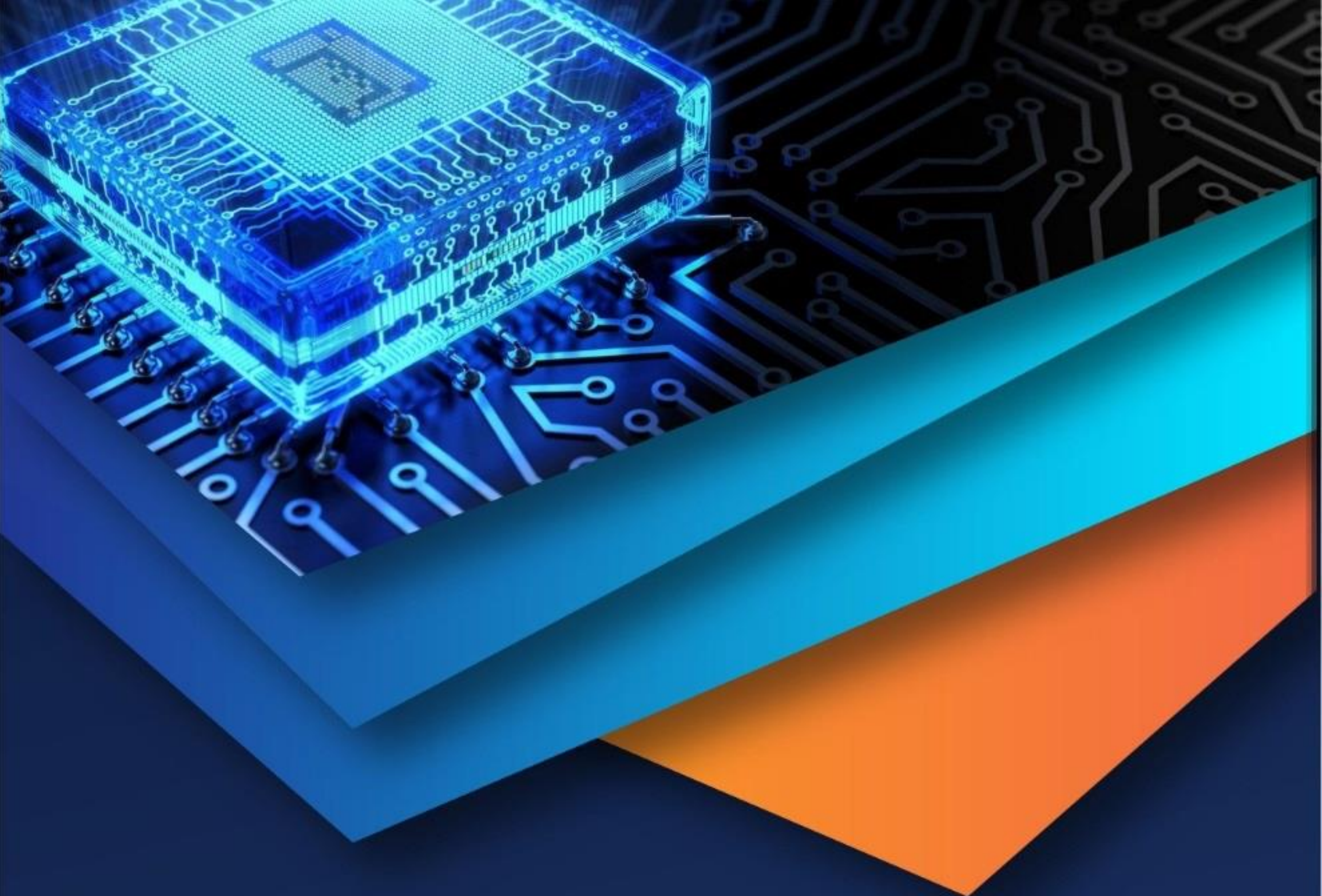

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