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A Review on the Titanium Sapphire Laser

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Abstract: Ti:sapphire, or titanium-doped sapphire laser, is a tunable laser with exceptional tunability and the ability to produce ultrashort pulses. It emits red and near-infrared light between 650 and 1100 nm. Peter Moulton carried out the first laser operation on Ti:sapphire in June 1982. It is frequently utilized in scientific study because it combines the best optical, physical, and thermal qualities of sapphire.[22]

Keywords: LASER, Energy Source, Gain Medium, Absorption, Spontaneous emission, Stimulated emission, the Titanium-Sapphire Laser.

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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, laser surgery and skin treatments, and cutting and welding supplies. T

hey 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 as LASER.[15] Due to the original acronym's extensive usage as a common noun, optical amplifiers are now also known as laser amplifiers.[17]

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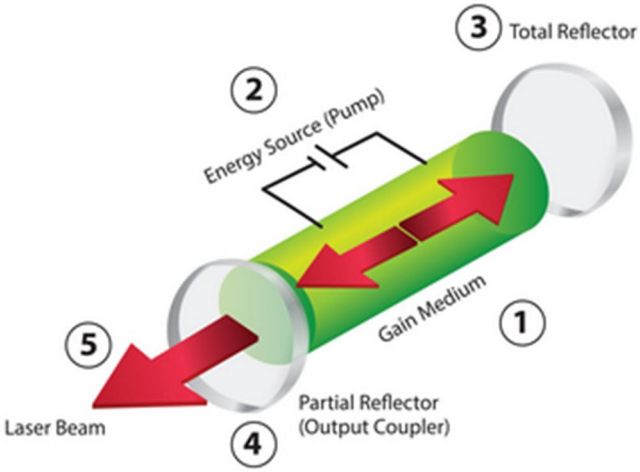


Figure 1: The components of a typical laser system [18]

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 an 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.

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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]

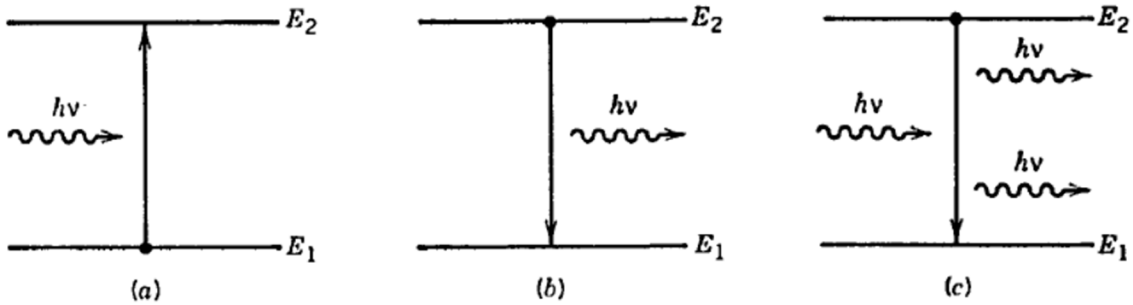


Figure 2: The three fundamental processes occurring between the two energy states of an atom [19]
(a) Absorption (b) Spontaneous emission and (c) stimulated emission

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.

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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.[21] 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 (5×10^{-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]

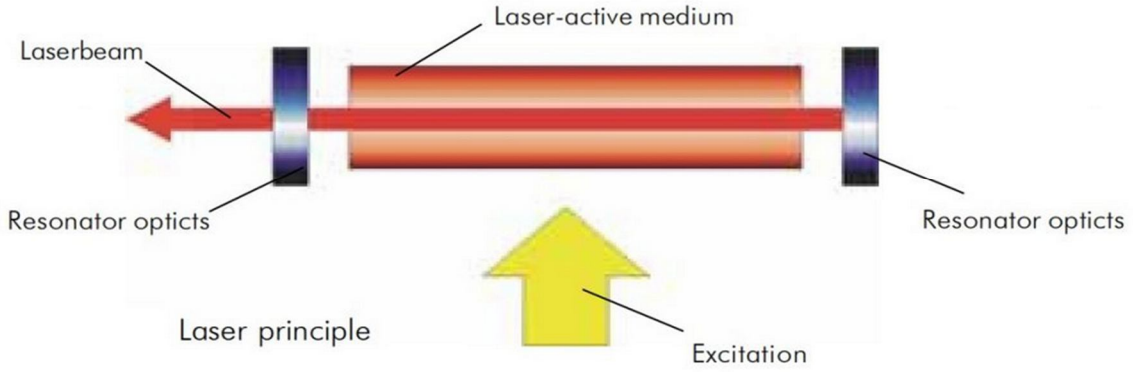


Figure 3: The basic principle of laser physics [20]

V. TITANIUM-SAPPHIRE LASER

Ti:sapphire, or titanium-doped sapphire laser, is a tunable laser with exceptional tunability and the ability to produce ultrashort pulses. It emits red and near-infrared light between 650 and 1100 nm. Peter Moulton carried out the first laser operation on Ti:sapphire in June 1982. It is frequently utilized in scientific study because it combines the best optical, physical, and thermal qualities of sapphire. High laser cross sections are another feature of the Ti:sapphire laser that reduces Q-switching instability. The Ti:sapphire laser is pumped using a different laser with a wavelength between 514 and 532 nm, such as an argon-ion laser, frequency-doubled Nd:YAG laser, or Nd:YVO laser.[22]

Laser Properties	
Laser type	Solid
Pump Source	Laser
Operating Wavelength	650 nm to 1100 nm

Figure 4: The properties of Titanium-Sapphire Laser.[22]

Ti sapphire lasers and amplifiers have been employed in basic research applications in physics, biology, and chemistry since their discovery in the early 1980s. Multiphoton deep-tissue imaging, cold micromachining, terawatt and petawatt physics, and multicolor ultrafast spectroscopy are just a few of the many photonics applications in which they are essential. Additionally, dense tissue samples, including in vivo specimens, can be imaged in three dimensions with excellent resolution.Additionally, multi-pass amplifiers and regenerative amplifiers use titanium sapphire. These devices use chirped-pulse amplification to reach large output peak power of many terawatts. Nonlinear optics and nuclear fusion studies can benefit from such enormous power.[22]

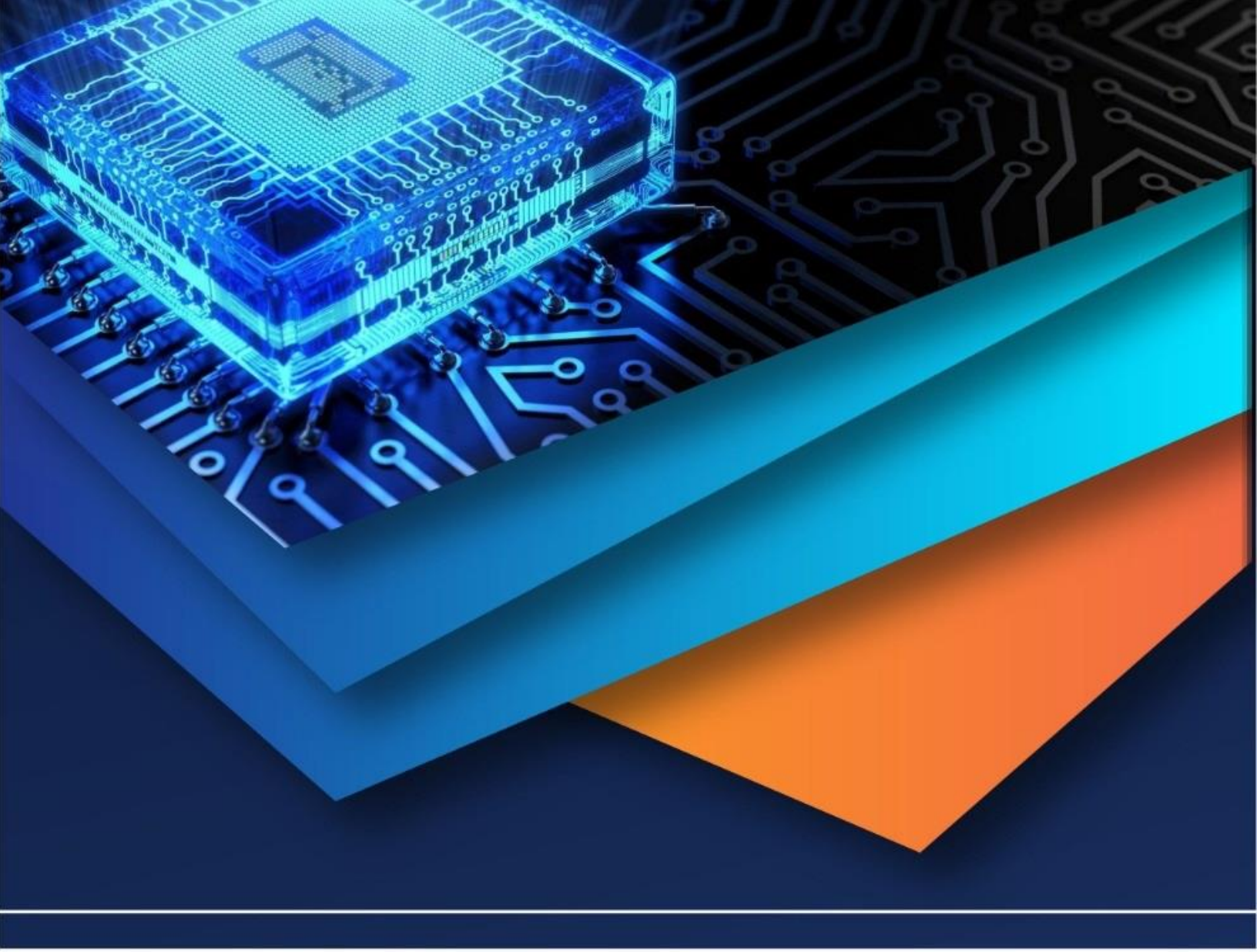
VI. CONCLUSION

The titanium-doped sapphire laser, or Ti:sapphire laser, is a tunable laser that can generate ultrashort pulses and has remarkable tunability. Between 650 and 1100 nm, it emits red and near-infrared light. In June 1982, Peter Moulton performed the first laser operation on Ti:sapphire. Because it combines sapphire's best optical, physical, and thermal properties, it is widely used in scientific research.[22]

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