Advances in laser fundamentals, classifications, and their applications

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Abstract. Laser technology continues to advance in tandem with the growth of modern technology, benefiting all aspects of daily human existence. The laser serves as the primary tool in modern technology and remains widely employed in communication operations, as well as in medical applications, military operations, and scientific exploration. The precise measurements require the laser's essential characteristics: high directivity, monochromaticity, and high energy density. The development of lasers has become crucial for advancing semiconductor technology and quantum computing, driving significant improvements in the industry and leading to numerous scientific discoveries. The technology is vital for both social development and national defense protection. Laser technology drives advanced semiconductor and quantum-computing research, serving as an engine for industrial transformation and scientific exploration. The technology is critical for both social development and defense security requirements. This paper examines the importance of lasers, alongside the development of laser classification research and various laser applications. Laser technology will advance by incorporating high power with brief pulses, expanded spectral coverage, and intelligent behaviors to create breakthroughs in quantum systems, superfast systems, optical transfer, and medical research. Miniaturization, integration, and low-cost technologies will accelerate industrial applications, serving as the fundamental force for the upcoming technological revolution.

Keywords: Laser Technology; Stimulated Emission; High-Power Lasers; Mid-infrared Lasers.

1. Introduction

The laser is one of the four major inventions of the 20th century, alongside atomic energy, computers, and semiconductors, as a significant human achievement. Modern technology has achieved lasers as a considerable accomplishment with numerous diverse applications. Laser cutting and welding technologies are essential for modern industrial production, as they enable efficient manufacturing operations. The constant output of laser beams creates dense energy fields that will allow detailed material processing, thereby enhancing industrial productivity and product quality. Medical technology continues to adopt lasers at an expanding rate. Modern medical treatment relies on laser cosmetology and laser therapy because they enable doctors to treat human tissue with precision, creating non-invasive procedures that decrease the discomfort patients experience. The scientific field benefits from lasers' ability to deliver stable light sources, and scientists rely heavily on laser interferometry and laser scattering technologies. Human society has undergone a profound technological transformation with the advent of laser technology. The practical value of the laser is inextricably linked to its historical development.

Historically, any scientific invention or discovery has invariably followed one of two paths: the first one is the existence of phenomena in nature that, when consciously or unconsciously observed by humans, lead to the development of theories, which are then validated and utilized. Examples include the discovery of universal gravitation, oxygen, and electromagnetism. This process is referred to as "scientific discovery." The second path involves phenomena that do not exist in nature, at least not in Earth's natural environment. In this case, humans theoretically derive and predict these phenomena and then strive to prove and realize them through experimentation and innovation. Examples include the theory of relativity, nuclear decay, and nuclear fusion. This process is referred to as "scientific invention". The latter path is more theoretically profound and challenging, and the birth of the laser exemplifies this category.

The theoretical foundation of the laser's invention can be traced back to 1917, when the renowned physicist Albert Einstein, while studying the interaction between light radiation and atoms, discovered that, in addition to the processes of stimulated absorption and spontaneous radiation transitions, there also exists the process of stimulated emission. In 1954, Charles H. Townes from the United States, along with Nikolai G. Basov and Aleksander M. Prokhorov from the Soviet Union, successfully realized the first ammonia molecular microwave quantum oscillator (Maser).

In 1958, Arthur L. Schawlow abandoned the concept of a closed resonant cavity with dimensions comparable to the wavelength and introduced the idea of using an open optical resonant cavity with dimensions much larger than the wavelength, thereby realizing a novel concept for the laser. Around the same time, Nicolas Bloembergen proposed a new idea of achieving population inversion in a three-level atomic system through optical pumping. The first ruby solid-state laser achieved success in July 1960, marking a significant milestone that established laser technology as a new field of scientific study. Theodore Maiman at Hughes Research Laboratories in California, USA, constructed a laser device that operated at a wavelength of 694.3 nm.

The advancement of laser technology through quantum electronics became the fastest scientific development in history after this breakthrough. A. Javan achieved the first successful development of a He-Ne gas mixture laser in February 1961. Q-switching technology emerged shortly after its proposal, leading to the development of the first Q-switched laser before the neodymium glass pulsed laser was created. Three American research groups simultaneously announced the operation of gallium arsenide (GaAs) semiconductor lasers in 1962. The semi-classical theory of lasers was established in 1963 to provide a comprehensive explanation of laser frequency and power behavior. Scientists developed the carbon dioxide gas laser successfully in 1964. The lithium niobate optical parametric oscillator became a reality in 1965, while mode-locking effects were first predicted through semi-classical theory.

The history of laser development showcases technological advancement while disclosing fundamental aspects of the core operation principles essential for understanding the device's behavior. The article provides an extensive review of laser basics, alongside classification schemes and recent developments in modern laser applications. The first part of this article offers a detailed examination of the physical foundations of lasers and existing classification structures. The article provides a thorough evaluation of laser applications across various industrial manufacturing, medical treatment, military technology, and scientific research sectors. The final part will include an analysis of research trends alongside prospects for the development of laser technology.

2. The Basic Principle and Composition of Lasers

2.1 Principles and Structure

A laser consists of three key components: the gain medium, the pump, and the resonator (Figure 1). The gain medium can be in the form of a liquid, a gas, or a solid. Its basic requirement is to generate photons instead of converting light into heat when stimulated. Additionally, the particles within the medium must be relatively isolated so that energy-level transitions can occur.

The pump source acts as an energy provider, providing energy to excite the gain medium. The photons emitted by the pump source lift the particles in the gain medium from the ground state to higher energy levels, achieving a state of population inversion. Among the standard excitation mechanisms, optical excitation (also known as optical pumping) is one of them. High-power semiconductor lasers (LDs) are often used as pump sources, mainly converting electrical energy into light energy.

The main functions of the resonant cavity are to "store" and "purify" the laser light. Generally, the resonant cavity comprises two mirrors; sometimes, couplers can create various ring-shaped resonant cavities. In an optical resonant cavity, photons are reflected back and forth between mirrors, continuously exciting the excited radiation process in the gain medium to produce a high-energy-density laser beam. The resonant cavity maintains a high degree of uniformity in the frequency, wavelength, phase, and propagation direction of the photons within the cavity through an optical feedback mechanism, thereby providing the laser with excellent directionality and coherence.

A laser system requires a gain medium as its core element, along with two mirrors: one mirror reflects all light, and the other reflects only part of the light. The pump source surrounds the resonant cavity to supply light energy that excites the gain medium atoms into higher energy states. Photons are emitted when electrons return from the excited state to the low-energy ground state. Once the initial photons are released, stimulated emission will be induced if other excited atoms are around. The photons reflect back and forth inside the resonant cavity, triggering more stimulated emissions, forming a chain reaction of photons, and amplifying the light intensity. This process is called optical amplification. Some of the photons pass through the partially reflective mirror and are output, forming a highly focused, coherent, monochromatic, and strongly directional laser beam.

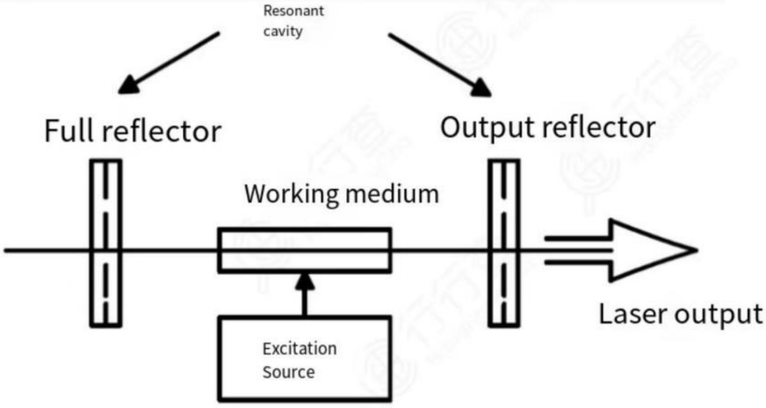

Fig. 1 The basic structure of a laser

2.2 Applications and Research Frontiers

The unique properties of lasers include their high directionality, monochromaticity, coherence, brightness, and energy density. The reliable base for laser applications stems from their distinctive properties. Lasers generate high energy density by concentrating power within brief periods, which enables their beneficial applications in material processing and medical practices. High-power pulsed lasers are excellent tools for precision machining, as they instantly melt metals. Besides that, the directionality of a laser refers to the tiny divergence angle of the laser beam in space, making the beam almost parallel with minimal spread. As a result, the directionality of the laser is exceptionally strong. The laser emitted by a laser device is inherently directed in one specific direction, with a minimal beam divergence of approximately 0.001 radians, which is nearly parallel. This characteristic allows the laser to maintain high directionality and energy concentration over long distances. When it comes to coherence, a laser's coherence can be divided into spatial and temporal coherence. Spatial coherence refers to the correlation of the light wave field at different points in space. The laser emits high spatial coherence because of its precise beam directionality and small beam diameter. Spatial coherence depends on beam divergence angle because narrow divergence angles indicate superior spatial coherence. Temporal coherence describes the correlation of the light wave field at the same point in space but at different times. Temporal coherence is directly related to the monochromaticity of the light source—the better the monochromaticity, the better the temporal coherence.

3. Classification and Research Progress of Lasers

3.1 Gas Lasers

3.1.1 Principles and Structure

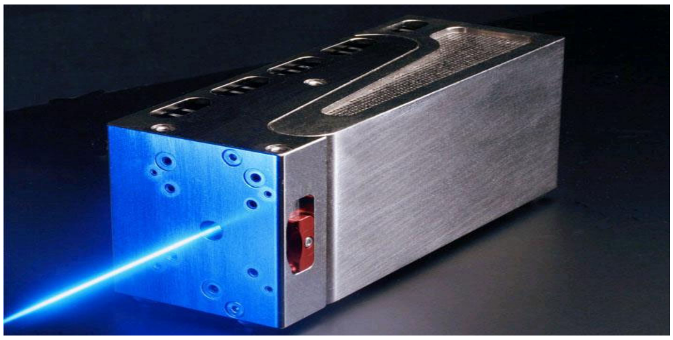

Fig. 2 A gas laser

"Gas lasers" utilize gas as the working medium (Fig. 2). They are currently the most widely used type of laser, encompassing both low-power He-Ne and high-power CO2 lasers. Most gas lasers can operate continuously, with relatively fixed energy levels involved in the excitation process, typically using electron collision excitation in a gas discharge. Based on the type of energy level transitions, gas lasers can be further divided into atomic, ionic, molecular, and excimer gas lasers. The working principle of a gas laser mainly revolves around gas discharge excitation and population inversion. It utilizes gas as the working substance and, through methods such as electrical excitation, pneumatic excitation, optical excitation, and chemical excitation, induces changes in the energy levels of atoms or molecules within the gas. In this process, low-energy-level particles absorb energy and transition to higher energy levels. When the number of high-energy-level particles exceeds that of low-energy-level particles, population inversion is achieved, and thus, laser output can be generated.

A gas laser mainly consists of an active gas, a resonant cavity, and an excitation source (Fig. 3). The active gas is the key to generating laser light. Gases such as helium (He), neon (Ne), argon (Ar), and carbon dioxide (CO2) are commonly used in these applications. In the discharge tube, these gases are excited by electrical, optical, or other means to generate laser light. For example, helium and neon gases are mixed in a proportionate ratio in a helium-neon laser. When an electric current is applied, helium atoms are first excited to high-energy levels and then transfer their energy to neon atoms, enabling the neon atoms to achieve population inversion, and laser light is generated.

The resonant cavity is composed of a plane mirror and a spherical mirror. Its function is vital. The light generated by stimulated emission reflects back and forth between these two mirrors. Each time it reflects, the intensity of the light increases. After repeated reflections, the light becomes stronger and stronger, and finally, the laser output is formed.

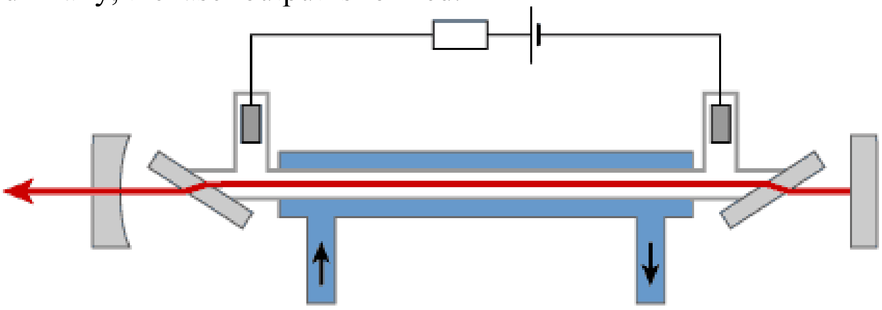

Fig. 3 The structure of a CO2 laser

3.1.2 Applications and Research Frontiers

Gas lasers have many advantages. They have a simple structure, low manufacturing cost, and easy operation. Ordinary people can get started with a bit of learning. Their beam quality is excellent. The emitted light is highly directional and does not disperse easily. Moreover, the light has high purity and a stable frequency.

Additionally, they can operate continuously and stably for an extended period without requiring frequent maintenance. Due to these advantages, gas lasers are widely utilized in various fields. In printing and typesetting, they can ensure high-precision graphic and text output. Carbon dioxide lasers are commonly used in industrial processing to cut a wide range of materials, including metals and non-metals. The cut edges are smooth and precise. In medical surgery, they can perform fine tissue cutting and hemostasis. In military range-finding, gas lasers can provide data quickly and accurately, with an exceptionally high application value.

Laser wavelengths of 3–5 μm are essential for gas detection and free-space optical communications. Hollow-core fiber (HCF) gas lasers represent a promising platform for mid-IR light generation, as they integrate the benefits of traditional gas lasers and HCFs. The Pu Wang group demonstrated a linear-cavity HCF laser filled with acetylene in 2024, which produced continuous-wave and self-Q-switched pulse outputs at 3.1 μm. Using a homemade 1535 nm single-frequency fiber laser as the pump source, the system achieved a CW laser output of 8.23 W at 3.1 μm, with a slope efficiency of 31.8% and excellent beam quality (\(M_x^2 = 1.18\), \(M_y^2 = 1.15\)). When the gas pressure was increased to 50 mbar, the laser produced a self-Q-switched pulse with an output power of 1.98 W, a pulse width of 45 ns, and a repetition rate of 4.59 MHz.

This work presents the inaugural demonstration of a self-Q-switched pulse in a hollow-core fiber (HCF) gas laser. The linear-cavity design enhances light source coherence, facilitating the efficient conversion of amplified spontaneous emission (ASE) into coherent laser output. The resonant cavity made from dichroic mirrors at both ends of the HCF functions as a critical element that reduces the lasing threshold while enhancing the output power.

The study also explored the effects of gas pressure on laser performance. The laser output increased with pressure at lower pressures due to improved pump absorption. However, collisional losses among gas molecules reduced the output power at higher pressures. The optimal pressure for CW operation was three mbar, while the self-Q-switched pulse was achieved at 50 mbar. The research demonstrates how HCF gas lasers can become viable for high-power mid-IR applications. The setup requires further optimization to enable direct picosecond pulse generation in the mid-IR spectrum through mode-locking techniques (Fig. 4).

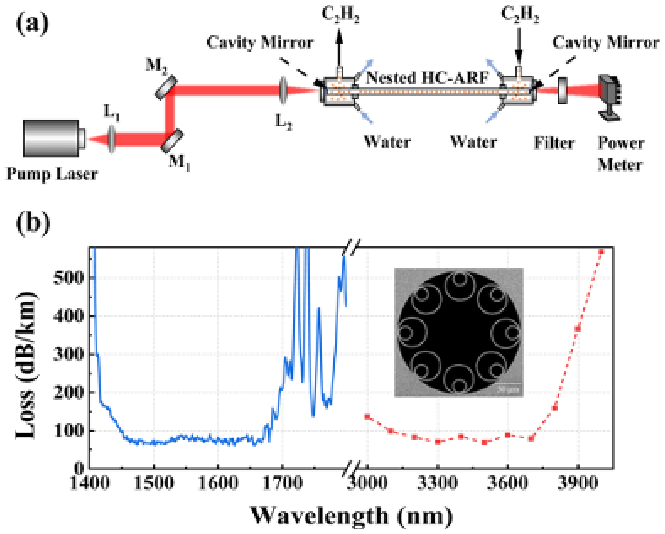

Fig.4 Summary diagram of the research structure of the Pu Wang Group

3.2 Liquid laser

3.2.1 Principles and Structure

"Liquid lasers" use liquid as the working medium. They can be divided into inorganic and organic liquid lasers, with dye lasers being the most representative of these types. Dye lasers offer several advantages, including continuous wavelength tunability (from ultraviolet to infrared), low cost, high gain, relatively high efficiency, ease of preparation, uniform laser output, output power comparable to that of solid-state and gas lasers, recyclable operation, and effective cooling. A typical example is the Rhodamine 6G dye laser. A liquid laser has three core components: the active medium, the pump source, and the resonant cavity (Fig. 5).

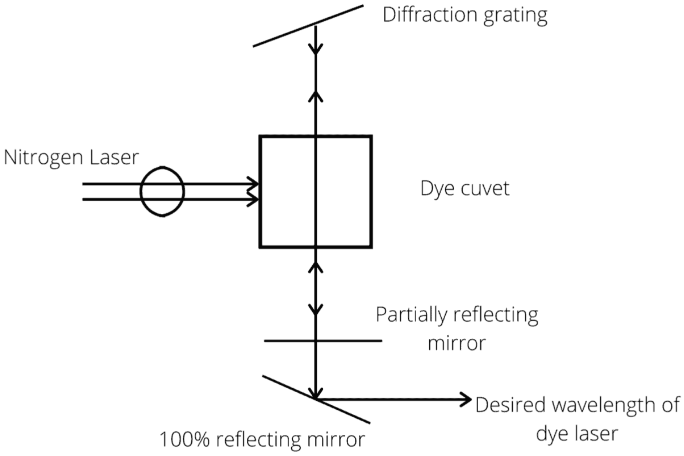

Fig. 5 The basic structure of a liquid laser

3.2.2 Applications and Research Frontiers

Liquid lasers serve multiple purposes because they excel in spectroscopic analysis. These lasers offer excellent analysis capabilities due to their easily adjustable emission spectra. The wavelength control of liquid lasers enables scientists to match their light output with the specific absorption frequencies of different molecules, allowing for detailed laboratory analyses of molecular structures. Precise chemical compound identification and quantification require this particular capability, which proves essential for analytical chemistry procedures. Medical professionals use liquid lasers to operate advanced imaging systems based on fluorescence technology. Biological tissues become observable because these lasers stimulate fluorescent dyes, creating detailed pictures of internal tissues and organs. Researchers utilize this imaging technique, which operates without any instrument or with minimal intrusion, to identify diseases such as cancer at an early stage. The wavelength-adjustable feature of lasers enables researchers to target specific fluorescent indicators effectively, thereby enhancing both the accuracy and reliability of imaging procedures.

The development of laser technology using organic dye molecules faces challenges because intermolecular quenching effects prevent the creation of pure dye aggregate lasers. The research group of Yong Sheng Zhao developed a molecular self-assembly method in 2022 that produced unconventional dye microcrystals for laser applications through kinetic control mechanisms. The temperature increase drives the self-assembly process to shift from thermodynamic to kinetic control. The tight molecular arrangement in thermodynamically controlled microcrystals enables charge transfer between molecules, producing excimers that block lasing. The lasing threshold remains low because kinetic control during microcrystal formation produces larger intermolecular gaps, which generate weak interactions that enable efficient monomer emission.

In this study, coumarin-153 (C153) was utilized as a model dye to investigate the lasing behavior of microcrystals. The results indicate that thermodynamically formed microcrystals fail to exhibit lasing due to strong π-π stacking interactions and subsequent excimer formation, which hinder efficient emission. The loosely packed structure of kinetic microcrystals results in better monomer emission compared to thermodynamic crystals. The photoluminescence quantum yield of kinetic microcrystals reaches 59.8%, exceeding the 22.1% quantum yield of thermodynamic crystals. Time-resolved photoluminescence tests confirm that kinetic microcrystals exhibit rapid recombination rates and enhanced radiative decay processes, establishing their exceptional capability for lasing behavior.

The optically pumped lasing tests of kinetic C153 microcrystals demonstrate that they reach low-threshold lasing at 160 μJ/cm2, producing laser modes at 510 nm with a narrow linewidth of 0.33 nm. The lasing mechanism becomes evident when Fabry-Pérot cavity effects show mode spacing that inversely correlates with cavity length. The research demonstrates that proper molecular packing control is a key method for reducing intermolecular quenching, which enables efficient lasing operations in dye single crystals. Using this research, scientists have demonstrated that single-crystal dye lasers are feasible while developing a framework to design materials that respond according to controlled molecular orientation. The study shows how to manage charge transfer in molecular self-assemblies, creating opportunities to develop high-performance solid-state lasers from organic dyes (Fig. 6).

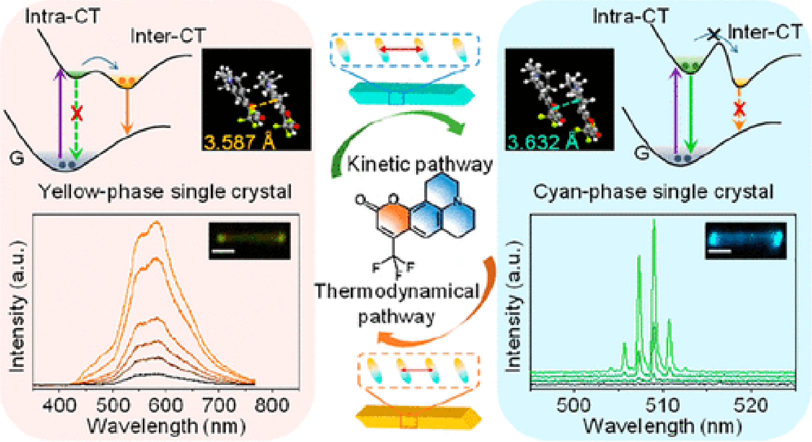

Fig. 6 Summary diagram of the research structure of the Yong Sheng Zhao group

3.3 Solid-state lasers

3.3.1 Principles and Structure

The active medium for laser generation in solid-state lasers consists of crystals that receive specific impurity atoms during crystal growth. Laser technology stands out due to its compact size, stable structure, straightforward maintenance requirements, and high power output. The ruby laser, the Nd: YAG (neodymium-doped yttrium aluminum garnet), and the titanium-sapphire laser represent significant examples of solid-state lasers (Figure 7).

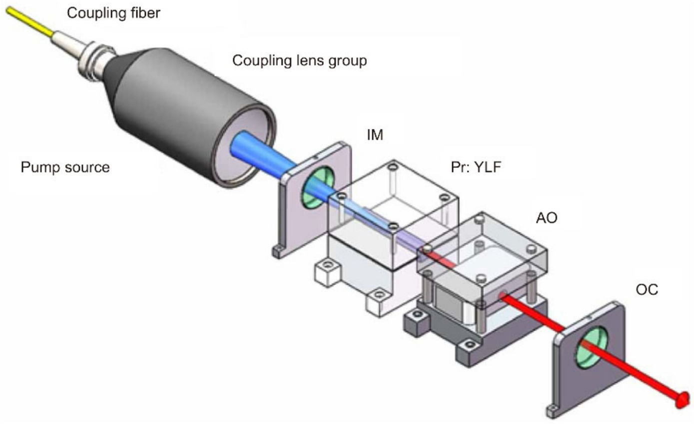

Fig. 7 The basic structure of a solid laser

3.3.2 Applications and Research Frontiers

Solid-state lasers serve multiple applications in the material processing industry through their use in cutting, welding, and drilling operations on metals, plastics, and ceramics. Thanks to their superior precision and high-energy capabilities, production groups can achieve complex designs with precise cuts. Solid-state lasers are utilized in the automotive sector for welding car body parts to create durable and accurate joints. The medical field benefits from solid-state lasers in multiple ways. Medical professionals utilize these lasers extensively for eye surgery and dermatological treatments, including the removal of tattoos, scars, and specific skin lesions. Laser treatment methods enable maximum patient success by promoting rapid recovery, minimizing complications, and reducing treatment time.

Single-mode operation of miniaturized solid-state lasers brings essential functionality to numerous photonic systems. In conclusion, the paper demonstrated that R-CD2 can be obtained by combining graphitic nitrogen doping and surface modification. The red emission was achieved without increasing the conjugated size, and the polymer coating significantly improved the PLQY and photostability. The PLQY of 65.5% is the highest for aqueous red emission from non-toxic aliphatic precursors, and the PL remained stable after one hour of UV irradiation. The ASE threshold of R-CD2 reached eight μJ cm^{-2} while its gain lifetime extended to 700 ps. The integration of R-CD2 with high-quality planar microcavity structures enabled the development of a solid-state laser that achieved single longitudinal mode operation with a 0.14 nm linewidth and a 14.8 dB signal-to-noise ratio (Q = 4600). The laser operated at high stability levels because it lost only 2% of its power during eight hours of continuous pumping without protective encapsulation. These results advance the development of CD-based luminescent materials and their applications in solid-state micro/nanolasers (Fig. 8).

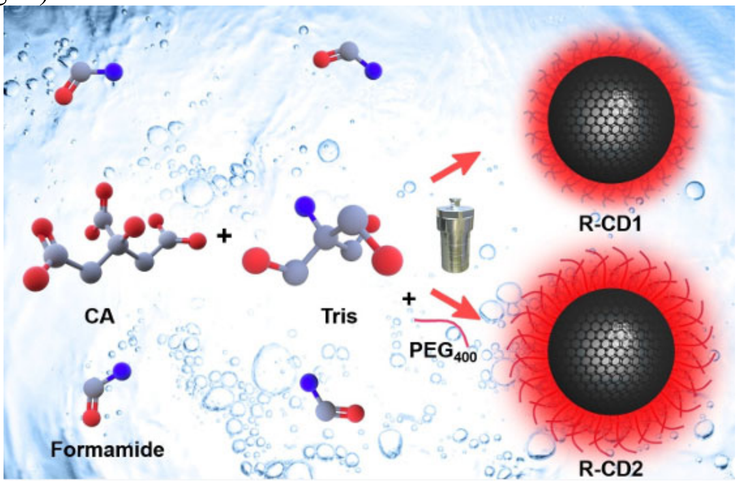

Fig. 8 Summary diagram of the research structure of the Siyu Lu group

3.4 Semiconductor laser

3.4.1 Principles and Structure

The structure of a semiconductor laser mainly consists of an active region, confinement layers, and cladding layers. The active region, composed of direct-bandgap semiconductor materials such as gallium arsenide (GaAs), is the core component where laser light is generated. Here, electron-hole recombination occurs, emitting photons. The confinement layers on both sides of the active region are crucial for restricting carriers and the optical field within the active region, thus enhancing the optical gain efficiency. The cladding layers surround the confinement layers and the active region. With a refractive index lower than that of the confinement layers, they confine the optical field within the active region for efficient laser output (Fig. 9).

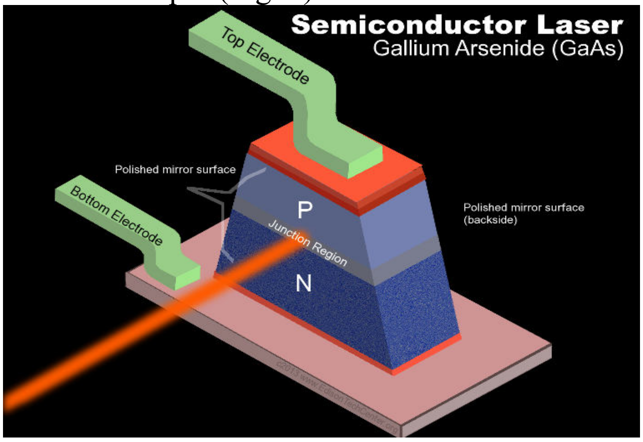

Fig. 9 The working principle of a semiconductor laser

3.4.2 Applications and Research Frontiers

Semiconductor lasers serve multiple applications across different fields. Semiconductor lasers serve as essential components in optical communication systems, converting electrical signals into optical signals that are transmitted through optical fibers at high speeds for long-distance communication, thereby forming a crucial part of contemporary network infrastructure. Semiconductor lasers direct a beam to a photosensitive drum through electrostatic imaging to generate high-quality image and text prints in laser printing systems. Semiconductor lasers are essential in medical procedures because they enable vision correction surgeries for ophthalmology patients and perform aesthetic treatments for freckle removal and hair removal. These lasers serve multiple industrial purposes, including cutting, welding, and drilling materials, thereby enabling precise and efficient processing.

Semiconductor lasers achieve their best power conversion efficiency (PCE) through edge-emitting lasers (EELs), which maintain the highest efficiency records. The advancement of EELs faces substantial hurdles to achieving greater efficiency. VCSELs experience performance limitations, making them perform poorer than the traditional edge-emitting lasers at room temperature. The research group under Shou-huan Zhou conducted studies in 2024 to evaluate whether multi-junction cascaded VCSELs could outperform EELs in terms of efficiency. A theoretical model and experimental work demonstrated that a 20-junction VCSEL achieved an efficiency of over 88% at room temperature, outperforming the best EEL efficiency obtained at low temperatures. A 15-junction VCSEL broke records by reaching a PCE of 74% with nanosecond pulse driving while surpassing all previous records for differential quantum efficiency exceeding 1100%.

This research introduces multiple active regions connected by tunnel junctions as its main innovation, as it enlarges the gain volume while maintaining stable resistance and internal loss rates. The design approach successfully reduces Joule heating and free carrier absorption, thus resulting in improved efficiency. The 15-junction VCSEL demonstrated a slope efficiency of 15.6 W/A, confirming the potential of multi-junction designs for efficient applications. Laser technology proves optimal for producing high levels of power, which helps drive LiDAR and advanced artificial intelligence systems in modern vehicles. Future research will focus on enhancing the reflectivity of the top distributed Bragg reflector (DBR) while exploring communication system applications that can benefit from its low current and high voltage characteristics for ultra-short pulse generation and high modulation rates. The research demonstrates that multi-junction VCSELs achieve exceptional efficiency levels, eliminating the performance difference between VCSELs and EELs. The 15-junction VCSEL achieves a power conversion efficiency (PCE) of 74% at room temperature, representing a significant advancement in semiconductor laser technology for energy-efficient sensing and communication applications, as well as other future uses (Fig. 10).

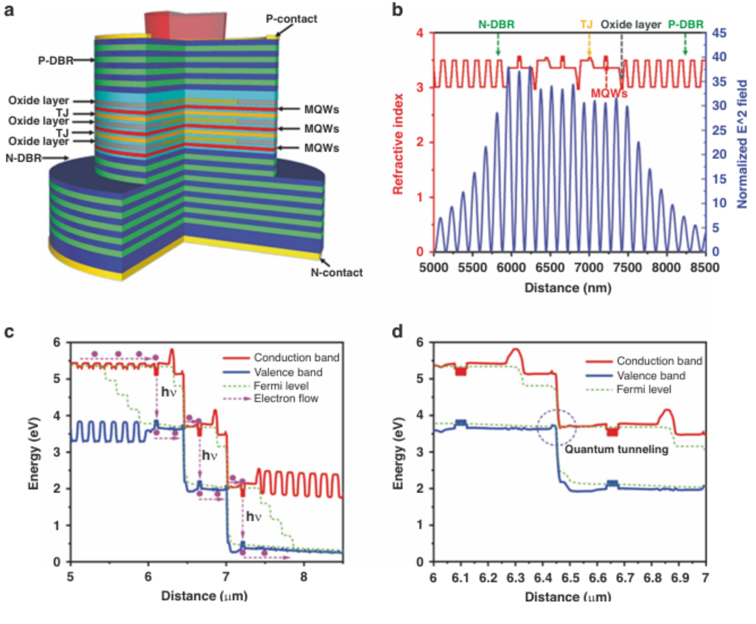

Fig. 10 Summary diagram of the research structure of the Shouhuan Zhou group

3.5 Fiber lasers

3.5.1 Principles and Structure

The structure of a fiber laser primarily consists of a gain fiber, pump sources, and a resonator. A gain fiber, also known as a doped optical fiber, is the heart of the laser, where light amplification occurs. The doping of rare-earth elements gives the fiber the necessary energy-level transitions for laser generation. Pump sources, typically high-power laser diodes, provide the energy required to excite the rare-earth ions in the gain fiber. They emit light at specific wavelengths efficiently absorbed by the doped ions. Two fiber-based reflectors, such as fiber Bragg gratings, form the resonator. These reflectors are designed to provide optical feedback, allowing the light to bounce back and forth within the gain fiber, further enhancing the amplification process. One of the reflectors is partially reflective, allowing a portion of the amplified light to be output as the laser beam (Fig. 11).

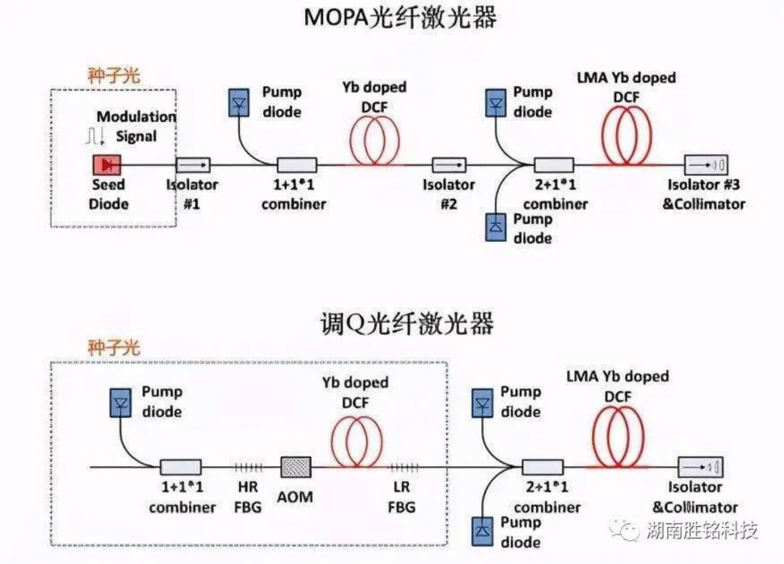

Fig. 11 The working principle of a fiber laser

3.5.2 Applications and Research Frontiers

Fiber lasers are widely used across various industries due to their exceptional characteristics and flexible operation. The processing industry utilizes fiber lasers for cutting and welding operations, as well as material marking on metals, plastics, and other materials, thanks to their high beam quality and efficient processing capabilities. Telecommunications utilize fiber lasers as the core components in extended optical fiber communication networks that quickly transfer data signals with minimal signal loss. Medical practitioners utilize fiber lasers to perform minimally invasive laser surgery and treat a wide range of medical conditions. Scientific research heavily relies on fiber lasers because these devices enable spectroscopic chemical analysis and metrological precision-based experiments.

In 2023, Stuart D. Jackson's group, which focuses on fiber lasers, presented the successful operation of a high-efficiency 3.05 μm dysprosium-doped fluoridate glass fiber laser, pumped in-band at 2.83 μm using an erbium-doped fluorozirconate glass fiber laser. The free-running laser achieved a slope efficiency of 82%, approaching 90% of the Stokes efficiency limit, with a record maximum output power of 0.36 W for fluoroindate glass fiber lasers. A high-reflectivity fiber Bragg grating (FBG) was directly inscribed into the Dy^3-doped fluoroindate glass to stabilize the wavelength. This innovation enabled narrow-linewidth operation at 3.2 μm, marking the first use of such a grating in active fluoroindate fibers. Fluoroindate glass demonstrates several advantages over fluorozirconate glass. Its lower maximum phonon energy (≈509 cm-1) extends mid-infrared transparency, allowing emission beyond 4.2 μm. Its superior water resistance makes it a more durable material for high-power mid-infrared applications (Fig. 12).

The experimental findings closely matched the numerical predictions. The system of rate equations, together with a BL assumption of 0.05 dB/m, enabled precise predictions of threshold and slope efficiency. The use of high Dy3+ ion concentrations enabled the reduction of background loss, which shortened the fiber length. A custom-made fiber Bragg grating (FBG) was inscribed into active fiber through femtosecond laser processing by using a line-by-line technique. The FBG achieved 98% reflectivity before being integrated into a high-Q cavity, enabling stable operation at 3.2 µm. The FBG-based cavity optimization process reduced threshold pump power to 0.35 W while achieving a slope efficiency of 66% and a maximum output power of 160 mW. The slope efficiency could achieve 80% according to simulation models, provided that additional losses are further minimized.

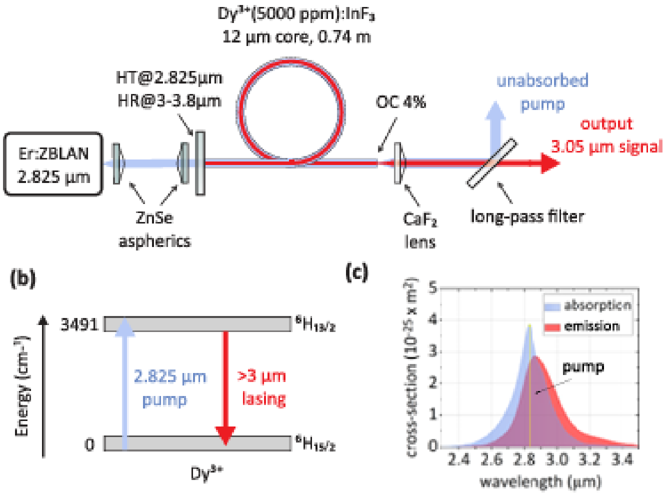

Fig. 12 Summary diagram of the research structure of the Stuart D. Jackson Group

4. Conclusion

The lasers are versatile in various fields, contributing energy and strength to the development of modern technology. The current research focus on lasers is undergoing a rapid transformation and is heading in several cutting-edge directions. Researchers in the field of "new laser materials" study three categories of materials, including two-dimensional structures such as graphene, transition metal sulfides, and perovskites, as well as quantum dots. Material innovation is expected to enhance the efficiency and stability of laser emission. Research on high-efficiency lasers is steadily advancing, encompassing ultrafast fibers, high-power semiconductor lasers, and innovative topological insulator lasers, to maximize power while minimizing energy consumption. Current laser research and development aim for stronger performance, taking into account short pulses, broad spectra, and integrating intelligent monitoring and unified design. Its continuous progress also provides key support for multiple emerging industries. The advancement of laser technology is expected to become a key driving force in technological innovation. Laser technological advancements, driven by design optimization and interdisciplinary research, will steadily lead to industry progress, despite ongoing challenges to system stability that require further investigation.

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