Laser in Medicine

Types of Lasers by Active Medium

Lasers are categorized based on the material used as the active medium where laser light is generated. Each type produces a different wavelength and has specific characteristics that make it suitable for certain medical applications.

• Gas Lasers: Use ionized gases such as CO₂, Argon, and He-Ne. These are common in surgical procedures like cutting and coagulation, as well as in dermatological and ophthalmic treatments.

• **Solid-State Lasers**: Use crystals like Nd:YAG or Ruby. They are versatile and used in deeper tissue applications, oncology, and skin rejuvenation.

• Liquid (Dye) Lasers: Use organic dye solutions in a liquid medium. These are tunable over a range of wavelengths and used mainly in research and treatment of vascular lesions.

• Semiconductor (Diode) Lasers: Made with semiconductor materials, compact and efficient, widely used in soft tissue surgery, dentistry, and hair removal.

• **Fiber Lasers:** Use doped optical fibers. Known for precision, reliability, and use in endoscopic surgery, imaging, and fine tissue applications.

Laser Operation Modes – Continuous vs. Pulsed

The laser can operate in different emission modes that significantly affect tissue interaction. Choosing the right mode depends on the desired effect, precision, and safety level.

• Continuous Wave (CW): Emits a steady laser beam. Ideal for cutting and coagulating large tissue areas where constant energy is needed.

• **Pulsed Lasers:** Emit energy in short bursts, minimizing heat damage. Useful for delicate structures like the retina or skin pigment removal.

• **Q-Switched Lasers:** Emit nanosecond pulses with very high peak power. Used for removing tattoos and pigmented lesions.

• **Mode-Locked Lasers:** Deliver ultra-short femtosecond pulses. Used in corneal surgery, nanoparticle generation, and high-precision applications.

Introduction to Nanotechnology

Nanotechnology focuses on materials and structures with sizes between 1 to 100 nm, where properties differ significantly from their bulk counterparts. The term Nano originates from the Greek word meaning "dwarf," and in metric scaling, nano-denotes 10⁻⁹ (one billionth of a unit). Nanoparticles exhibit unique optical, electrical, and biological properties, making them valuable for medical applications.



Fig. 1 Nanoparticles scale

Laser-Induced Nanoparticle Generation (LNP)

Laser ablation in liquid is a technique where a high-energy pulsed laser beam is focused on a solid target immersed in a liquid. The interaction creates a plasma plume and results in the formation of nanoparticles (NPs).

Advantages:

- No chemical contaminants
- Precise control of size and shape
- High purity and biocompatibility

Pulsed Laser Ablation (PLA) is a highly effective and clean method for producing nanoparticles, especially for medical applications. One of its biggest advantages is that it does not require any chemical additives or surfactants. This means the nanoparticles produced are pure, contamination-free, and safe for sensitive applications like drug delivery or imaging in the human body.



Another benefit of PLA is its versatility. It can be used with a wide variety of materials including metals like gold and silver, semiconductors, ceramics, and even complex composites. This makes it a flexible technique for researchers and industries working on different kinds of nanomaterials.

PLA also allows for excellent control over nanoparticle size and shape. By adjusting the laser parameters such as energy, wavelength, and pulse duration, scientists can fine-tune the properties of the nanoparticles according to their needs. This level of control is essential when nanoparticles are used for targeted therapies or specific biomedical functions.

Furthermore, the setup for PLA is relatively simple. All you need is a pulsed laser, a solid target material, and a container filled with a liquid medium. Compared to chemical synthesis methods, PLA involves fewer steps, produces no harmful byproducts, and generates nanoparticles that are already suspended in liquid.

Lastly, the nanoparticles formed through PLA are usually stable and highly biocompatible, making them ideal for medical applications like cancer therapy, biosensing, and diagnostic imaging.

In summary, PLA offers a clean, flexible, and controllable way to create highquality nanoparticles, which is why it is becoming increasingly popular in the field of nanomedicine and beyond.

Key Parameters That Affect Nanoparticles in PLA

Parameter	Effect on Nanoparticles
Laser wavelength	Determines how much energy the material absorbs. Affects ablation efficiency.
Pulse energy	Higher energy = more material removed, possibly larger particles.
Pulse duration	Shorter pulses (e.g., femtoseconds) = finer, more uniform nanoparticles.
Repetition rate	Affects the speed of production and heating in the liquid.
Liquid type	Affects cooling rate and stabilizes the nanoparticles.
Target material	Different materials respond differently to laser energy.

Medical Applications of Laser-Generated Nanoparticles

Laser-generated NPs are used in multiple fields of medicine due to their functionality, size, and compatibility.

• Gold Nanoparticles (AuNPs): Gold NPs are extensively used in cancer research and clinical trials. They are applied in:

- **Photothermal therapy (PTT):** Gold NPs absorb laser energy and convert it to heat, selectively destroying tumor cells.

- **Drug delivery:** Used as carriers to deliver chemotherapy directly to tumors with minimal side effects.

- Imaging: Serve as contrast agents in CT and optical imaging for better tumor

visibility.

Gold NPs are at the forefront of laser-assisted targeted anticancer therapy.

Silver Nanoparticles (AgNPs): Silver NPs are known for their strong antimicrobial properties and are also explored in cancer treatment:

-Used in wound care and antimicrobial coatings.

- Exhibit antifungal and antibacterial effects.

- Induce apoptosis in cancer cells via reactive oxygen species (ROS) generation.

Iron Oxide Nanoparticles (Fe₃O₄)

Iron oxide NPs are magnetic and highly useful in both imaging and therapy:

- Used as MRI contrast agents.

- Magnetic hyperthermia: Produce heat under a magnetic field to destroy cancer cells.

- Targeted drug delivery: Guided to tumors using external magnets.

Silicon Nanoparticles (SiNPs): Silicon NPs are biodegradable and biocompatible, making them ideal for sensitive applications:

- Gene and RNA delivery in cancer therapies.

- Components in biosensors for tumor detection and monitoring.

- Safe for long-term use in biological systems.

Zinc Oxide Nanoparticles (ZnO NPs): ZnO NPs are multifunctional and have shown promise in several medical fields:

- Anticancer: Induce ROS and apoptosis selectively in tumor cells.

- **Antibacterial:** Effective in killing drug-resistant bacteria and promoting wound healing.

- UV Protection: Used in sunscreens and skin applications.
- **Biosensing:** Employed in detection of cancer-related biomarkers.

Physical Examination Techniques for Laser-Generated Nanoparticles

Characterization of nanoparticles generated by lasers is essential to ensure their size, shape, structure, and composition meet the requirements for medical use. Several physical examination techniques are employed to analyze these properties:

• UV-Vis Spectroscopy:

This technique measures the absorbance of ultraviolet and visible light by nanoparticles. It helps determine the concentration, size, and optical properties of particles, especially for metal nanoparticles like gold and silver.



Scanning Electron Microscopy (SEM):

SEM provides high-resolution images of the nanoparticle surface, revealing details about morphology, particle shape, and size distribution. It uses a focused beam of

electrons to scan the sample and create detailed 3Dlike images.

Fig. 4 SEM image of Nano particles.



• X-ray Diffraction (XRD):

XRD is used to determine the crystalline structure of nanoparticles. It identifies the crystal phase, lattice spacing, and degree of crystallinity. This technique is essential for assessing the purity and phase composition of the particles.



• Transmission Electron Microscopy (TEM):

TEM offers extremely high magnification and resolution, making it suitable for viewing internal structures of nanoparticles. It can detect crystal defects and coreshell formations in nanoscale materials.

Fig. 6 TEM image of Nanoparticle



• Dynamic Light Scattering (DLS):

DLS measures the hydrodynamic diameter of particles in suspension by analyzing fluctuations in scattered light. It provides rapid estimation of size distribution in colloidal nanoparticle systems.

• Zeta Potential Analysis:

This technique evaluates the surface charge of nanoparticles, which influences their stability in suspension. High zeta potential values indicate good colloidal stability, which is important for drug delivery and medical formulations.