Basic principles of lasers

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Learning objectives

After reading this article you should be able to:
- describe the structural components of a laser
- understand how a laser beam is produced
- list the three principal properties of a laser beam
- outline the safety measures employed when a laser is used during a surgical procedure

Abstract

The word laser is an acronym of Light Amplification by Stimulated Emission of Radiation. A laser emits a beam of electromagnetic radiation that is always monochromatic, collimated and coherent in nature. Lasers consist of three main components: a lasing medium (solid, liquid or gas), a stimulating energy source (pump) and an optical resonator; and have a wide variety of uses in clinical medicine. Lasers cause tissue damage by various mechanisms and these are mainly determined by power density (irradiance) of the beam and exposure time. It is imperative to be aware of the risks associated with laser use in terms of tissue damage (burns and eye injuries) and fire hazards. Strict controls should be implemented governing the safe use of lasers in hospital practice, and all staff must be familiar with all safety measures to prevent injury and fires.

Keywords Damage; fire; lasers; physics; properties; safety

Introduction

> *"Suddenly a light from hell appeared in the middle of the ruby. Then, from the end of a cylinder, a hundred thousand times brighter than the sun, burst forth a thin red light, a perfectly parallel monochromatic beam. Maiman and his assistants were silent for some time, enthralled by the beauty of this spectacle... 'Einstein was right' he murmured, 'light can be concentrated and coherent.'"*

This newspaper extract describes the public demonstration of the first working laser constructed by Theodore Maiman in 1960.[1] It consisted of a ruby crystal shaped into a rod 4 cm long and 0.5 cm diameter. The ends were polished, flat and parallel, with one fully silvered and the other partially silvered. An electronic flash tube was coiled around the ruby.

Ruby is a crystalline form of aluminium oxide in which chromium atoms have replaced some of the aluminium atoms to give the crystal its red colour. The flashlight excites electrons in the chromium atoms to higher energy levels. Upon returning to their normal state, the electrons emit their characteristic ruby-red light. The mirrors reflect this light back and forth inside the crystal, stimulating other excited chromium atoms to produce more light until the crystal's stored energy is eventually dissipated.

The word laser is an acronym of **Light Amplification by Stimulated Emission of Radiation** and aptly describes the theory behind the mechanics of laser generation. Lasers are devices that produce or amplify a beam of narrow, convergent light with a well-defined wavelength within the electromagnetic spectrum. Wavelengths in the infrared, visible and ultraviolet regions of the spectrum are most commonly used for commercial applications.

Laser design

A laser consists of three main components (Figure 1):

Lasing medium: which may be solid (crystals or semiconductors), liquid (organic dyes) or a gas (or gas mixture).

Excitation system or **'pump':** this creates the conditions for light amplification by supplying the necessary energy to the lasing medium. There are different kinds of pumping systems: optical (flash lamps, continuous arc lamps, tungsten-filament lamps or even other lasers), electrical (gas discharge tubes, electric current in semiconductors), or chemical pumps.

Optical resonator: which in its simplest form consists of two mirrors arranged such that the photons pass back and forth along the length of the lasing medium. Typically, one mirror is partially transparent to allow the beam to exit (**output coupler**).

Laser physics

A lasing medium can be considered as consisting of atoms with a central nucleus of protons and neutrons surrounded by electrons in discrete orbital shells. These electrons move between different energy levels as the atom absorbs or releases external energy. Three different mechanisms exist which highlight the interaction between electrons and photons of energy (Figure 2).

- **Absorption**: an electron in its ground-state energy level (E_1) absorbs a photon of energy hv and moves to an upper level (E_2).

  h is Planck's constant (6.63×10^{-24} J/s) and v is frequency.
- **Spontaneous emission**: an electron in an upper level (E_2) can decay spontaneously to the lower level (E_1). In so doing, a photon of energy hv that has a random direction and phase is emitted.
- **Stimulated emission**: an incident photon causes an upper-level electron to decay, emitting a 'stimulated' photon whose properties (direction, wavelength and phase) are identical to those of the incident photon. Hence, duplication of the photon.

These three mechanisms are always present concurrently. An incident photon has an equal chance of being absorbed by a ground-state electron as being duplicated by interacting with an

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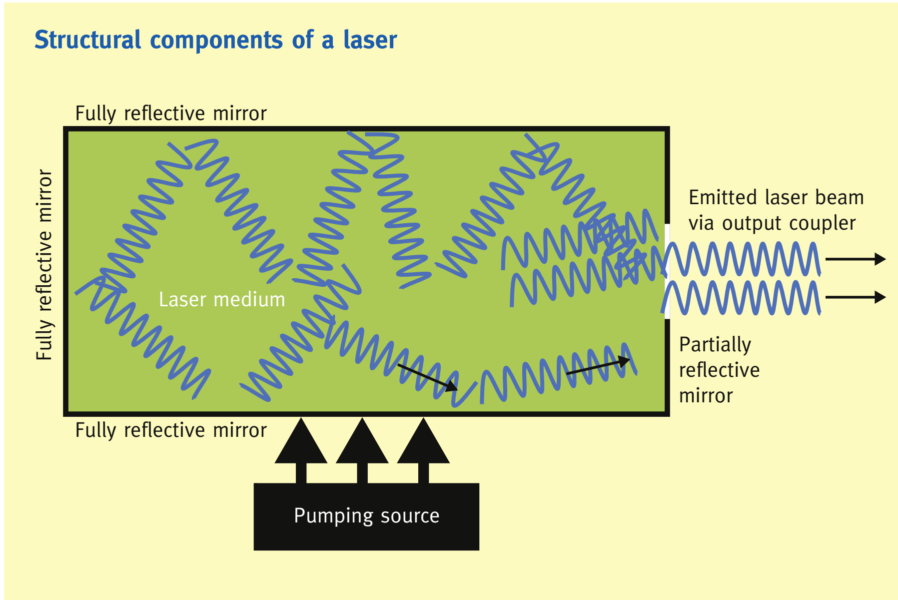

Figure 1

excited-state electron, that is, absorption and stimulated emission are two reciprocal processes subject to the same probability. For a laser to function, conditions have to favour stimulated emission over absorption and spontaneous emission, so that there are more excited-state electrons than those in the ground-state (‘**population inversion**’). This is achieved by the input of energy from the pump; which may be supplied continuously, or intermittently in the case of a pulsed laser.

The optical resonator, with its arrangement of mirrors, allows amplification or optical gain to occur as photons stimulate the emission of more and more photons. The laser light travels to and fro along the same axis with some photons eventually exiting the partially silvered mirror at one end.

Properties of a laser beam

The three Cs can be used as a simple *aide-mémoire*:

- **C**olour: consisting of just one wavelength of light (monochromatic)
- **C**oherence: all light particles (photons) are in phase
- **C**ollimated: the photons minimally diverge from their point of origin and are considered as being parallel.

Damage mechanisms

Lasers cause tissue damage through various mechanisms, mainly determined by power density or irradiance (W/cm^2) and exposure time.

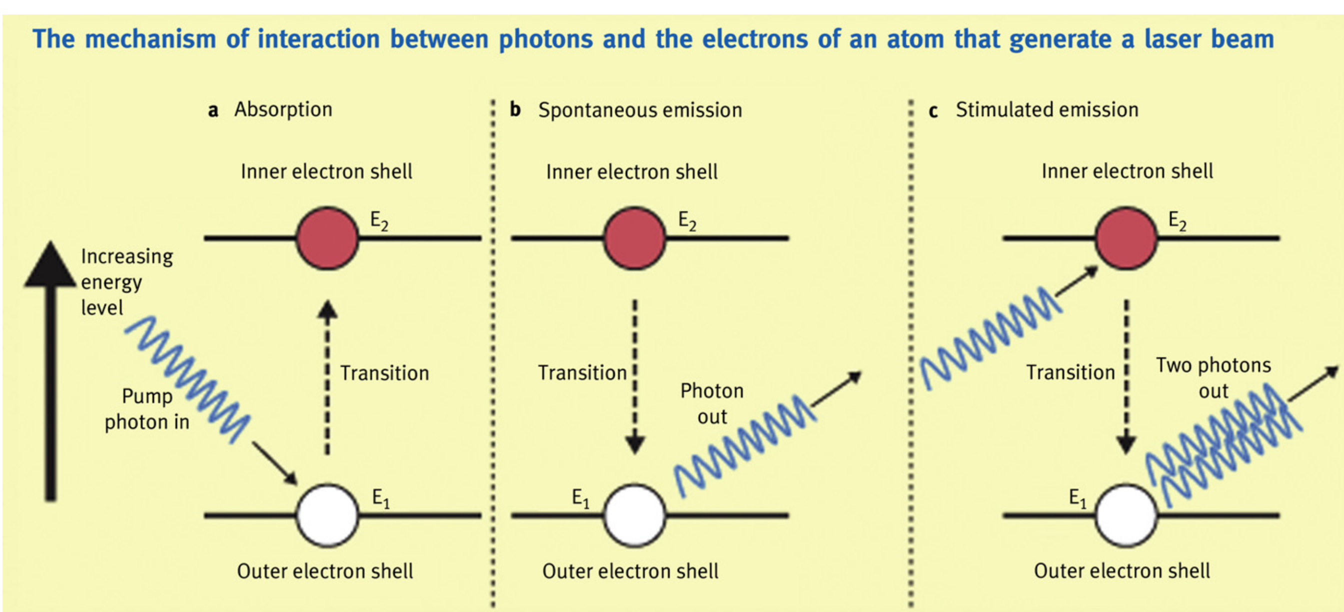

Figure 2