Moving into the nanometer world with femtosecond lasers

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1 Introduction

On May 16, 1960, Theodore H. Maiman operated the first functioning laser at Hughes Research Laboratories (Malibu, California). Maiman's laser used a solid-state flashlamp-pumped synthetic ruby crystal to produce red laser light, at 694 nanometers wavelength. This device only was capable of pulsed operation because of its pumping design.

When lasers were invented in 1960, they were called "a solution looking for a problem". Since then, they have become ubiquitous, finding utility in thousands of highly varied applications in every section of modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement, entertainment, and the military. Fiber-optic communication using lasers is a key technology in modern communications, allowing services such as the Internet. The first use of lasers in the daily lives of the general population was the supermarket barcode scanner (introduced 1974). The laserdisc player (1978), was the first successful consumer product to include a laser but the compact disc player was the first laser-equipped device to become common (1982) followed shortly by laser printers. Nowadays, lasers are a multi-billion dollar business.

2 Laser principle

A laser is constructed from three principal parts:
1) An energy source (usually referred to as the pump or pump source)
2) A gain medium or laser medium
3) Two or more mirrors that form an optical resonator or cavity

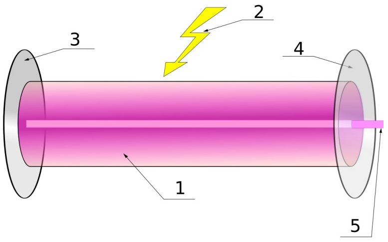

Figure 1: Components of a typical laser: (1) Gain medium, (2) Laser pumping energy, (3) High reflector, (4) Output coupler (partial reflector), (5) Laser beam

The gain medium is a material with properties that allow it to amplify light by way of stimulated emission. Light of a specific wavelength that passes through the gain medium is amplified (increases in power). The gain medium is the major determining factor of the wavelength of operation, and other properties, of the laser. Gain media with wide spectra allow tuning of the laser frequency. There are hundreds if not thousands of different gain media in which laser operation has been achieved. The gain medium is excited by the pump source to produce a population inversion, and it is in the gain medium that spontaneous and stimulated emission of photons takes place, leading to the phenomenon of optical gain, or amplification.

For the gain medium to amplify light, it needs to be supplied with energy in a process called pumping. Examples of pump sources include electrical discharges, flashlamps, arc lamps, light from another laser, chemical reactions and even explosive devices. The type of pump source used principally depends on the gain medium, and this also determines how the energy is transmitted to the medium. A helium–neon (HeNe) laser uses an electrical discharge in the helium-neon gas mixture, a Nd:YAG laser uses either light focused from a xenon flash lamp or diode lasers, and excimer lasers use a chemical reaction. Examples of different gain media include solids (semiconductors, crystals, glasses), liquids (dyes in organic solvents), and gases (CO_2, Ar, ...).

The optical resonator, or optical cavity, in its simplest form is two parallel mirrors placed around the gain medium which provide feedback of the light. The mirrors are given optical coatings which determine their reflective properties. Typically one will be a high reflector, and the other will be a partial reflector. The latter is called the output coupler, because it allows some of the light to leave the cavity to produce the laser's output beam. Light from the medium, produced by spontaneous emission, is reflected by the mirrors back into the medium, where it may be amplified by stimulated emission. The light may reflect from the mirrors and thus pass through the gain medium many hundreds of times before exiting the cavity. In more complex lasers, configurations with four or more mirrors forming the cavity are used. The design and alignment of the mirrors with respect to the medium is crucial for determining the exact operating wavelength and other attributes of the laser system. Most practical lasers contain additional elements that affect properties of the emitted light, such as the polarization, wavelength, and shape of the beam.

3 Laser applications

3.1 Laser machining

Laser cutting is a technology that uses a laser to cut materials, and is typically used for industrial manufacturing applications, but is also starting to be used by schools, small businesses, and hobbyists. Laser cutting works by directing the output of a high-power laser most commonly through optics. The laser optics and computer are used to direct the material or the laser beam generated. A typical commercial laser for cutting materials would involve a motion control system to cut the desired pattern onto the material. The focused laser beam is directed at the material, which then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish. Industrial laser cutters are used to cut flat-sheet material as well as structural and piping materials. In order to be able to start cutting from somewhere other than the edge of a workpiece, a pierce is done before every cut. Piercing usually involves a high-power pulsed laser beam which slowly makes a hole in the material.

Advantages of laser cutting over mechanical cutting include easier workholding and reduced contamination of workpiece (since there is no cutting edge which can become contaminated by the material or contaminate the material). Precision may be better, since the laser beam does not wear during the process. There is also a reduced chance of warping the material that is being cut, as laser systems have a small heat-affected zone. Some materials are also very difficult or impossible to cut by more traditional means.

The work horse in industry, the CO_2 laser, is used for cutting of many materials including mild steel, aluminium, stainless steel, titanium, Taskboard, paper, wax, plastics, wood, and fabrics. YAG (Yttrium-Aluminum-Garnet) lasers are primarily used for cutting and scribing metals and ceramics. Fiber lasers are a type of solid state laser that is rapidly growing within the metal cutting industry. With a significantly shorter wavelength, fiber lasers produce an extremely small spot size compared to CO_2 lasers, making it ideal for cutting reflective metal material.

3.2 Laser lighting displays/laser light shows

Laser light is useful in entertainment because the coherent nature of laser light allows a narrow beam to be produced, which allows the use of optical scanning to draw patterns or images on walls, ceilings or artificial fog without refocusing for the differences in distance. This inherently more confined beam is also extremely visible, and is often used as an effect.

Laser scanners reflect the laser beam on small mirrors which are mounted on galvanometers to which a control voltage is applied. The beam is deflected a certain amount which correlates to the amount of voltage applied to the galvanometer scanner. Two galvanometer scanners can enable X-Y control voltages to aim the beam to any point on a square or rectangular raster. This enables the laser lighting designer to create patterns such as Lissajous figures (such as are often displayed on oscilloscopes); other methods of creating images through the use of galvanometer scanners and X-Y control voltages can generate letters, shapes, and even complicated and intricate images. A planar or conical moving beam aimed through atmospheric smoke or fog can display a plane or cone of light known as a "laser tunnel" effect.

A less complicated way of spreading the laser beam is by means of diffraction. A grating splits the monochromatic light into several rays, and by using complex holographic gratings, the beam can be split into various patterns.

Uninterrupted stationary beams from one or more laser emitters are used to create aerial beam effects, which are turned on and off at varying intervals to create a sense of excitement. As the laser beam is not manipulated in any way, this could be considered the simplest form of a laser light show and also the least dynamic. Although this method is not as commonly used today due to the availability of scanners, many would argue that these shows were vital precursors to laser light shows.

3.3 Laser rangefinding

A laser rangefinder uses a laser beam to determine the distance to an object. Laser rangefinding can be performed on various principles:

Time of flight: ToF rangefinders measure the time a light pulse needs to travel to the target and back. With the speed of light known, and an accurate measurement of the time taken, the distance can be calculated. Many pulses are fired sequentially and the average response is most commonly used. This technique requires very accurate sub-nanosecond timing circuitry.

Multiple frequency phase-shift: The phase shift of multiple frequencies on reflection is measured. From that, some simultaneous equations are solved to yield a distance measurement.

Interferometry This technique is most appropriate for the measurement of distances smaller than micrometers.

4 My research in laser science and technology

4.1 Femtosecond pulse shaping

Femtosecond pulse shaping refers to manipulations with temporal profile of an ultrashort laser pulse. Pulse shaping can be used to shorten/elongate the duration of optical pulse, or to generate complex pulse shapes.

Generation of sequences of ultrashort optical pulses is key in realizing ultra high speed optical networks, Optical Code Division Multiple Access (OCDMA) systems, chemical and biological reaction triggering and monitoring etc. Based on the requirement, pulse shapers may be designed to stretch, compress or produce a train of pulses from a single input pulse. The ability to produce trains of pulses with femtosecond or picosecond separation implies transmission of optical information at very high speeds.

A pulse shaper may be visualized as a modulator. The input pulse is multiplied with a modulating function to get a desired output pulse. The modulating function in pulse shapers may be in time domain or a frequency domain (obtained by Fourier Transform of time profile of pulse). However, application of direct pulse shaping technique on a femtosecond time scale faces the same problem as direct femtosecond pulse measurement: electronics speed limitations. An ultrashort pulse with a well-defined electrical field can be modified with an appropriate filter acting in the frequency domain. Mathematically, the pulse is Fourier transformed, filtered, and back-transformed to yield a new pulse. It is possible to design an optical setup with an arbitrary filter function.