THE LITTLE BOOK OF BIG LASERS

Everything you ever needed to know about LASERS and their uses
LASER light is a very special form of man-made light that doesn’t exist in nature. Laser devices generate an intense beam of highly-focused light that can be used for anything from drilling and cutting, delicate surgery, reading barcodes and DVDs to probing the atomic building blocks of nature.

LASERS come in all sorts of shapes and sizes. They can be smaller than a microchip and emit tiny amounts of low-energy infrared light, or huge room-filling multi-laser systems that blast out high-energy radiation. Their uses are even more diverse.
**WHAT IS LIGHT?**

a) Light is made up of photons. A photon is a little packet of light that carries electromagnetic energy.

b) But light is also a wave – as you can see from this diagram of the electromagnetic spectrum (above), which covers everything from radio waves, through microwaves and visible light, all the way to X-rays and gamma rays.

c) The amount of energy a photon carries determines where it fits in the electromagnetic spectrum.

d) Thanks to Quantum Mechanics (the theory that describes the world of particles), particles (like photons) can be described as being both a particle and wave.

e) Because they are also waves, photons also have a wavelength. The more energy a photon carries, the shorter its wavelength is.

An X-ray photon carries thousands of times more energy than a photon from the visible light part of the spectrum.

An X-ray photon's wavelength is around a millionth of a millimeter (one nanometre) whereas a radio photon’s wavelength can be tens of kilometres long.

f) A photon of red light has less energy (and a longer wavelength) than a photon of blue light.
**How do you make laser light?**

LASER stands for ‘Light Amplification by Stimulated Emission of Radiation’.

Lasers rely on a quantum process that causes an atom to absorb and emit photons.

1. Atoms are made up of a nucleus surrounded by electrons that move in orbits that occupy different energy levels. Electrons can change their orbit by gaining or losing energy.

2. An electron can gain energy by absorbing a photon. When it does so, it gets ‘excited’ and leaps up to a higher-energy orbit (a quantum leap).

---

**How is LASER light different to torch light?**

**Torch light** is made up of many different wavelengths (colours) that travel only roughly in the same direction. This means the photons interfere with each other and the peaks and troughs arrive at different times.

**Laser light** is monochromatic (consists of just one colour) and the peaks and troughs of its wavelength line up (coherent), so they don’t interfere.

Its waves also travel parallel to each other (collimated) - allowing a laser to remain tightly focused over great distances.
2. Excited electron jumps to higher orbit

3. But the electron wants to return to its original orbit, so it emits a photon and drops back down. This process is called **spontaneous emission**.

4. If another photon is absorbed by the excited electron before it can drop its orbit, the electron will emit two photons. This process is called **stimulated emission**.

Because these photons are emitted by the same atom, they are twins. They are the same colour (known as **monochromatic** light) and the peaks and troughs of their waves are lined up, or ‘in phase’ (known as **coherent** light).
5. At its most simple, a laser consists of a crystal (the ‘lasing material’), two mirrors and a flash bulb. The flash bulb pumps energy (photons) into the lasing material and excites the crystal’s atoms, which spontaneously emit photons of their own.

7. The mirrors only reflect photons with a specific wavelength and phase. The parallel mirrors also ensure that only photons travelling perfectly parallel to each other (called ‘collimated light’) are reflected back into the crystal to be amplified.

8. One of the mirrors is only partly reflective and it lets some photons escape. The monochromatic, coherent, collimated light that leaves the mirror is the laser beam.
6. The emitted photons reflect off the mirrors and travel back and forth through the lasing material. As they do so, they stimulate the already excited atoms to emit more photons. As each individual photon stimulates the emission of two photons and the light is amplified.

9. To make a more powerful laser, the initial ‘seed laser’ beam can be split into narrower beams (or short pulses), which are then individually amplified.

10. These can be further amplified or split into more beams, or pulses, to be amplified. Pulses can be compressed and focused to increase power and intensity.
The **Vulcan laser** at the STFC’s Central Laser Facility at the Rutherford Appleton Laboratory is capable of producing laser pulses that, for a fraction of a second, can deliver 10,000 times more power than the whole of the UK’s National Grid. To achieve this power, the seed laser undergoes many stages of amplification.

1. A ‘seed’ laser pulse is generated.
2. The pulse is amplified and split into eight beams.
iii. Pulses pass through 1st stage amplifiers to increase power.

iv. Pulses pass through 2nd stage amplifiers.

v. Six pulses are sent to Target Area West.

vi. Two pulses can be sent to Target Area West where they are compressed to increase power and focused using a parabolic mirror.

vii. Or, one of the pulses can be sent to the 3rd stage amplifiers and on to the Petawatt Area where it is compressed to further increase its power and then focused with a parabolic mirror.
TYPES OF LASER

Although a simple solid-state laser uses a crystal as its lasing material (the very first working laser, in 1960, used ruby), today, there are many different types of laser. Anything from gases and liquids, to semi-conductors and free-flowing electrons can be used for lasers.

Some lasers are designed to emit light continuously, while others can spit out trains of light pulses, each lasting less than one-trillionth of a second. These can be used to carry information, or to take snapshots of fast processes such as chemical reactions.

Lasers can produce beams covering a wavelength range right across the electromagnetic spectrum.

A laser’s wavelength determines what it can be used for – the shorter the wavelength, the smaller the object it can be used to study. A visible light photon can’t be used to see a single molecule, for example, because it’s wavelength is so long in comparison.

A Blu-ray disc can hold so much more information than a DVD because the laser used to read it is blue, which has a shorter wavelength than the red laser used by a DVD player.
Lasers are now essential to modern life.

- They can read out and transmit information, as in barcode scanners, DVD and Blu-ray players, printers, and fibre-optic broadband.
- They offer precision measurement - for example, as laser tape-measures and spirit levels, and for accurately measuring distances in space.
- In Industry, lasers cut, weld and strengthen or harden materials, etch microelectronic circuits, and in hospitals, doctors use them to carry out delicate surgery.

- The precise wavelength of laser beams means that they can be used for very accurate chemical, biochemical and environmental analysis.
- They are the key components in advanced microscopes used in biomedical research, and in holography – the creation of 3D images.
- Laser beams can even trap, levitate and move particles and small objects.
- Ultra-intense laser light is used to probe the fundamental properties of matter and accelerate particles.
- In the future, lasers could provide us with clean energy.
SEEING BENEATH THE SURFACE
How lasers ‘look inside’

1. Laser
2. Scattered photons
3. Incoming photon
4. Raman scattered photon
5. Molecule vibrates
6. Raman scattered photon
An ingenious laser technique called spatially-offset Raman Spectroscopy (SORS), developed at the STFC’s Central Laser Facility (CLF), allows us to ‘see’ through opaque objects.

It can be used at airports to detect hidden explosives and is also being developed to scan for breast cancer and bone disease.

1. A laser beam is directed at a container, such as a bottle. Most of the photons interact with the container’s molecules and scatter off its surface.

2. But some photons make it through and penetrate the contents.

3. A small percentage of those photons will be absorbed by molecules inside the container. The photon excites the molecule and makes it vibrate.

4. When a photon does this, it loses energy to the molecule – so when it scatters (emitted by the molecule) the photon’s wavelength has shifted and it changes colour. This is called Raman scattering.

5. The Raman scattered photon ‘bounces’ around inside until it finally exits the container – where it is picked up by a detector.

6. From the amount of energy the photon has lost, scientists can identify the chemical properties of the molecule it scattered from – and so identify the contents of the bottle without ever opening it.
CREATING A STAR ON EARTH
How lasers recreate a star

1. A tiny gold capsule, containing a hydrogen fuel pellet, is zapped by high-power laser pulses.

2. This super-heats the capsule and creates powerful X-rays that heat the pellet to millions of degrees. The pellet’s outer shell vapourises – creating a shockwave that crushes the pellet.

3. A final laser pulse heats the pellets to more than 100 million degrees.
Nuclear fusion (the process that makes the stars shine) could provide a near-endless supply of clean, safe energy.

To create fusion on Earth, scientists must recreate the sort of heat and pressure that exists in the heart of a star.

Facilities like the Vulcan laser are exploring ways to make this possible.

4. This creates enough heat and pressure to force the atoms within the fuel pellet to fuse together. Two hydrogen atoms fuse to create one helium atom.

5. Fusion releases a huge amount of energy. Most of this is carried off by a neutron, which can be captured and used to heat water, drive a steam turbine and generate electricity.
MINI PARTICLE ACCELERATORS

How lasers accelerate particles

1. A powerful laser pulse is fired at a target material – a solid foil or a puff of gas

2. The laser’s electric field rips the electrons from the orbits of the foil’s atoms and tears apart their nuclei (made of protons and neutrons).
We are used to thinking of particle accelerators as being huge underground rings but scientists are working on accelerators that could fit on a desktop.

The CLF’s high-power lasers are being used to develop the next generation of compact particle accelerators. These laser-driven accelerators could be used in areas such as cancer diagnosis and treatment, security inspection and in industry.

3. As it passes through, the laser pulse picks up the electrons and protons and accelerates them to high speeds – creating powerful electron and proton beams.

The electrons also emit photons in the form of high-energy X-rays.
PROBING THE BUILDING BLOCKS OF MATTER

Because light is made up of photons, which carry electromagnetic energy, high-power lasers generate very strong electric, or magnetic fields. These fields can be used to manipulate particles of matter to explore their properties.

DETECTING WAVES IN SPACE AND TIME

The Universe has a ‘fabric’ known as spacetime. Einstein predicted that massive events – such as colliding black holes, or supernova explosions – would create ripples in spacetime, called gravitational waves. These have never been detected, but lasers could make it possible by measuring the tiny changes in the Earth’s surface predicted to occur when gravitational waves pass through.

MAKING ATOMS DANCE

Lasers can be used to ‘excite’ atoms or molecules to make them ‘jiggle’ about, or even break the chemical bonds between them.

A second laser can be used to measure the way the molecule moves and any energy changes. This allows scientists watch chemical reactions as they happen.
LASERS AT THE STFC

The Central Laser Facility (www.clf.stfc.ac.uk), at the STFC Rutherford Appleton Laboratory near Oxford, is one of the world’s leading laser facilities:

VULCAN

Vulcan is a high-power petawatt (10,000 million million watts) laser system, based on neodymium/glass. Plans are in place to upgrade Vulcan to 20 petawatts to study materials under extreme temperatures and pressures.

GEMINI

Gemini is a high-power two-beam system, based on titanium/sapphire, delivering high-power ultra-short pulses of near-infrared light.

ARTEMIS

Artemis works in the extreme ultraviolet (XUV) part of the spectrum, just beyond ultraviolet, and is used to study ultra-fast electronic processes in physics and chemistry.

ULTRA

ULTRA encompasses a range of pulsed light sources, from ultraviolet to infrared, plus various support equipment to capture chemistry in action, and manipulate particles.

OCTOPUS

Octopus offers a wide range of laser microscopy techniques needed for biological and medical research.
The Central Laser Facility (CLF) is a partnership between its staff and the large number of members of UK and European universities who use the specialised laser equipment provided to carry out a broad range of experiments in physics, chemistry and biology.

Useful links

About the Central Laser Facility  
www.stfc.ac.uk/clf/  
www.stfc.ac.uk/585.aspx

Lasers and plasmas  
www.stfc.ac.uk/913.aspx

Lasers for life (article)  
www.stfc.ac.uk/3180.aspx

About the STFC  
www.stfc.ac.uk

Free resources for schools and publications  
www.stfc.ac.uk/teachers  
www.stfc.ac.uk/pepublications

YouTube Backstage Science

Super Intense Laser (Vulcan)  
www.youtube.com/watch?v=P5WltfXcq9A

Octopus laser  
www.youtube.com/watch?v=1_YueZ29dYM

Science & Technology Facilities Council

The Science and Technology Facilities Council operates world-class, large-scale research facilities; supports scientists and engineers world-wide; funds researchers in universities and provides strategic scientific advice to government.

The Council’s Public Engagement team offers a wide range of support for teachers, scientists and communicators to facilitate greater engagement with STFC science which includes astronomy, space science, particle physics and nuclear physics.

Graphics, text and layout: Ben Gilliland  
Other images: STFC  
Copyright: Ben Gilliland/STFC