GCE A level

1325/01-A

PHYSICS

ASSESSMENT UNIT PH5

A.M. MONDAY, 27 June 2011

CASE STUDY FOR USE WITH SECTION B

Examination copy
To be given out at the start of the examination.
The pre-release copy must not be used.

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Paragraph

Lasers and their Applications

With over a billion lasers manufactured per year these elegant devices have proved their worth
since the first ruby laser started ‘lasing’ in 1960. At least seven Nobel prizes are attributable to the
theory or uses of lasers but, still, their applications seem to increase daily. Some uses of lasers are
slightly inelegant in that they just use their high power to vaporise, fuse, melt, blind or destroy 1
but many applications are more subtle - relying on their highly directional nature, their ability
to produce ultra short pulses or their monochromatic or coherent nature. Here are some wide-
ranging examples encompassing these invaluable properties of lasers.

Medical Uses of Lasers

The highly collimated beam of a laser can be further focused to a microscopic dot of extremely
high energy density. This makes it useful as a cutting and cauterizing instrument. A focused laser
can act as an extremely sharp scalpel for delicate surgery, cauterizing as it cuts. (“Cauterizing”
refers to long-standing medical practices of using a hot instrument or a high frequency electrical 2
probe to singe the tissue around an incision, sealing off tiny blood vessels to stop bleeding.) The
cauterizing action is particularly important for surgical procedures in blood-rich tissue such as the
liver.

Lasers have been used to make incisions half a micrometre wide, compared with about 80 μm for 3
the diameter of a human hair.

Surveying and Ranging

Helium-neon and semiconductor lasers have become standard parts of the field surveyor’s
equipment. A fast laser pulse is sent to a corner reflector at the point to be measured and the time 4
of reflection is measured to get the distance.

Some such surveying is long distance! The Apollo 11 and Apollo 14 astronauts put corner
reflectors on the surface of the Moon for determination of the Earth-Moon distance. A powerful
laser pulse from the MacDonald Observatory in Texas had spread to about a 3 km radius by the 5
time it got to the Moon, but the reflection was strong enough to be detected. We now know the
range from the Moon to Texas within about 15 cm, a nine significant digit measurement. A pulsed
ruby laser was used for this measurement.

Laser Sights and Firearms

The laser has in most firearms applications been used as a tool to enhance the targeting of
other weapon systems. For example, a *laser sight* is a small, usually visible-light laser placed
on a handgun or a rifle and aligned to emit a beam parallel to the barrel. Since a laser beam by 6
definition has low divergence, the laser light appears as a small spot even at long distances; the
user places the spot on the desired target and the barrel of the gun is aligned (but does not allow
for bullet drop, wind or the target moving while the bullet travels).

Another limitation of a laser sight is that light leaving a laser is slightly diverging due to 7
diffraction of the beam as it exits the aperture. The beam divergence is given by equation 1.

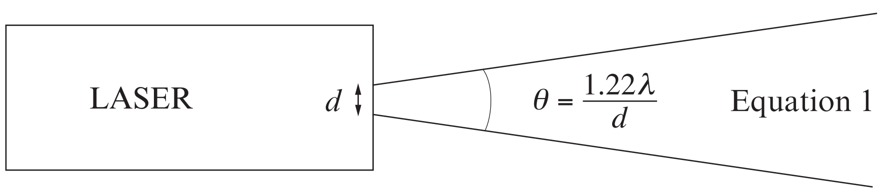


Diagram 1

Typical divergence of a laser beam is around 1 milliradian but this is far less accurate than that obtainable by a good marksman with a large telescopic lens.

Lasers in Communication
Fibre optic cables are a major mode of communication partly because multiple signals can be sent
with high quality and low loss by light propagating along the fibres. The light sources are lasers
or LEDs but lasers have significant advantages because they are more nearly monochromatic and 8
this allows the pulse shape to be maintained better over long distances. If a better pulse shape can
be maintained, then the communication can be sent at higher rates without overlap of the pulses.

Telephone fibre drivers may be solid state lasers the size of a grain of sand and consume a power
of only half a milliwatt. Yet they can send 50 million pulses per second into an attached telephone 9
fibre and encode over 600 simultaneous telephone conversations.

CD-ROMs and DVD-ROMs
Today, most CD-ROM and DVD-ROM disc drives use a single highly concentrated laser beam
to read the digital signal that is encoded onto tracks of an optical disc (CD or DVD). The single
laser beam is directed at a single track of information, which forms a continuous spiral on the disc 10
that begins at the disc centre and spirals outward towards the outer edge. Variations (in data pit
length) on the disc surface cause variations in the reflected laser beam, which are detected by an
optical sensor.

The disc drive rotates the disc and the tracks run under the laser beam. The drive system has an
optical motor control that allows the laser to exactly focus and follow the spiral path of the pits
and lands, to stay focused on the "track". The laser is reflected at different intensities for different
amounts of time (the length of a pit or land) as it passes over the spiral track. A zero actually
corresponds to high reflected intensity off a flat pit or a flat land section. A one corresponds to 11
low reflected intensity at the edge of a pit and land where destructive interference occurs between
the two reflections. In order to maximise the interference between light reflected from 'land' and
light reflected from a 'pit', the pit depth is chosen as a quarter of a wavelength. The reflected laser
light is then directed to a light sensitive detector that turns the light variations into a stream of
serial data, representing the pattern of pits and lands on the disc. This data stream is amplified
and sent to a microprocessor for interpretation. The laser, lenses to focus the beam, a mirror to
point the reflected beam and the light sensitive detector, combined are known as an "optical pick-
up".

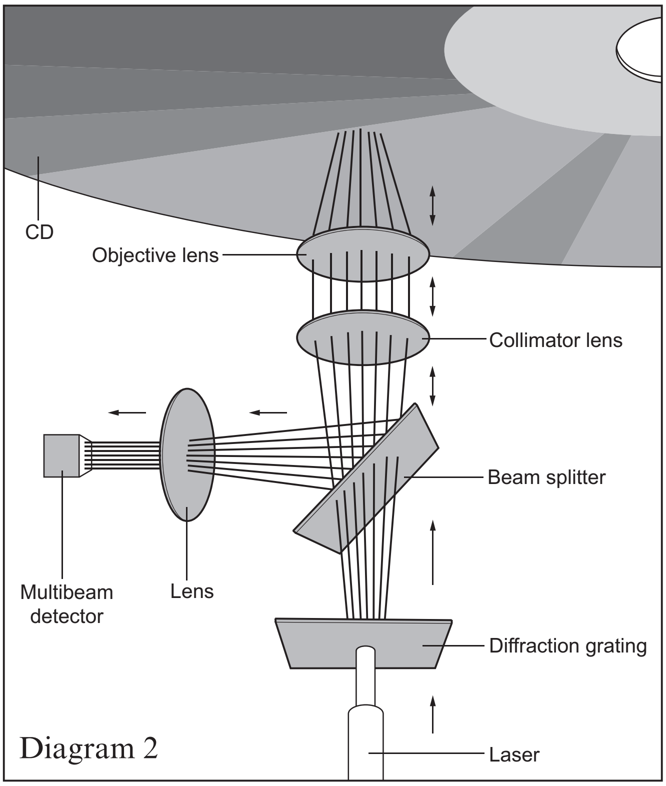


Diagram 2

The Multiple Beam approach to
illuminating and detecting multiple tracks
(see diagram at left) uses a diffracted laser
beam in conjuction with a multiple beam
detector array. The laser light from a
conventional laser diode is sent through a
diffraction grating, which splits the beam
into seven discrete beams, spaced evenly to 12
illuminate seven tracks. The seven beams
pass through a beam splitting (two-way)
mirror to the objective lens and onto the
surface of the disc. Focus and tracking are
accomplished with conventional detection
elements on the central beam. The three
beams on either side of the centre beam are
readable by a multibeam detector array as
long as the centre beam is on track and in
focus.

The reflected beams return from the disc via the same path and are directed to the multiple beam detector array by the reflective surface of the beam splitter. The detector contains seven discrete detectors spaced to align with seven reflected tracks. Note that a standard single beam pick-up is 13
very similar. In a single beam pick-up, the diffraction grating would be removed and the detector would have a single data detection point.

Laser Cooling

Starting in about 1985, the use of lasers to achieve extremely low temperatures has advanced to the point that temperatures of 10^{-9} K have been reached. If an atom is travelling toward a 14
laser beam and absorbs a photon from the laser, it will be slowed by the fact that the photon has momentum

$$p = \frac{E}{c} = \frac{h}{\lambda} \qquad \text{Equation 2}$$

If we take a sodium atom as an example, and assume that a number of sodium atoms are freely moving in a vacuum chamber at 300 K, the rms velocity of a sodium atom from kinetic theory would be about 570 $\mathrm{ms^{-1}}$. Then if a laser is tuned just below a sodium emission line (about 2.1 eV), a sodium atom travelling toward the laser and absorbing a laser photon would have its momentum reduced by the amount of the momentum of the photon. It would take a large number 15
of such absorptions to cool the sodium atoms to near 0 K since one absorption would slow a sodium atom by only about 3 cm/s out of a speed of 570 $\mathrm{ms^{-1}}$. A straight projection requires almost 20,000 photons to reduce the sodium atom momentum to zero. The change in speed from the absorption of one photon can be calculated from

$$\Delta v = \frac{p_{\text{photon}}}{m_{\text{sodium}}} \qquad \text{Equation 3}$$

That seems like a lot of photons, but a laser can induce in the order of 10^7 absorptions per second so that an atom could be stopped in a matter of milliseconds.

A conceptual problem is that an absorption can also speed up an atom if it catches it from behind, so it is necessary to have more absorptions from head-on photons if your goal is to slow down the atoms. This is accomplished in practice by tuning the laser slightly below the resonance absorption of a stationary sodium atom. From the atom's perspective, the head on photon is seen as Doppler shifted upward toward its resonant frequency and it is therefore more strongly absorbed than a photon travelling in the opposite direction which is Doppler shifted away from the resonance. In the case of our room temperature sodium atom above, the incoming photon 16
would be Doppler shifted up 0.97 GHz, so to get the head on photon to match the resonance frequency would require that the laser be tuned below the resonant peak by that amount. This method of cooling sodium atoms was proposed by Theodore Hansch and Arthur Schawlow at Stanford University in 1975 and achieved by Chu at AT&T Bell Labs in 1985. Sodium atoms were cooled from a thermal beam at 500 K to about 240 μK. The experimental technique involved directing laser beams from opposite directions upon the sample, polarised at 90° with respect to each other. Six lasers could then provide a pair of beams along each coordinate axis.

Continuing to cool the sodium atoms by this method requires the tuning of the laser upward in frequency toward the atomic resonance frequency because the Doppler shift will be smaller. This places a practical limit on how much cooling can be achieved, because the differential cooling rate 17
is reduced and at a certain point the cooling mechanism is foiled by heating due to the random absorption and re-emission of photons.

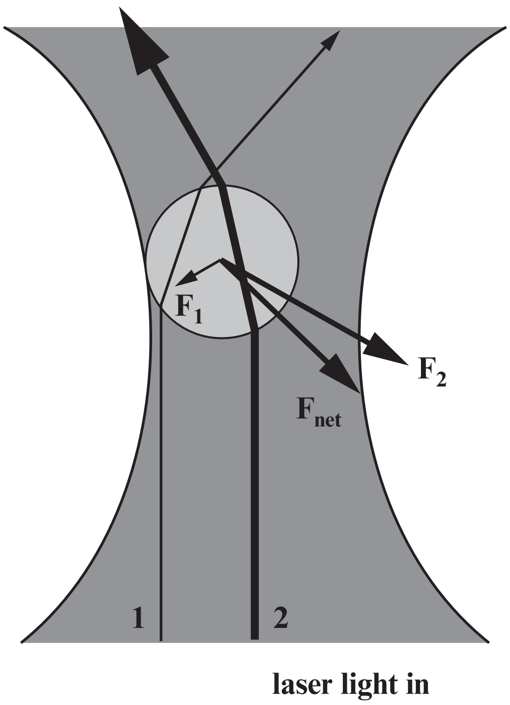
Optical Tweezers

Optical tweezers are capable of manipulating nanometre and micrometre-sized high refractive index particles by exerting extremely small forces via a focused laser beam. The beam is typically focused by sending it through a microscope. The narrowest point of the focused beam, known as the beam waist, contains a very high light intensity gradient. It turns out that particles are attracted along the gradient to the region of strongest light intensity, which is the centre of the
beam. This is called an optical trap because it holds the particle in the centre of the beam. This 18
beam can then be moved so that the trap moves the particle and acts like an optical tweezers. The force applied to the particle is actually linear with respect to its displacement from the centre of the trap as long as the displacement is small. In this way, an optical trap can be compared with a simple spring which follows Hooke's Law.

Optical traps are very sensitive instruments and are capable of the manipulation and detection of
sub-nanometre displacements for sub-micrometre particles. For this reason, they are often used to 19
manipulate DNA. The proteins and enzymes that interact with DNA are also studied in this way.

Here's an explanation of how the optical tweezers work based on refractive index (this theory 20
only applies to larger particles where we can use ray theory).

In cases where the diameter of a trapped particle is significantly greater than the wavelength of light, the trapping phenomenon can be explained using ray optics. As shown in diagram 3, an individual ray of light emitted from the laser will be refracted as it enters and exits the particle.
As a result, the ray will exit in a direction different from which it originated. Since light has a 21
momentum associated with it, this change in direction indicates that its momentum has changed. Due to Newton's third law, there should be an equal and opposite momentum change on the particle.



Ray optics explanation.
When the particle is displaced from the beam centre, the larger momentum change of the more intense rays cause a net force to be applied back toward the centre of the trap

Diagram 3

The particle is displaced from the centre of the beam, as in diagram 3, and we consider light rays on both sides of our spherical particle (see rays 1 and 2). Ray 1 veers to the right which means that
it exerts a force (F_1) to the left on the particle (due to Newton's third law). Ray 2 veers to the left 22
which means that it exerts a force (F_2) to the right on the particle (again, due to Newton's third law). However, force F_2 is greater than F_1 because of the higher intensity of the beam towards the centre of the beam waist; hence the net force is towards the centre of the beam.

Now all we have to do to move our tiny particle is to move the laser beam and the particle follows 23
in the ‘optical trap’. Thus our focused laser beam is acting like optical tweezers.

Nuclear fusion

Some of the world’s most powerful and complex arrangements of multiple lasers and optical amplifiers are used to produce extremely high intensity pulses of light of extremely short duration. These pulses are arranged such that they impact pellets of deuterium-tritium simultaneously from all directions, hoping that the squeezing effect of the impacts will induce atomic fusion in the pellets. This technique, known as “inertial confinement fusion”, so far has not been able to
achieve “breakeven”, that is, so far the fusion reaction generates less power than is used to power 24
the lasers. However, research continues and the recent introduction of a technique called ‘fast ignition’ along with improvements in laser efficiency means that inertial confinement fusion might soon be profitable. When you consider that 10 mg of deuterium-tritium mixture contains the same amount of energy as a barrel of oil (6 GJ) and that the sea contains around 10^{16} kilograms of both deuterium and lithium (from which tritium is made), laser nuclear fusion might well be the energy source of the future.