Appendix A

Details of Laser Display Systems

A.1 Introduction

This appendix reviews some of the laser display systems used in more detail than chapter 3 and is based on discussions with a number of laser companies. Although there was a belief that they all had unique systems, they were all very similar in concept, if not in detail. The appendix starts with the types of lasers known to have been used in laser displays. Then the optical systems are introduced, both in terms of the processing close to the laser and in the display environment. Finally, the control systems are introduced.

A.2 Lasers

There are a great many types of lasers commercially available. This section describes only those lasers known to have been used for mainstream entertainment applications. It is possible that other lasers have been used, especially in research environments.

A.2.1 Helium-neon Laser

The helium-neon (He-Ne) is the most popular of the so-called gas lasers, representing 64% of the units sold in the UK in the early 1990s (Vassie et al 1993). The most common wavelength is 632.8 nm which is red. However, units are also available which emit at other visible wavelengths - 543.5 nm (green); 594.1 nm (yellow); 604 nm (orange); 611.9 nm (orange) and 640.1 nm (red).

The 632.8 nm laser is available at radiant powers up to about 75 mW. Radiation at other wavelengths is produced less efficiently and therefore the maximum radiant powers may be only a few milliwatts. However, the response of the eye at each wavelength also needs to be taken into account. This response depends on the level of light as well as wavelength: at high light levels this is the photopic response (peak at 555 nm - see figure 3.2); at low light levels this is the scotopic response (peak at 510 nm). The shift in the peak response wavelength is the Purkinje Effect (Longhurst 1973). The reason for the shift is the different receptors in the eye. Cones, are most densely located in the central fovea, a small depression in the centre of the macula lutea. These cones are responsible for colour vision and the sharpness of vision in bright light. It is thought that there are three different types of cones which each have their own relative response as a function of wavelength, peaking in the red, green and blue parts of the electromagnetic spectrum. Colour is determined from the differential output of the three types of cone (Tortora and Anagnostakos 1990). The rods are located away from the macula lutea in the remainder of the nervous retina. These respond to low light levels and produce an essentially black and white image. The rods are good for identifying shapes, shades of light and dark, and movement.

The relative photopic and scotopic responses for the He-Ne visible wavelengths are presented in table A.1 along with the radiant power required to produce the same perceived brightness as from a 1 mW 632.8 nm He-Ne laser. In most situations the photopic response will dominate, even though the ambient light levels may be low. As explained in chapter 5, the damage response of the eye is taken to be independent of wavelength from 400 nm to 700 nm for exposure times up to 10 s. Therefore, if the colour of the radiation is not important a green He-Ne is preferable to, for example, a red He-Ne.

Table A.1 Comparison of Photopic and Scotopic Eye Responses to He-Ne visible laser wavelengths

Wavelength (nm)	Photopic Response (Relative to Peak Response at 555 nm)	Radiant Power (mW) to Stimulate the Same 'Brightness' as 1 mW at 632.8 nm Assuming Photopic Response	Scotopic Response (Relative to Peak Response at 510 nm)
543.5	0.95	0.25	0.67
594.1	0.75	0.32	0.08
604	0.60	0.40	0.05
611.9	0.48	0.50	0.04
632.8	0.24	1.00	<0.01
640.1	0.17	1.41	<0.01

The divergence of the He-Ne laser will depend on the cavity length and can range from 8 milliradians for a short laser down to about 0.5 milliradians for a long, high powered model (Hecht 1992). Exit beam diameters are of the order of 1 to 2 mm.

He-Ne lasers are available as single units or as separate laser heads and power supplies. The laser pumping is produced by a discharge in the laser tube, which contains a mixture of helium and neon gas (usually in the ratio 5 - 12 to 1). An initial ignition voltage of 10 kV is required and thereafter 1 - 2 kV at a few milliamperes. Although it is possible to purchase low power (about a milliwatt) lasers which are battery powered, most require a standard mains supply (230 V).

Cooling is provided by passive air cooling although forced air cooling may be used for higher radiant power devices. The efficiency is in the range of 0.01 to 0.1 percent. Therefore, a 75 mW laser would be expected to produce from 75 to 750 W of heat.

The main hazard from a He-Ne laser is the laser radiation. However, the high voltage presents an electric shock hazard if the casing is open. It is also possible to receive a shock from the connector to the laser tube in separate units if the connector is removed before the charge on the laser tube has decayed.

He-Ne lasers are generally used for small venues, where the complete laser display system is enclosed in a single cabinet. However, they can also be used, for example, in pantomimes as a dancing light such as Tinkerbell in Peter Pan. Here colour is important. Although green light would be ideal from the perspective of maximum brightness for a given power, this colour represents bad or evil. Therefore, a compromise of orange has been used.

A.2.2 Argon-ion laser

The argon-ion (Ar-ion) laser comes from a family of noble gas ion lasers. It has been the mainstay of the medium-to-large laser display systems since the beginning. The principal wavelength depends on the construction of the laser. Low radiant power air-cooled Ar-ion lasers tend to have a predominant emission at 488.0 nm (blue) with an additional emission at 514.5 nm (green). However, the larger water-cooled lasers tend to predominate at 514.5 nm. Most Ar-ion lasers used in display applications make use of both the 488.0 nm and the 514.5 nm emissions. The quoted radiant power of commercial Ar-ion lasers generally includes the total radiant power at both wavelengths. There are also a number of minor wavelengths from the Ar-ion laser.

The two of interest for display purposes are 476.5 nm and 457.9 nm, both in the blue part of the electromagnetic spectrum.

Ar-ion lasers can range in radiant power from a few milliwatts to about 50 W. Air cooled lasers up to about 100 mW are used in indoor venues. Water-cooled lasers up to 20 W have been used for outdoor events although the typical unit is 3 - 5 W. The beam divergence is typically in the range 0.4 to 1.2 milliradians with an exit beam diameter in the range 0.6 to 2 mm (Hecht 1992).

The Ar-ion laser is excited by a high-current discharge that passes along the length of the laser tube. An initial spike of a few thousand volts breaks down the gas, then the voltage drops to between 90 and 400 V, while the current increases to between 10 and 70 A. High current densities in the centre of the laser tube provide the energy that both ionises the argon atoms and provides the pumping to the upper excited states.

Cooling is provided by forced air or by water. The power supplies of multi-watt lasers may also require cooling. The efficiency of Ar-ion lasers is between 0.001 and 0.2 percent and will be lower for lasers emitting a single wavelength as opposed to both primary wavelengths. Quoted electrical inputs are 8 to 26 kW for a typical 3 to 5 W multiline output (Hecht 1992).

Air-cooled lasers up to about 100 mW can be powered from a standard 230 V supply. Higher radiant powers will require a three-phase supply at 415 V.

A typical Ar-ion laser will consist of several components, most of which are heavy. A small air-cooled laser may consist of a power supply, a control module and the laser head, where the latter contains integral cooling fans. Higher radiant power lasers will consist of a power supply (which may require input from a three-phase generator, especially if used out-of-doors), a control module (possibly with a remote radiant power/current control), laser head, cooling water pump and cooling water supply, which may be direct from a mains supply or may be from a storage tank. The water may also be passed through a cooling plant.

A 20 W laser head alone may weigh 100 kg and be 2 m long with a cross section of 0.2 m by 0.2 m. An important consideration for peripatetic laser display work is the ability to safely move, install and dismantle the laser system. The mixture of high voltages (at high currents) and water is potentially hazardous.

As described in section A.2.1, the cones on the retina, which give the perception of colour, are believed to have peak responses in the red, green and blue parts of the electromagnetic spectrum. Therefore, combining a He-Ne laser operating at 632.8 nm with the green and blue emissions from an argon laser should provide a white light source. From the data plotted in figure 3.2, the ratio of the radiant powers would have to be 1:0.34:0.93 for 632.8, 514.5 and 488.0 nm, respectively. Since the maximum radiant power from a He-Ne laser is about 70 mW, this means that the maximum power in the 514.5 nm line is restricted to 24 mW and 65 mW for the 488.0 nm line. This can be achieved easily using an air-cooled argon laser, but the absolute brightness will only be sufficient for small venues.

A.2.3 Krypton-ion Laser

The operation of the krypton-ion (Kr-ion) laser is similar to the argon-ion described in section A.2.2. However, this laser has a strong emission at 647.1 nm (red). There are also emissions at a number of other wavelengths, principally 406.7 nm (violet), 413.1 nm (violet), 468.0 nm (blue), 530.9 nm (green), 568.2 nm (yellow) and 676.4 nm (red).

The Kr-ion laser is less efficient than the Ar-ion laser, requiring about ten times more electrical power for the same radiant power. Most Kr-ion lasers are therefore water-cooled. Typical lasers used in the entertainment industry have a maximum radiant power of less than 1 W.

A.2.4 Mixed Gas Lasers

Mixed gas or white light lasers have a combination of krypton and argon in order to produce a range of wavelengths. It is possible to generate any colour from a combination of red, green and blue light. Therefore, the emissions from a laser generating these three colours can, in theory, be combined to produce any colour, including white light. Originally, the 488.0 nm and the 514.5 nm emissions from the Ar-ion laser were combined with 647.1 nm emission from Kr-ion. However, the addition of these wavelengths could not generate a brilliant white light. The next stage was to include the 568.2 nm emission to add some yellow. Modern white light lasers aimed at the entertainment industry are quoted as emitting radiation at eight wavelengths. These are stated in table A.2, along with the ion source and the relative radiant power for a modern commercial laser (Cambridge Lasers 1994).

Table A.2 Emission Wavelengths from a Commercial White Light Laser

Wavelength (nm)	Ion Source	Relative Radiant Power (514.5 nm = 1)	Relative Photopic Response (to 555 nm, 514.5 nm =1)
676.4	Kr	0.2	0.006
647.1	Kr	1.0	0.175
568.2	Kr	0.3	0.375
530.9	Kr	0.3	0.430
514.5	Ar	1.0	1.000
488.0	Ar	0.8	0.290
476.5	Ar	0.3	0.068
457.9	Ar	0.1	0.001

As discussed in section 3.1.1, the response of the eye is wavelength dependent. Ideally the relative proportion of the total emission of the laser at each wavelength should be in inverse proportion to the response of the eye to give white light. This is usually achieved by attenuating the output at particular wavelengths. However, if this is done at manufacture, the radiant power at some wavelengths (particularly the green) may be less than desirable for some of the effects which do not require multiple colours. As can be seen from the last column in table A.2, the eye's response to the standard output from a Kr/Ar laser at 457.9 nm is a factor of 1000 less than that at 514.5 nm. The useful emissions in terms of a laser light show tend to be restricted to the six lines from 647.1 nm to 476.5 nm.

The means of combining and attenuating radiation at individual wavelengths external to the laser is described in the section on optical components.

A.2.5 Helium-cadmium Laser

The helium-cadmium (He-Cd) laser has been used in the past for entertainment applications but is not widely used today. The main visible emission is at 441.6 nm (blue) at up to about 150 milliwatts. The other major emission is at 325 nm in the ultraviolet, but there are also emissions in the red (636.0 nm) and green (537.8 nm). The use of the three colours potentially could be used to develop a white light laser but it is not believed that this has been used in the entertainment industry.

The He-Cd laser contains metallic cadmium, which has to be heated to about 250°C, and helium gas. The excitation energy is provided by a direct-current discharge, typically of about 1.5 kV. The laser pumping is provided by excited helium atoms which excite and ionise cadmium atoms.

A typical He-Cd laser is between 0.002 and 0.02 percent efficient. Therefore, between 500 and 5000 W of electrical power is required to produce 100 mW laser radiant power. Most models operate on a standard 230 V supply. Convection air cooling is adequate for low radiant powers: the larger units require forced-air cooling.

Beam diameters are between 0.2 and 1.2 mm with a divergence of between 0.5 and 3 mradians (Hecht 1992).

Special hazard considerations include the high voltages which are direct current. If access is gained to the interior of the laser casing then the heater may present a potential burn hazard. If the 325 nm ultraviolet emission is accessible during maintenance or alignment work then special attention to prevent exposures above the maximum permissible exposure at this wavelength is required.

A.2.6 Copper Vapour Laser

The copper vapour laser has recently been used for display purposes in a tour by Pink Floyd (Oxford Lasers 1994). This laser produces emissions at 510 nm (green) and 578 nm (yellow). The main difference between the copper vapour laser and the other lasers discussed so far is that the emission is pulsed rather than continuous. This is inherent in the physics of the laser. Copper metal is heated to about 1500°C to provide adequate metal vapour pressure. Neon is generally added to the cavity to improve the quality of an electrical discharge which directly excites the copper atoms. The atoms can be excited to one of two upper lasing levels. The lifetime is very short (several nanoseconds) so high vapour densities (5×10^{19} m^{-3}) are required to ensure sufficient atoms remain in an excited state to produce stimulated emission. The lower laser levels are metastable with a relatively long relaxation time (tens to hundreds of microseconds). This means that these lower levels fill up and laser action stops. The laser process can only start again when these lower levels have emptied. Therefore, the requirement is to produce a lot of excited atoms in a very short period of time and then try to empty the lower levels sufficiently that the upper levels can be populated again. Typical commercial copper vapour lasers operate at between 4 and 12 kHz.

The copper vapour laser is inherently very efficient compared with most other lasers. The pulse of optical radiation may be of the order of 10 ns duration. From a velocity of light of approximately 3×10^8 m s^{-1} (actually slightly less than this in a vapour), a photon travels about 3 m during this time. If the cavity is about 1 m long, the maximum number of passes through the cavity will be 3.

The maximum average power is about 25 W for commercial copper vapour lasers. Individual pulses last from 8 to 80 ns. Assuming 10 ns and a pulse repetition rate of 10 kHz, this gives a peak power of 250 kW for each pulse (25/10000 J/pulse divided by 10 ns to give the peak power per pulse).

The beam diameter for copper vapour lasers range from 20 to 80 mm while the divergence is from 3 to 5 milliradians. The lasers are between 0.2 and 1 percent efficient so a 10 W laser dissipates about 2 kW of heat. This can be removed by forced-air cooling. This laser can operate from a single phase 230 V supply but larger, water cooled devices, require three-phase mains at 415 V (Hecht 1992).

The copper vapour laser uses up the copper metal during operation because it condenses on parts of the assembly where it cannot be heated up again. Therefore, copper wire is added approximately every few hundred hours of operation.

The high voltage, high current, discharges which drive copper vapour lasers present a potential electrocution hazard. A charge may be maintained on the circuit after the laser has been switched off. The high temperatures will present a burn hazard. The switching circuit will normally consist of a thyratron. There may be significant radiofrequency radiation from this device and, potentially, x-rays. The cabinet should provide adequate shielding but caution will be required during maintenance and servicing with the covers removed.

The laser radiation presents a particular concern because of the pulsed nature of the emission.

A.2.7 Gold Vapour Laser

The gold vapour laser operates in a similar manner to the copper vapour laser. The principal visible emission is at 628 nm (red). A gold vapour laser was used alongside a copper vapour laser recently at an outdoor show at Huilongtan Park, Shanghai, China (Messenger 1995).

A.2.8 Neodymium:YAG Laser

The neodymium:YAG (Nd:YAG) laser comes from a family of solid state lasers where the active medium is a solid. The solid is mainly a crystal of yttrium aluminium garnet (YAG) which is doped with impurity ions of neodymium. The principal emission is at 1064 nm, which is in the near infrared. However, the output beam can be frequency doubled to produce 532 nm radiation (green) using a potassium titanyl phosphate (KTP) crystal. These lasers have found widespread use in medical applications and most of the entertainment lasers tend to be modified medical lasers. It is believed that the first use of an Nd:YAG for entertainment took place at Stanford University in November 1993 (Anderson 1994).

The laser rod can be excited by either using a flashlamp, an arc lamp or by using another laser. The last technique is more efficient and increasing use is being made of semiconductor lasers. These can be used in an array and most of the laser radiation can be focused into the Nd:YAG crystal. The optimum pumping wavelength is about 800 nm which is a region of efficient GaAlAs semiconductor lasers. When a flashlamp or an arc lamp is used a small fraction of the emitted radiation is in the pumping wavelength region.

Nd:YAG lasers used in the entertainment industry are operated either continuously or Q-switched. Q-switching produces very short pulses of laser radiation from a few nanoseconds to hundreds of nanoseconds. The average power is no greater, but the energy is delivered in a short pulse.

An example Nd:YAG which is commercially available for use in the entertainment industry has the following specification: output power 40 W (assumed to be the average power); pulse repetition rate 25 kHz and beam divergence 8.0 milliradians (Laser Rays 1994). The laser is pumped using a krypton arc lamp, operates from a single phase 230 V mains supply, generates 4.4 kW of heat and is water cooled. The system comprises a head (0.81 m x 0.41 m x 0.20 m), weighing 36 kg, and a power supply (1 m x 0.66 m x 0.46 m), weighing 118 kg. The laser is controlled via a laptop computer.

The continuing development of semiconductor lasers will ensure that higher powered Nd:YAG lasers will become available in smaller packages with lower electrical power requirements. This will make them increasingly attractive to the entertainment industry because they are generally much more robust than ion lasers producing the same level of brightness.

Nd:YAG lasers containing flashlamps or arc lamps will contain high voltage power supplies and, in the case of the flashlamp, potentially charged circuits when the laser is switched off. These optical sources will also present a risk to the eye and skin of persons working on the laser with the covers removed. The lamps may also be hot and subject to shattering, especially when hot, if mechanically mistreated.

The primary laser radiation from the Nd:YAG laser is invisible (1064 nm). Radiation at this wavelength is still focused by the eye onto the retina and unintentional viewing could therefore result in retinal burns. This radiation should only be accessible during servicing work with the cover removed. However, checks should be made to ensure that the infrared radiation is blocked adequately during normal use of the laser.

The Q-switched laser radiation presents a particular concern because of the pulsed nature of the emission. It would be possible to receive several pulses in the eye from a scanned beam.

A.2.9 Semiconductor Lasers

The semiconductor or diode laser is likely to have a great deal of impact on the laser entertainment industry in the future. Early semiconductor lasers emitted radiation in the infrared region of the electromagnetic spectrum. However, devices are now commercially available which emit at 635 nm (equivalent to the red helium-neon laser) and at lower wavelengths. As technology advances it should be possible to have red, green and blue semiconductor lasers so that multi-colour displays using these lasers will be possible.

Each individual semiconductor laser may emit up to several milliwatts but it is possible to have arrays of these lasers to build up to radiant powers of a few watts. The power source for each laser is usually a few volts. This combined with the small physical dimensions of each laser make the laser system small compared with the alternatives. The use of such lasers for pumping other lasers, for example the Nd:YAG, make the lasing process extremely efficient.

The beam from an individual semiconductor laser is highly divergent. Therefore, collimating optics is required. This may form an integral part of the individual laser package or may be mounted externally. Semiconductor lasers are also available in so-called pigtailed configuration with an optical fibre attached.

Semiconductors generally present a much reduced risk of electric shock but the power supplies required for large banks of diodes may still present a risk. The assumption that a laser is only powerful if it is big does not apply here. For this reason special attention is required to the laser radiation hazard.

A.2.10 Other Lasers

There are a number of other types of laser which could potentially be used for entertainment purposes. One family is the dye laser which makes use of an organic dye in a solvent. These require optical pumping from either a flashlamp/arc lamp or from another laser. The main problem with the dye laser is the potential health effects from the dyes and disposal problems.

A variation of the Nd:YAG laser is the Nd:YVO_4 laser which is commercially available with a 0.5 mm thick chip of Nd:YVO_4 in close contact with a 2 mm thick KTP crystal. Pumping is provided by a 500 mW semiconductor laser at 809 nm (Randolph 1995). The current maximum radiant power is about 100 mW continuous and the unit is about 38 mm x 38 mm x 100 mm. One suggested application for this laser, albeit at a lower radiant power, is direct projection of images onto the retina.

A.2.11 Summary of Lasers Used in Entertainment

There are a number of lasers used in the laser light show industry. They each have advantages and disadvantages. As technology progresses there is likely to be a trend towards solid state and semiconductor lasers.

A.3 Optical Connection

The laser may be contained within an optical processing system (OPS), it may by coupled directly to the OPS, or the link may be via a fibre optic cable.

Mounting the laser inside the OPS is an ideal option for systems using lasers which are physically small and which require no cooling. Most of the alignment can be carried out before installation. However, for a fixed installation it is still possible to install a large ion laser head within the OPS, especially if the OPS is already of similar dimensions to the laser head.

The most common method of connection for larger lasers is to mount the laser head directly beside the OPS. This requires alignment between the two assemblies.

As fibre optic cables reduce in price and the transmission efficiency improves, remote connection of the laser head and the OPS becomes more attractive. In its simplest form the laser head could be floor or vehicle mounted thus reducing the manual handling problems and the strength of the off-ground support. The fibre optic cable may then be a few metres long at most. However, it is also reasonable to run the fibre over tens of metres, possibly splitting the beam into several fibres. The OPS could then be mounted some way from the laser. The additional factors to be considered from a safety perspective include the quality of the protection of the fibre, probability of damage and accessibility to non-authorised persons. Some of these fibres may be carrying several watts of laser power.

A.4 Primary Optics

The optical systems used for laser light shows are usually separated into primary optics, which covers the optical components connected to the laser head (whether directly or by a fibre optic cable), and secondary optics, which are around the venue and physically remote from the laser radiation source.

The primary optics will vary in complexity depending on the budget available and the type of effects to be produced. Laser effects generally fall into two categories: beam effects, where the beam is made visible, and images, where the beam is projected onto a screen (which may be an actual screen or, for example, a tree or a building). The simplest effect is a straight beam coming directly out of the laser head. Some of the earlier displays, such as that forming part of the Christmas lights down Oxford Street in London, were straight beams. However, to see a laser beam part of it must be scattered into the eye. If there is no scattering medium in the air the beam will not be visible. The laser companies usually use some form of smoke generator (although vapour generator is perhaps a more precise term), but fine rain or light mist is equally effective out-of-doors.

The laser beam can be directed through dispersive optics or it can be scanned. The optical components will be described in the following sections. An image can be generated on a screen by scanning a laser beam. In this situation the ideal is for the beam travelling to the screen to be invisible, which conflicts with the beam effect requirement. If the beam is scanned such that the same point on the image is revisited once approximately every 0.1 s the brain perceives a picture, although there is significant flicker. Once the scan rate reaches about 30 Hz, the image is perceived as solid by most observers and it is not possible to see that it is made up of a scanned spot. The persistence of vision with regard to moving objects was studied by Roget and he presented a paper on this to the Royal Society (Roget 1824). Wertheimer produced a monograph on the perception of motion in 1912. This has been reviewed by Sekuler (Sekuler 1996). This early work formed the basis for the movie film industry. However, it has implications for generating animations using lasers. The work by Roget demonstrated that a solid image could be generated by a scanned object; Wertheimer showed that the brain required a ‘blank’ between images to produce movement. For movie film this is achieved by presenting a series of still photographs to the viewer. The zoetrope also achieves the illusion of motion by presenting a series of still images to the observer. In this case sequential images are viewed through slits. However, for a proportion of the time, the eye sees no image at all.

The generation of laser animations relies on the image being presented as a series of frames. Therefore it is usual, but not essential, to blank the laser beam between frames. Control data used to achieve this is presented later, with an indication of the relative on to off times. Another significant factor observed by Wertheimer was the ability of the eye to generate motion. An example of one of the experiments performed by

Wertheimer was to present a vertical bar to an observer and then present a horizontal bar, ie the vertical bar rotated about its bottom edge by 90°. The observer perceives the bar falling over, or adds information that does not exist.

A.4.1 Scanning Systems

The simplest form of scanning system is to use a hand-held mirror. The beam can be made to dance around and relies on the dexterity of the operator. The control of the beam is limited and there is a high risk of the laser beam going in an unplanned direction. There have been anecdotal reports of this means of scanning being used in, for example, village-hall discotheques with ion lasers up to a few hundred milliwatts.

The laser operator can make use of the movement of a loudspeaker to modulate the laser beam in time with the music. This can be achieved by stretching a rubber membrane over the front of the loudspeaker and mounting the mirror on the membrane. The mirror could also be mounted directly on the central part of the loudspeaker or a cantilever system could be used to amplify the movement (McComb 1988).

Mirrors mounted on mirror shafts can be used to produce Lissajous-type patterns on a screen. An article in a hobby electronics magazine (Goodman 1988) describes a two-motor system which is available in kit or assembled form, complete with a controller. The rotation rate of each motor can be controlled manually, automatically, or by an external source (such as from an audio system).

Most laser display companies use galvanometer scanning. There are currently two models which comprise most of the market: the General Scanning (GS) G120D and the Cambridge Technology (CT) 6800H. The principal difference between the two scanners is that the G120D has a torsion spring which returns the scanner to the central position if the drive signal is lost whereas the 6800H does not. Both scanners operate by rotating to an angle when a voltage is applied to the coil. The technology has been developed for military applications and has been applied through industry to the light show industry. Therefore the precision of the scanners is probably much better than required to produce laser light show effects. A comparison of some of the features of the two types are scanner are presented in table A.3.

Table A.3 Comparison of General Scanning and Cambridge Technology Galvanometer Parameters

Parameter	GS G120D	CT 6800H
Body size	33.0 mm x 33.0 mm x 22.9 mm	34.5 mm x 25.4 mm diameter
Mirror size	10 mm diameter maximum	Typically 24 mm x 12 mm maximum
Mechanical scan angle (peak-to-peak)	20°	40°
Rated maximum scan rate	300 Hz	Not specified but 600 Hz used during setup
Rotor inertia	0.028 g-cm^2	0.015 g-cm^2

Galvanometers used for scanning are usually installed in pairs. The laser radiation is incident on a mirror mounted at the end of the rotating shaft. Rotation of the mirror about its centre line provides a scanning motion in one plane. The beam is reflected from the first mirror onto a second mirror on a second galvanometer mounted at 90° to the first, thus providing a scanning motion in another plane. Complex patterns can be built up by programmed movements of the relevant galvanometers.

The position of the galvanometer is determined by sending a current signal to the coil. Position sensors relay a signal back to the drive card. The movement of the galvanometer is determined by the error in the sensor. The GS units use a capacitive system whereas the CT units use an optical system. The GS units require a drive signal to maintain an angle away from the central position (to drive against the torsion spring). The CT units require no drive signal once the required angle has been reached.

The drive circuit boards provided by the manufacturers are matched to their galvanometers. In the case of the CT units, each board is matched to an individual galvanometer before supply. The GS boards generally drive two galvanometers. Both manufacturers provide position and velocity (differential of position signal) which can be used to ensure that the galvanometer is operating correctly.

Some laser companies opt to manufacture their own drive boards and there are a number of manufacturers in the United States who specialise in drive boards for the entertainment industry. Drive boards are available which are switchable between the two manufacturer's galvanometers and which claim to match the GS units to the performance of the CT units (Makhov 1995). Some of the 'home-made' boards will tend to drive the galvanometers harder than intended by the manufacturer. With the GS scanner this can result in failure of the torsion spring. The galvanometer should still work but the performance will be degraded. Both types of galvanometer may be subject to accelerated bearing wear and potential failure.

The input signal to the drive card is likely to be ± 5 or ± 10 V to achieve the full swing of the mirror. This voltage level may be supplied from an analogue source such that the galvanometer moves smoothly in sympathy with the source signal (assuming the galvanometer can physically keep up with the drive signal). An analogue square wave can be used to test the performance of a galvanometer system. Alternatively the drive signal may be derived from a digital number, converted into a voltage level from an digital to analogue converter (DAC). The number of bits available will determine the resolution of angular movement of the galvanometer.

There are no uniformly accepted standards for providing signals to the drive boards. However, the International Laser Display Association (ILDA) are working towards a series of standards which have been accepted by several companies, especially in the United States. These standards specify the rate at which signals should be sent to the galvanometers - either 12,000, 24,000 or 30,000 points per second (ILDA 1995). If the show consists of graphics or writing on a screen then the number of points available to generate an image can be determined from the image refresh rate. At 30 Hz, 400, 800 or 1000 points would be available. Not all of these points would necessarily be available for producing an image. Some may be anchor points (used to ensure that a sharp edge appears on an image) or blanked (to ensure that an animated image runs at the same rate independent of how much of the image is actually seen on the screen and to move between images).

The data used to generate an image is usually stored in binary format. One such format used in the UK is as follows (Brown 1996). Each image or animation file consists of twelve bytes of filename, 80 bytes of description, 44 bytes of control values which indicate the animation sequence, 74 unused bytes, followed by the frame data. Each frame consists of a 32 bit word. Y is in bits 0 to 11; x is in bits 16 to 27; bit 12 is blanking and the colour is bits 13 to 15 (bit 13 is on for reflect red; bit 14 for reflect green and bit 15 for reflect blue). The first point in the frame is repeated eleven times (five blanked, followed by six unblanked). The last point is repeated twelve times, eight unblanked followed by four blanked.

An example file for a flat scan is plotted in figure A.1. The y values are constant with time, only the x values change.

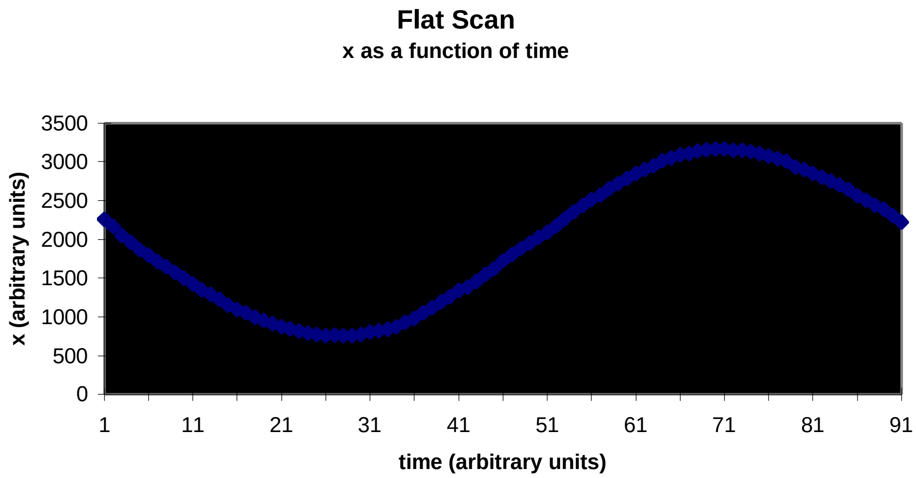

Figure A.1 Values of x as a function of time for a flat scan (y is constant)

The image generated on a screen is shown in figure A.2.

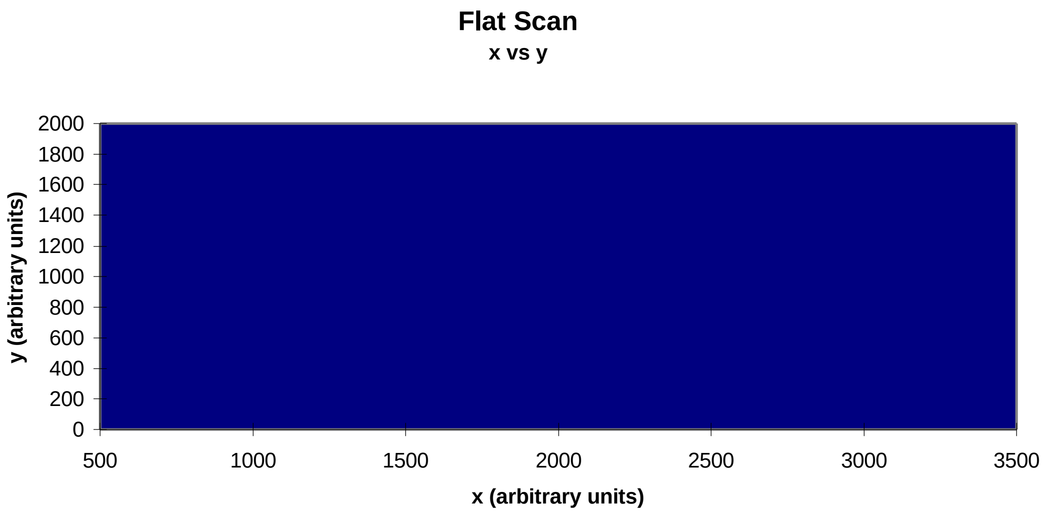

Figure A.2 Flat scan plot of x vs y over a complete cycle (scan to the right and back)

Figure A.3 shows the left hand section of figure A.2 amplified to demonstrate how the spacing of the points used to plot the scan changes with x.

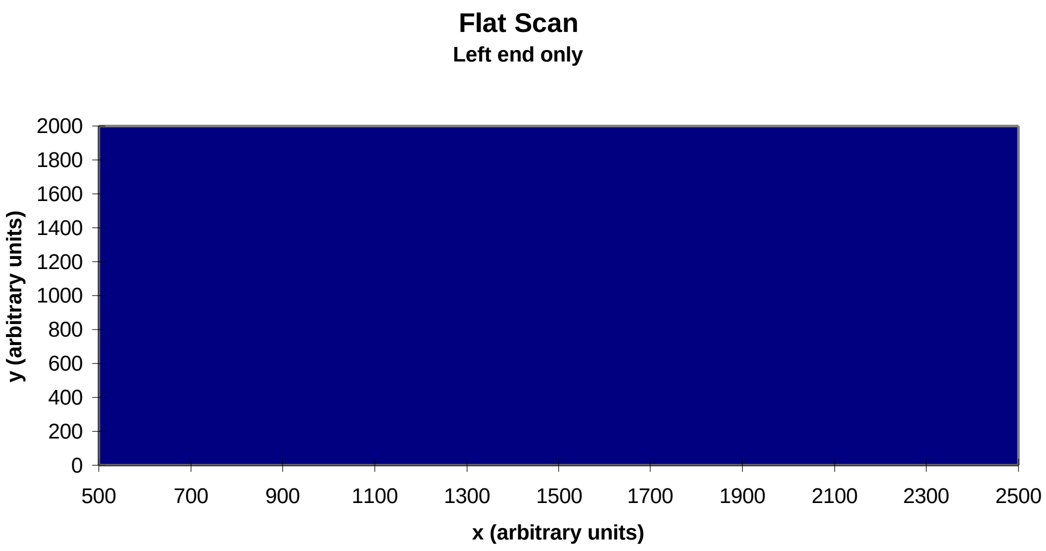

Figure A.3 Left hand end of flat scan (scan from left to right only)

The transfer of laser shows between systems and companies depends on similar performances of the galvanometers. A number of test patterns are available which can be used to demonstrate that the parameters have been optimised. One such test pattern is plotted in figure A.4.

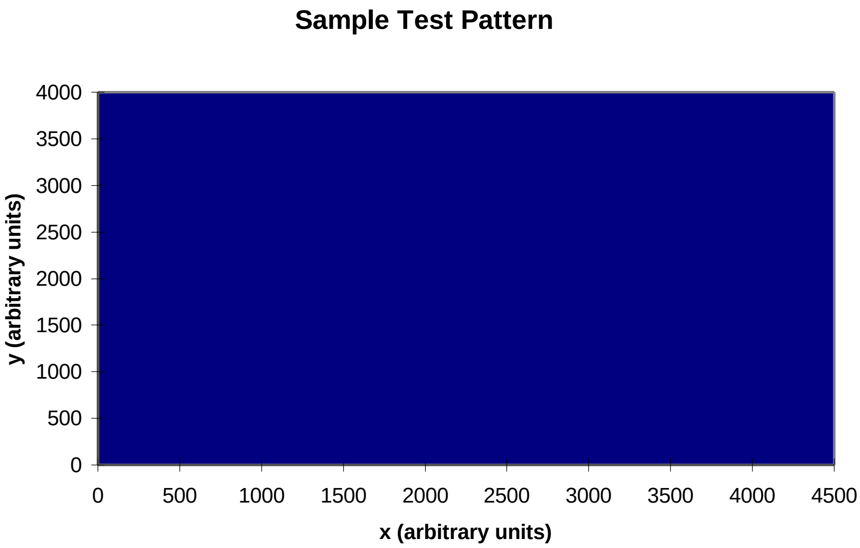

Figure A.4 Galvanometer setup test pattern

It is also possible to use an acousto-optic modulator (AOM) to scan the laser beam. These are normally limited by their scan angle and generally utilise lenses to both reduce the beam diameter before it enters the AOM and to amplify the movement of the beam after the AOM. An advantage of the AOM is that there are no moving parts. The deflection angle (for example about 3° at 70 MHz for 632.8 nm laser radiation) is directly proportional to a radiofrequency (RF) drive signal. Therefore if the RF signal is removed the deflection stops in a time dependent on the acoustic velocity - there is no mechanical inertia in the system. Typical acoustic velocities are a few km s^{-1} (NEOS 1984).

A.4.2 Beam Blanking

If the laser beam is scanned to produce writing, for example, the image produce will be similar to that produced on paper without lifting the pen off the paper. To overcome this problem the laser beam needs to be switched on and off very quickly. This can be achieved by using a galvanometer which is driven using a square wave signal. Typically the beam will be deflected to a beam dump when the galvanometer is at the central position. A voltage is applied to direct the beam through to the scanning galvanometers. The movement of the galvanometer need not be great. The response time for a CT 6800H driven 2° (relating to a change in drive voltage of about a volt) is about 300 μs (Langram-Goldsmith 1995). It is also possible to use an AOM as a blanking device.

Many laser display systems will be provided with test patterns for setting up the blanking. One such test pattern is presented in figure A.5. The blanking is adjusted until the horizontal tail of the 4 is invisible, with the cut-off between the two vertical bars.

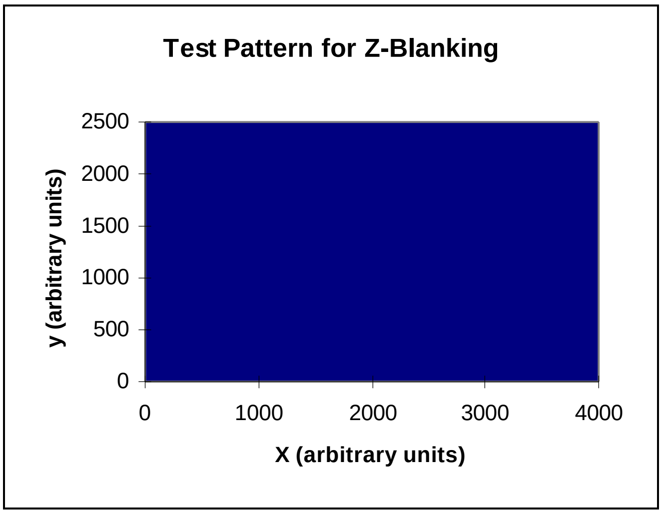

Figure A.5 Test Pattern for Aligning Z-Blanking

A.4.3 Rotary Actuator

It may be necessary to switch the laser beam down different paths to introduce different effects, such as straight beams onto mirrors, or through different optical components. One method of achieving this is to use a mirror which is switched into the beam under operator control. A popular actuator in the UK is the General Scanning GM20 although models are available from a number of other manufacturers. An arm is connected to the shaft of the rotary actuator. With no current applied the actuator is at rest with the arm and mirror lying flat. When the drive current is applied to the actuator the arm rotates lifting the mirror into the path of the beam. A schematic of an actuator is presented in figure A.6 and an example of the application of them is in figure A.7.

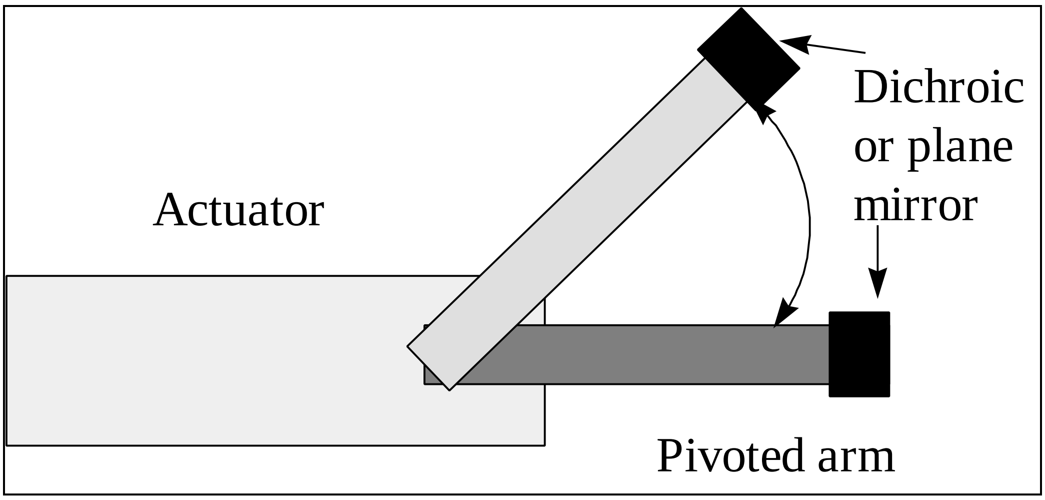

Figure A.6 Schematic of an Actuator

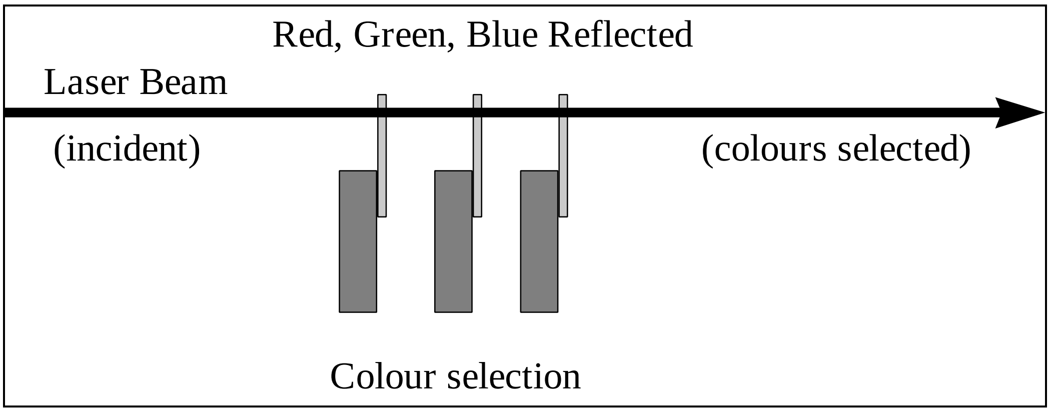

Figure A.7 Example of the Use of Actuators to Select Colours

A.4.4 Beam Splitter

A single laser can be used to produce a number of effects at the same time by splitting the beam into two or more beams. The beam splitter may be a partly transparent metal film, specially designed prisms or may reflect laser radiation at one polarisation and transmit at the orthogonal polarisation. It is also possible to use multilayer interference coatings to selectively reflect particular wavelengths.

Beam splitters are generally rigidly mounted. The laser radiation either always passes through the beam splitter or it is directed to it (for example using a rotary actuator) when required. The beam split may be 50-50 or it may be any other ratio required.

A.4.5 Diffraction Grating

Diffraction gratings are passive dispersive optical devices. The incoming beam is split into a number of output beams. The grating may be either a transmitting device or a reflective device. Transmitting devices are more common in the primary optics. The degree of dispersion is a function of the lines per mm.

If a diffraction grating is used with a laser emitting radiation at a single wavelength, a series of secondary diffracted beams will be produced. There will also generally be the undiffracted central maximum or zero order which, when assessing the irradiance, will represent the worst case exposure situation. If the diffraction grating is used with a laser emitting several wavelengths, such as the mixed gas laser, the diffracted beams will be split into the different wavelengths. The longer wavelength emissions will be diffracted more than the shorter wavelength emissions. The dominant blue and green wavelength emissions from a mixed gas laser can be seen clearly separated from the dominant red emission. The lower intensity remaining wavelength emissions can be perceived by careful observation. Again, the undiffracted central maximum will have the same appearance as the primary beam.

Some installations inhibit the central undiffracted maximum by the use of a beam stop but this is not believed to be common practice.

An optical system may contain a number of different diffraction gratings to give different degrees of dispersion. Diffraction gratings which diffract in two dimensions are also routinely used. The different grating may be mounted on an effects wheel called a ‘gobo’ in the lighting industry. There is generally a straight-through position with no diffraction grating and then a number of positions with gratings. The gobo is usually driven by a stepper motor under operator control. The gobo may be mounted on the external side of the galvanometers such that any scanned patterns are diffracted. By this means an image can be generated and then replicated a number of times, dependent on the diffraction grating used.

Some installations rotate the diffraction grating. This is especially effective if the output of one diffraction grating is transmitted through a second diffraction grating rotating in the opposite direction. This produces a sea of beams which, if used in conjunction with a mixed gas laser are rainbow coloured.

It is also possible to use diffractive elements to produce images, such as logos from a single input beam. This has the advantage of no moving parts but requires greater input power to produce the same brightness as a similar image scanned image. Currently, each diffractive element is custom made but research is progressing on active diffractive elements where the output image can be changed under programme control.

A.4.6 Luminaire Effects

Laser companies experiment with a number of reflective and transmissive objects to produce interesting effects. A piece of shower glass is effective at randomly refracting an incident laser beam. If this is rotated a wash of colour can be produced on a screen from a mixed gas laser. This is sometimes used in conjunction with a beam splitter such that part of the beam passes through the luminaire to give a background on a screen while the remainder of the beam is directed to scanning system to produce graphical images on the same screen. The beam from a multi-line laser may be passed through a prism before the luminaire.

A.4.7 Three-Dimensional Images

There are several approaches to producing three-dimensional images and all currently have limitations. The first is to use two colours which are scanned onto a screen in slightly different positions. The audience are provided with spectacles which are fitted with different colour filters. Therefore the each eye only sees one of the two images. The limitation with this is that it is restricted to a few colours. There is also the inconvenience and cost of providing all spectators with spectacles.

A second technique is to use polarisation rather than colour to provide two separate images. This technique can provide full colour images but still relies on the audience being provided with spectacles - this time with polarising filters. The technique also relies on the polarisation being maintained and therefore its effectiveness out-of-doors may depend on the weather.

The third technique is the so-called volumetric display. In this case the laser is scanned onto a helical display screen which rotates. Essentially the surface on which the beam is incident is moving in space. Therefore the position of the observer relative to the helix will be important to ensure that parts of the screen are not observed. This system is currently restricted to small-scale displays but is does overcome the problem of the observer wearing spectacles (Belfatto 1995).

A.4.8 Colour Selection

Most of the larger lasers used in the entertainment industry emit laser radiation at more than one wavelength (see section A.1). A diffraction grating can be used to separate out the individual colours but this results in significant losses or complicated optics to regain the energy from all of the diffracted orders. A significant proportion of the incident beam is still contained in the undiffracted order. Dichroic mirrors or filters can be used to separate out the individual wavelengths. For an argon-ion laser this will require one device. For a mixed gas laser this will require up to seven stages to separate the eight wavelengths. The losses in such systems can be considerable.

A recent introduction to the laser light show industry is the polychromatic acousto-optic modulator (PCAOM). Models are available aimed at the laser light show industry (MVM 1995 and Crystal Technology 1993). These devices are polarisation dependent so the input beam needs to be polarised to the manufacturer's specification to gain maximum transmission efficiency (claimed to be typically greater than 90%). Input apertures are generally 3 mm and devices can accept up to 16 W of laser input power.

The PCAOM operates in a similar manner to the AOM described earlier. However, each wavelength can be selected individually, depending on the frequency of the radiofrequency (RF) radiation used to excite the crystal (for example tellurium dioxide). The significant advantage with a PCAOM is that the different wavelengths can be added independent of each other. Typical RF frequencies as a function of wavelength and the RF drive power are presented in table A.4.

Table A.4 Typical Drive RF Radiation Frequencies and Drive Power as a Function of Wavelength for a PCAOM

Channel	Wavelength (nm)	Frequency (MHz)	Drive Power (mW)
1	676	110.25	290
2	647	116.14	260
3	531	149.30	245
4	515	155.87	225
5	488	167.79	170
6	476	173.68	140
7	466	179.35	140
8	458	184.69	140

A.4.9 Lenses

Lenses may be used within the optical system. They may be used to ensure that the beam is focused onto the mirror of a blanking galvanometer. This in turn ensures that the blanking edge is sharp. After the blanking mirror a second lens is required to re-collimate the beam. This simple piece of optics means that the divergence of the laser beam, as quoted by the manufacturer, is no longer valid. The divergence will have to be determined for the system as used.

A second use of lenses is to create a more divergent beam, for example to irradiate an external optical device, such as a mirror ball which is discussed in section A.5.3. The laser beam is likely to be switched to the lens using a rotary actuator. There is also likely to be some form of adjustment or a range of interchangeable lenses to take into account the different distances to the mirror ball in different venues or peripatetic operations.

As has already been discussed, lenses may be used in conjunction with AOMs because of the small degree of scan available with these devices.

A.4.10 Mirrors

The direction of the laser beam within the primary optics will be changed using mirrors. Ideally the mirrors should have the reflecting surface on the front face otherwise ghost reflections will occur from the surface of the glass. Such mirrors are more expensive than standard rear reflection mirrors and may be substituted. The path of any stray reflections should be monitored carefully.

The steering mirrors will normally be adjustable by some means. Mounts are available which can be adjusted from above the beam path. However, these tend to be more expensive and are not commonly used in laser light show systems.

The mirrors mounted on the galvanometers are subject to considerable rotational forces when the galvanometers are driven at high accelerations and decelerations. They need to be able to withstand this.

It should also be recognised that components other than intentional mirrors can produce reflections. These could include the structure of the primary optical cabinet, support structures and tools, rings and watches, etc.

A.4.11 Beam Losses

The various optical components in the primary optical system will cause losses, the degree of which will often depend on the quality of the optics. A fundamental consideration is that what is not reflected or transmitted, is absorbed. At high input laser powers, or more strictly, irradiances the percentage absorption does not need to be very high before the component suffers significant thermal stress. Most laser quality optical components should easily withstand such insults but lower quality components may be used in some installations.

A.4.12 Beam Dump

There may be times when part of the beam is not required. An example is when only the green or the blue emission from an argon-ion laser is required. The other emission needs to be dumped somewhere. Laser radiation above 500 mW is capable of starting a fire, depending on the diameter of the beam and the exposure duration. Therefore the intentional dumping of the beam should be to a part of the system which can cope with the full radiant power of the laser.

A.4.13 Beam Stop

A special form of beam dump is a beam stop. This is likely to be a relatively slow acting (few hundred milliseconds) solenoid with a circular cross section. At rest the tip of the solenoid rod projects (normally down) into the path of the laser beam. When the solenoid is activated, the rod is pulled up out of the beam. Failure of the control system power supply should ensure that the solenoid falls back to the stop position.

The location of the beam stop depends on the design of the optical system. Normally it will be before any splitting of the beam to ensure that only one is required. However, on a simple system it may be in the final optical path before the pair of scanning galvanometers.

It is also possible to use an AOM as a beam stop. However, these are more expensive than electromechanical systems.

A.4.14 Masking Plates

In order to physically restrict the direction of the laser beam from the primary optics it is possible to have a shaped aperture through which the laser beam it emitted. For an installed system this can be a permanent plate attached to the aperture with an appropriate shape. For a peripatetic display, it may be possible to have adjustable plates which can be tailored to each event. As with the beam dump, the masking must be able to absorb the primary laser beam without adverse effect. The edges of the blanking plates should also not be reflective. Otherwise, if a beam clips the edge it will be reflected in an uncontrolled manner.

Masking plates are a simple engineering control which can provide a high degree of protection from the consequences of failure of many of the components in the primary system.

A.5 Secondary Optics

Secondary optics cover the optical components not included within the primary optical processing system. These may be fixed or moving components around a venue and the laser beam normally travels through the air to get to them. Optical systems, such as pairs of galvanometer scanners, which are fed from fibre optic cables are considered primary optical systems although they may be some distance from the laser head.

Nearly all of the secondary optics are mirrors of some form or other. However, the screens used to project images are also included. Examples of each are described in the following sections.

A.5.1 Plane Mirrors

The simplest form of secondary optical component is the plane mirror. There may be a number of these in any venue. Normally they are fixed but some may be under operator control and move using servo motors. The control signals may be transmitted by wire, but some use radio-controlled model servo systems.

The amount of laser radiation reflected from a mirror will be essentially the same as that incident on it. The divergence is also likely to be conserved. Therefore the laser radiation from a mirror should be considered as hazardous as that incident upon it. There is a widely held view among laser display operators that once the beam has been reflected from two mirrors it is "safe". This should not be accepted without a careful consideration of the actual situation.

The mounting and attachment of the mirror are important. For a permanent installation the mirrors may be fixed in position. However, they are more likely to have some degree of adjustment. Mirrors mounted in discotheques and night clubs are likely to be subject to significant vibration. Therefore the mounting brackets should be of such a design that the fixings do not become loose. The attachment of the mirror itself to the support bracket or backing plate also needs to be considered. The most effective system is to have a mechanical attachment system rather than just relying on double-sided adhesive tape.

It is a simple process to mask the mirror position in a fixed installation to ensure that the reflected path is restricted. Should the mirror move, the laser beam would strike a beam dump. Such an arrangement is also possible with some thought for a peripatetic installation but would have to be straightforward to implement.

A.5.2 Diffraction Mirrors

Diffraction mirrors of either one or two dimensional dispersement are used as targets either directly from the primary optical system or from beams reflected from external mirrors. The comments relating to primary mirrors also apply here. Occasionally, diffraction mirrors are mounted in rotating assemblies.

A.5.3 Mirror Balls

Mirror balls have been popular since the early part of the twentieth century for use in ballrooms. Their use has extended to discotheques and night clubs. The mirror ball contains a number of plane mirror facets. They are most effective when rotating at a few revolutions per minute and when illuminated by optical radiation from a number of different directions and the radiation covers the diameter of the mirror ball. Therefore, the most effective optical source is a spot light rather than a laser.

In order to make a laser effective on a mirror ball, the beam needs to have diverged to be at least a significant fraction of the diameter of the mirror ball. This can be achieved by using distance or a diverging lens. A third option is to make the laser beam appear to be a larger diameter than it actually is. This is achieved by using the mirror ball as a target for a spiral graphical image.

The reflections from a mirror ball go in all directions. If the mirror ball is rotated, the reflections will also rotate. In order to assess the exposure condition for the audience who may be subjected to the reflected beams it is important to know the technique used to irradiate the mirror ball, the size of the facets and the rotation speed.

Some laser companies use mirror balls which have either parts of the mirror ball masked off or sections with no reflective facets. This can be used to ensure that the reflections only go up towards the ceiling, for example.

The use of mirror balls out-of-doors may need special consideration. Although a stationary mirror ball can be clamped in position (although they rarely are), a rotation mirror ball will be suspended from the drive motor. The mirror ball will be subject to movement by the wind which, in extreme cases could mean that the laser beam misses the mirror ball completely.

A similar device to the mirror ball is the pyramid spinner. This device projects the reflected beams in one direction - if mounted with the axis vertical, the beam would be reflected down or up, depending on which way up the pyramid was. There are also other variations on this concept of a rotation reflective device which may be encountered.

A.6 Screens

Screens may be purpose designed projection screens, they may be the sides of a building, trees, clouds or any other surface on which the laser radiation is projected to form an image. One of the main benefits of using laser radiation for image projection is that, generally, there is no focusing of the beam. Therefore, the image is in focus irrespective of the distance. This means that non-flat surfaces can be readily used.

A.6.1 Projection Screens

Projection screens may be mounted on walls, permanently suspended from ceilings, on motor drives from ceilings, or temporary installations. Standard photographic projection screens can be used provided they are able to accommodate the irradiance levels without damage. The ideal screen provides diffuse reflections where a fraction of the incident radiation is reflected equally into the eyes of the spectators, such that they can all see the image. However, the amount of radiation incident on the eye will be a function of the distance the observer is from the screen. Many such screens also have a specular reflection component.

Photographic projection screens are designed to be viewed from one side only. However, screens of similar construction are also available for use as back-projection screens. In some laser display applications in discotheques, for example, the projection screen may be in the centre of the dance floor and therefore may be viewed from any angle. These screens are normally a mesh such that a proportion (perhaps 50%) of the laser radiation passes through the screen. However, some screens are solid and act as a Lambertian emitter from both the front and back surfaces. The optical density of such screens is generally about 2, but caution should be exercised in evaluating any directly transmitted component of the incident beam.

The eye hazard from the diffuse reflection from screens should be considered. This will depend on the irradiance at the screen and the closest that persons will reasonably be from the screen. Consideration also should be given to the method used to construct the image: a scanned image will mean that the scattered radiation reaching the eye is also a scanned image on the retina. The path of the laser radiation having passed through the screen also needs to be analysed.

A.6.2 Water Screens

As has already been stated, water forms a good reflector of laser radiation. A fountain of water can be formed into a water screen. This can be used as a target for laser generated images. Again, the degree of transmission of the laser radiation needs to be considered during the display. In addition, the consequences of the water supply failing such that the screen disappears need to be addressed.

A.6.3 Cloud Screens

Depending on the cloud ceiling level, and the density of the water vapour in the clouds, it is possible to use clouds as a screen. In common with other out-of-door laser displays the potential for laser exposure of aircraft need to be considered. Such displays tend to use lasers around 10 W upwards.

Cloud displays are visible over large distances and the potential for distraction of, for example, motorists should be borne in mind.

A.6.4 Trees and Buildings

For large out-of-door laser displays it is common to make use of the surrounding environment. At a stately home or in a park there are likely to be trees surrounding the audience area. The buildings may provide a large convenient screen area. The structure of the stage may also be used as a screen.

Since the screen may not be a flat surface or may be irradiated at an oblique angle, it is possible to use geometric correction hardware on the laser effect control system to correct for this (LSDI 1995).

In all cases the potential for personal exposure needs to be addressed, both under the planned display condition and the reasonably foreseeable incidents.

A.7 Control Systems

There are essentially three types of control systems and any particular performance may make use of one or all of them: manual control; dedicated programmable control; or computer control. The last two may be operated manually or automatically. Examples of the type of control systems are described in this section. Particular safety issues are identified.

A.7.1 Manual Control

The simplest form of laser display control is manual. This can mean manual control of the laser itself, the primary optics and, possibly, the secondary optics. At its most basic level this will be a laser and a hand-held mirror. However, it may be a primary optical system containing a scanning system where the drive signals to the scanning system are controlled, for example, from a signal generator. A line scan can be generated by providing a sine wave drive signal to a single galvanometer. Providing the same drive signal will produce lissajous figure graphics.

Such manual control is unlikely to be seen at anything other than low-budget discotheques, for example. This manual technique is likely to present the greatest risk of inadvertent exposure of people. However, this should be balanced against the likely use of lower radiant power lasers.

A.7.2 Programmable Controllers

Laser display programmable controllers may be truly programmable by the laser operator of may be pre-programmed by the supplier. However, most have some form of operator control. These controllers may be operated by pressing buttons to trigger effects or they may be controlled by, for example, pre-programmed tapes. Pre-programmed laser displays are attractive at night clubs where the disc jockey has control over the music and lights. At specific times they run a show from tape which has been programmed, and the effects aligned, by the laser company.

Graphical images can also include text. An effect from each of the three categories can be assigned to each of the alphabetical keys. The alignment for each effect assigned to each key can be independent and is controlled using the tracker ball. The effects can be made to rotate, flip, etc. They can also be made to change size. Effects can be linked together in a sequence which produces simple animations. The beam shutter is controlled from the `blackout' key. This controller is typical in that it requires password access before the controls become effective. In this case it requires a different password before any of the programmable parameters can be changed.

Automatic systems providing pre-programmed shows generally present less of a risk than those operated by a person. However, a pre-programmed show may be presented by a person with limited training in laser safety.

A.7.3 Computer-Based Controllers

It is possible to complement the programmable controllers with additional control signals provided from a personal computer. However, there are a number of computer-based laser display controllers. In its simplest form, the computer-based system consists of digital to analogue converters (DACs) plugged into a personal computer. The position of one or two scanners (usually galvanometers) are decided by software. The respective angle of each scanner is then determined by the analogue voltage generated at the output of each DAC.

Computer based systems became widely available as computer processing power became available at a reasonable price. Probably one of the first such computerised systems was based on the Commodore Amiga which was designed to control external devices. Lasershow Designer for Windows (Pangolin 1995) has been developed from the Amiga system and uses a Motorola 68030 microprocessor running at 40 MHz on a plug-in board as the main graphics generator. Up to four boards can be used to control up to four scanner pairs at the same time. The computer also controls up to six colour channels.

The advantage of the sophisticated computer based systems such as Lasershow Designer is that the laser show can be developed using the graphical interface in Microsoft Windows. The operator sees the graphical images on the computer screen as they will appear on a projection screen. It is also possible to carry out the development work live, such that the images are developed and projected at the same time.

Lasershow Designer is also able to interface with the musical content of a laser show. The pre-recorded music can be on CD-ROM which can be read by the compact disc reader in the computer. The timing information from the music can be related to particular laser effects using timing codes. The whole show can then be pre-recorded. The growth of standardisation amongst the laser display companies in the United States has meant that Alesis Digital Audio Tape (ADAT) and Aquila SMPTE standards can be exchanged with some assurance that the laser show will perform exactly as planned by the programmer.

A.8 Communication Between Controller and Optics

Most systems use hard wired communication between the laser display controller and the optical systems. This is likely to remain the best technology for permanent installations. However, for events out-of-doors where, for example, several lasers are used, the cable runs may present a hazard to the audience or may be subject to damage. Some laser companies have experimented with the use of radio links between their control consoles and the optical systems. High gain directional antenna systems can be used between two points which should be relatively interference free. However, consideration has to be given to what will happen if the radio link does fail, or if the signals are not understood at either end.

If several lasers are used, each should have an operator who is in a position to take control of the laser if necessary. The communication link between the operators may be by a hard-wire system but it is more likely to be by personal mobile radio (PMR). As is cited in chapter 3, it is possible for such communication systems to interfere with the operation of galvanometers.

A.9 Summary

Laser display systems can be simple devices with a laser and hand-held optical components. They can also be complex computer controlled systems with multiple beams, sometimes from one laser, sometimes from several lasers. However, each system is a product of individual components. Each has its own function and potential hazards. The operation of each of the components of the optical system has been described.