Unit 126: Principles of Photonics

NQF Level 3: BTEC National

Guided learning hours: 60

Unit abstract

Photonics has played a major role in changing the way we live. The ability to mass produce optic and electro-optic components and integrate them with powerful electronic computing devices has revolutionised many aspects of our lives including consumer electronics, telecommunications, the automotive and medical sectors.

Broadly speaking photonics covers the generation, manipulation, transmission and detection of light. Many aspects of our daily lives use devices which cover one or more aspects of photonics. The need to understand the nature of light and basic optical principles is fundamental to enable electronic devices to capture and process light and the information it represents.

This unit will give people looking to work in photonics related industries an understanding of the underlying principles which govern any optic system. This knowledge can be used to interpret specifications and performance of imaging or lens systems and the fundamental characteristics associated with them.

The unit will develop learners' understanding of how light is produced and how it behaves as a wave and a particle. The unit will cover interaction of light with lenses, mirrors, prisms, beam-splitters and diffraction-gratings using ray diagrams. Paraxial formulas are used to analyse single lenses and then combinations of lenses. Learners will analyse ray diagrams in terms of objects, images, focal lengths, focal points, focal planes, refraction, reflection and magnification. The wave characteristic of light is developed by the theory of diffraction and interference. Learners will have the chance to construct, measure and interpret optic systems to build on the theory they have learnt.

For learners wishing to follow a photonics programme this unit is an essential building block that will provide the underpinning knowledge required for *Unit 127: Further Principles of Photonics*.

Learning outcomes

On completion of this unit a learner should:

1 Understand the characteristics of light by looking at the way light is generated and its behaviour as both a wave and a particle

2 Be able to construct simple ray diagrams and apply paraxial formulae to determine the operating parameters of a lens

3 Be able to determine reflection and refraction at a boundary and measure the refractive index of different materials

4 Understand the theory of diffraction and interference

Unit content

1 **Understand the characteristics of light by looking at the way light is generated and its behaviour as both a wave and a particle.**

Characteristics of light: sources of light eg Sun, stars, incandescent, fluorescent tubes, lasers, LEDs; light as a wave eg velocity, wavelength, frequency, colour, electromagnetic spectrum; light as a particle (photon) eg line spectra, operation of lasers, Bohr's atomic model to explain particle behaviour, line emission spectra (eg sodium and mercury lighting), quantised energy, stimulated emission by light particles (photons); polarisation eg E and H fields, types - circular, linear, elliptical, use of dichroic materials, analysis as a vector quantity E wave, Malus' law to explain effect of a series of polarising filters placed at an angle θ where $E=E_o\cos(\theta)$

2 **Be able to construct simple ray diagrams and apply paraxial formulae to determine the operating parameters of a lens**

Ray diagrams: eg for lenses, for various object positions, real and virtual images, focal plane, object height and position, image height and position, focal length, focal plane

Formulae: Gaussian thin lens equation linking focal length with object and image position $1/f=1/d_i + 1/d_o$; combining lenses eg Astronomical telescope or microscope, magnification factor $M= f_o/f_e$, derive by ray diagrams using angles subtended

Types of lenses: lens types and shapes eg convex, concave, plano-convex; lens function eg doublets, reduction of aberrations

3 **Be able to determine reflection and refraction at a boundary and measure the refractive index of different materials**

Reflection and refraction: review of reflection, incident angle = reflected angle, basic ray diagrams, use of normals; refraction of light at a dielectric boundary, Snell's law $n_r/n_i = \text{sine}(\theta_i)/\text{sine}(\theta_r)$; definition of refractive index n = speed in vacuum/speed in medium, determining refractive index for various media (water, glass), safe use of lasers and optic components, prediction and measurement of critical angle, use of beam-steering components, mirrors, prisms, mounting devices and their assembly and laser sources

4 **Understand the theory of diffraction and interference.**

Diffraction: use of wave model to predict diffraction of an aperture, Airy disc, Fraunhofer single slit diffraction pattern observation and analysis, Huygen's principle, derive and use of equation $a\sin(\theta) = m\lambda$ for minima using small angle approximation, minima separation $y=m\lambda D/d$, coherence of light sources, safe observation of these effects

Interference: principle of wave superposition, constructive and destructive interference, interference using Young's two-slit method, derivation of condition for maxima $d\sin(\theta)=m\lambda$ using small angle approximation, maxima separation $y=m\lambda D/d$, observation of effects eg Newton's rings, oil films

Grading grid

In order to pass this unit, the evidence that the learner presents for assessment needs to demonstrate that they can meet all of the learning outcomes for the unit. The criteria for a pass grade describe the level of achievement required to pass this unit.

Grading criteria		
To achieve a pass grade the evidence must show that the learner is able to:	**To achieve a merit grade the evidence must show that the learner is able to:**	**To achieve a distinction grade the evidence must show that the learner is able to:**
P1 describe the characteristics of light with regard to wave and particles and how light propagates, linking these to observed behaviour and describe the principles of how light is generated P2 describe the basic aspects of polarisation of light regarding the E H fields and observed phenomena P3 determine graphically the image position, orientation and height for a convex lens with 3 different object positions (relative to focal point) P4 use the Gaussian lens formulae to calculate object, image and focal length using a single lens P5 describe the types and function of three different kinds of lenses P6 determine, by experiment or analysis, the refractive index and critical angle of an optic medium	M1 use Malus' law to determine light intensity of a series of polarising filters placed at varying angles M2 use the theory of diffraction and interference to evaluate and explain observations of diffraction patterns using a single slit and Young's two-slit experiments M3 design a lens system consisting of at least 2 lenses to meet a given requirement for a telescope or microscope.	D1 evaluate the benefits and disadvantages of designing a multi-lens system D2 analyse the effects of varying light/optical frequency, spacing, aperture size and intensity for a diffraction grating and explain the resulting interference patterns.

Grading criteria		
To achieve a pass grade the evidence must show that the learner is able to:	**To achieve a merit grade the evidence must show that the learner is able to:**	**To achieve a distinction grade the evidence must show that the learner is able to:**
P7 describe the basic operation of a laser and the characteristics of the light produced P8 describe the principles of diffraction and interference of light.		

Essential guidance for tutors

Delivery

It is important that *Unit 4: Mathematics for Technicians* has been delivered or is being delivered concurrently with this unit to give learners the necessary mathematical skills. A basic level of computer skills will also be needed to use any computer-based software.

Each of the four learning outcomes of this unit are linked and the delivery strategy should ensure that these links are maintained. Learning outcome 1 is the most likely starting point for delivery, as it will establish much of the underpinning knowledge and skills required for the remaining learning outcomes. The unit could be delivered through a combination of theory lessons and demonstrations, reinforced through practical work in an optic laboratory. It is important that learners have a thorough understanding of lenses if they are to be able to recognise, handle and select relevant components.

Initially, delivery could use paper-based or computer-based exercises (eg calculating the object position and height in a ray diagram for a convex lens). However, even at this stage it may be beneficial to introduce learners to real optic components. The ability to handle optic components and mount pieces on an optic work-top is an important part of this learning outcome and will support the rest of the unit. Most centres will probably start with paper-based methods of drawing simple ray diagrams (eg convex lens with various object positions). It is likely that centres will move on to real components, using optical bread boarding techniques.

Learners should be given the opportunity to practise using the formulae identified in the unit content but are not required to memorise them. However, they should be expected to select the most appropriate formulae to determine the required values of object position/height, image position/height, magnification etc. In addition, learners should have the confidence to transpose equations to meet their needs (eg use Snell's law). Clearly, the ability to transpose formulae is a mathematical skill and tutors will need to ensure that appropriate support is provided during both the delivery of this learning outcome and the unit as a whole.

Wherever possible, centres should enable learners to experience a range of equipment that reflect typical and current industry usage. It would not be appropriate to only use computer-based simulation packages. Tutors should ensure the safe use of optical sources and an awareness of their use in a laboratory/workshop and industrial setting.

The use of computer-based software packages for analysis and simulation of optics together with practical laboratory work will help to corroborate theoretical results.

Centres are encouraged to relate theory to real engineering applications wherever possible. Industrial visits or work experience could be used to support learning and provide learners with an appreciation of the industrial applications of optical principles.

It is essential that learners are given full training on health and safety issues before using any photonics equipment. Learners should never use a laser source un-supervised. It is recommended that only low-power lasers be used during practicals and demonstrations. Any laboratory should be assessed by a laser safety officer in addition to any normal health and safety certification.

Note that the use of ‘eg’ in the content is to give an indication and illustration of the breadth and depth of the area or topic. As such, not all content that follows an ‘eg’ needs to be taught or assessed.

Assessment

Much of the evidence for the pass criteria can be achieved through practical experimentation with real components.

It is likely that at least four assessment instruments will be required for this unit. If practical work and tests are also used then the total number of pieces of assessed work could be even more than this. This should be carefully considered so that it does not place an unduly high assessment burden on learners or the tutor.

Wherever possible, practical work should lead to a final product that can be handed in for assessment at the end of the session without further need for report writing. This will help control authenticity of evidence and also keep the assessment activities short, sharp and relevant.

Centres should combine any testing with practical hands-on experience of real optic systems and components. This could be achieved by building prototype optic systems on breadboards according to values the learner has determined theoretically. This will allow learners to build the optic system and check theory against actual results by measurement. Whichever method is used, centres need to ensure that sufficient product evidence is available of the optic systems being used/developed and the formulae selected/used to determine the required values. This is particularly important where computer software is used that does not have a facility to print results or where print-outs do not show sufficient detail to meet the criteria.

P1 should include the main characteristics of light, where it can come from and how it forms a part of the electro-magnetic spectrum. Learners will also need to know how light is generated. This can be achieved by looking at the atomic model and extending the ideas to include the Neils Bohr model to explain the release of photons due to changes in energy levels of electrons.

The characteristics of light as a combination of electric E and magnetic H fields for P2 should be used to develop the idea of light as a wave and the resulting wave-like characteristics. The orientation of these fields and the resulting kinds of polarization should be discussed. Learners should know what a dichroic material is and examples should be looked at eg sunglasses with polarising filters.

P3 involves the determining of image position for three cases of object position - object beyond focal point, object at focal point and object between focal point and lens. This exercise is to help the learner differentiate between a real and virtual image and to see the pattern of image position as the object is brought in from ‘infinity’ ie beyond 2 times the focal length. Other examples of real and virtual images should be given, eg reflection in a bathroom mirror as a virtual image; a real image can be projected onto a screen. A graphical method (ray diagrams) should be used to explore these types of image using the 3 key rays.

For P4 learners will need to have a good grounding in the use and meaning of the thin lens equation and be able to re-arrange the formula. Learners should be able to use graphical and analytical methods to solve these problems. P5 should look at other kinds of lenses and give a qualitative analysis of their application eg doublets, aspherics etc.

The determining of the critical angle of a medium (P6) will require the use of a light source (laser) and a beam steering assembly with the ability to measure angles accurately. Software simulations can be used as a less desirable alternative. An analytical approach can be done by application of Snell's Law. The manipulation of the equation to determine the sine of the angle should be included. The case for critical angle should be explained (ie sine r = 1). Angles greater than the critical angle should be understood as well ie total internal reflection. Examples should be discussed, eg looking upwards from underwater in a swimming pool and transmission of light in fibre-optic cables

P7 looks to introduce learners to laser light and why it is special. A basic understanding of light being emitted by changes in electron energy levels should be included. Also the idea of photons and the inability of waves models of light to explain lasers. The extra properties of laser light should be included eg coherence, monochromatic, narrow beamwidth etc.

The evidence for P8 will be descriptive and requires learners to provide a basic explanation of the principles and concepts of light as a wave to explain diffraction and interference. This should include the ideas of interference, both constructive and destructive. Use of ray diagrams to explore path length differences, eg Fraunhofer diffraction and Young's two slits interference pattern should be used to give a qualitative understanding of these phenomena.

M1 builds on the idea of polarisation and develops them further to investigate how a series of polarising filters can be arranged and analysed to evaluate the transmitted wave's orientation and magnitude. This topic can be related to LCD displays and linked to vector theory covered in other units. (Intensity or amplitude of the transmitted wave is sufficient for the analysis, where intensity is proportional to the amplitude squared)

For M2 learners need to evaluate the wave-like behaviour of light using a single slit to produce a diffraction pattern followed by Young's double slit experiment to produce an interference pattern. The leaner needs to apply the theory of constructive and destructive interference to explain the patterns observed. The link between wavelength and fringe spacing should be predicted and measured. Learners should be able to produce representative ray diagrams to derive the equations for the maxima (2-slit interference) and minima (single slit diffraction) fringe separations. Use of small angle approximations is needed to simplify the final equations.

M3 allows learners to build on basic lens theory to design and construct a simple telescope or microscope. This should include investigating the design principles, predicting the magnification and testing the telescope.

For D1 learners should be able to analyse the trade-offs when combining lenses and discuss the problems that may arise. This analysis will be drawn from the theory that has been covered within the unit and observations made through practical experiments. Examples may include a discussion of the Galilean vs the Newtonian telescopes as well as the use of doublets and aspherics in modern imaging systems.

D2 requires learners to predict the behaviour of diffraction gratings and resulting interference patterns as certain parameters are varied. This may follow practical work where the learner has had a chance to vary these parameters. The analysis should draw on mathematical models of diffraction and interference and show a thorough understanding of the observed effects.

Links to National Occupational Standards, other BTEC units, other BTEC qualifications and other relevant units and qualifications

This unit relates strongly to *Unit 4: Mathematics for Technicians* and *Unit 127: Further Principles of Photonics*. It would be useful to study the maths unit concurrently as this unit has a reliance on strong mathematical skills involving problem solving and graphical plots. Data from experiments within this unit can be manipulated mathematically and so provide evidence for both units. The Further Photonics Principles unit is best studied after this unit.

These units should be delivered to meet the underpinning knowledge in the Photonics Engineering Pathway in the Mechanical Manufacturing Engineering National Occupational Standards.

Essential resources

It is essential that learners have access to a well-equipped photonics laboratory with up-to-date resources and instruments such as light sources, lasers, photo-diodes, lenses, beam-splitters, prisms, mirrors, optic breadboards, associated mounting and alignment equipment digital and analogue multimeters, function generators and oscilloscopes. With the increased use of computer-based methods for simulation, centres are strongly advised to consider the provision of suitable hardware and software.

Indicative reading for learners

Born, M and Wolf, E — *Principles of Optics* (Cambridge University Press, 1999) ISBN 9780521642224

Hecht, E — *Optics* (Pearson Education, 2003) ISBN 9780321188786

Kingslake, R — *Lens Design Fundamentals* (Academic Press, 1978) ISBN 9780124086500

Kingslake, R — *Optical Systems Design* (Academic Press, 1983) ISBN 9780124086609

O'Shea, DC — *Elements of Modern Optical Design* (John Wiley & Sons, 1985) ISBN 9780471077961

Smith, W — *Modern Optical Engineering: The Design of Optical Systems* (McGraw Hill, 2000) ISBN 9780071363600

Key skills

Achievement of key skills is not a requirement of this qualification but it is encouraged. Suggestions of opportunities for the generation of Level 3 key skills evidence are given here. Staff should check that learners have produced all the evidence required by part B of the key skills specifications when assessing this evidence. Learners may need to develop additional evidence elsewhere to fully meet the requirements of the key skills specifications.

Application of number Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• planning and presenting their descriptions and explanations when comparing practical and theoretical information • solving problems and interpreting results in any of the four learning outcomes using conventional methods and/or computer-based software packages.	N3.1 Plan an activity and get relevant information from relevant sources. N3.2 Use this information to carry out multi-stage calculations to do with: a amounts or sizes b scales or proportion c handling statistics d using formulae. N3.3 Interpret the results of your calculations, present your findings and justify your methods.

Information and communication technology Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• researching and using a variety of different sources for product/component information • developing and presenting information on photonics principles to meet the unit criteria/content eg description of light sources, optical components etc.	ICT3.1 Search for information, using different sources, and multiple search criteria in at least one case. ICT3.2 Enter and develop the information and derive new information. ICT3.3 Present combined information such as text with image, text with number, image with number.

Problem solving Level 3	
When learners are:	**They should be able to develop the following key skills evidence:**
• solving problems photonics using conventional methods and computer-based software analysis and simulation packages.	PS3.1 Explore a problem and identify different ways of tackling it. PS3.2 Plan and implement at least one way of solving the problem. PS3.3 Check if the problem has been solved and review your approach to problem solving.