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# PHOTONICS AND OPTICAL MEASUREMENT: EDUCATION FOR TODAY'S ENGINEERS

The paper presents an illustration of the use of photonics and optical measurements in today's engineering world and emphasizes the need for and value of the field which is seen as a key subject for current engineering education. The paper emphasizes the place of photonics when viewed within a systems approach to measurement and instrumentation, but also stresses the value of the appreciation of the fundamentals of physical science to achieve a full understanding of modern devices of this type. The relationship of photonic measurement systems to optical communications systems is stressed, as is the commonality of the approach to the two. The role of modelling as a key tool in the system design is emphasized, and an illustration given of a modern fibre optical measurement system to exemplify the points raised.

*Keywords: photonics, optical measurement, education.*

## 1. INTRODUCTION

The field of optical engineering and photonics is one that is comparatively new to engineers – a generation ago optical instrumentation and the measurements made with devices of that type were seen legitimately as part of a University *physics* course, but not, on the whole, as a subject for engineers. The world has changed. The term *photonics*, emphasizing the quantum nature of light, is now familiar. The Internet has become such a ubiquitous tool that almost everyone – including engineers – would find it hard to imagine a world without it. The power behind the Internet is the power of the photon, carried along multi-kilometer lengths of optical fibre. The optical computer may still be only a concept and as a practical device, something for future

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engineers, but with electronic computing continuing to respond to the power of Moore's Law, optoelectronics and photonics coupled with today's computing capability is powerful indeed. The laser, the fibre optic and the use of digital techniques now have the power to impact widely on many branches of engineering and to contribute greatly to achieving better engineering solutions for the future.

Optical measurements are a key part of this photonics revolution. There is a need to make measurements in all spheres of engineering and the use of optical techniques is inherent to photonic communications systems which transmit signals and data. However, optical methods have a wider application and the growth of open air path and fibre-based techniques has had a major impact on industry, from the process industries to structural engineering, from steel making to fire alarm systems. Coupled with effective modelling techniques, they enable the engineer to understand more fully the nature of the devices used and thus to design better instruments for present and future engineering applications. The photonics revolution is set to carry on through the 21st century.

## 2. EDUCATION IN PHOTONICS FOR TODAY'S ENGINEERS

At the outset, the authors have reflected upon the need for a change in the role of optics, from that in the engineer's education of a generation ago to something better fitted to current needs. The preceding discussion has emphasized clearly the value of photonics to today's engineer – but what are the essential features of the syllabus that fit into a busy engineering course, where digital techniques, new computer languages, computer systems and the internet compete for time in what is an otherwise overcrowded curriculum. "The essentials" of the subject are where the discussion begins.

### 2.1. THE ESSENTIALS

The relationship between electrical engineering and applied physics has often been stormy and turbulent – is electrical engineering merely the application of physics? Clearly not, but whatever may be the merits (or otherwise) of that argument, the fundamentals of science, coupled with a creation of a skills base in mathematics play a key role in the curriculum, for the development and ultimate formation of engineers. This is the ideal place to introduce the essentials of the subject of optics. The optical fibre depends for its existence upon the materials science of glass, a clear understanding of the key principles of total internal reflection, the conditions under which it occurs (and how it is prevented from occurring in a bent fibre, for example) and the principles of ray optics. A better understanding of optical modes is achieved through a knowledge of electromagnetic theory in optics. Wavelength effects and dispersion underpin the propagation of data in digital form and the student must understand why a fibre cannot propagate a series of short optical pulses indefinitely and preserve the digital encoding therewith. Fortunately the physics here is simple and straightforward and coupled with basic mathematics, the student can understand the essentials of fibre optics and thus should readily have a clear idea of how and when they are to be used. Experiments can be carried out in the laboratory to reinforce this – on ray optics, on total internal reflection at the interfaces of common optical materials and with optical fibres. The costs of the equipment needed are small and devices are rugged for regular use by student groups. Laser diodes provide excellent sources, at prices as low as only one euro each. Lenses again are essential for coupling of light into the fibre optic – what are the conditions where fibre coupling occurs, when does it fail and why? To understand the absence of a parallel in the optical fibre to the electrical connection of a coaxial cable is valuable for a student, and again an appeal to simple ray optics and elementary geometry will reveal clearly how the optimum coupling conditions may be created. Lenses of course are not simply curved glass surfaces – the use of the GRIN (graded index refractive index) lens in modern optics has provided an excellent, compact means to bring light into a fibre from a laser source. Again ray optics provides a ready explanation of much of the function and variety in modern optics.

The laser is the powerhouse of the photonics revolution – especially the semiconductor laser. Students must be introduced to the concepts which underpin its operation – stimulated emission, spontaneous emission and stimulated absorption. The variety of laser devices must be explained – this represents an excellent study in materials science, in electrical devices and in the integration of many of the components of modern optolectronics, as well as being an excellent example of how personalities and different working styles can impede scientific progress [1].

The concepts of coherence are easily explained diagrammatically after a discussion of wavelength, frequency and phase, and open up the understanding of the prime differences between the laser and conventional optical radiation. Semiconductor materials play a vital role in today's photonics – both as sources and detectors of radiation and here a knowledge of basic solid state physics and the light handling properties of these materials is essential, complementing as it does the knowledge of the electronic properties of their use in electronic devices.

## 2.2. THE SYSTEMS APPROACH TO PHOTONICS AND OPTICAL MEASUREMENTS

In the spectrum of activities from education through to practical instrument design, adopting a systems approach to instrumentation is essential – to its understanding, to optimize and thus to educate today's students in key concepts of lasting educational value. The approach taken by Finkelstein and Grattan [2] in the Concise Encyclopedia of Measurement and Instrumentation is that taken here: to create a functional decomposition of the instrument and to understand it at both a "signal" level and a "physical science" level – the latter being in terms of the essential physics and materials science that underpins its function as an operational device. This latter aspect is essential in photonics: a "box" in the system labelled "source" and representing a laser could designate a device of size ranging from that of a pinhead to an aircraft hanger – with power requirements scaling from three flat "button-type" cells to an electrical sub-station. Lasers they all are, depending on stimulated emission and producing a coherent, directional beam – but there the similarity ends. Their physical characteristics distinguish them, and over the range of laser devices on the market, there is wide and ample choice for the optical instrument designer.

A typical functional decomposition of a familiar and valuable optical instrument, a spectrophotometer, is shown in Figure 1. The source used may be a laser, an LED or be conventional in nature, but the principle in the supply of photons is the same. The source may be acted upon by external influences – modulated – for ease of detection. Here again the knowledge of the physical science base is critical. The modulation of a semiconductor diode laser, at up to ~ a few GHz by switching of the drive current is relatively easy – the modulation of a continuous wave (c.w.) laser such as an a He-Ne or $Ar^+$ laser requires an external modulator using typically an external electro-optic device and this is very different – requiring careful materials selection, cut, alignment and activation. For the photonics system designer to specify a modulated source without this fundamental knowledge could lead to catastrophic costs or adverse reliability and packaging difficulties.

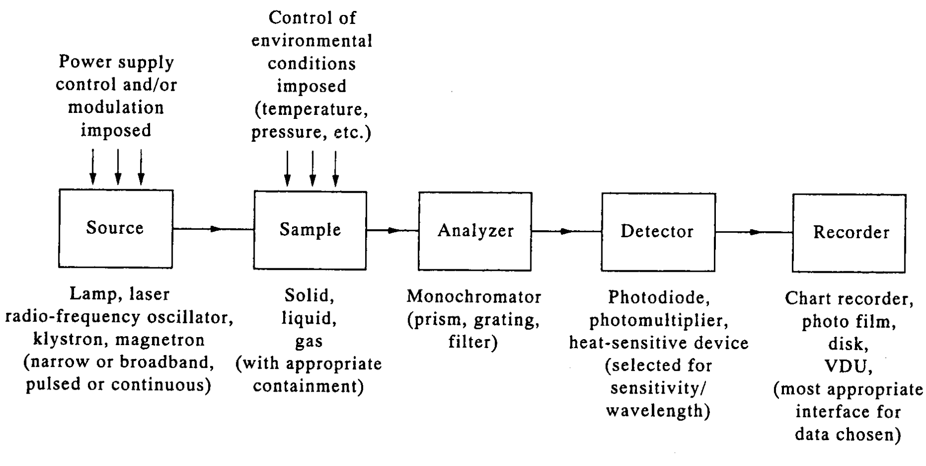


Fig. 1. Functional decomposition of a spectrophotometer

Similarly with the detection of the optical signal – after transmission through air or optical fibre, through the sample to be interrogated, the optical signal must be converted to an electrical signal for further processing. The detector is placed after a wavelength selection device – a wavelength modulator – which is used to determine a particular wavelength for analysis and to record the response of the system to that wavelength. Conventionally a ruled diffraction grating and photomultiplier were used – both devices where their performance depends crucially on the knowledge and use of the physical science base from which they were developed. Diffraction is a well-known phenomenon relying on the wave picture of light propagation and the photomultiplier is an effective and sensitive detection device for small signal levels. However, both are bulky and fragile – the photomultipler uses high voltage in operation and may readily be damaged. The advent of the diode array spectrometer using a series of discrete devices each individually addressed by light of a particular wavelength, through careful systems design, has revolutionized the spectrophotometer in terms of cost, size and capability. Here again a close knowledge of how these devices work is critical for effective design – wavelength effects, overall sensitivity and the material aspects of semiconductor detectors are critical for optimized performance. The use of detectors on a single chip and Bragg grating wavelength selection elements written in-fibre stretch the requirement for a clear knowledge of the fundamental physics in order that the total system design may be understood clearly and thus optimized.

Further signal processing in the electronic domain is needed – filtering and amplification, for example and interfacing to a PC – techniques which are part of the curriculum but beyond the scope of this paper. Even the output display technology of the computer is a reflection of use of modern photonic systems: the affordable bright, high colour display of today's laptop computers owes much to the knowledge of semiconductor photoemissive materials.

### 2.3. NUMERICAL MODELLING FOR TODAY'S ENGINEERING DEVICES

Traditionally instruments were designed, built and tested – and refined when performance problems were identified. The approach to instrument design has been revolutionized by the use of numerical modeling, applicable to a wide variety of engineering sectors. The ability to take the systems approach, to adopt a functional decomposition of the system and to analyze the components is applicable to instruments and devices, both optical and mechanical. Research by Khan et al [3] has shown the value of the technique in electromagnetic modelling, designing systems as diverse as miniature actuators for food sorting to optimizing variable transformers for use in large scale industrial plant. Modelling of optical and photonics systems involves the understanding of Maxwell's equations and materials technology, and with that the ability to model the design and function of a range of photonics devices. Work by Rahman and his colleagues [4] have enabled a wide range of devices to be explored and developed, most especially directional optical couplers and laser diodes. The old "craft" approach to the design and refinement of the device is hardly applicable when that fabrication costs are in the region of hundreds of thousands of euro, as they are for some sophisticated optoelectronic devices. Here the savings of time and cost, coupled to the flexibility and convenience show the value of the approach.

Education in the modelling techniques used is essential for today's engineers – not just to have experience of the range of commercial software packages available but to understand why and how they may be used – indeed abused if care is not taken – and most especially the fundamentals of science and mathematics that underpin their use. Coupled to an ability to relate to the scientific fundamentals, there is indeed a powerful approach offered to today's engineers to tackle better the tasks ahead.

## 3. OPTICAL FIBRE SENSORS FOR INDUSTRIAL MEASUREMENT

These concepts have been employed in a range of optical fibre sensor devices, discussed in some detail in a series of texts by Grattan and Meggitt [5]. However, an important illustrative examples is given, revealing the use of a systems approach to the design of an effective sensor system.

### 3.1. FIBRE OPTIC FLUORESCENCE THERMOMETER

The combination of optics and electronics, of fibre optics and optoelectronics, of a systems approach and the use of advanced signal processing is seen in the above device. Work by Zhang et al [6] and Sun et al [7] has enabled this to progress from concept to device for industrial applications, for measurements from temperatures in the cryogenic region to >1000°C. The device is used here both as an illustration of an effective measurement system, whose operation and purpose can be well understood through a functional decomposition, and also a device which has enabled a response to the challenge to create industrially-relevant instruments. Figure 2 illustrates the system – a laser diode source is square wave modulated and light from it used to excite fluorescence in a piece of doped optical fibre located at the distal end of the fibre probe. The light is passed through a fibre optical coupler into the probe, which comprises a piece of rare earth doped material, typically 5 – 10 mm in length, fusion spliced to a piece of conventional "telecoms" fibre. The fibres are enrobed in a metal coating tube and fitted with a connection to the fibre coupler.

The fluorescence excited from the system is monitored using a phase-locked-loop system and the output may be displayed on an oscilloscope (to check the fidelity of the signal) or passed to software such as HPVee to provide a user-friendly interface and display the output data. The device is calibrated in an oven against a thermocouple and the temperature monitored by the probe is displayed on the PC screen.

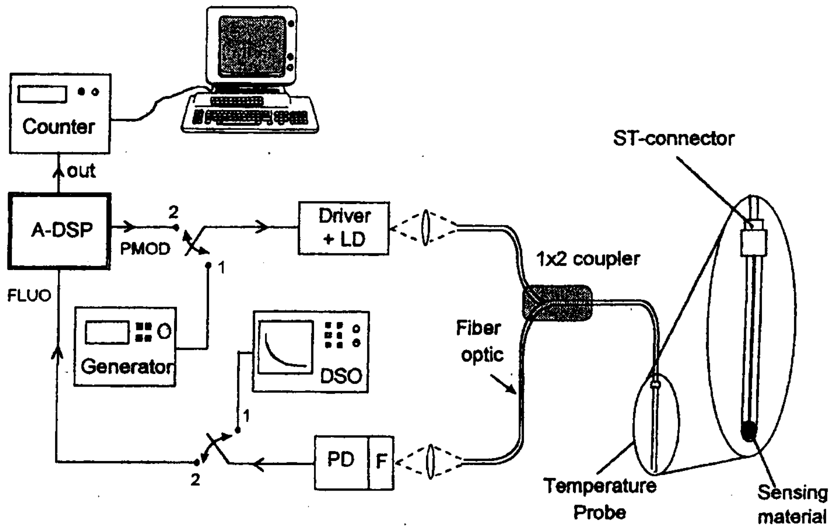


Fig. 2. Block diagram of the lifetime measurement system; switch in position1: the decay data are directly acquired by DSO to determine $\tau$, switch in position 2: the system operation is based on an A-DSP module whose output is a modulation period T, and is measured by a counter. DSP – digital signal processor, LD – laser diode, PD – photodetector, F – filter (optical), DSO – digital oscilloscope, FLUO- fluorescence signal

The system is currently being developed as a high temperature (<700°C) probe for use by Corus plc in the UK for monitoring of furnace lings – to determine heat flow in the linings and thus to monitor wear and minimize “down time”. The view here is that this advanced photonic device provides an illustration of the thesis proposed on education in photonics for today’s engineers. The choices in the design process, as can be seen, require a knowledge of the fundamentals of optics for the fibre optic and optical coupling system, of materials science to optimize the fluorescent species and the probe design, of optoelectronics in the laser device and detector in their choice and optimization, of electronics and signal processing in the circuit design and implementation and of IT and interfacing to enable the output to be produced in a user-friendly way. An appreciation of the ergonomic factors is vital when relatively unskilled operators will use the system and in addition to being ruggedized for the purpose, the device must be cost-effective and low in its maintenance requirements. Examples such as these show to students a “real world” problem and solution an offer interesting lessons in comparing performance, costs and reliability against those of conventional technology. Many other examples could be chosen, but the lesson is the same – a functional decomposition, a systems approach, an understand of the essentials of the subjects involved and an attitude of innovation enable new devices to be created, to meet industrial needs and thus to enhance student education.

## 4. SUMMARY

The contention of this work is that an accurate and carefully constructed systems approach, founded in a clear and sound knowledge of the physical sciences base and complemented by an ability to create and use accurate models is essential for good design of photonic-based instrument systems. Thus this must form part of the curriculum for engineers – for electronic and instrument engineers in particular, but also for those studying topics intimately involving the use of optoelectronic devices, such as communications engineers, for example. Photonics and optical measurements are vital to industry in the rapidly expanding EU – and thus these topics must be reflected in the educational formation of today's engineers. For those whose formal education was some time ago, the need may remain equally valid - the opportunity for continuing professional development (CPD), for training periods and short "hands on" courses is something that should be taken. At City University, London, such a course has run twice or three times annually for over 10 years [8], updating and developing optical fibre and laser skills for engineers on a variety of industries. Education for all today's engineers should be a priority of our Universities if they are to serve effectively our industries and the communities that depend for their well being on them.

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