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Photonics laboratory experiments for modern technology based courses

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ABSTRACT

The modern photonics and optical communications industries have placed ever increasing demands on the supply of skilled graduates who are competent in the design, installation and operation of photonics systems. In response to this demand, we have developed a range of photonics laboratory teaching experiments to support accompanying lecture courses by underpinning fundamental principles with hands-on experimental experience. These systems enable students and trainees to experimentally investigate the basic principles, characteristics and design of optical waveguides, optical communications systems, optical amplifiers and fault location techniques for optical networks, with additional scope for open ended investigative work. The experiments have been designed with the constraints of academic teaching budgets firmly in mind whilst still allowing the investigation of real technical issues such as mode spectrum analysis in optical waveguides and optical pulse dispersion / bit rate limits in fibre communications systems. The educational and overall system design philosophies, hardware and experiments are reported in this paper.

Keywords: educational experiments**,** photonics education, fibre-optics education, optical communications, optical amplifiers, EDFA.

1. INTRODUCTION

Optical fibre links now dominate the world's major trunk telecommunications systems. They provide the core telecommunications for the global internet and are penetrating ever deeper into the access and local area networks(1). In addition, photonics is having an ever increasing affect on our daily lives through a myriad of industrial and consumer applications(2, 3). Consequently, there is a rapidly growing demand for scientists, engineers and technicians who can design, install and operate optoelectronic components and systems. In response to this demand, Colleges and Universities throughout the World are introducing appropriate courses in optoelectronics and optical communications at under graduate and post graduate level. Such courses need to be supported by practical laboratory programmes to provide the students with the essential hands on experience of photonic components and systems and to experimentally reinforce the fundamental principles of such systems as taught in the lecture classes.

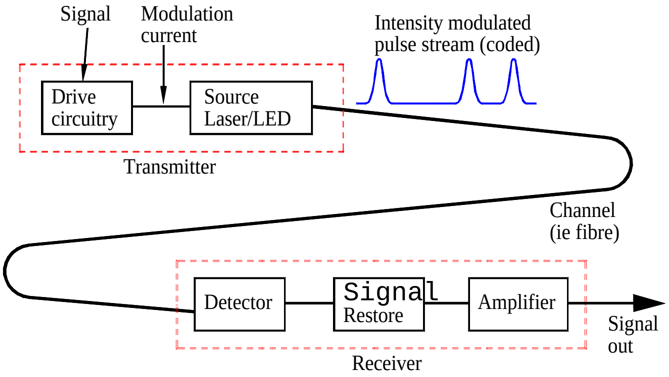

***Figure 1:** Schematic of a point to point fibre optic communications link.*

Any broad based course on photonics or a more specific course on fibre optic communications must address the principles, characteristics and applications of optical waveguides, optical fibres, optical amplifiers, lasers (in particular semi-conductor lasers), light emitting diodes (LEDs), photo-diode optical detectors and optical receivers. Fibre optic telecommunications is the most important single application of photonics. An optical fibre transmission system (Figure 1), comprising a semi-conductor laser diode or LED transmitter, an optical fibre (the guided wave communications channel), optical amplifiers (repeaters) and a photo-diode receiver, embraces most of the important principles, components and system technologies of both guided wave and non-guided wave photonics. For these reasons we have developed a photonics laboratory teaching programme which is centred on fibre optic communications systems to provide specific experimental experience of this field as well as broad exposure to many of the most important principles of photonics in general. This programme utilises four custom designed kits of photonics hardware which enable comprehensive experimental investigations on optical waveguides, a 1km point to point fibre optic communications link, an in-line optical amplifier (namely the erbium doped fibre amplifier - EDFA) and a fibre optic network analysed by a standard test instrument (an optical time domain reflectometer - OTDR). With these four experimental systems we cover most of the essential elements of photonics courses as noted above. The experiments have been designed for intermediate and advanced level courses aimed at under-graduates in the upper years of their studies or post graduates at Masters level. In addition, they may be useful for technical colleges and training institutes where students are undertaking specific vocational training courses in photonics or optical communications technologies.

The overall educational aims of the experimental exercises are to enable students to consolidate their understanding and knowledge of photonics as presented in an accompanying lecture course and to acquire practical experience of the design, analysis and characteristics of photonics components and systems. To achieve these aims it is essential to take a fully integrated approach to the design of laboratory based photonics teaching packages including the design of dedicated hardware, experimental procedures, exercises and manuals. To ensure that all desirable educational objectives are met and that all of the most important scientific and technical principles, issues and phenomena are addressed, we have developed our suite of four fully integrated laboratory based teaching packages in accordance with the following design rules:

- Define the educational objectives in terms of the physical principles, important technical features, design issues and performance characteristics which must be addressed, with particular attention to facilitating student understanding and ability to implement concepts.
- Define the experiments to meet these performance objectives.

- Design the dedicated (custom) hardware to enable the proposed experimental investigation whilst keeping costs within realistic academic teaching budgets.
- Formulate the experimental procedure and manuals to guide the students through the investigation and results analysis (in some cases more open ended investigations may be formulated with minimal guidance to the students).
- Formulate tutorial exercises and case studies to relate the results to real world devices and systems.

The primary constraint is cost and the final packages must be affordable within higher education budgets. In general, the packages have been designed as far as possible to be self contained in that as little ancillary equipment as possible is required. However, where it is advantageous and cost effective to use equipment normally available in student laboratories, the packages have been designed to be compatible with the capabilities of such equipment e.g. 20 or 50MHz oscilloscopes and waveform generators.

The four packages now fully developed on the basis of the above approach cover the following topics: Principles of Optical Waveguides, Fibre Optic Communications Systems, Erbium Doped Fibre Amplifiers and Lasers and Optical Network Analysis. Here, we present outline descriptions of the educational objectives, the hardware and the experimental procedures of these four packages which are fundamental to any course in photonic systems as taught in physics or electrical engineering departments throughout the world. In addition, some sample results are presented in the appendices.

2. PHOTONICS EDUCATION - THE BROAD CONTEXT

Our aim in designing and implementing this laboratory programme has been to illustrate how basic physical concepts in photonics lead into the engineering design principles which in turn yield components and sub-systems for the complex optical fibre networks we all use on a daily basis. This flow of ideas is illustrated conceptually in Figure 2. In parallel with demonstrating this linkage our students should benefit through exposure to design exercises and data analysis, as well as gain some confidence in using these processes which are illustrative of generic engineering philosophy. The students who have participated in this experimental programme are typically in the third year of a four year undergraduate course in the UK, at a level equivalent to a US junior year within a general course in physics or electronic and electrical engineering. The experimental programme is also used with instructed masters courses.

The four experiments mentioned in the last paragraph of the preceding section map effectively into the concept flow diagram of Fig. 2 and illustrate both the application of science and the need for problem solving skills in engineering.
The simplest of these experiments illustrates the waveguiding process in a planar dielectric slab guide. Conceptually the important parameters here are phase matching – achieved through prism coupling and, implicit in the phase matching process, the observation that different modes in waveguides travel at different phase and group velocities. The M lines illustrate these very basic principles most effectively. Students are accustomed to the basic concept that the deflection angle through a prism depends upon the difference between the velocity of light in the medium from which the light is injected into the prism and the velocity of light in the prism itself. The prism spectrometer is an example of this process where the velocity of light in the source medium is broadly constant with wavelength. The prism coupling structure neatly turns this concept on its head since the velocity of red light is obviously fixed in the prism but the velocity in the source medium (the waveguide) is different for the two modes. This difference can be evaluated from the positions of the M lines.

The velocity difference leads into two very important concepts, namely modal dispersion and velocity matching criteria for coupling. The former can give some hints as to the potential dispersion performance of hypothetical waveguides constructed using the same format as the slab. The coupling process leads into the concepts of phase matching as required in directional couplers and also – with a little thought – can illustrate differential dispersion between the coupling prism and the waveguide which in effect leads towards one mechanism whereby wavelength division multiplexing may be achieved. The students see also the impact of a mode cut off by examining different waveguide geometries with different slab depths and observing the numbers of modes on each occasion. This in turn leads on to the design concepts for achieving single mode waveguides. In addition, they are able to estimate through dispersion characteristics whether the guides have step or graded index profiles and have samples of both made available to them. So whilst this is a basic and simple experiment it demonstrates several most important engineering principles and their applications into components. The introductory part of the experiment illustrating reflection and refraction is very straightforward but is also extremely important as refresher material leading into the concepts of waveguiding in modes.
The most important building block in optical networks is the point to point communication link and our aims in producing this experimental demonstrator have been to illustrate the limiting factors which constrain the performance of

a point to point link and thereby emphasise the very precise engineering control which must be brought into effect to produce a 100 km link operating a bit rate of 5 Gbit/s or greater. The challenge from an experimental design perspective is to produce an equipment set which illustrates the principles effectively at a realistic cost without introducing artificial constraints (for example control of the mode fill at the launch end of an optical fibre can very efficiently demonstrate that a laser source produces less dispersion than an LED, though not for the desired reason that the material dispersion has been kept under control). Our cost target remains of the order of a few PCs and within this target we can only examine systems with bandwidths of the order of a few 10s of megahertz and total length of the order of a kilometre. That said, with ingenuity and very careful experimental design it is in fact possible to demonstrate intermodal dispersion, material dispersion, the addition of different dispersion types through a square law process, attenuation and receiver properties and then to extrapolate into signal to noise ratios, bit error rates and inter symbol interference. The conceptual grounding which this experiment consolidates is more towards illustrating the principles of systems analysis and extrapolating into the necessary properties required of sources, waveguides and detectors in modern single mode communications system. It links back to the waveguide experiment through the concepts of intermode dispersion and the idea of cut off determining the maximum dimensions of the core of an optical fibre. Basic material properties dictating scatter and absorption tie into a discussion of attenuation mechanisms, optimum wavelengths, and the impact of both attenuation and dispersion on network transmission characteristics.

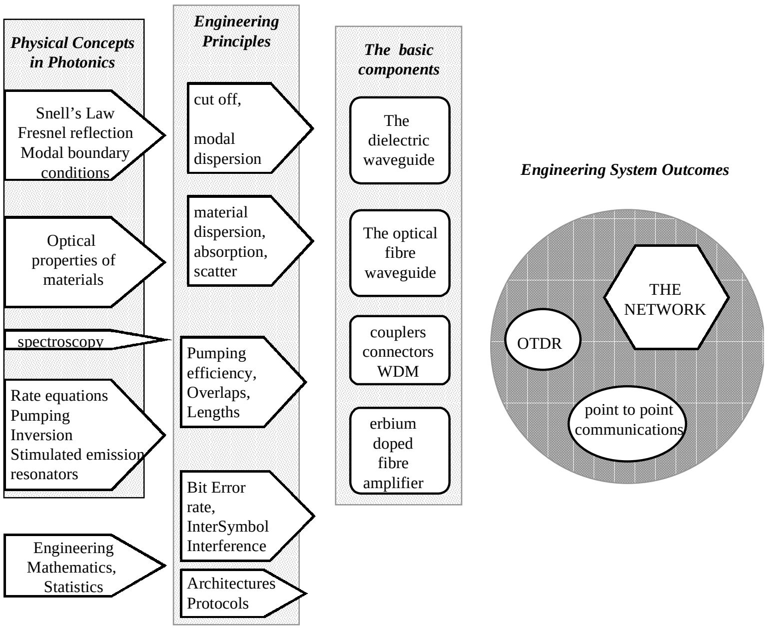

Figure 2: *Flow diagram illustrating the evolution of physical concepts in photonics through engineering principles into components and systems.*

The erbium doped fibre amplifier (EDFA) experiment illustrates the operation of an essential – and in the electronics context rather esoteric – component in modern optical telecommunication systems. The function of the experiment is two fold. Initially, we illustrate the application of basic physics in predicting the operational characteristics of the optical amplifiers in general. This leads into the characterisation of the EDFA as a "circuit element" with specific gain, noise, distortion and cross-talk characteristics. These measured characteristics are linked into an analytical model of the processes inherent in the EDFA and finally the results can be combined with the basic characteristics demonstrated in the point to point optical communications experiment to assess the influence of the amplifiers on the bit error rate performance of a practical link.

The focus in the three experiments above has been on simple point to point links and the elements therein. The global objective has been to illustrate the applications of photonic principles into a very important user sector – namely optical communications. The intellectual process has been in the application of physical models into the design of devices and systems. In practice, optical communication networks are more complex and wavelength division multiplexing is a key concept though its basis is essentially technological rather than riveted in physical principles. The wavelength selectivity of guided wave devices is obviously a founder element of wavelength division networks and the very basics of this are illustrated in the coupling phenomena way back in the waveguide experiment. Understanding networks is however where engineering intuition plays as great a part as analysis and synthesis through rigorous techniques and one of our educational objectives must be to encourage our students to develop such intuition. The network analysis experiment has this in mind. Here a dual wavelength OTDR is used to address a branch network comprising a mixture of wavelength flattened directional couplers and wavelength multiplexers. The students are asked to deduce a map of the network and also to identify fault conditions in the network, some provided by an actual "hardware" fault within a sample others from OTDR traces supplied on disc for analysis. The students emerge from this experiment with the awareness that engineering common sense is also important and that it can and often must be applied to practical situations. They are also exposed to the broader range of OTDR applications including sensor networks, primarily to indicate that guided wave optics, whilst critical in communication networks, also contributes to a much broader range of application sectors.

These experiments require skill and experience to put into operation and the optical design is critical – especially to ensure that the final experimental system stays within a budget comparable in price to at most a few personal computers. The experimental suite has been developed and refined at Strathclyde University, with input from our colleagues at Heriot Watt University in Edinburgh, over a period of a decade or thereabouts. During that time the university has evolved very comprehensive sets of instructor notes and supporting material, student assessments and design exercises and student guidance notes. We believe that the package is unique in offering an illustration of basic photonic principles and analysing its application within an engineering context. Encouraged by the reaction of our student populace, the University has collaborated with OptoSci Ltd to make these experiments more widely available and to ensure that they can be used – through the provision of a very comprehensive supporting material – by enthusiastic instructors who have not necessarily been exposed, through research, to the complexities of guided wave photonics, thereby enabling any confident instructor in physics or electrical engineering to convey with excitement the application of these important concepts.

The principal features of the four experiments in the suite are described very briefly in the sections which follow.

3. OPTICAL WAVEGUIDES

Information transmission along an optical fibre is governed by the principles and characteristics of optical waveguiding. The simplest approach to introducing students to the concepts and properties of optical waveguides is to begin with the principles of total internal reflection and then address the ray model of firstly step index, and then graded index planar waveguides. To support lecture courses on these topics, the overall objectives of the Optical Waveguides package are to enable students to experimentally investigate and consolidate their understanding and knowledge of:

- the principles of refraction, reflection and total internal reflection.
- the principles of optical waveguiding using the ray model and the concept of guided modes.
- the principles and practice of the prism coupling technique for the measurement of modal parameters and the investigation of mode spectra, and as an illustration of phase matching.
- elementary waveguide analytical techniques and
- basic waveguide design processes including concepts of mode cut-off and the design of single mode waveguides.

The apparatus (Figure 3) comprises an optical rail and mounting system supporting a 633nm collimated laser diode, a polariser, a lens and a rotational table which can be translated transversely and vertically. The table may be fitted with a semi cylindrical optical element and photodiode power meter for the refraction / reflection experiments or a waveguide prism coupling assembly (Figure 3) which is used to address a selection of step and graded index planar waveguides of various thickness.

The students carry out the following investigation:

- Verification of Snell's law.
- Measurement of the Fresnel relationships for both polarisation states with observations of Brewster's angle, the critical angle and total internal reflection. Comparing results with theory.
- Establishment of prism coupling to selective waveguide modes and observing output coupled mode lines (m line spectra).
- Measurement of mode coupling angles and mode effective indices / propagation constants for
  - Step and graded index planar waveguides.
  - Both polarisation states.
- Determination of waveguide parameters (index profiles and thickness) from the mode effective indices, highlighting polarization dependence.

- Calculation of mode cut-off conditions using the waveguide parameters.
- Design and test of single mode waveguides.

Examples of typical results and analytical procedures for this investigation are given in Appendix A. At the end of this experiment the students will have related the different mode effective indices into dispersion parameters and also deduced that the dispersion of such simple guides is excessive for long distance system applications. They will have confirmed the polarisation selectivity of thin films, observed the polarisation dependence of the guiding properties of thin films and seen the selectivity of phased matched coupling, beginning to relate this into coupled mode devices such as directional couplers and wavelength multiplexers. Furthermore, they will have become familiar with the basic Eigen value equations for step and graded index waveguides through using them in the analysis of the waveguide parameters from the measured mode spectra. This experiment is an essential precursor into the investigation of an optical communications point to point link which follows.

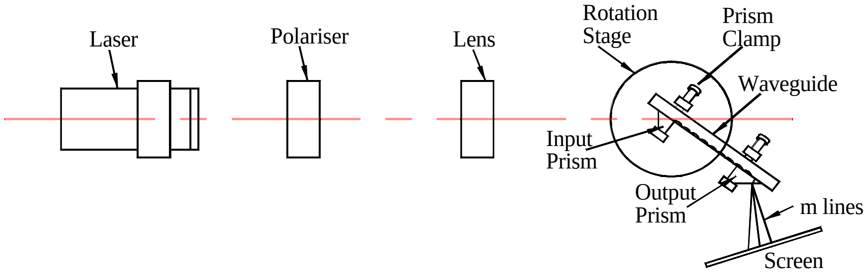

Figure 3: *Top view of prism coupling system*

4. OPTICAL COMMUNICATIONS

Optical fibre information transmission links enable more information to be transmitted over greater distance than any other communications technology. Hence, they have all but completely replaced copper based systems as the primary choice for global and local telecommunications systems. The objectives of the Optical Communications experiments are to enable students to experimentally investigate and build upon their knowledge and conceptual understanding of, and their ability to interpret:

- The main characteristics of the major components of a fibre optic communications system i.e. the source / transmitter, the fibre channel (attenuation, dispersion, pulse spreading etc.) and the receiver
- The overall system performance limitations imposed by the component characteristics
  - the maximum possible link length limited by attenuation
  - the bit rate (& bandwidth) / length products determined by fibre dispersion
- System design and performance analysis.

The custom designed equipment for this investigation comprises a LED transmitter, a laser transmitter and a receiver (Figure 1). The transmitter drive currents are displayed, as is the received power. Both transmitters have a modulation signal input and a waveform generator is included in the package to provide a variable frequency sine wave or a square wave to enable simulation of analogue or digital modulation. The photodiode receiver output may be fed to an oscilloscope to investigate the received signals. Short patch cords, connectors and a long length of fibre (1 - 1.5km) are provided to make up various links. The selected wavelength is 0.82µm and the fibre is of the multi-mode step index variety. These choices ensure readily measurable attenuation and dispersion effects (step, impulse and frequency responses) using standard student laboratory support equipment such as 20 - 50MHz oscilloscopes. In addition, the effective numerical aperture of the launch has been limited to enable the effects of material dispersion for the LED to be observed against a background of strong intermodal dispersion. The system has been arranged to allow measurement of step function responses and analogue frequency responses. However, since the frequency response is the Fourier transform of the impulse response (i.e. pulse spread response) which in turn is the derivative of the step function response, we derive simple formula relating the analogue bandwidth, the step function risetime and the rms pulse spread (i.e. the impulse response). In this way the students can calculate pulse spreading and dispersion coefficients as well as bit rate / length products from their measured data on step and frequency responses. If a waveform or pulse generator is available the impulse response can then be measured directly and compared to the value inferred from the step or frequency response measurements.

The system described above has been greatly simplified relative to a state of the art system in order to achieve a realistic cost and to ensure that measurements of attenuation and dispersion can be made using standard student laboratory support equipment. We believe that nothing is lost in this approach since all of the key technical phenomena in optical communications systems (attenuation, material and modal dispersion etc.) are addressed. However, to make the point the students are given exercises to analyse the performance of state of the art systems and compare the results to those of the system they have investigated.

Using this equipment the students carry out the following investigations in 3 stages:

Stage 1. Power Budgets

- Measurement of the power / current characteristics , bias points and launched powers of the laser and LED transmitters.
- Measurement of connector losses.
- Measurement of the fibre attenuation coefficient.
- Measurement of the receiver noise and sensitivity.
- Calculation and comparison of the attenuation limited link lengths for the laser and LED transmitters.

Stage 2. Temporal Characteristics

- Measurement of the step function response of the transmitter / receiver, the system and the fibre using both the laser and the LED. This enables the determination of -
    - the fibre impulse response for both the laser and the LED,
    - the modal and material dispersion coefficients and
    - the bit rate distance products for both the laser and LED transmitters.
- Measurement of the analogue signal frequency response of the transmitter / receiver, the system and the fibre, leading to determination of:
    - the analogue bandwidth and bandwidth . distance products of the fibre for both the LED and laser sources. It is interesting to compare the directly measured bandwidth with that obtained from the step response.
- Measurement of the impulse response with direct determination of the dispersion coefficients.

Stage 3. System Performance and Analysis

- The design of systems to meet a given specification using the measured data.
- Analysis of the performance of systems to determine if they will meet a required specification.
- Design and performance analysis for state of the art systems at 1.3 & 1.55μm to compare with those of the system investigated.

Again a few examples of typical results and their analysis are presented in Appendix B. On completing this experiment the students have been exposed to the complex mix of ideas which define the performance of an optical communication network. Material, waveguide and intermodal dispersion all contribute towards eventual inter symbol interference whilst attenuation influences the receiver signal to noise ratio. Our simple measurements enable students to see these in operation and the supporting calculation and design exercises indicate the very substantial distinction, in detail rather than concept, between our laboratory system and a fully engineered communications link. It is the evolution of materials properties, waveguide geometry, signalling concepts and data recovery into a full design analysis which makes this particular experiment so very useful. This is the most popular experiment among the student body with almost unanimous feedback indicating that it provides excellent practical experience and insight into the principles, performance and design of optical communications systems.

5. OPTICAL FIBRE AMPLIFIERS (EDFAS) AND LASERS

Direct optical amplification using erbium doped fibre amplifiers (EDFAs)(4,5) is now preferred over optoelectronic repeaters as the primary means of restoring the signal power in long distance fibre optic links and branched networks. In addition, lasers (essentially optical oscillators) are simply optical amplifiers with positive feedback, again highlighting the importance of optical amplifiers in modern photonics systems(4). The objectives of the EDF optical amplifiers and lasers experiment are to enable students to investigate and become practically familiar with the principles and characteristics of optical amplifiers and lasers in general, and erbium doped fibre amplifiers and lasers in particular. To achieve these objectives the EDF amplifier and laser experiments enable:

- measurement and analysis of small and large signal gain as a function of pump power,
- measurement of gain as a function of signal power and pump power,
- investigation of gain saturation,
- determination of saturated output power as a function of pump power,
- Investigation of amplified spontaneous emission (ASE) and ASE noise. This will include a study of their dependencies on pump and signal power and
- the construction of an EDF laser and investigation of its output characteristic (threshold and slope efficiency) as a function of the output coupling ratio and the intra-cavity loss.
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The equipment for these experiments comprises two units: the EDFA and a Signal Source and Receiver Unit which is used to provide input signal power to the amplifier and to measure the output power. Erbium doped fibre (EDF) is a 3 level optical gain medium providing amplification by stimulated emission at 1550nm when pumped at 980nm. The complete amplifier package including the EDF is of a fairly standard design (see Figure 4) pumped by a 70mW 980nm diode laser via a 980 / 1550nm wavelength division multiplexer (WDM). It is capable of gains in excess of 20dB and saturated output powers in the range of 20-25mW making it useful as a stand alone amplifier in real applications. The pump power, and hence the gain of the amplifier, is varied by adjusting the pump diode bias current. Residual pump power is measured by the monitor photodiode at the redundant arm of the WDM and, with appropriate calibration, the actual pump power is displayed on the front panel in mW. An optical isolator and angle polished connectors eliminate problems with optical feedback and any possibility of oscillation. The WDM at the output of the erbium doped fibre dumps any residual pump power preventing significant levels of potentially eye damaging 980nm radiation from reaching the output connector.

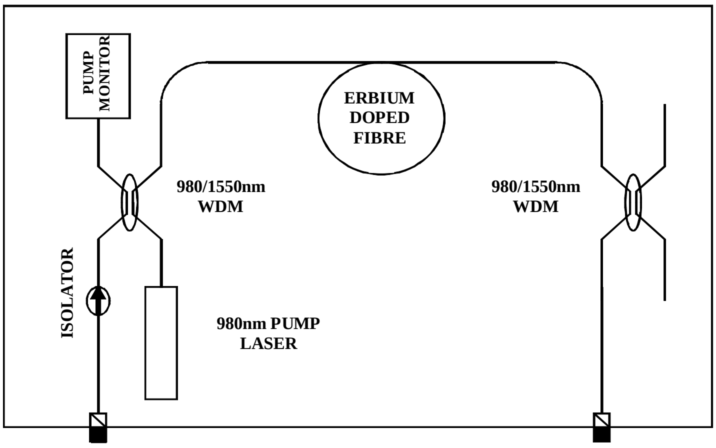

Figure 4: *Schematic diagram of EDFA*

The Signal Source and Receiver Unit is a two part instrument consisting of a Signal Laser module which provides the input signal for the experiments on the EDFA and a Photo-receiver module which measures the powers of the input / output signals used. The signal source is a single frequency DFB laser to eliminate mode partition noise and it may be operated with constant output power or modulated with a 100kHz sinusoid. The signal power delivered to the amplifier input may be varied in a 45dB dynamic range (0dBm[1mW] to -45dBm [30nW] approximately) by adjusting a variable optical fibre attenuator mounted in the source unit. This enables small and large signal gain conditions to be investigated without any change in the wavelength characteristics of the source

The Photo-receiver module uses a standard In GaAs photodiode with a 100kHz lock-in amplifier (LIA) detection scheme which may be engaged or not as required. A signal frequency of 100kHz is significantly greater than the relaxation frequency of the amplifier and hence, the amplified spontaneous emission (ASE) and the population inversion is not modulated significantly in response to the signal. With the LIA engaged, the receiver unit thus measures only the modulated amplified signal power, rejecting the CW amplified spontaneous emission. In Average mode, the total averaged incident power including constant power components such as the ASE contribution is measured. To enable investigation of the signals using an oscilloscope or spectrum analyser the direct signal from the photodiode output is available at the BNC on the front panel. These features provide the flexibility required to measure AC signal power only and separate out constant power levels from the amplified spontaneous emission.

Inserting a fused fibre coupler from the EDFA output back to the input provides the necessary feedback for laser operation with the output emerging from one of the spare arms of the coupler. Two fused fibre couplers (a 20:80 and a 40:60) are used to enable the investigation of 4 possible output coupling ratios. In addition, a fibre optic variable attenuator can be inserted into the feedback loop to allow a study of the effects of intra-cavity loss. All are fitted with angle polished connectors to minimise parasitic feedback and oscillation

A few sample results from the experimental investigations are presented in Appendix C. The erbium doped fibre amplifier is a complex physical system and the principal student benefit from this experiment is to appreciate that a relatively straightforward physical model can provide good insight into the operation and performance limits of a complex entity such as the EDFA or the EDF ring laser. In the student manual a simple plane wave model of a 3 level bulk optical amplifier predicts such features as point of transparency, gain efficiency, signal and pump saturation and ASE based noise contributions and the relationship of the noise and signal outputs to pumping rate, population inversion, upper state lifetime and input power. The students measure these features in the EDFA and are able to relate their results in a relative manner to the model presented. Hence, the experimental investigation reinforces the student understanding of the phenomena which determine the characteristics of EDFAs. Exercises using these results then illustrate the performance of the EDFA as a black box component in the context of a fibre link and the impact of their performance characteristics upon the use of the EDFA in communication networks.

As a continuation to the amplifier investigation the students construct various laser cavities with equipment described above and investigate the laser threshold and slope efficiency as a function of intra-cavity loss and output coupling ratio. A simple model of the output power characteristics of a ring laser(6) is developed in the accompanying notes and the students are able to relate the relative variations in threshold and slope efficiency to the intra-cavity loss, output coupling ratio and gain of the amplifying medium. The experiment thus provides genuine insight into the performance of laser systems as a function of their most important design parameters.

The basic physics of fibre amplifiers and lasers is extremely challenging. Feedback confirms that our students gain considerable satisfaction and confidence from seeing such complex physics in action as an engineering component.

6. OPTICAL NETWORK ANALYSIS

The optical network analysis experiment completes the set within the communications oriented photonics suite. The emphasis here is somewhat different. The previous three experiments examined relationships between basic physics and, eventually, component or system performance. In this experiment the emphasis lies in demonstrating the application and use of technology in the solution of real life measurement requirements. The aim in the network experiment is to indicate how complex multipath optical fibre networks including both branched tree elements (in other words directional couplers) and wavelength selective elements may be characterised and analysed using an optical time domain reflectometer (OTDR) and to indicate how fault finding can be achieved in practice. The experiment is then really concerned with obtaining a characteristic network signature, interpreting the variations in this signature with wavelength in terms of wavelength multiplexed channels and also interpreting changes in one or both of these signatures to locate and characterise network faults. The necessary principles are not so much concerned with optical physics but with the application of effective logical reasoning in data interpretation.

The equipment package for the OTDR / Network investigation comprises a state of the art field OTDR unit with dual wavelength capability (1.3μm & 1.55μm), a 2 km length of fibre and a variety of networks up to 1km long to which the 2km length of fibre may be connected. The networks are all packaged in a single unit and include a point to point link with connectors and splices, a simple branched network with a power splitter (fused fibre coupler) and a WDM network with a 1.3μm single line branch and a 1.55μm branched network containing 2 couplers and 4 branches. This enables the students to begin with the analysis of simple OTDR traces and, as their skills develop, progress to ever more complex networks and traces. Simple analytical tools and procedures are developed in the notes for the analysis of OTDR traces from branched networks, allowing the determination of coupler insertion loss and excess loss and the precise location of line faults to particular network branches and their losses. The students are given the opportunity to characterise these networks at the two operating wavelengths and interpret the OTDR signatures in terms of the network architectures. Artificial faults are then introduced in the network and the students are set the task of locating and characterising the fault.

In this experiment the OTDR is a relatively expensive single item and students are encouraged to take readings on the OTDR and use OTDR simulation software on a regular personal computer to complete the analysis procedures. In this way they the measurements can be made very quickly and many students can be cycled through the measurement procedure within a realistic time scale.

The principal benefit to the students within this experiment lies in exposure to the OTDR processes. The students also gain some insight into the relationship between scattering and attenuation and see clearly the variation in backscatter (and therefore attenuation) and bend loss with wavelength between the 1.3 and 1.55μm lines, neatly illustrated by bend loss being higher and scatter (line) loss being lower at the longer wavelength. Other important features such as the impact of the dead zone and the very large Fresnel reflection from the end of the network on OTDR performance also become evident during the experiment. Most of all though, the experiment does demonstrate that network analysis even for a simple system can be quite a complex issue and that ambiguities in even relatively simple systems must be accommodated. Students also gain some insight into the potential use of software algorithms to characterise faults in highly complex networks including the situations in which ambiguities in interpreting the signatures may arise. Finally, but by no means the least important, they measure and gain a practical appreciation of the characteristics of network components and network configurations.

7. CONCLUSIONS

A suite of laboratory based experimental teaching packages has been developed for modern optics, photonics and optical communications courses. They are suitable for both physics and engineering based courses since they address fundamental physical principles, key technical issues, component and system performance characteristics and design processes (many of which, such as dispersion in optical fibres, hitherto precluded by cost from the teaching environment). In all cases the educational objectives were firstly defined and the necessary custom hardware and experimental procedures were then designed to achieve these objectives. This approach has ensured that all of the key physical principles and their technological implementation in the chosen topics are addressed.

The waveguide and the optical communications systems have been used for over 10 years at Strathclyde University in the third year of an under graduate degree course in Electrical Engineering and in a Masters course in Optical Electronics. The optical amplifier experiments have only been introduced in the past year. The student benefits in all cases have been very substantial. Feedback from the students has been very positive with claims that they have not only enjoyed these laboratory exercises but that they feel they have learned a great deal that is both fundamental and directly useful in the real technical world beyond their studies(7). This is borne out by the quality of their laboratory reports which are among the best in all years at all levels, exhibiting both physical understanding and technological critique – surely the essential aim in the educational process in applied science and engineering.

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APPENDIX A - A SELECTION OF SAMPLE WAVEGUIDE RESULTS

Reflection / refraction experiments

Figure A.1 shows the plot of the measured reflection coefficient as a function of angle for p polarised light incident from the high index side of a glass / air interface ($n_{glass} = 1.45$) compared to that calculated using the Fresnel relationships. The students clearly observe Brewster's angle, the critical angle and total internal reflection. They also measure the Fresnel relationships and compare them to the theory for several other combinations of polarisation and direction of incidence onto the interface.

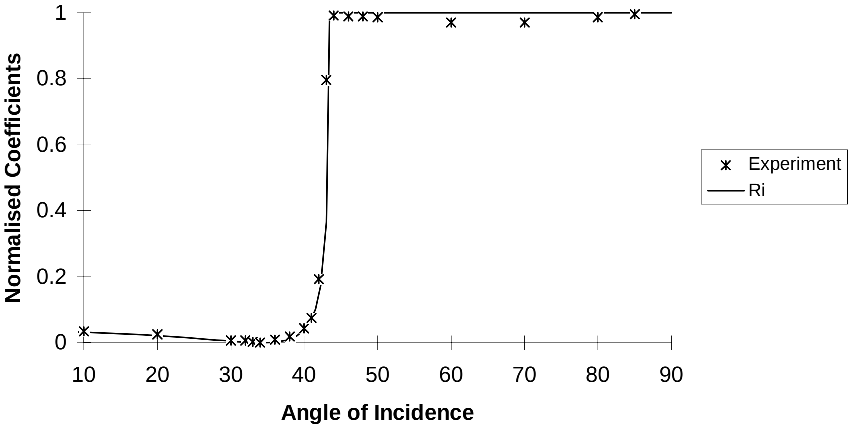


Figure A.1: *Comparison of measured and theoretical values of the Fresnel reflection coefficient at a Hi-Lo interface (horizontal p polarisation).*

Step index waveguide investigation

The principles of optical waveguides are developed in the notes and the necessary waveguide equations are derived. Analysis of the results for the step index planar waveguides is then carried out using the standard step index planar waveguide Eigen value equation. For a planar waveguide of thickness d and refractive index n_2, the mode effective indices, n_e, for each mode of number m are given by the following Eigen value equation$^{(4)}$:

$$\frac{2\pi d(n_2^2 - n_e^2)^{\frac{1}{2}}}{\lambda_o} = m\pi + \Phi_1 + \Phi_3 \tag{A.1}$$

where λ_o is the wavelength of the input light (633nm), m is an integer (m = 0,1,2....) called the mode number and the terms Φ_1 and Φ_3 are the evanescent field phase shifts at the waveguide boundaries with the surrounding material given by

$$\Phi_i = \tan^{-1} \xi \sqrt{\frac{n_e^2 - n_i^2}{n_2^2 - n_e^2}} \tag{A.2}$$

where n_i (i = 1, 3) are the refractive indices (1 & 1.501 respectively) of the surrounding materials and ξ, which depends on the polarisation state of the guided light, is equal to 1 for the TE modes and n_2^2/n_i^2 for the TM modes.

As we reduce the thickness of a waveguide, the modes are successively cut off and cease to be guided. The precise thickness at which a mode is cut-off is referred to as the cut-off thickness, d_c, which can be found by substituting the cut-off condition ($n_e = n_3$) into equation A.1 to give:

$$d_c = \frac{(m\pi + \Phi_1)\lambda_o}{2\pi(n_2^2 - n_3^2)^{1/2}} \tag{A.3}$$

Equation A.3 gives the cut-off thickness of both the TE and the TM modes of an asymmetrical waveguide for which the modes cut-off into the surrounding material of higher refractive index, n_3 (Figure A2). At the precise point of cut-off, the evanescent field phase shift at the n_3 boundary, Φ_3, (see equation A.2) goes to zero leaving only the Φ_1 term in equation A.3. For many applications a single mode waveguide is required. A waveguide supports only a single mode when its thickness is below the cut-off thickness of the m = 1 mode but above that of the m = 0 mode. Equation A.3 can be used to calculate the cut-off thickness of the m = 0 and m = 1 modes for both the TE and TM polarisation states. These values are then used to decide the design thickness to maximise the probability of achieving the required mode operation from a manufacturing process.

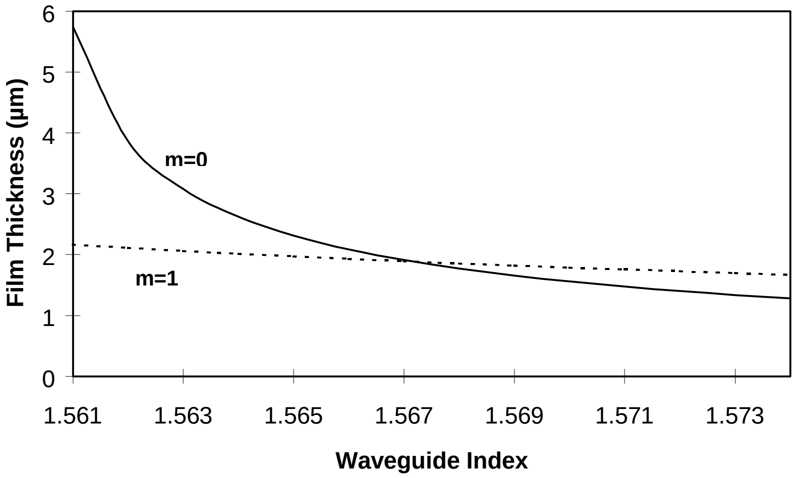


Figure A.2: *Determination of guide index and depth of a step index waveguide (TM polarisation)*

Figure A.3 shows the plots of n_2 versus d calculated by substituting the mode effective indices ($n_e(0) = 1.565$ & $n_e(1) = 1.551$ measured by prism coupling) into equation A1 for two TM polarisation modes of a step index planar waveguide under investigation. The actual thickness and index of the waveguide can be read from the point at which the plots cross as $n_2 = 1.567$ and d = 1.89µm. From the deduced value of n_2, the students may then calculate the cut-off thickness of the m = 1 and m = 0 modes from equation A.3 ($d_c(0) = 315$nm & $d_c(1) = 1017$nm). Hence, the design thickness for a single mode waveguide is about 650nm. Students can also estimate dispersion between these two modes, with effective indices differing by 0.9%.

The students carry out the above procedures for graded index as well step index waveguides of more than one thickness and for both polarisation states using pre-prepared samples. Safety regulations prevented our use of guides fabricated by the students.

APPENDIX B - SAMPLE RESULTS FOR OPTICAL COMMUNICATIONS

Attenuation Limits - Laser Diode:

(i) Connector loss:

In a typical experiment the following measurements were made

P_{in} = Detected power through one fibre patchcord = $1000\ \mu W$
P_{out} = Detected power through two fibre patchcords and the fibre connector = $847 \mu W$
Hence, the connector Loss = $10 \log_{10}(P_{in} / P_{out}) = 0.72\ dB$

(ii) Attenuation coefficient, α

P_{in} = Detected power through 1 metre fibre patchcord = $1000\ \mu W$
P_{out} = Detected power through two fibre patchcords, two fibre connectors and a 1km fibre reel = $245\ \mu W$
Attenuation over system = $10 \log_{10}(P_{in} / P_{out}) = 6.1\ dB$
Losses due to the two fibre connectors = $1.44\ dB$
Therefore, the fibre attenuation over the 1km link length = $6.1 - 1.44 = 4.7\ dB$, so $\alpha = 4.7 dB/km$

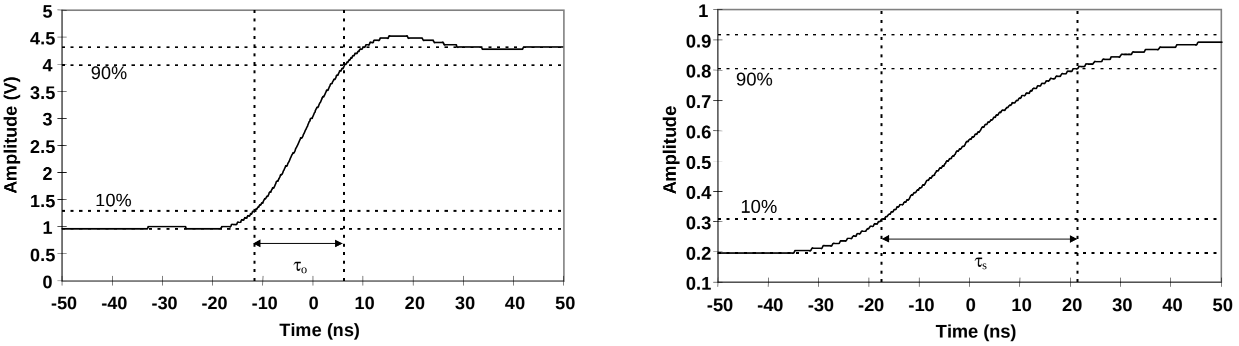
The attenuation limited link length, L_{max}, is then given by:

$$\alpha L_{max} = 10 \log_{10} [P_{in}/P_{min}]$$

where P_{in} is the launched power and P_{min} is the received power which produces a signal to noise ratio of 12. In a typical investigation P_{in} and P_{min} were determined to be 1 mW and 17µW giving L_{max} = 3.8km

Dispersion limits - laser diode

Figure B.1(a) shows the step function response of the laser diode transmitter and receiver system (connected by a short patchcord). The 10% to 90% risetime of the square wave modulation signal (τ_o) is 18 ns.



(a) **(b)**

Figure B.1: *Rise time of (a) laser / receiver system and (b) laser, fibre link and receiver system*

The risetime of the complete system (τ_s), including the 1 km length of fibre, is displayed in Figure B.1(b) and is determined to be τ_s = 38 ns. Thus the fibre risetime (τ_F) is deduced to be

$$\tau_F = \sqrt{(\tau_s^2 - \tau_o^2)} = \sqrt{\left(38^2 - 18^2\right)} = 33.47 \text{ ns}$$

Given that the fibre impulse response is the derivative of the step response and the frequency response is the Fourier transform of the impulse response(5) we can derive the following relationships:

$$BW = \frac{0.48}{\tau_F} = \frac{0.187}{\tau_R} \qquad \text{and so} \qquad \tau_R = 0.39\ \tau_F$$

where BW is the 3dB analogue signal bandwidth and τ_R is the rms pulse width of a Gaussian output pulse arising from a launched impulse. Using this relationship and the measured fibre step function response, τ_F, we can deduce that the analogue bandwidth of the fibre is 14.34 MHz and that a launched impulse will spread to have an rms width of τ_R = 13.05 ns. The fibre link length here was 1.2km.

Given that the maximum level of pulse spreading which is tolerable in a receiver is 0.25 times the bit period(6) i.e. $\tau_R = 0.25/BR$ (BR = the bit rate), then the maximum bit rate is $BR_{max} = 0.25/13.05 \times 10^{-9} = 19.15$ Mbit/sec.

The above process is repeated for the LED. Due to the much narrower linewidth of the laser the dispersion effects are dominated by intermodal dispersion, whereas for the LED the relative contribution of material dispersion is significant and is clearly observed. By appropriate analysis of the laser and LED responses the material and intermodal dispersion coefficients of the fibre may be determined.

APPENDIX C - SAMPLE RESULTS FOR THE EDF AMPLIFIER AND LASER EXPERIMENTS

In the accompanying notes we develop a plane wave model of an optical amplifier(6) with a three level gain medium arriving at an expression for the small signal gain, $G_0(\nu)$, of an amplifier of length *l*

$$G_0(\nu) = \exp[\gamma_0(\nu)l] \tag{C.1}$$

where $\gamma_0(\nu)$ is the small signal gain coefficient.

It is customary to express the gain of an amplifier in dB and from equation C.1 we get:

$$Gain(dB) = 10\log_{10} G_0(\nu) = 10\log_{10} e^{\gamma l} = 4.34\gamma l \tag{C.2}$$

As we increase the pump power the population of the upper gain state increases linearly as does the population inversion and the gain coefficient. At very low pump powers the population inversion is insufficient to provide gain and the signal is attenuated (by an amount depending on the population of the lower gain state). As the pump power, the population inversion and stimulated emission increase, the attenuation decreases and the system becomes transparent. Beyond the point of transparency (gain = 0dB), the gain (in dB) increases linearly with γ and hence with pump power.

It must be noted that the above model only applies for small input signals under weak pumping conditions for which we can assume insignificant depletion of the ground state. From a detailed analysis(6) of a 3 level gain medium, such as erbium doped glass, in which weak signals and weak pumping are not assumed we get an expression for the gain coefficient, $\gamma(\nu)$ at a signal intensity level of I_ν, as follows:

$$\gamma(\nu) = \frac{1}{I_\nu} \cdot \frac{dI_\nu}{dz} = \frac{(I_p^* - 1)\sigma_{SE} N_t}{1 + 2I_\nu^* + I_p^*} \tag{C.3}$$

where N_t is the atomic density of the medium, σ_{SE} is the stimulated emission cross-section, $I_\nu^* = I_\nu / I_s$ and $I_p^* = I_p / I_{ps}$ (I_{ps} and I_s are constants referred to as the saturation pump intensity and saturation signal intensity respectively).

For a fixed pump power, equation C.3 indicates that, as the signal intensity increases, the term $2I_\nu^*$ in the denominator increases and the gain falls off as the system experiences the phenomenon referred to as gain saturation, resulting from significant depletion of the upper gain state population by the high rate of stimulated emission. The saturated output power of the amplifier is that for which the gain has fallen by 3dB with respect to the small signal gain. In addition, for a fixed input signal intensity, equation C.3 indicates that the gain coefficient and hence the overall gain in dB (see equation C.2) initially increases linearly with pump intensity, I_p, but then flattens out as I_p approaches and exceeds I_{ps}, increasing I_p^* in the denominator. Intuitively such behaviour is expected (and observed experimentally, see results discussed below) since a large pump power will result in severe depletion of the ground state leading to reduced absorption and pumping rate. This phenomenon, referred to as pump saturation, prevails in all operating 3 level systems where the lower gain state is the ground state which by definition must be at least 50% depleted simply to obtain a population inversion. It is also evident in 4 level systems under strong pumping conditions.

By varying the current to the pump laser and the level of in-line attenuation at the signal laser output the students study the gain characteristics of the EDFA as a function of pump power and input signal power. Figure C.1 shows sample results for the variation of gain with input signal power at several levels of pump power. The students can clearly see and report on the effects of gain saturation as the signal level becomes large enough to significantly deplete the population inversion and the amplifier gain falls off in accordance with equation C.3. Figure C.2 shows the variation of gain with pump power at several levels of signal input power. Here the students can clearly observe and report that initially the gain (in dB) increases linearly with pump power until the effects of pump saturation become evident as the high level of pump light significantly depletes the population of the ground state. They can also determine the point at which the amplifier is transparent (i.e. gain =1), the gain gradient and gain efficiency (see Figure C.2). In addition, they carry out exercises on saturated output and input power which can be measured from these curves and relate their findings to the conceptual understanding gained from the model presented in the notes and briefly annotated above.

Noise associated with amplified spontaneous emission (ASE) is the limiting factor in determining the ultimate signal to noise ratio in any system using optical amplifiers. Figure C.3 shows the variation of the level of ASE with increasing signal power at several levels of pump power. ASE is responsible for degradation of the signal to noise ratio in systems using optical amplifiers by contributing ASE-ASE beat noise and Signal ASE beat noise. In Figure C.3 the students can clearly see that the ASE levels fall dramatically the input signal level increases into the gain saturation region and the population inversion of the amplifier falls with a corresponding decrease in spontaneous emission and gain. Further studies also show the decrease in optical noise levels such as signal-ASE beat noise as we go into the region of signal saturation. Again a simple model of the ASE generation enables the students to relate their findings on ASE level changes and optical noise variations to the basic physical processes of the gain medium. Further exercises also illustrate the impact of noise and the amplifier operating conditions on the performance of optical communications systems.

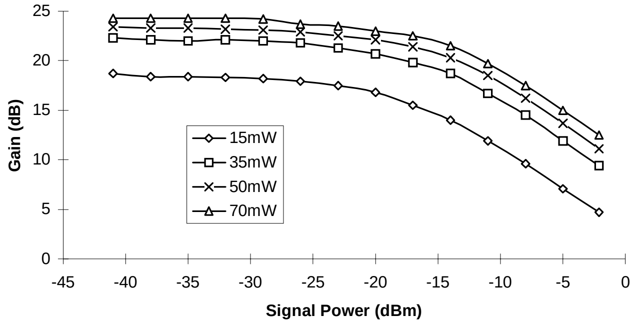


Figure C.1: *Gain versus signal power for various pump powers*

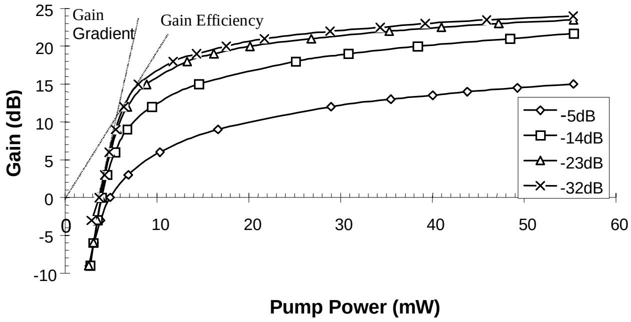


Figure C.2: *Gain versus pump power for several input signal levels**(Gain Gradient=5.56dB/mW , Gain Efficiency=2dB/mW)***

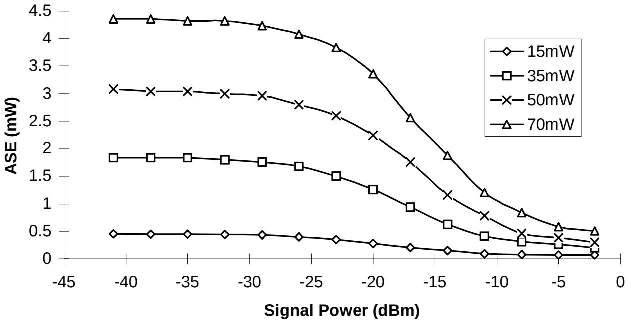


Figure C.3: *ASE power versus signal power for several values of pump power*

Following a full characterisation of the amplifier including a complete study of the gain and noise characteristics, the students use the fused fibre feedback couplers to construct an erbium doped fibre ring laser. They then measure the output power characteristics as a function of the output coupling ratio and the intra-cavity loss. Figure C.4 shows one example of the variation in threshold and slope efficiency with output coupling ratio for an internal loss of 13dB. Clearly the threshold and the slope efficiency increases with output coupling ratio. A simple model of a 3 level ring laser is developed in the accompanying notes resulting in an expression for the output power, P_o, as a function of the small signal gain coefficient, with intra-cavity loss (L_i) and output coupling ratio (T_o) as variables:

$$P_0 = \frac{T_o P_s \gamma_o(\nu) l}{1-L_i(1-T_o)} + \frac{\ln[L_i(1-T_o)]T_0 P_s}{1-L_i(1-T_o)} \tag{C.4}$$

where P_S is the saturation power.

Since $\gamma_o(\nu).l$ is proportional to the pump power, P_p, and letting C be the proportionality constant we can write the output power in terms of the pump power as:

$$P_0 = \left(\frac{T_o P_s C}{1-L_i(1-T_o)}\right).P_p + \frac{\ln[L_i(1-T_o)]T_0 P_s}{1-L_i(1-T_o)} \tag{C.5}$$

This is the equation of a straight line intersecting the pump power axis at the laser threshold point determined by the intra-cavity loss, L_i, the output coupling ratio, T_0 and the saturation power, P_s. The threshold is the point at which the pump power provides a small signal gain which exactly offsets the total intrinsic loss around the cavity, $L_i(1-T_0)$. The gradient of the line, known as the slope efficiency (SE) of the laser is given by:

$$SE = \frac{T_0 P_s C}{1 - L_i (1 - T_0)} \tag{C.6}$$

Since the EDF laser is identical in principle to that analysed above all of the equations presented here apply. Comparing their measurements with theory the students observe that the relative variations of threshold and slope efficiency with L_o and T_o agree well with equations C.5 and C.6.

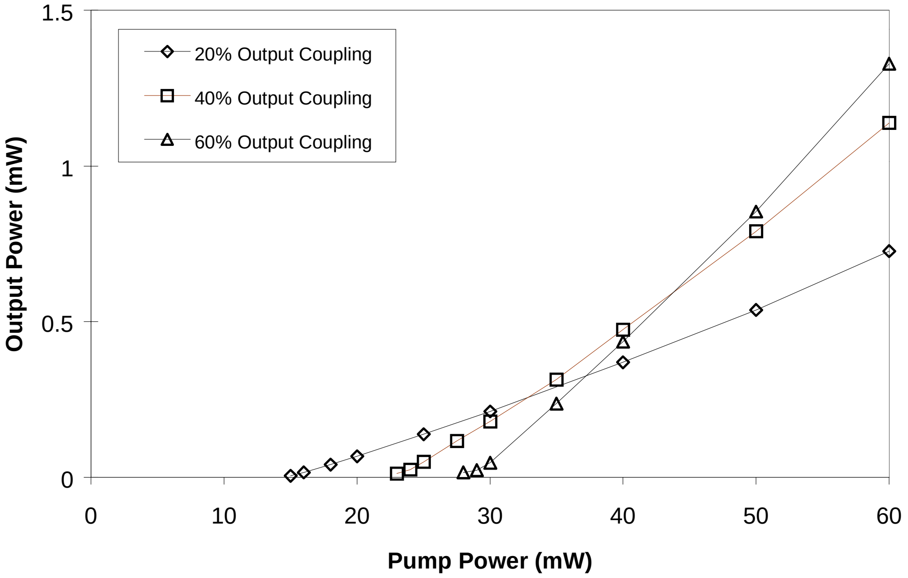


Figure C.4: *Output power vs. pump power for the various output coupling ratios at –13dB intra-cavity loss*