Optoelectronic laboratory experiments for modern technology based courses

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ABSTRACT

To satisfy the growing skilled manpower demands of the modern optoelectronics industry, Strathclyde University in collaboration with OptoSci Ltd have developed a range of optoelectronic laboratory experiments to provide the hands on practical training required by engineers and scientists who will be involved in the design, installation and operation of optoelectronic systems. The hardware and experimental procedures developed so far enable students and trainees to investigate the basic principles, characteristics and design of optical waveguides, optical communications systems, fault location techniques for optical networks and optical amplifiers. The experiments have been designed with the constraints of academic teaching budgets firmly in mind but still enable 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 design philosophies, hardware and experiments are examined in this paper.

Keywords: Optoelectronic educator kits, optical communications, waveguides, optical networks, optoelectronics experiments

1. INTRODUCTION

Optical fibre links now dominate the world's major trunk telecommunications systems and are penetrating ever deeper into the access and local area networks. In addition, optoelectronics is having an ever increasing affect on our daily lives through a myriad of industrial and consumer applications. Consequently there is a rapidly growing demand for scientists, engineers and technicians who can design, install and operate optoelectonic components and systems. In response to this demand Colleges and Universities throughout the World are introducing appropriate courses in optoelectronics and optical communications at graduate and post graduate level. Such courses need to be supported by practical laboratory programmes to provide the students with valuable hands on experience of optoelectronic components and systems.

Despite the obvious need, highlighted above, very little is commercially available in the way of dedicated hardware for optoelectronics teaching packages, and what is available tends to demonstrate features of the technology rather than enable students to investigate important physical principles or key technical issues. In many instances, both within academic institutions and within the potential commercial suppliers, the general approach taken is to design student experiments around existing optoelectronic hardware, probably originally conceived for research or industrial markets. The result of this approach is that the educational objectives and issues addressed in the ensuing laboratory experiments are dictated by the available equipment. Often, therefore, the demonstration or investigation of certain key technical issues and principles are excluded, implying that desirable educational objectives are not realised. It is essential to have a fully integrated approach to the design of laboratory based optoelectronics education packages including the design of dedicated hardware, experimental procedures exercises and manuals.

Strathclyde University in collaboration with OptoSci Ltd. have developed a suite of fully integrated laboratory based optoelectronics teaching packages in accordance with the following design philosophy:

- Define the educational objectives in terms of the physical principles, key technical features, design issues and performance characteristics which must be addressed.
- Define the experiments to meet the objectives.
- Design the dedicated (custom) hardware to enable the proposed experimental investigation.
- 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.

Of course, in practice, the design process does not exactly follow the above approach in a step by step manner and there is much iteration between steps in order to achieve the educational objectives within the constraints imposed by the academic environment. 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 as possible of ancillary equipment 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.

A number of packages are fully developed on the basis of the above approach covering the following topics: Principles of Optical Waveguides, Fibre Optic Communications, Optical Network Analysis and Principles of Fibre Amplifiers. In addition, development is in progress on packages addressing the Principals of Lasers, Basic Optics (polarisation, reflection , refraction, diffraction, interference and coherence), optical instrumentation and optical metrology. Here, we present outline descriptions of the educational objectives, the hardware and the experiments covered by the four packages developed to date.

OPTICAL WAVEGUIDES

The overall objectives of the Optical Waveguides package are to enable students to experimentally investigate and gain practical familiarisation with:

- the principles of refraction, reflection and total internal reflection.
- the principles of optical waveguiding 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.
- elementary waveguide analytical techniques.
- basic waveguide design processes including concepts of mode cut-off and the design of single mode waveguides.

The apparatus (Fig 1) 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 (Fig 1) which is used to address a selection of step and graded index planar waveguides of various thickness.

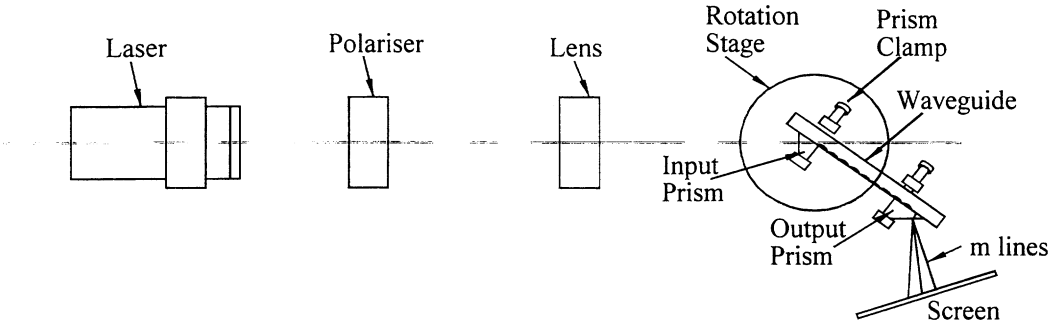

Figure 1: *Top view of prism coupling system.*

To meet the educational objectives stated above the students carry out the following investigation:

- Measurement 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 (comparisons are carried out with theory).
- Establishment of prism coupling to selective waveguide modes and observation of 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 the waveguide parameters (index profiles and thicknesses) from the mode effective indices.
- 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 certain aspects of this investigation are given in Appendix A

OPTICAL COMMUNICATIONS

The objectives of the Optical Communications experiments are to enable students to experimentally investigate and acquire a practical familiarisation with:

- The key 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 key 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 an LED transmitter, a laser transmitter and a receiver. 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 for investigation of 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 attenuations 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. 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.

The system described above has been greatly simplified relative to a state of the art system in order to achieve a realistic cost which is compatible with academic budgets and to ensure that measurements of attenuation and dispersion can be made using standard student laboratory support equipment. We beleive 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 enable 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.

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.

OPTICAL NETWORK ANALYSIS

The main objectives of the network analysis laboratory exercises are the investigation and practical familiarisation with:

- Network configurations
  - point to point, branched and WDM networks
- The principles and characteristics of network components
  - connectors, splices, couplers and WDMs
- The use of an optical time domain reflectometer (OTDR) - trace acquisition and manipulation
- OTDR trace analysis, feature identification and component / fibre loss assessment
- Fault identification and location.

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 have been developed for the analysis of OTDR traces from branched networks, allowing the determination of coupler insertion loss, excess losses and the precise location of line faults to particular network branches and their losses. Finally, a set of OTDR traces of networks with deliberately introduced faults is provided to allow the students to develop fault identification and location skill on the basis of the principles learned during the laboratory investigation.

The students carry out the following investigation in four stages to build up skills and knowledge towards the analysis of complex networks:

Stage 1. OTDR trace acquisition and analysis for point to point links at both 1.3μm and 1.55μm

- OTDR operation and functions
  - trace acquisition, cursor controls and zoom functions
- Identification of trace features and loss events: dead zones, Fresnel reflections, loss events and ghost reflections

- Measurement of distances and losses at events (splices, connectors, faults etc.)
- Measurement of the fibre attenuation coefficients and its wavelength sensitivity (1.3μm & 1.55μm).
- Measurement of bend losses and their wavelength sensitivity (1.3μm & 1.55μm).

Stage 2. Branched networks with fibre couplers - Coupler loss analysis

- Measurement and interpretation of losses across a fused fibre coupler event.
- Estimation of the coupler insertion and excess losses from the OTDR trace loss measurements (given knowledge of the coupling ratio, K).
- Estimation of the coupling ratio, K, from the loss measurements.
- Determination of the wavelength sensitivity of K (1.3μm & 1.55μm).

Stage 3. WDM networks with multiple fibre coupler branches

- Trace acquisition and investigation of the 1.3μm & 1.55μm branches of a WDM network.
- Measurement of WDM insertion loss and isolation.
- Detailed investigation of the 1.55μm branch beyond the WDM with analysis of coupler losses.

Stage 4. Fault location and identification

- Identification of line faults and determination of their losses.
- Identification and loss analysis of faults at couplers and WDMs - coupler degradation or splice degradation and which splice.
- Identification, location (distance and which branch?) and loss analysis of line faults in particular branches of a multi branch network.

OPTICAL FIBRE AMPLIFIERS

The optical fibre amplifier teaching package is not yet fully developed. The projected objectives are to enable students to investigate and become practically familiar with the principles and characteristics of erbium doped fibre amplifiers. To achieve this objective the development of an experimental kit is near completion to 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,
- investigation of gain saturation,
- determination of saturated output power as a function of pump power and
- investigation of amplified spontaneous emission (ASE) and ASE noise. This will include a study of their dependencies on pump and signal power.

CONCLUSIONS

A suite of laboratory based experimental teaching packages has been developed for modern optics, optoelectronics and optical communications courses. We believe that 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 as far as possible that all of the key principles and technical issues associated with the chosen topics are addressed.

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 ($n_{glass} = 1.52$) 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.

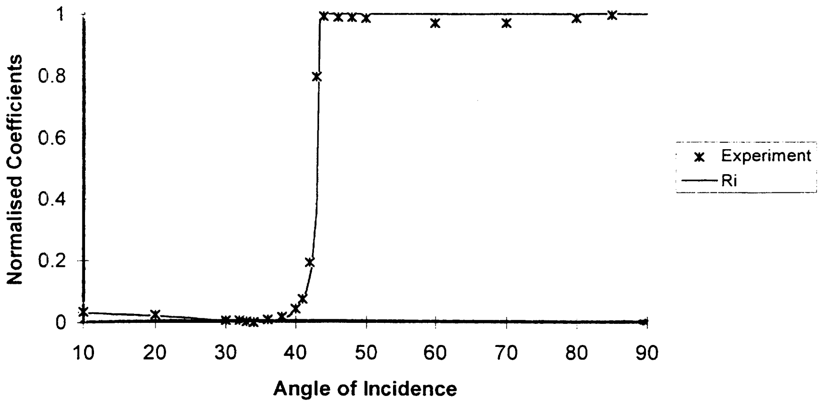

Figure A.1: Comparison of measured and theoretical values of the Fresnel reflection coefficient at a Hi-Lo interface (horizontal p polarisation).

Step index waveguide investigation

Analysis of the results for the step index planar waveguides is carried out using the standard step index planar waveguide eigenvalue 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:

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

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

$$\Phi_i = \tan^{-1} \xi\sqrt{\frac{n_e^2 - n_i^2}{n_2^2 - n_e^2}} \qquad \text{(A.2)}$$

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.2 to give:

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

Equation A.3 gives the cut-off thicknesses 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. 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 thicknesses 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.

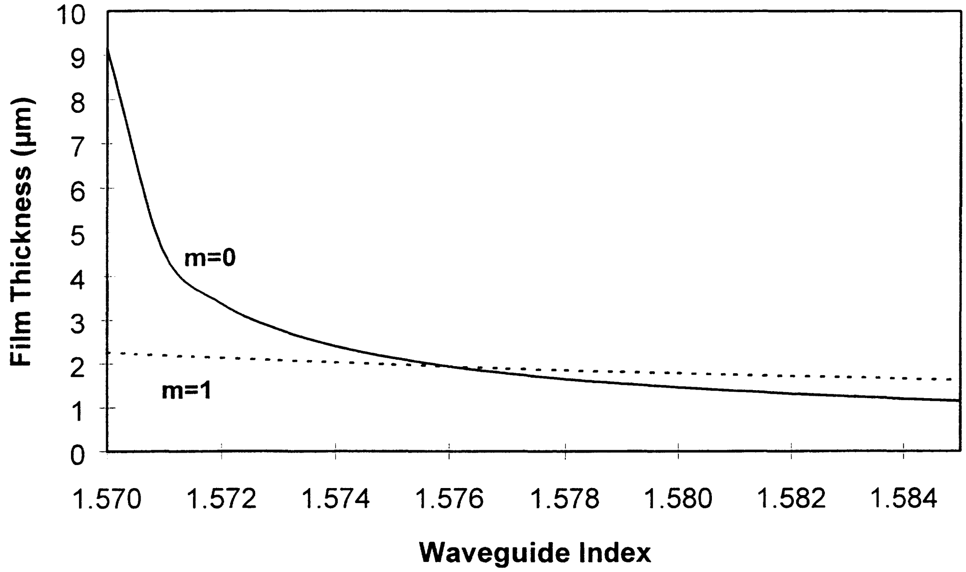

Figure A.2: Determination of guide index and depth of a step index waveguide (TM polarisation).

Figre A.2 shows the plots of n_2 versus d calculated by substituting the mode effective indices (n_e(o) = 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 = 1.576 and d = 1.89µm. From the deduced value of n_2, the students may then calculate the cut-off thicknesses of the m = 1 and m = 0 modes from equation A.3 (d_c(0) = 315nm & d_c(1) = 1017nm). Hence, the design thickness for a single mode waveguide is about 650nm.

The students carry out the above procedures for graded index as well step index wavegudes of more than one thickness and for both polarisation states.

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 μW*
P_{out} = Detected power through two fibre patchcords and the fibre connector = *847μW*
Hence, the connector Loss = $10\ log_{10}(P_{out}/P_{in}) = -0.72\ dB$

(ii) Attenuation coefficient, α

P_{in} = Detected power through 1 metre fibre patchcord = *1000 μW*
P_{out} = Detected power through two fibre patchcords, two fibre connectors and a 1km fibre reel = *245 μW*
Attenuation over system = $10\ log_{10}(P_{out}/P_{in}) = -6.1\ dB$
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 & α = 4.7dB/km*

The attenuation limited link length, L_{max}, is then given by:
Fibre loss = $\alpha L_{max} = 10 \log_{10} [P_{min}/P_{in}]$
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.1a 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.

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

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

Given that the the fibre impulse response is the derivative of the step response and the frequency response is the Fourier transform of the impulse response 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 widthof 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

Given that the maximum level of pulse spreading which is tolerable in a receiver is 0.25 x the bit period i.e. 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 laser may be determined.

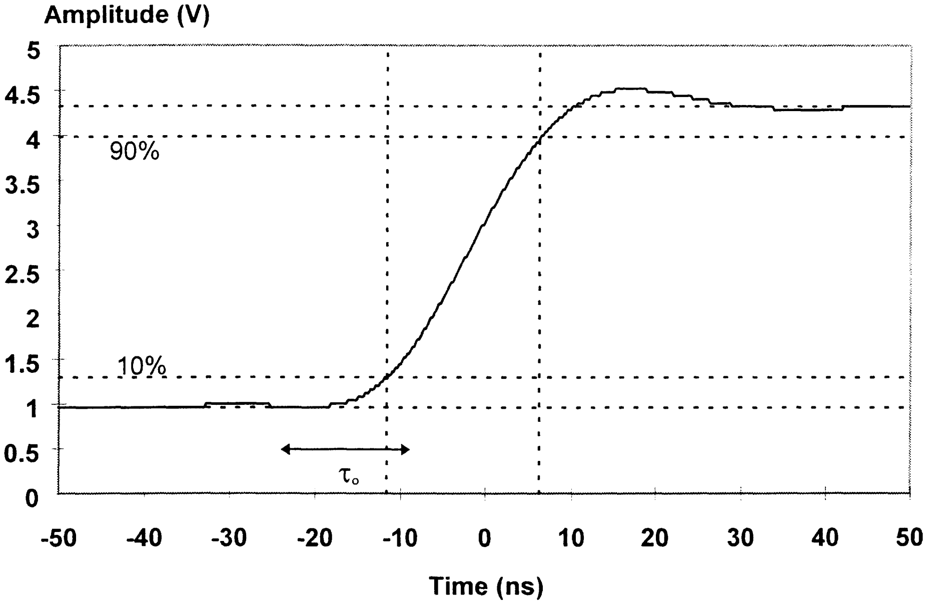

Figure B.1(a): Rise time of laser / receiver system

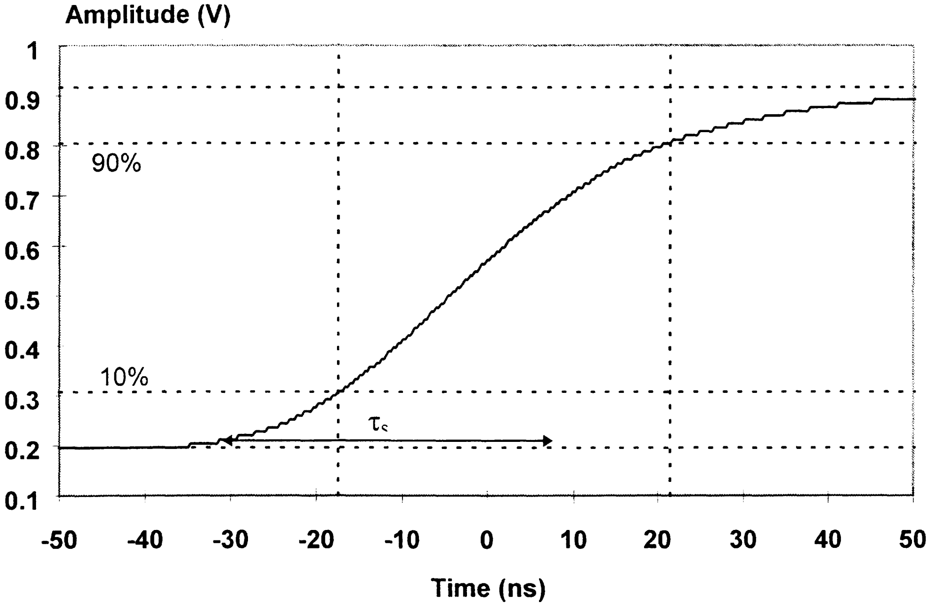

Figure B.1(b): Rise time of laser, fibre link and receiver system