Photonics laboratory teaching experiments for scientists and engineers

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ABSTRACT

In response to industry's need for scientists and engineers skilled in the design, manufacture and operation of photonics systems, Strathclyde University and OptoSci Ltd. have developed a suite of Photonics Educator Kits, which enable students to experimentally investigate all of the major technical features, principles and design issues of optical waveguides, optical communications systems, erbium doped fiber amplifiers and lasers. To support these applications experiments we have recently added a range of kits enabling students to experimentally investigate the basics of physical optics covering reflection, refraction, polarisation, diffraction, coherence and interference. In this paper, we will describe the educational objectives and the design philosophies behind the development of these kits. To illustrate these, full details of the experimental procedures, the results and the benefits to the student will be discussed for the recently upgraded optical communications kit and the erbium doped fiber amplifier (EDFA) system, in particular addressing the crucially important noise characteristics of optical amplifiers.

1. INTRODUCTION

Modern Optics and Photonics currently drive major technical advancement in such a diversity of technologies as telecommunications, measurement science, industrial and environmental sensing, medical diagnostics and bio-sciences. In particular, the world's main trunk telecommunications systems, the global internet and mobile phone communications systems are all founded on Photonics networks. Companies operating in these fields have an ever increasing demand for highly skilled scientists and engineers who can design, build, analyse, install and operate photonic systems. There is no doubt that the learning experience of these professional technologists is greatly enhanced during their graduate or under-graduate studies by exposure to hands on, practical experience of photonics components and systems. Strathclyde University, in collaboration with OptoSci Ltd., have developed a suite of Photonics Educator Kits which enable students to experimentally investigate all of the major technical features, principles and design issues of optical waveguides, optical communications systems, erbium doped fiber amplifiers and lasers. These applications kits are now supported by a range of experiments examining the fundamentals of physical optics, covering reflection, refraction, polarisation, diffraction, coherence and interference. In the development of all of these systems we adhere to a strict design philosophy and procedure, which ensures that all of the important educational objectives are met.

A working knowledge and understanding of the components of a fiber optic communications system and the limits imposed on the system performance by the component characteristics are invaluable for any student going on to work with photonic systems. Hence, two of the most important kits address optical communications systems and their component parts including optical amplifiers. Details of a previous version of the optical communications system kit and some aspects of the EDFA kit have been reported in the past[1,2]. Recently, we have upgraded the communications kit to use 62.5/125μm graded index fiber (replacing the multi mode step index fiber). This enables the students to more clearly explore the separate effects of material and modal dispersion and their effects on the system performance. The most important characteristic of optical amplifiers as regards the limitations they impose on system performance is noise. Recent adaptations to the EDFA kit enable students to investigate the noise characteristics of the amplifier and simple exercises based on their noise measurements allow them to appreciate the effects of amplifier noise on the overall system performance. Here we describe these two kits in detail covering educational objectives, design philosophies, the hardware involved, the experimental procedures followed by students and sample results. For the EDFA kit we will concentrate on the noise characteristics as the gain characteristics have been addressed in previous publications[1,2].

2. DESIGN PHILOSOPHY

The overall educational aims of experimental exercises in photonics 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 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.

3. OPTICAL FIBER COMMUNICATIONS SYSTEM

3.1 Description of experimental system

Optical fiber 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. An optical fiber transmission system (Figure 1), comprising a semi-conductor laser diode or LED transmitter, an optical fiber (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. The objectives of the Optical Communications experiments are to enable students to build upon their knowledge and conceptual understanding of optical fiber communications systems by experimentally investigating:

- The main characteristics of the major components of a fiber optic communications system i.e. the source / transmitter, the fiber 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 fiber 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 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 and two long length of fiber (1km and 2km) terminates by ST connectors are provided to make up various links. The selected wavelengths are in the 800nm region and the fiber is

62.5/125μm graded index with a non ideal index profile. 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. 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 rise time 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.
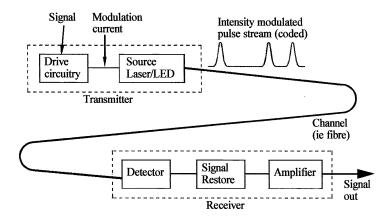

Figure 1: Schematic of a point to point fiber optic communications link.

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 fiber 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 fiber using both the laser and the LED. This enables the determination of -
    - the fiber 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 fiber, leading to determination of:
    - the analogue bandwidth and bandwidth . distance products of the fiber 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.

3.2 Sample results and analysis

Attenuation and dispersion, the two primary signal degradation mechanisms in optical fibers, define the system limitations in terms of maximum link length and operating bit rate[3]. The attenuation (in dB) is given by:

$$Attenuation(dB) = 10Log_{10}\frac{P_{out}}{P_{in}} = \alpha L \qquad (1)$$

where P_{in} and P_{out} are the input and output power of the link, α is the attenuation coefficient in dB/km and L is the length in km. Given that we can determine the receiver sensitivity from the receiver noise and the signal to noise ratio (SNR) required, we can find the attenuation limited link length if α is known.

In multi-mode fiber, both modal dispersion and intra-modal dispersion contribute to pulse spreading. For intra-modal dispersion acting alone, the root mean square width of the Gaussian output pulse, τ_1, arising from a launched impulse is given by:

$$\tau_1 = D_{im} \times \Delta\lambda \times L \qquad (2)$$

where D_{im} is the intra-modal dispersion coefficient and $\Delta\lambda$ is the wavelength linewidth of the transmitter source. For modal dispersion we have:

$$\tau_2 = D_m \times L \qquad (3)$$

where D_m is the modal dispersion coefficient.

The total rms pulse width, τ_R, at the output (i.e. the impulse response of the system) is then

$$\tau_R = \sqrt{(\tau_1^2 + \tau_2^2)} \qquad (4)$$

Rather than measure the impulse response, it is often more convenient to measure either the frequency or step function response and to calculate the impulse response from well defined relationships. In the step response measurement the optical source is modulated by a square wave with a sharply rising edge and the 10-90% rise time, τ_0, of the transmitter / receiver combination is measured by inspection of the oscilloscope trace of the signal received via a short length of fiber. The measurement is repeated with the fiber reel connecting the transmitter to the receiver to obtain the 10-90% rise time, τ_s, of the entire system - the transmitter, receiver and the fiber. The 10-90% rise time of the fiber, τ_F, may then be obtained from the following relationship

$$\tau_F = \sqrt{\left(\tau_s^2 - \tau_o^2\right)} \qquad (5)$$

A given length of fiber may be uniquely characterised by measuring either its frequency response, its step response or its impulse response. The impulse response is the derivative of the step response and the frequency response is simply the Fourier transform of the impulse response. On this basis we can derive simple approximate expressions which relate the 3dB optical bandwidth to the 10-90% rise time, τ_F, and the output rms pulse width, τ_R, arising from a launched impulse as follows:

$$BW = \frac{0.48}{\tau_F} = \frac{0.187}{\tau_R} \qquad (6)$$

So

$$\tau_R = 0.39 \, \tau_F \qquad (7)$$

The Bandwidth Length Product (BWL) for the fiber is then simply BW × L.

In digital systems it can be shown that if the rms widths of Gaussian received pulses exceed 0.25T (where T is the bit period), then the power penalty necessary to maintain a bit error rate of 10^{-9} becomes intolerable. This imposes an upper limit on the amount of allowed pulse spreading relative to the bit period and hence the upper limit on the bit rate for a given link length (and vice versa) is defined by:

$$BR = \frac{1}{T} = \frac{0.25}{\tau_R} \qquad (8)$$

The bit rate distance product is then simply BR × L.

Attenuation limits
(i) Connector loss:
In a typical experiment the following measurements were made:

P_{in} = Detected power through one fiber patch cord = 1000 µW
P_{out} = Detected power through two fiber patch cords and the fiber connector = 945µW
Hence, the connector Loss = 10 $\log_{10}(P_{in} / P_{out})$ = 0.25 dB

(ii) Attenuation coefficient, α:
Using the 790nm laser transmitter:
P_{in} = Detected power through 1 metre fiber patch cord = 1000 µW
P_{out} = Detected power through a fiber reel = 352 µW
Attenuation over system = 10 $\log_{10}(P_{in} / P_{out})$ = 4.53 dB

Using a phase delay technique the fiber reel length was measured as 1122m, so α = 4.0dB/km.

Similar measurements using the 850nm LED transmitter yielded an attenuation coefficient of 3.0dB/km. The difference in the measured coefficients is exactly attributed to the difference in wavelength with greater scattering loss for the laser light at the shorter wavelength.

The attenuation limited link length, L_{max}, is then given by:
$\qquad \alpha L_{max} = 10 \log_{10} [P_{in}/P_{min}]$
where P_{in} is the launched power and P_{min}, obtained from a direct measurement of noise, is the receiver sensitivity for a bit error rate of 10^{-9} i.e. the received power which produces a signal to noise ratio of 12. In a typical investigation using the laser, P_{in} and P_{min} were determined to be 1 mW and 5 µW giving L_{max} = 23/4.0 = 5.75km. For the LED, the equivalent measurements were 415µW and 5 µW, giving L_{max} = 19.2/3 = 6.3km.

Dispersion limits

Figure 2 shows the step responses for the LED transmitter and receiver connected by a short patch cord, τ_0, [Figure 2(a)] and for the complete system with the 2.23km fiber reel, τ_s [Figure 2(b)].

The 10–90% rise times, τ_0 and τ_s, were determined to be 7.5ns and 16.5ns respectively. Thus, using equation (5), the fiber rise time, τ_F, is 14.7ns, the optical bandwidth from equation (6) is 32.7MHz and the BW.L product is 72.7 MHz.km

Given τ_F = 14.7ns, the root mean squared pulse width, τ_R , arising at the output from a launched impulse is 5.73 ns [equation (7)]. Hence, the maximum operating bit rate of the 2.23km link is 43.8Mbit/s [equation (8)] and the bit rate distance product is 97Mbit/s.km.

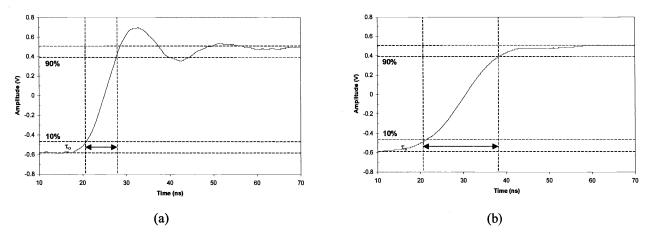(a)   (b)

Figure 2. Rise time of (a) LED / receiver system, and (b) LED, 2.23km fiber reel and receiver system

Figure 3 shows the step responses for the Laser transmitter and receiver connected by a short patch cord, τ_0, [Figure 3(a)] and for the complete system with the 3.46km fiber link, τ_s [Figure 3(b)]. The 10–90% rise times, τ_0 and τ_s, were determined to be 7.5ns and 10.25ns respectively. Applying the same analysis as above, we obtain a fiber rise time, τ_F, of 6.98ns, giving a bandwidth of 68.7MHz and a bandwidth-distance product of 230MHz.km. As above, the root mean squared pulse width, τ_R, arising at the output from a launched impulse is 2.72 ns [given by equation (7)] and hence the maximum operating bit rate from equation (8) is 91.8 Mbit/s with a bit rate-distance product of 307 Mbit/s.km.
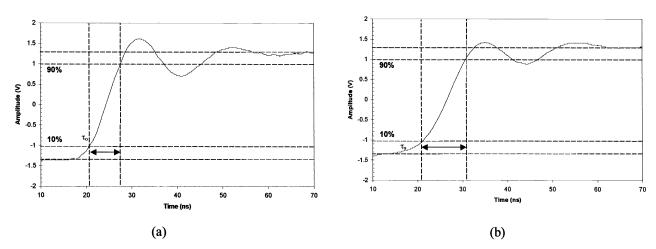

(a)   (b)

Figure3: Rise time of (a) the laser / receiver system, and (b) the laser, the 3.46km fiber link and the receiver.

Within a graded index multimode fiber the principal dispersive contributions arise from intra-modal (material) and modal dispersion. Since the Laser Diode source has a very narrow linewidth (1nm) compared to that of the LED source (30nm) we can assume that the light launched from the Laser source experiences negligible intra-modal dispersion relative to modal dispersion. Therefore, the r.m.s pulse width measured when using the Laser Diode source (2.72 ns) can be assumed to arise only from modal dispersion. In contrast the total rms pulse width measured with the LED source along the same fiber link (8.48 ns) contains a significant contribution from intra-modal dispersion. Using equation 4, we can determine the intramodal dispersion parameter for the fiber. Therefore, from the analysis above we have $\tau_2 = 2.72$ ns, and $\tau_F = 8.48$ns, so $\tau_1 = 8.03$ns [from equation (4)]. Applying equation 2, D_{im} was found to be 80ps/km.nm which at the LED wavelength of 850nm arises entirely from material dispersion.

The modal dispersion coefficient, D_m, is simply 2.72 ns/ 3.46km = 813 ps/km.

Thus for narrow linewidth sources, intermodal dispersion is the major contributor to the overall fiber dispersion. However, as the spectral linewidth of the source increases the fiber's material dispersion becomes more significant until it eventually becomes dominant.
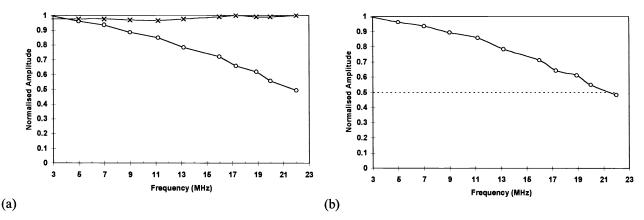

(a)   (b)

Figure 4: (a) The measured frequency response of the transmitter/receiver {o} and of the full optical system with 3.46km of optical fiber {x} and (b) the optical fiber frequency response calculated from the other two

Figure 4a shows the frequency responses of the LED transmitter-receiver combination, Ψ_o (ω), [connected by short patch cord] and the of the whole system using 3.46 km of optical fiber, Ψ_s (ω). Figure 4b shows the frequency response of the fiber alone obtained from Ψ_s $(\omega)/ \Psi_o$ (ω). The 3dB optical bandwidth of the fiber as measured from Figure 4b is 21.9MHz and the bandwidth-distance product is 75.8MHz.km. This direct measurement of the optical bandwidth compares very well with that deduced from the step response measurements [72.7 MHz.km – see above].

4. THE ERBIUM DOPED FIBER AMPLIFIER

4.1 Description of the experimental system
Direct optical amplification using erbium doped Fiber amplifiers (EDFAs) is now preferred over optoelectronic repeaters as the primary means of restoring the signal power in long distance Fiber optic links and branched networks. The objectives of the EDF optical amplifiers experiments are to enable students to investigate and become practically familiar with the principles and characteristics of optical amplifiers in general, and erbium doped Fiber amplifiers in particular. To achieve these objectives the EDF amplifier 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 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 Fiber (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 5) 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 Fiber dumps any residual pump power preventing significant levels of potentially eye damaging 980nm radiation from reaching the output connector.

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 Fiber 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.
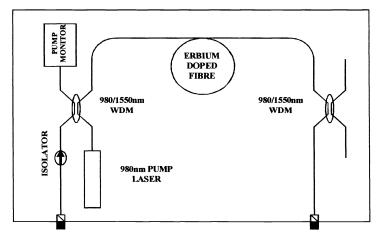

Figure 5: Schematic diagram of EDFA

4.2 Results and analysis

In previous publications we have reported the experiments on the gain characteristics of an EDFA in some depth[1, 2]. Arguably, however, the noise characteristics are much more significant in determining the performance of a system containing amplifiers[3-6]. Recently, we have fully developed a set of experiments to enable students to investigate and gain a practical appreciation of the noise characteristics of and EDFA. Here we concentrate on these noise measurements.

At the output of the amplifier, amplified spontaneous emission (ASE) accompanies the amplified signal and is guided by the fiber to the receiver where it beats with itself and with the signal to produce ASE-ASE beat noise, $\sigma_{ASE-ASE}$, and Signal-ASE beat noise σ_{S-ASE}. In most applications of EDFAs these noise sources dominate at the receiver and determine the signal to noise ratio (SNR). They are given by

$$\sigma_{S-ASE} = 4R^2 GP_0 \rho_{ASE} B_e = 4R^2 GP_0 P_{ASE}^{B_e} \tag{9}$$

$$\sigma_{ASE-ASE} = 2R \ \rho_{ASE}^2 B_o B_e = 2R^2 P_{ASE}^{B_o} P_{ASE}^{B_e} \tag{10}$$

where R is the photodiode responsivity (R = $\eta q/h\nu$, η being the quantum efficiency), B_e is the receiver bandwidth, B_o is the optical bandwidth, P_0 is the signal input power to the amplifier and $P_{ASE}^{B_o}$ and $P_{ASE}^{B_e}$ are the polarisation selective ASE powers in the optical and electrical (receiver) bandwidths respectively.

The signal to noise ratio at the receiver is therefore given by:

$$SNR_{out} = \frac{(RGP_0)^2}{4R^2 GP_0 P_{ASE}^{B_e} + 2R^2 P_{ASE}^{B_o} P_{ASE}^{B_e}} \tag{11}$$

For low signal levels and when the amplifier is not in saturation, the ASE-ASE beat noise is dominant and we can neglect the first term in the denominator. However, as the signal level increases the first term in the denominator grows and must be considered. Indeed, as we approach and enter gain saturation, the ASE power drops dramatically as the stimulated emission process suppresses the spontaneous emission and thus the second term in the denominator decreases. In such cases the Signal-ASE beat noise dominates and the received SNR is given by:

$$SNR_{out} = \frac{(RGP_0)^2}{4R^2 GP_0 \rho_{ASE} B_e} = \frac{GP_0}{4P_{ASE}^{B_e}} \tag{12}$$

Often it is convenient to characterise the noise and SNR of optically amplified systems using a parameter known as the amplifier noise figure, NF. NF is the ratio of the optical SNR at the amplifier input to the optical SNR at the output, as detected by a receiver whose intrinsic noise level (thermal noise) is less than the optical noise in both cases. The optical noise at the input is simply the signal shot noise and the SNR is given by:

$$SNR_{in} = \frac{(RP_0)^2}{2eRP_0 B} = \frac{P_0}{2h\nu B_e} \tag{13}$$

where we have used the substitution R = e/hν (e is the electronic charge and we have assumed a quantum efficiency of 1).

Using equation 12 the noise figure is given by:

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{P_0}{2h\nu B_e} \bigg/ \frac{GP_0}{4P_{ASE}^{B_e}} = \frac{2P_{ASE}^{B_e}}{Gh\nu B_e} \tag{14}$$

If the noise figure is known under the conditions at which the amplifier is operated then we can use it to calculate the output SNR. From equation 14, SNR_{out} in terms of the noise figure is:
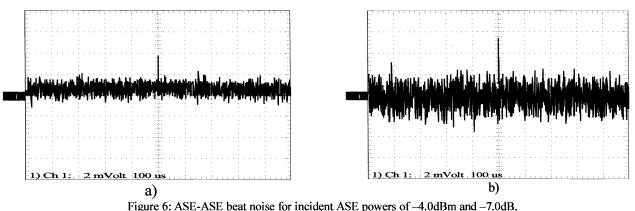
$$SNR_{out} = \frac{P_0}{2h\nu B_e \cdot NF} \qquad (16)$$

For a system containing a large number (n) of amplifiers, the output SNR is given by

$$SNR_{out} = \frac{P_0}{2h\nu B_e \cdot nNF} \qquad (17)$$

Clearly from the above analysis the noise and the noise figure are of crucial importance in determining the signal quality at the output of any system.

For constant incident optical power, the receiver noise may be examined by switching the oscilloscope to AC coupling and increasing its voltage sensitivity to maximum. For low pump power (i.e. small ASE) and zero input signal, thermal noise dominates. As we increase the pump power, the ASE level increases and ASE-ASE beat noise begins to exceed the thermal noise. Figures 6a and 6b show the ASE-ASE beat noise for incident ASE powers of –7.0dBm and –4.0dBm respectively. Clearly the noise amplitude increases linearly with the ASE power. This is consistent with equation (10) which indicates the noise power increasing with the square of the ASE power.

a)   b)

Figure 6: ASE-ASE beat noise for incident ASE powers of –4.0dBm and –7.0dB.

To observe the Signal-ASE beat noise, the pump power is fixed to provide an ASE power of –10dBm (100μW) with no signal present. Under these conditions the observed ASE-ASE beat noise is just greater than the receiver thermal noise. Initially, as we increase the input signal power from low levels, the noise remains constant as the ASE-ASE beat noise is much greater than the Signal-ASE beat noise. At output signal levels of greater than -10dBm, the noise begins to increase. Figures 7a and 7b show the noise for output signal levels of –8.5dBm and –2.5dBm. Clearly from Figure 7 the noise amplitude approximately doubles for a four fold increase in signal power. Again this is entirely consistent with the expression for Signal-ASE beat noise [equation (9)].

For an input signal power of 20μW and a gain of 13.5, we estimate the bright band noise voltage to be about 2mV. It is generally accepted that a good estimate for the rms noise voltage is about one fifth of the bright band noise voltage, implying about 0.4mV rms noise. Switching the oscilloscope to DC coupling we measure the signal at 3.4V giving a voltage/current SNR of 8500 i.e. 7.23×10^7 in terms of mean square noise current. The input SNR, defined by signal shot noise is calculated from equation (13) as 2.24×10^8. Hence, from our direct measurements of noise and SNR we estimate the noise figure [equation (14)] as 3.1 (i.e. $2.24 \times 10^8 / 7.23 \times 10^7$).
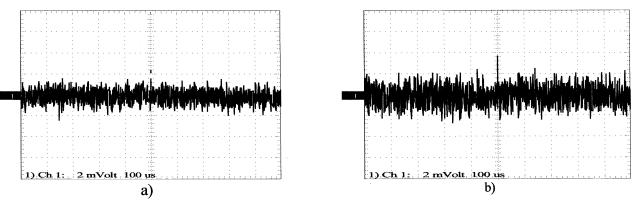
a)

b)

Figure 7: Signal-ASE beat noise for incident signal power of a) –8.5dBm and b) -2.5dBm and ASE noise power of –10dBm

It is useful for the students to calculate SNR$_{out}$ and the noise figure from spectral density measurements and to compare them with these values obtained from direct estimates made from the measurements of noise. The SNR$_{out}$ is given by equation (12) where $P_{ASE}^{B_e} = \rho_{ASE}.B_e$ (and ρ_{ASE} is the ASE spectral power density in Watts/Hz in the region of the signal and B$_e$ is the receiver bandwidth = 350KHz).
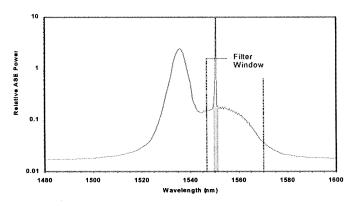

Figure 8: Relative variation of ASE power with wavelength from the EDFA showing the fraction of power in a 1nm band (shaded region) around the signal wavelength.

From Figure 8 the power per nm of bandwidth at 1550nm is 0.008 × ASE power. The total measured ASE power under the conditions for which the SNR was measured is 54µW and hence the spectral power density is 0.008 × 54 × 10^{-6}W/nm = 4.32 × 10^{-7}W/nm.

Using $\quad \Delta v = \dfrac{c}{\lambda^2}.\Delta\lambda$ we calculate $\rho_{ASE} = 3.456 \times 10^{-18} W / Hz$ (where $c = 3\times10^8$, $\lambda = 1550$nm, and $\Delta\lambda = 1$nm)

Hence $\quad P_{ASE}^{B_e} = \rho_{ASE}.B_e = 3.456 \times 10^{-18} \times 350 \times 10^3 = 1.21 \times 10^{-12} W$

and $\quad SNR_{out} = \dfrac{GP_o}{P_{ASE}^{B_e}} = \dfrac{270 \times 10^{-6}}{4 \times 1.21 \times 10^{-12}} = 55.6 \times 10^6$

Thus the calculated voltage SNR = (SNR$_{out}$)$^{1/2}$ = 7456

Therefore the calculated voltage SNR of 7456 is in excellent agreement with the value 8500 estimated directly from noise measurements on the oscilloscope.

Assuming that the input optical SNR is limited by signal shot noise the noise figure is thus given by

$$\frac{SNR_{in}}{SNR_{out}} = \frac{2.24 \times 10^8}{5.56 \times 10^7} = 4.01$$

Once again the noise figure calculated from the spectral density (NF = 4.01) is in excellent agreement with that obtained from the direct noise measurements.

5. CONCLUSIONS

On completing the above experimental programme the students have been exposed to the complex mix of factors which define the performance of an optical communication network. Material, waveguide and intermodal dispersion all contribute towards eventual inter symbol interference and define the bit rate limits, whilst attenuation influences the receiver signal to noise ratio and determines the maximum possible transmission distance. In systems deploying EDFAs, the presence of ASE sets the noise levels on received signals and ultimately defines the distance limitations on transmission. Our simple measurements enable students to see these factors in operation and to directly determine the limitations they impose on system performance. In addition, supporting calculations 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, signaling concepts and data recovery into a full design analysis which makes these particular experiments so very useful. These are the most popular experiments among the student body with almost unanimous feedback indicating that they provides excellent practical experience and insight into the principles, performance and design of optical communications systems.

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