...OPTOELECTRONIC SYSTEMS, COMPONENTS, INSTRUMENTATION...

FIBRE OPTIC COMMUNICATIONS EDUCATOR KIT (ED-COM)

STUDENT MANUAL

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FIBRE OPTIC COMMUNICATIONS STUDENT MANUAL

1. INTRODUCTION

Optical fibre links now dominate the World's major trunk communications systems and are penetrating ever deeper into the access and local area networks. Industries operating in these markets require highly skilled scientists, engineers and technicians who can design, install and operate optical communications systems. In order to expedite the development of the necessary hands on practical skills and to experimentally demonstrate basic principles, the objectives of the experiments described here are:

- to characterise all of the major components of a fibre optic telecommunications system (i.e. the transmitter, the fibre and the receiver)
- to build a simple point to point link, and
- to experimentally assess the performance of that link including the determination of the upper limits on the link length, bit rate and analogue bandwidth as defined by attenuation and dispersion.

In addition, a number of exercises have been included to ensure good overall appreciation of the design and performance of state of the art systems relative to the simple system measured here.

2. PRINCIPLES OF FIBRE OPTIC COMMUNICATIONS SYSTEMS

In a digital fibre optic communications system (Figure 1), a coded electrical current bit stream modulates a diode laser which launches optical pulses corresponding to digital 1's into the fibre. As the pulses propagate down the fibre they become weaker due to power loss in the fibre (i.e. attenuation) and they spread in time due to dispersion. The primary implication of these phenomena is that the longer the fibre link the smaller the received signal to noise ratio leading to an increasing probability of error.

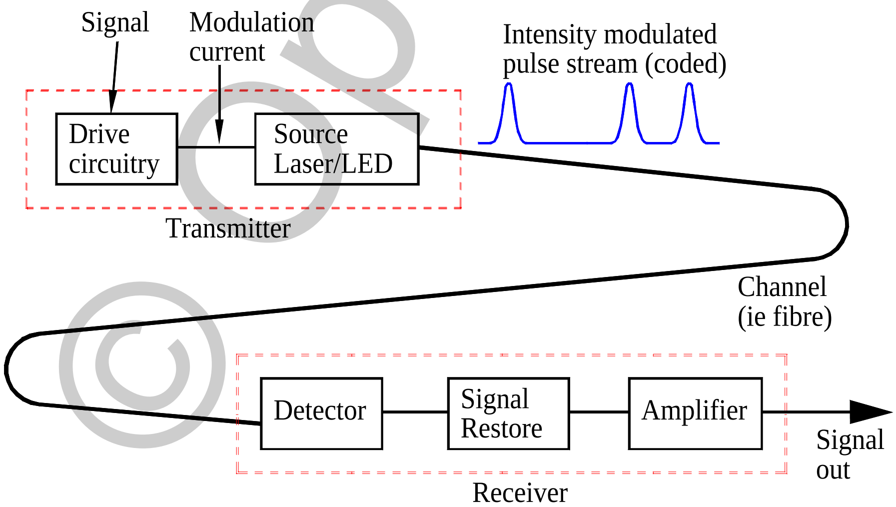


Figure 1: *Schematic of a point to point fibre optic communications link.*

In an analogue system, attenuation simply means that the peak to peak amplitude of the demodulated received baseband signal decreases with increasing link length, as does the signal to noise ratio (SNR). Dispersion results in loss of phase definition between the frequency components of the modulation signal superimposed on the carrier resulting in an increasing element of destructive interference with increasing link length. Again this leads to degradation of the peak to peak amplitude and hence SNR of the demodulated baseband signal with increasing link length.

Attenuation and dispersion are the major sources of signal degradation in optical fibre communications systems and they impose limits on the maximum link length and bit rate or bandwidth of any particular system.

2.1 Attenuation Limits

Attenuation in an optical fibre is measured as the optical power loss in dB at any point along the fibre length relative to the input power. The attenuation of an optical fibre of length, L, is given by

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

where α is the attenuation coefficient of the fibre (in units of dB/km) and P_{in} and P_{out} are the launched and output power of the link respectively. The attenuation for a given link length is then simply αL dB.

In the design of a digital telecommunications system it is standard practice to specify the maximum probability of an error occurring when detecting the transmitted signal. This probability is termed the Bit Error Rate (BER) and is usually specified as being 10^{-9} (i.e. that only one error in 10^9 bits will be tolerated). The source of errors is noise in the receiver which can result in situations in which random positive noise spikes can be interpreted as digital 1 pulses or large negative noise spikes coinciding with real signal pulses may pull the overall signal level down to such an extent that the pulses are not detected. Clearly, the larger the signal to noise ratio, the smaller the BER will be. From a full statistical analysis of noise in the receiver it can be shown that to achieve a BER of 10^{-9}, we require an amplitude signal to noise ratio (SNR) of 12 at the receiver output. The incident optical power required to generate a SNR of 12 is referred to as the receiver sensitivity, P_{min} , and if the received signal is allowed to fall below this level the error rate will become unacceptable. Hence, the maximum possible link length is that for which the launched power has decayed in the fibre to the minimum detectable power at the receiver, $P_{min.}$ This is the attenuation limited maximum link length and is determined by the attenuation coefficient, the launched signal power and the photoreceiver noise level. The attenuation limited link length, L_{max}, may be found from equation (1) if the attenuation coefficient, the launched power and the receiver sensitivity are known. Since the voltage or current generated in the receiver is proportional to the incident optical power the ratio, P_{in} / P_{min} is equal to A_{sig} / A_{min}, where A_{sig} is the voltage signal generated in the receiver with the launched power incident on it and A_{min} is the voltage signal generated for P_{min} incident on the receiver i.e. A_{min} is 12 times the rms noise voltage.

In analogue systems, the minimum usable received SNR is defined by the particular application (e.g. video signal transmission requires a much greater SNR than voice transmission in order to generate an acceptable picture definition). Attenuation limits the maximum link length to that for which the signal has decayed to such an extent that the received SNR falls to the minimum level required by the application.

2.2 Dispersion Limits

Pulse spreading arising from dispersion results in a decrease in the peak power of the pulse and hence received SNR, as well as the spreading of power into adjacent bit periods. Again this ultimately leads to an unacceptable error rate if its magnitude exceeds certain limits. Clearly, the smaller the bit period (i.e. the greater the bit rate) the less tolerant the receiver will be to a given amount of pulse spreading in terms of absolute time and hence the upper limit to which pulses are allowed to spread is defined as some fraction, γ, of the bit period, where γ is typically 0.2 to 0.25. This implies that, for a given length of fibre with a fixed amount of pulse spreading, τ , dispersion limits the maximum bit rate to that for which the bit period (T) is equal to τ/γ. On the other hand, for a given bit rate it limits the maximum length of the link to that for which τ is equal to γT. Clearly the upper limit on the bit rate is inversely proportional to the link length and dispersion thus determines the bit rate-distance product of the system.

In analogue systems dispersion results in the loss of temporal synchronisation (and thus phase definition) between the frequency components of the modulated carrier. This leads to an increasing element of destructive interference at the signalling frequencies resulting in decreasing received signal amplitude, and hence SNR, with increasing link length. Since dispersion results in time differences between the signals carried by the various carrier components, its degrading influence on the received SNR becomes worse for increasing signal frequency. Hence, any given length of fibre will exhibit an amplitude roll off characteristic with increasing modulation signal frequency and the signal frequency for which the received signal amplitude has decayed by 3dB relative to the launched signal is defined as the system bandwidth. Again the bandwidth is inversely proportional to the fibre length and the characterisation parameter determined by dispersion is the Bandwidth-Distance Product which once known can be used to obtain the maximum bandwidth or fibre length given the other parameter.

3. PRINCIPLES OF FIBRE DISPERSION AND SYSTEM RESPONSE MEASUREMENTS

3.1 Frequency domain response measurements

The temporal response characteristics of an optical fibre may be measured either in the frequency domain or the time domain. In the *frequency domain* the optical source is modulated with a variable frequency sine wave generator and the frequency response (detected signal amplitude versus frequency) of firstly the transmitter / receiver combination and then of the complete system including the fibre reel are measured. The frequency response at the output of an optical communications link ($\Psi_s(\omega)$) is determined by a combination of the transmitter/ receiver response, ($\Psi_o(\omega)$), with that of the optical fibre, ($H_F(\omega)$), where ω denotes the baseband angular frequency. This means that:

$$\Psi_s(\omega) = \Psi_o(\omega) . H_F(\omega)$$

Thus the fibre response is determined from

$$H_F(\omega) = \Psi_s(\omega) / \Psi_o(\omega) \qquad (2)$$

When this response is plotted, the *optical* bandwidth of the fibre link can then be obtained by measuring the frequency at which the received signal amplitude is 3 dB down (i.e. half maximum amplitude point) from its value at low frequencies.

3.2 Time domain response measurements

In the *time domain* we can measure the step function response or the impulse response of the fibre. In the step response measurement the optical source is modulated by a square wave with a sharply rising edge and the 10-90% risetime, τ_0, of the transmitter / receiver combination is measured by inspection of the oscilloscope trace of the signal received via a short length of fibre. The measurement is repeated with the fibre reel connecting the transmitter to the receiver to obtain the 10-90% risetime of the entire system - the transmitter, receiver and the fibre, τ_s. The 10-90% risetime of the fibre, τ_F, may then be obtained from the following relationship

$$\tau_F = \sqrt{\left(\tau_s^2 - \tau_o^2\right)} \qquad (3)$$

For an impulse response measurement a sharp pulse (strictly speaking it should be a Delta function impulse) is applied as a modulation signal to the optical source and the width of the received pulse is measured for a short link and for the long link giving the impulse response of the transmitter/receiver combination and that of the entire system. For most systems the received pulses are approximately Gaussian and we are primarily interested in the root mean square (rms) pulse widths. Given the transmitter / receiver and system response measurements, the rms pulse width, τ_R , arising from pulse spreading in the fibre (i.e. the impulse response of the fibre) may be obtained from an expression analogous to equation (3). It is this figure which is used in the calculation of the dispersion coefficient and the BR.L product.

3.3 Calculation of the BW.L and BR.L products

A given length of fibre 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 bandwidth to the 10-90% risetime, τ_F, and the output rms pulse width, τ_R , arising from a launched impulse as follows (see Appendix A):

$$BW = \frac{0.48}{\tau_F} = \frac{0.187}{\tau_R} \qquad (4)$$

So

$$\tau_R = 0.39\ \tau_F \qquad (5)$$

The Bandwidth Length Product (BWL) for the fibre 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 an upper limit on the bit rate for a given link length (and vice versa) defined by (see Appendix A):

$$BR = \frac{1}{T} = \frac{0.25}{\tau_R} \qquad (6)$$

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

3.4 Measurement of the material and intermodal dispersion contributions

In multimode fibres the principal dispersive mechanisms responsible for pulse broadening are intermodal and material dispersion (though in graded index fibre the contribution from intermodal dispersion is reduced significantly from that experienced in step index fibre). The total rms impulse response of the fibre, $\tau_{R(tot)}$, arising from the combination of material and intermodal dispersion is given by

$$\tau_{R(tot)} = \sqrt{\left(\tau_{im}^2 + \tau_{mat}^2\right)} \qquad (7)$$

where τ_{mat} and τ_{im} are the rms impulse responses for material and intermodal dispersion acting separately

For the narrow linewidth laser source, material dispersion is small and its contribution to the total risetime via the relationship of equation (7) is insignificant. Hence, the measured total risetime is assumed to be entirely due to intermodal dispersion. Given that we then measure the total risetime for the broad band LED source, for which the contribution from material dispersion is significant, we can obtain τ_{mat} from equation (7). The material dispersion parameter (D_{mat}) in the fibre at a wavelength λ can then be obtained from the following expression:

$$D_{mat} = \tau_{mat} / \Delta\lambda\, L \text{ ps/nm. km} \qquad (8)$$

where $\Delta\lambda$ is the rms spectral linewidth of the source in nm.

The intermodal dispersion coefficient, D_{im}, may be obtained from

$$D_{im} = \tau_{im} / L \qquad (9)$$

4. DESIGN OF THE EDUCATOR KIT

The equipment is designed to demonstrate the principles and effects of both attenuation and dispersion phenomena in optical fibre communication systems - and to do so effectively but at a cost which is affordable within the constraints of academic budgets. A direct consequence of this is that we have chosen to operate in the 800nm wavelength region where the optical fibre attenuation and dispersion are large compared to the values typical of the commercial communications windows around 1300nm and 1550nm.

Another requirement is that the dispersion of the optical fibre link must be sufficiently high (resulting in a low system bandwidth) to be compatible with standard teaching laboratory equipment (i.e. a 50MHz oscilloscope). Consequently, a graded index optical fibre with non-ideal refractive index profile was chosen for the fibre link. Typically a 3km length of this fibre yields bandwidths below 25MHz when using a large spectral linewidth source (e.g. LED), without seriously compromising the attenuation performance of the transmission link.

Even though the Fibre Optic Communications Educator Kit has been deliberately downgraded in order to ensure that the essential features of the fibre link and the overall system performance can be investigated using low cost standard teaching laboratory instrumentation, the experiments still allow the student to fully appreciate the limitations that attenuation and dispersion impose on fibre optic communications links. Indeed, the insight gained by the practical investigation of this simple optical communications system is equally applicable to state of the art long haul, high capacity fibre links. A student exercise at the end of the manual relates the results gained in the experiments to the performance of real world state of the art systems.

5. APPARATUS

The OPTOSCI Fibre Optic Communications Educator Kit consists of the following hardware elements:

5.1 Equipment supplied

- An 850nm, ST receptacled, light emitting diode (LED) transmitter with adjustable drive current and modulation signal input. The drive current (in mA) is displayed on an integral panel meter. The rms spectral linewidth of the source is 30nm.
(The maximum drive current and maximum modulation amplitude which can be applied to the LED is limited internally.)
- A 785nm, ST receptacled, laser diode transmitter with adjustable drive current and modulation signal input. The drive current (in mA) is displayed on an integral panel meter. The rms spectral linewidth of the laser at its operational current is approximately 1nm.
(The maximum drive current and maximum modulation amplitude which can be applied to the Laser Diode is limited internally.)
- Two reels (approximately 1 km and 2 km in length) of graded index 62.5μm core diameter silica multimode fibre with ST connectorised output leads. The numerical aperture (NA) of the fibre is 0.275 and its effective group refractive index is 1.497.
- 1m ST connectorised graded index 62.5μm core diameter silica multimode fibre patchcord (a spare patchcord is also supplied).
- One ST receptacled Si pin photodiode receiver with a 50Ω BNC output port. The detected optical power (in μW) is displayed on an integral panel meter.
- A waveform generator which can be switched between a 4MHz square wave pulse generator with a fast rise time, and a variable frequency (1 to 28 MHz) sine wave generator. The waveform generator has a separate enable/disable switch and the output signal is available via a 50Ω BNC output port. The output signal for both waveforms is 10V pk-pk maximum.
- One bulkhead ST connector.
- An integrated power supply (on/off switch at the rear of the unit) and all required electrical interconnects, 50Ω BNC cables and a BNC T-piece connector.

5.2 Additional equipment to be supplied by the user

- A two channel laboratory oscilloscope with a minimum bandwidth of 50MHz and a time base which can display at least 5ns/div. This is the **minimum** requirement to perform the risetime measurements.
- A frequency counter ***(optional)*** could be employed when performing the bandwidth measurements in the frequency domain. This would allow the direct reading of the output frequency from the signal generator rather than estimating the frequency from the oscilloscope trace.

6. LASER SAFETY

IT IS IMPERATIVE THAT YOU READ AND UNDERSTAND THE FOLLOWING SAFETY INFORMATION BEFORE ATTEMPTING ANY OF THE EXPERIMENTS DETAILED HERE. IF YOU HAVE ANY QUERIES PLEASE CONSULT YOUR LECTURER OR DEMONSTRATOR.

6.1 Operational Hazard - Semiconductor Laser Diode

The **Laser Diode** source emits infrared radiation at 785nm which is invisible to the human eye and may cause **eye damage** if the output beam is viewed directly. When in use, **never** stare at the optical output port of the Laser Diode when its dust cap is removed to connect an optical fibre and always replace the device dust cap when the fibre is removed. Always leave the dust caps for the fibre patchcords in position until ready to make a connection and never stare at the end of a fibre patchcord connected to the Laser Diode output port or point the fibre end at yourself or anyone else in your vicinity before making a connection. **Never** use external optics (i.e. collimating lenses) to view the Laser Diode emission at close range.

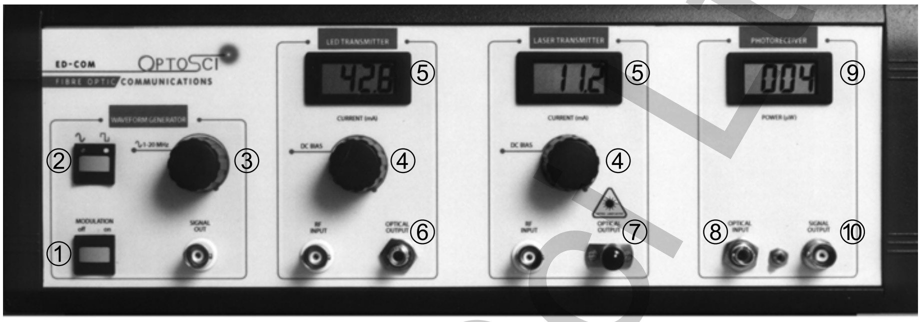
The semiconductor laser diode is compliant with IEC 60825-1:2002. The output power of less than 5mW at 785nm meets Class 1M limits as defined within that standard.

7. OPERATING INSTRUCTIONS

IT IS IMPERATIVE THAT YOU READ AND UNDERSTAND THE FOLLOWING OPERATIONAL INFORMATION BEFORE ATTEMPTING ANY OF THE EXPERIMENTS DETAILED HERE. IF YOU HAVE ANY QUERIES PLEASE CONSULT YOUR LECTURER OR DEMONSTRATOR.

7.1 Front Panel Layout

The ED-COM front panel layout is as shown in Figure 2. It is separated into four functional areas: the Waveform Generator, the LED transmitter, the Laser Diode transmitter and the Photoreceiver.



① **Modulation ON/OFF**	⑤ **Drive Current Displays**	⑨ **Received Power Display**
② **Sine/Square Select**	⑥ **LED Output**	⑩ **Receiver Signal BNC**
③ **Sine Frequency Control**	⑦ **Laser Output**	
④ **DC Bias Controls**	⑧ **Photoreceiver Input**	

Figure 2: *Front Panel Layout*

7.2 Before Switching On

Before powering up ED-COM ensure that the knobs to control the DC bias current ④ to the LED and Laser Diode Transmitters are turned fully anti-clockwise (e.g. to zero) and that the dust caps for their optical outputs ⑥ and ⑦ are in position. The mains power can then be switched on at the rear of the unit. Power on is indicated by a digital readout on the panel meters, ⑤ and ⑨. The unit should be allowed to warm up for ten minutes while preparing to start the experiments.

7.3 Use of Optical Fibres

The principal requirements for handling fibres are

1. the end faces of the fibres are clean when in use (to achieve optimum transmission of light), and protected with their individual dust caps when not in use (to avoid scratching the fibre end face which would reduce the coupling efficiency of light into the fibre).
2. the fibres should not be subject to a tight bend radius. The general recommendation is that under normal operation the fibre should form a loop not less than 50mm in diameter. Note that tight loops and kinks in the fibre may occur by trapping the fibre against an edge or bending the fibre sharply at the end of the strain relief boot used on fibre patchcord connectors.

3. when making and breaking connections using optical patchcords care should be taken to grip the main connector body, not the strain relief boot or the cable itself. A fuller description of Optical Connector styles and their use is given in ***Appendix: Working With Optical Fibres.***

If a degradation in optical performance of the fibre optic cables (patchcords) is experienced during the experimentation please notify your instructor.

> ***Practical Note:*** *All optical connections necessary in OptoSci educator kits are made using external fibre patchcords fitted with industry standard optical connectors (ST, FC, SC etc.). Please refer to* **Appendix: Working With Optical Fibres** *which contains more details on the use of optical connectors.*

7.4 Setting the Bias Points for the Optical Sources

The operating point and modulation depth for the laser and LED are chosen to make optimal use of the dynamic range of the receiver unit. The appropriate operational position (bias point) for the LED source is at a drive current of 50mA. The bias point of the Laser Diode is the current setting which yields half the maximum output power from the source. During operation the bias current reading on the LCD display ⑤ for each source should be checked periodically and if necessary the DC bias ④ should be adjusted slightly to account for any drift in operational position.

> ***Practical Note:*** *In general the bias point setting for an optical transmitter is dependent upon whether the modulation signal is applied either via direct modulation of the drive current or by using a bias T arrangement (as is used in the ED-COM system). The bias T arrangement allows analogue or digital modulation to be applied to the sources without ambiguity when the sources are biased about their half maximum output power point. However for strict digital transmission the source drive current is often directly modulated, in which case the LED is generally biased at zero current and the Laser Diode at just below its threshold current.*

7.5 Use of the Waveform Generator

With the mains power on, the Waveform Generator can be turned on or off independently of the rest of the unit ①. It also has a switch ② to change from a fixed frequency square wave output to an adjustable frequency sine wave output ③. When the Waveform Generator is ***on*** one LED on the mode selection switch will illuminate to indicate that either sine or square wave output is available from the output BNC. When not in use it is preferable to switch ***off*** the waveform generator (no LEDs will be illuminated).

To faithfully transmit an analogue or digital signal from the waveform generator using either the LED or the Laser Diode source, the drive current for each transmitter must be set at its operational position before applying the modulation signal. This will ensure that the modulated output signal from the transmitters will respond linearly to the input driving signal and will not get distorted.

If a modulation signal is being applied to either transmitter, ensure that the waveform generator is disabled before making large adjustments to the source's drive current (e.g. when powering down).

7.6 Before Switching Off

When the experimental laboratory session has finished, firstly, disable the waveform generator ①, then reduce the drive current ④ for both the LED and Laser Diode Transmitters to zero (e.g. turn anti-clockwise), disconnect all the fibre patchcords and replace their dust caps as well as those for the transmitters, ⑥ and ⑦, the receiver ⑧ and also those on the fibre reels. Finally, remove all of the BNC cables and switch off the mains power at the rear of the unit.

8. EXPERIMENTS

8.1 Comparison of LED and Laser Diode Characteristics

This series of experiments will investigate the operation of the two standard transmitter sources employed in optical fibre communications systems; the laser diode and the light emitting diode (LED).

BEFORE PROCEEDING WITH THESE EXPERIMENTS READ AND ADHERE TO THE IMPORTANT SAFETY AND OPERATIONAL INFORMATION DETAILED PREVIOUSLY.

Practical Notes:

1. *When taking power readings in Sections 8.1 and 8.2 take care not to move or tug the ST connector connected to the transmitter as this can cause variations of up to 1dB in the launched power. If the connector is inadvertently moved during the measurements and the coupled power changes significantly then it may be possible to reset it close to its original value of coupled power by remaking the connection.*
2. *All of the ends of the fibre patchcords are numbered. Please note the number at the end of the patchcord when first connecting to the transmitter and continue to connect this end to each transmitter when performing the experiments. This should minimise any significant variations in the coupled power into the fibre when performing your measurements.*

8.1.1 Optical Output Power against Drive Current

1. Connect the 1m fibre patchcord between the LED (note the number on the end of the patchcord) and the Photoreceiver, record the detected optical power at the receiver as a function of the drive current and plot the results. The operational position (bias point) for the LED can now be set at a drive current of 50mA (see section 7.4).
2. Repeat the power out versus drive current measurements for the Laser Diode source (remembering to follow the safety precautions). Again, plot the results and determine the threshold current and the bias point (i.e. the current setting which yields half the maximum output power from the source) for the Laser Diode.

8.1.2 Launched Optical Power

1. Note the optical power launched into the 1m patchcord from both the LED and Laser Diode transmitters when they are set at their bias points.

The sources should be maintained at these bias currents while conducting the remainder of the experiments.

8.2 Attenuation in Optical Fibre Links

This set of experiments examines a number of properties of the optical fibre link.

8.2.1 Optical Fibre Connector Loss

In this experiment the optical loss at a bulkhead ST connector is determined. The connector loss is determined following transmission through fibre reel #1 to establish an equilibrium mode distribution in the fibre. When making these measurements it is important to adhere to the Practical Notes listed in Section 8.1.

1. Connect the LED transmitter to the receiver using fibre reel #1 and record the detected power. Now determine the optical loss resulting from the use of a fibre connector in the system by inserting the bulkhead ST fibre connector and 1m patchcord between the end of fibre reel #1 and the receiver.
2. Repeat the measurement of connector loss using the Laser Diode source.

8.2.2 Attenuation of the Optical Signal over the Link Length

Check the launch power into the 1m patchcord for the LED and Laser Diode sources. Now measure the total attenuation of the launched signal from each optical transmitter after propagation through fibre reel #1 (remember to note the number on the end of the patchcord connected to the transmitter). Repeat the measurements for fibre reel #2.

8.2.3 Determination of Fibre Link Length and Fibre Attenuation Coefficient

Practical Note: *If the* ***BER(COM)*** *extension module to ED-COM is available in the laboratory, alternative (easier and more accurate) methods of estimating the length of the fibre reel, compared to the method described below, are detailed in Appendix C.*

In this experiment you will estimate the length of the fibre reel by measuring the delay between a signal directly from the Waveform Generator (see Section 7.5) and the same signal transmitted via the optical fibre link (see Appendix B for a mathematical description).

Important Note: *Before connecting the analogue or digital modulation signal to the modulation input of either optical transmitter, ensure that each source is biased at its operational position (see Section 7.4).*

- Connect the BNC T-piece to the output of the ED-COM Sinewave Generator and connect a BNC cable to each output end of the BNC T-piece. Connect one BNC cable direct to Channel 1 of the oscilloscope. Set the oscilloscope to trigger on this channel, select a time base of 1 μs/div and adjust the vertical position of the Channel 1 signal to display it in the top portion of the oscilloscope window. Using fibre reel #1 make the optical connections from the ED-COM Laser Diode to the ED-COM Photoreceiver and then modulate the Laser with the signal from the remaining BNC T-piece output. Connect the photoreceiver output to Channel 2 of the oscilloscope and adjust the vertical position of the Channel 2 signal to display it in the bottom portion of the oscilloscope window. With both signal waveforms displayed on the oscilloscope vary the sinewave frequency back and forth relatively quickly (between about 0.75 and 3 MHz) and locate the point on the Channel 1 waveform for which the phase remains unchanged as the frequency is altered (i.e. this point on the Channel 1 waveform – the zero delay position – will remain static on the screen). Adjust the horizontal position of the traces to ensure that the zero delay position on Channel 1 appears at the left-hand side of the oscilloscope screen. Then, when the sinewave frequency is altered as above, the phase matched position on Channel 2 will appear towards the middle of the oscilloscope screen. These are the points where the two signals are in phase and satisfy condition B3 (see Appendix B). Using the time divisions (or horizontal cursors) on the oscilloscope measure the delay between these phase matched points on the Channel 1 & 2 waveforms. Repeat the measurement for fibre reel #2 (the time base will need to be set at 2.5 μs/div for this measurement). From the results determine:

1. the length of each optical fibre reel, and
2. the attenuation per km of the optical fibre (take an average value for both reels) for the respective transmitter using the results previously obtained in 8.2.2.

8.2.4 Determination of Attenuation Limited Link Lengths

> ***Practical Note:*** *For noise estimation purposes, it is generally accepted that the rms noise voltage is approximately one fifth of the amplitude of bright band noise observed on an oscilloscope trace. It should also be noted that absolute measurements of noise voltage made from an oscilloscope are notoriously inaccurate and may be in error by up to a factor of 2 in either direction.*

1. Connect the Laser Diode directly to the photoreceiver with the 1m patchcord, apply the square wave modulation signal and measure the peak to peak amplitude of the launched optical signal. Then, estimate the rms receiver noise amplitude by examining the receiver output (for no incident light) on the oscilloscope (set the oscilloscope to an amplitude of 10mV/div and time base of 100ns/div) and from the measurement determine the receiver sensitivity. From your results and the fibre attenuation coefficient measured earlier, calculate the attenuation limited distance for a communications system using the Laser Diode transmitter (see Section 2.1 *Attenuation Limits*).

2. Repeat this exercise for the LED source and comment on the results obtained for the attenuation limited link lengths.

8.2.5 Exercises

1. Outline the fundamental mechanisms responsible for signal attenuation in an optical fibre and, strictly on this basis, indicate why modern optical communication systems moved their operating wavelength from 800nm further into the infrared to 1300nm and 1550nm.

2. State of the art fibre has an attenuation coefficient of 0.2dB/km at 1550nm. With the receiver sensitivities and launched powers measured in your experiment, what would the attenuation limited link length be if the fibre used had this attenuation coefficient?

8.3 Bandwidth and Fibre Dispersion Measurements

This series of experiments addresses two methods of determining the bandwidth of a fibre optic communications system. The results are then employed to determine the Bandwidth-Length product and the Bit Rate-Length Product of the link for both the laser and the LED source as well as the individual contributions of intermodal and material fibre dispersion.

8.3.1 Time domain measurements

1. Digitally modulate the LED transmitter (using the square wave) and, from appropriate measurements of pulse risetimes (10% to 90%) on the oscilloscope, determine the signal bandwidth, Bandwidth-Length Product (BW.L) and bit rate-distance product (BR.L) of fibre reel #1, fibre reel #2, and then both reels connected together (use the bulkhead ST connector). Note that you must make measurements of the transmitter / receiver risetime as well as the complete system risetime before you can extract the fibre risetime and then calculate the BW.L and BR.L for the fibre (see Section 3.2 and 3.3). Compare the results from your measurements on the individual reels with those obtained from the two combined fibre reels.

2. Repeat the risetime measurements using the Laser Diode transmitter with fibre reel #2 and then both fibre reels connected together, and determine the signal bandwidth, Bandwidth-Length Product (BW.L) and bit rate-distance product (BR.L) for this system.

3. From your results calculate the material and intermodal dispersion coefficients of the fibre (remember to use the results from the same fibre or combination of fibres).

8.3.2 Frequency Domain Measurement

1. Repeat the measurement of the bandwidth and BW.L product with the LED transmitter and both fibre reels connected together using analogue techniques. To do this, modulate the LED with the sine wave signal and measure the amplitude roll off of the photoreceiver signal on the oscilloscope as the modulation frequency is increased in steps from about 2MHz to 28MHz. By taking measurements for both the transmitter / receiver system and the whole system including both fibre reels, the frequency response for the fibre can be obtained. Plot your results for the fibre frequency response and determine the optical bandwidth and BW.L for the fibre.

> ***Practical Note:*** *You may have been supplied with a frequency counter to allow direct reading of the sine-wave signal frequency.*

8.3.3 Exercises

1. Briefly describe the principal dispersive mechanisms which contribute to the overall dispersion in multimode, graded index optical fibres and then outline why there was a difference in the measured bandwidth of the fibre reel when employing the LED and Laser Diode sources.

2. The OPTOSCI Fibre Optic Communications Educator Kit is designed to demonstrate the effects of both attenuation and dispersion phenomena in optical fibre communication systems. A direct consequence of this is that the optical transmitters operate in the 800nm wavelength region where the optical fibre attenuation and dispersion are large compared to the values typical of the commercial communications windows around 1300nm and 1550nm. Hence, calculate the attenuation limited link length and Bit Rate-Distance Product for the following practical optical communications systems described in Table 1 and discuss the differences between these results and those obtained in your experiments.

Table 1: *System specifications for Exercise 2*		**System A**	**System B**
Source	Type	1300nm LED	1550nm DFB laser
	Linewidth (nm)	40	0.1
	Launch Power	50μW	4mW
Fibre	Type	1300nm multimode graded index fibre	1550nm singlemode fibre
	Attenuation Coefficient (dB/km)	0.32	0.24
	Intermodal pulse spreading (ps/km)	100	---
	Material dispersion (ps/km.nm)	4	---
	Dispersion coefficient(ps/km.nm)	---	2.5
Receiver	Type	InGaAsP PinFET	
	Minimum detectable power	1 μW	
	Maximum pulse spread	0.25T	
Losses	Connector loss (1 dB) + Margin (6 dB)	7 dB	

APPENDIX A: DISPERSION PHENOMENA IN OPTICAL FIBRES

Dispersion is most conveniently viewed in terms of the impulse response. A signal pulse of negligible duration launched into the optical fibre as a very short pulse of light emerges at the other end spread out in time (and, of course, attenuated) with a half width τ_d (Figure A1). τ_d is referred to as the dispersion time of the link.

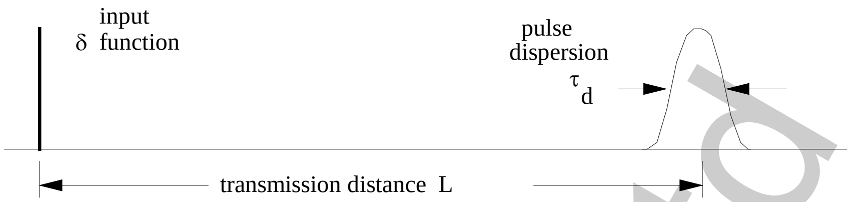


Figure A1: *The basic definition of optical pulse dispersion.*

The Origins of Dispersion

Most definitions of dispersion concern the differences in propagation time, through a particular medium, of different components of the signal spectrum. Usually these components correspond to the spectral content of a modulated carrier signal. In this case the attenuation of each component of the signal is effectively the same but the phase relationship between these various components when they arrive at the receiver is distorted. This kind of dispersion may be viewed through a phase plot such as that shown in Figure A2. For a given delay in the absence of dispersion the phase advances linearly with frequency. In this case, provided the attenuation is independent of frequency, there will be no distortion of the received signal. However if the temporal delay increases linearly with frequency this in turn produces a quadratic phase term which does introduce distortion. In optical fibres this is only important when narrowband laser systems are modulated with broadband data and transmitted over very significant lengths of single mode fibre. In this case the combination of material dispersion and waveguide dispersion does indeed give rise to signal distortion through quadratic phase phenomena operating on the transmitted spectrum.

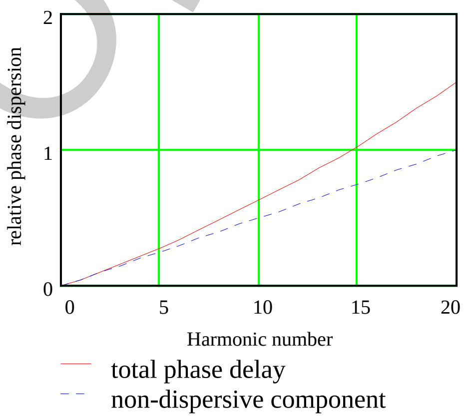


Figure A2: *Quadratic phase dispersion and the linear (non-dispersive) contribution.*

In other optical fibre systems multipath phenomena dominate the dispersion process. These multipath phenomena may either be a consequence of different components of the carrier frequency (for example a light emitting diode) experiencing different delays due to the variation in optical fibre refractive index across the carrier bandwidth (material dispersion) or due to differential delays between different modes (intermode dispersion), or both. When these differentially delayed components arrive at the receiver the modulation components add at slightly different modulation frequency phases. In practice the different paths through the fibre can be considered as a continuum of delays. To show the principle, the situation for a dual path case is shown in Figure A3 illustrating the contribution to both the impulse response and the frequency response. The effect is clearly to broaden the impulse response or to decrease the amplitude and delay the phase of the frequency response.

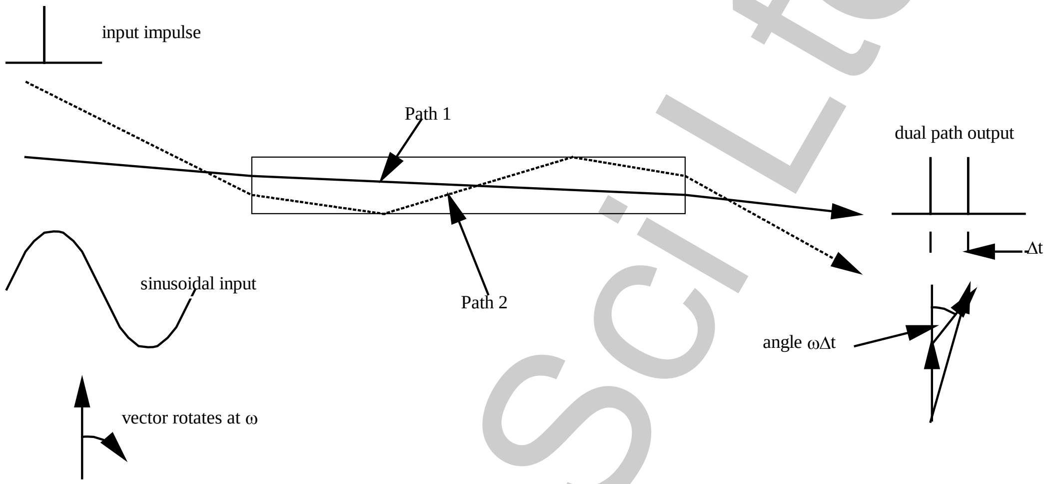


Figure A3: *Impulse and frequency responses of a dual path network.*

The frequency response and the impulse response are therefore intimately related. It is straightforward to show that one is the Fourier transform of the other:

$$h(t) = \Im(f(\omega)) \quad \text{(A1)}$$

where $h(t)$ is the impulse response $f(\omega)$ the frequency response and $\Im$ represents the Fourier transform operation.

Experimentally we determine either $f(\omega)$ or the step response $s(t)$. It is relatively unusual to make measurements which directly determine the impulse response. The step response is illustrated in Figure A4 where τ_s is the 10% to 90% rise time which is the parameter which we can measure. Within a linear time invariant system we can relate the input to the output either as the product of the frequency spectra of the input with the frequency response of the network or as a convolution of the time dependent input with the impulse response, as shown schematically in Figure A5. The impulse response can therefore be directly related to the step response, which is itself the integral of the impulse response and hence to the frequency response using the processes illustrated in Figure A5 and equation A1.

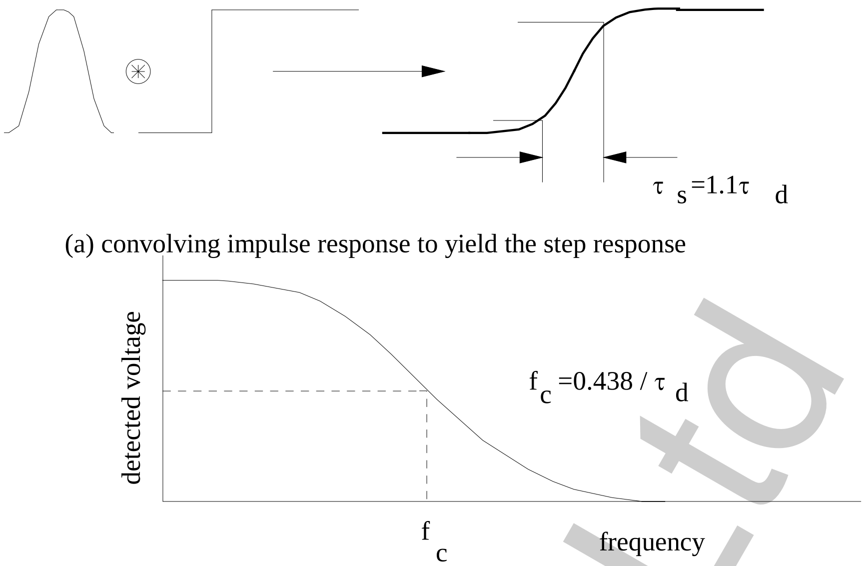


Figure A4: *Relating step and frequency responses to dispersion time.*

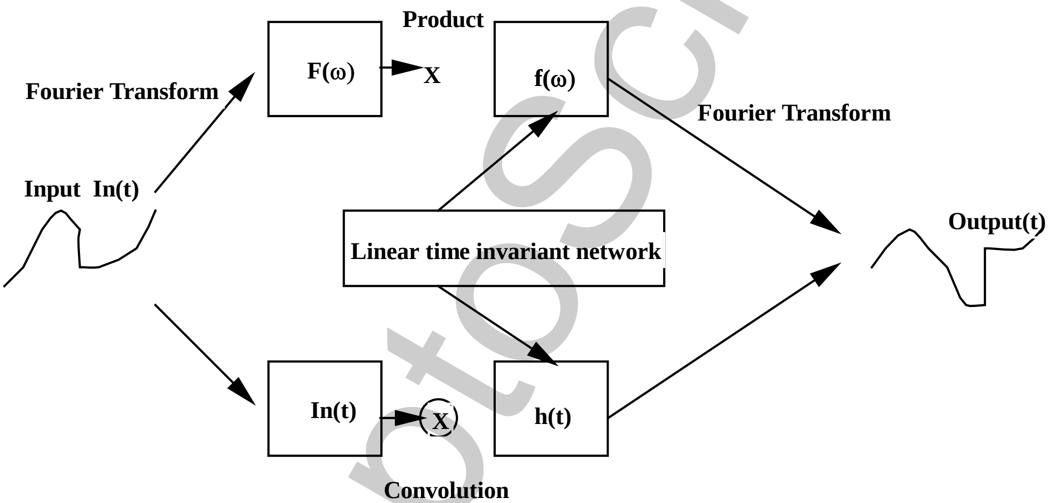


Figure A5: *Spectral and impulse response approaches to analysing linear time invariant networks, of which optical fibre links are one example*

Step and Frequency Responses

These very basic observations immediately indicate that the detail of the step response/frequency response relationship will depend upon the form of the impulse response. To illustrate this let us consider two simple cases where the impulse response is given by (a) a Gaussian and (b) a square pulse (Figure A6). In physical terms the former corresponds to a dispersive medium in which the multiple paths are bunched around the central value and for which the number of paths varies as a Gaussian from this central value. The second case corresponds to a multiple path medium with equal spacing between all available paths. These two cases also illustrate the dependence of system response in the optical fibre case on input launch conditions. The population of an individual set of modes within a multimode fibre can be varied very considerably by launching different spatial spectra at the input.

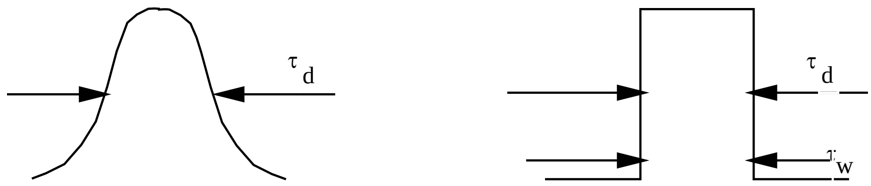


Figure A6: *Dispersion times and pulse widths for Gaussian and square pulses The dispersion time is defined as the FWHM, the pulse width as the time containing half the pulse energy.*

Considering first of all the Gaussian the impulse response is given by:

$$P(t) = \frac{1}{\tau_R \sqrt{2\pi}} e^{-t^2/2\tau_R^2} \quad \text{(A2)}$$

The value of *P(t)* is the perceived optical power as a function of time and τ_R is the standard deviation (rms width) which is related to the dispersion time (the half power points) through:

$$\tau_d = 2.35\tau_R \quad \text{(A3)}$$

The step response in this system can be obtained by convolving the Gaussian with the unit step which gives an error function rise time for which the difference between the 10% and 90% points is given by τ_s:

$$\tau_s = 2.56\tau_R \quad \text{(A4)}$$

Consequently the pulse dispersion and this rise time are related by:

$$\tau_d = 0.91\tau_s \quad \text{(A5)}$$

If we now consider the frequency response *R(f)* this is related to the impulse response through the Fourier transform:

$$R(f) = e^{-2\pi^2 \tau_R{}^2 f^2} \quad \text{(A6)}$$

Here *f* is the modulation frequency and *R* is the ratio of the magnitude of the output at this particular frequency to that at low frequencies. This ratio is 0.5 at $f_{½}$ where:

$$f_{½} = \frac{0.187}{\tau_R} = \frac{0.438}{\tau_d} = \frac{0.479}{\tau_s} \quad \text{(A7)}$$

Hence with the Gaussian case we can relate the step response to the dispersion time to the half ***optical*** power response for equation A7. At the electrical detection stage the half power optical point corresponds to the frequency at which the current through the photodetector is a half of that at very low frequencies.

We can go through a similar process for the square pulse impulse response. If the total width of the impulse is τ_w then convolving this with a step gives us a step response time between the 10 and 90% mark of:

$$\tau_s = 0.8\tau_w = 0.8\tau_d \quad \text{(A8)}$$

The Fourier transform of the impulse response in this case is a Sinc function giving for *R(f)*:

$$R(f) = \frac{\sin(\pi f \tau_w)}{(\pi f \tau_w)} \quad \text{(A9)}$$

This response drops to the 50% mark when:

$$f_{½} = \frac{1.894}{\pi\tau_w} = \frac{0.603}{\tau_w} = \frac{0.603}{\tau_d} \qquad \text{(A10)}$$

Since in this case the pulse width is equal to the dispersion time - the half power points are at each end of the pulse width - then by using equations A8 and A10 we can relate the half power frequency response to the dispersion time and the step response time, τ_s, through:

$$f_{½} = \frac{0.603}{\tau_d} = \frac{0.48}{\tau_s} \qquad \text{(A11)}$$

These two simple cases have been calculated in detail to illustrate the fact that this relationship (exemplified in equations A11 and A7) depends somewhat on the form of the impulse response. The square pulse impulse response (Figure A6) is an extreme case and for almost all practical impulse response shapes τ_d is less than the total pulse width τ_w. For all practical situations $f_{½}$ in terms of τ_d is less than the value given in A11 and is typically closer to the values given in equation A7. However the relationship between the step response and the half power frequency in both equations A7 and A11 is remarkably similar. As a general guideline:

$$f_{½} \simeq 0.5 / \tau_s \qquad \text{(A12)}$$

is a very useful approximate relationship between the 10:90 step response and the half ***optical*** power frequency response. This relationship is accurate to within a few percent for most practical impulse response shapes. However relating this to the value of the dispersion time must be done carefully with due recognition of the shape of the impulse response and the definition of the dispersion time in terms of the half power points. For most practical pulse shapes an approximation whereby the product of the half power point and the dispersion time is in the region of 0.5 suffices but is considerably less accurate than equation A12 relating the step response to the half ***optical*** power frequency.

Dispersion and Bit Error Rate

The effect of noise on bit error rate in digital systems has been introduced in the main text. As a brief recap Figure A7 indicates the basic calculation process. The probability density functions for additive noise on the zero and one levels always overlap and the probability of an error occurring is given generally by:

$$BER = p(1) \cdot p(1 < D) + p(0) \cdot p(0 > D) \qquad \text{(A13)}$$

where BER is the bit error rate, $p(1)$ and $p(0)$ are probabilities of a 1 or a 0 respectively occurring and $p(1<D)$ is the probability of the 1 level signal descending below the threshold D due to additive noise. Similarly the $p\ (0 > D)$ is the probability of the 0 level exceeding the decision threshold due to additive noise.

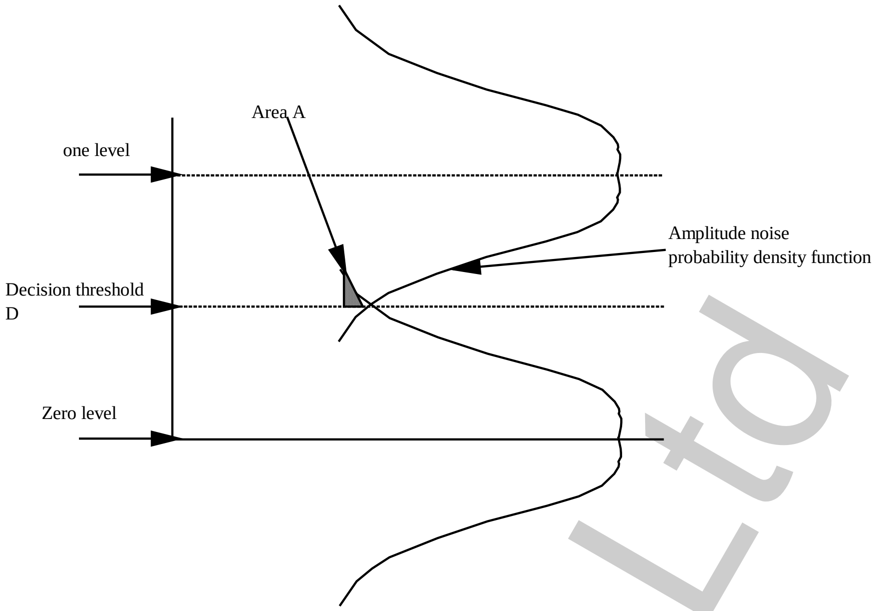


Figure A7: *Noise level overlap integrals giving error probabilities*

For Gaussian noise sources the probability of error can be determined by evaluating the area A in Figure A7 and from this the rule of thumb that the signal to noise ratio of 12 is necessary to achieve a bit error rate of 10^{-9} can be derived.

In a practical system the decision threshold is also located in time within the pulse train as well as in height between the 0 and 1 levels (Figure A8). It is simple to show that the decision level is ideally where the additive noise distributions at the 0 and 1 signal levels cross. Similarly the decision time can be shown to be optimum at the temporal centre of gravity of the transmitted pulse - as indicated in the figure.

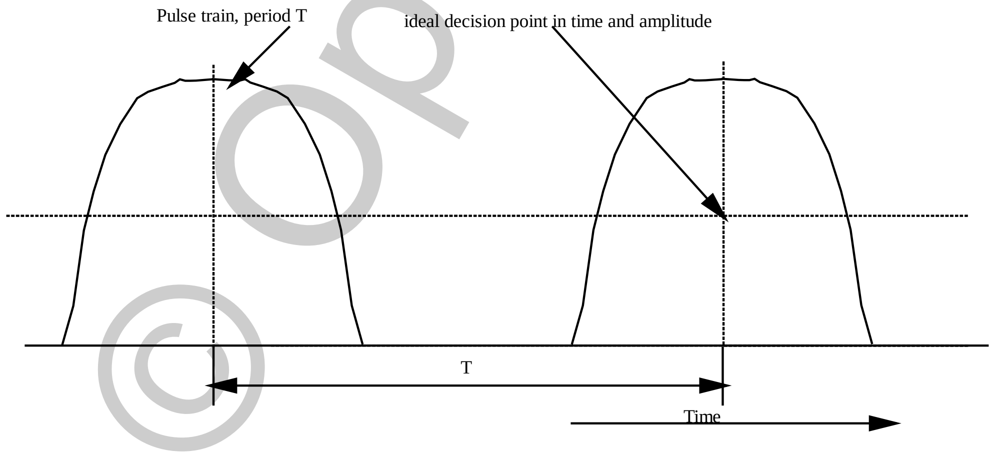


Figure A8: *Position in time and amplitude of the "ideal" decision point in a digital system. In practice the time sample is spread over an integration time of the order of the pulse width.*

The impact of dispersion on bit error rate is effectively to close the gap between the 0 and 1 levels and there are two contributory reasons to this, both arising because the total pulse energy with and without dispersion must be considered to be constant. Consequently the dispersion will both lower the 1 level and increase the 0 level

(Figure A9). The area A in Figure A7 is a very sensitive function (the error function) of the separation so dispersion can rapidly increase the error rate even for very small effective changes in the 0 and 1 level.

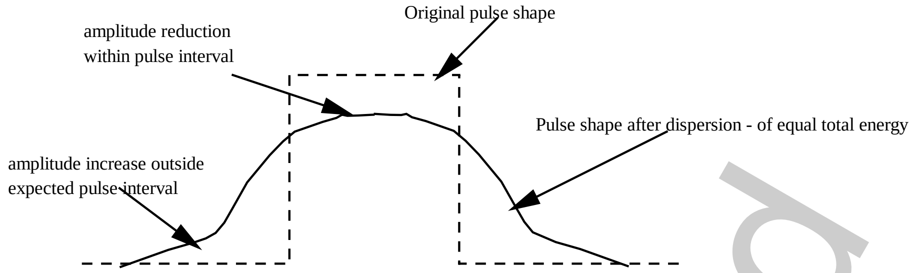


Figure A9: *Effect of pulse dispersion on energy distribution of the received pulse.*

The impact which this overlapping phenomenon has on bit error rates is difficult to predict accurately. However the general principles can be gleaned with reference to Figure A10. The areas labelled B1 and B2 contribute to the effective closing of the gap between the 0 and 1 levels due to overlap from the preceding and following pulses respectively. The distance C corresponds to the reduction in the 1 level due to the spreading of the pulse under examination. The decision process in practice is not accurately located at a point in time but is a response to an integral of the pulse energy over some time interval which is a significant fraction of the pulse duration. For Gaussian spreading, the tail of the Gaussian decreases very rapidly within the overlap B1 and B2 and there is also an effective roll off in the time distribution of the pulse energy represented qualitatively by the area labelled D in Figure A10.

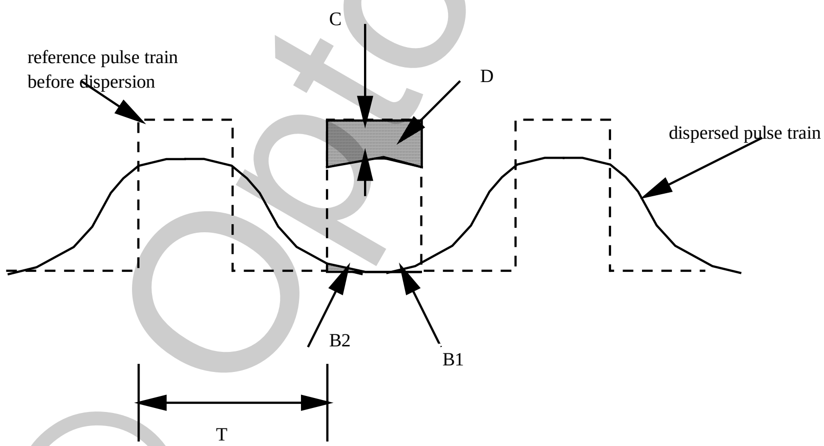


Figure A10: *The origin of the pulse power penalty in dispersion -energy is extracted from the "one" level and introduced into the "zero" level, thereby increasing the error rate.*

Pursuing all these integrals and evaluating the impact of dispersion both experimentally and theoretically provides a rule of thumb which is that:

$$\frac{\tau_d}{2.35} = \tau_R \leq 0.25T \qquad \text{(A14)}$$

where τ_R is defined as the root mean square pulse width and τ_d is the half power dispersion time as related to τ_R through equation A3. The estimate is clearly reasonable since a 2dB penalty corresponds to increasing the signal (that is the 0 to 1 level spacing) by some 35%. This may be confirmed from a consideration of the overlap of a Gaussian with the standard deviation determined by equation A14 into the next pulse and estimating both the value of the error function at this overlap and the height reduction of the received pulse for a constant pulse energy. In order to achieve a bit error rate of 10^{-9}, the dispersion indicated in equation A14 requires a signal to noise ratio increase of typically 2dB compared to the ideal case.

Dispersion Effects - A Brief Investigation

It is a relatively simple matter, given the availability of one of the mathematical shells such as Matlab, Mathcad or Mathematica or even through using some of the more advanced spreadsheets to model the impact which dispersion phenomena can have upon a transmitted signal. The procedure is straightforward - take the signal, evaluate its Fourier transform, modify the Fourier transform to take into account the phase and/or amplitude transmission characteristics of the channel then take the inverse transform to get the resultant signal. It is instructive to model this to get some feel of the magnitude of the phenomena which are involved.

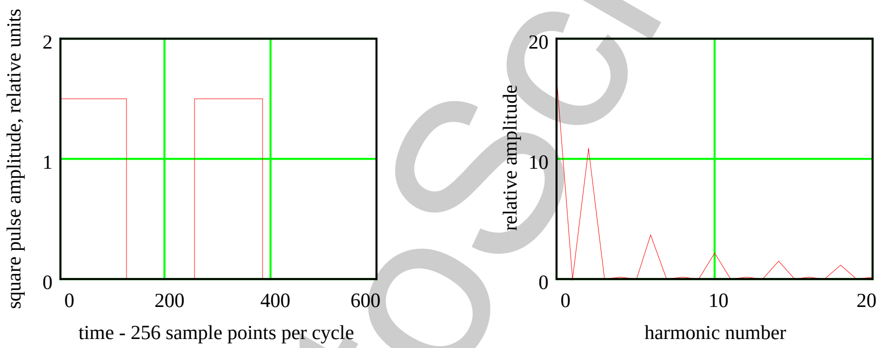


Figure A11: *Pulse train and the corresponding spectrum.*

The simplest input signal is a square pulse shown in Figure A11 together with the first twenty harmonics of its spectrum. The results of introducing a very modest quadratic phase dispersion on this pulse shape are shown in Figure A12 together with a phase dispersion which produced these changes - only of the order of 1/2 of a radian at the twentieth harmonic. The impact of phase dispersion is obviously far more pronounced at the higher harmonics exemplified in this case by the pronounced ringing introduced as a consequence of these relative phase changes.

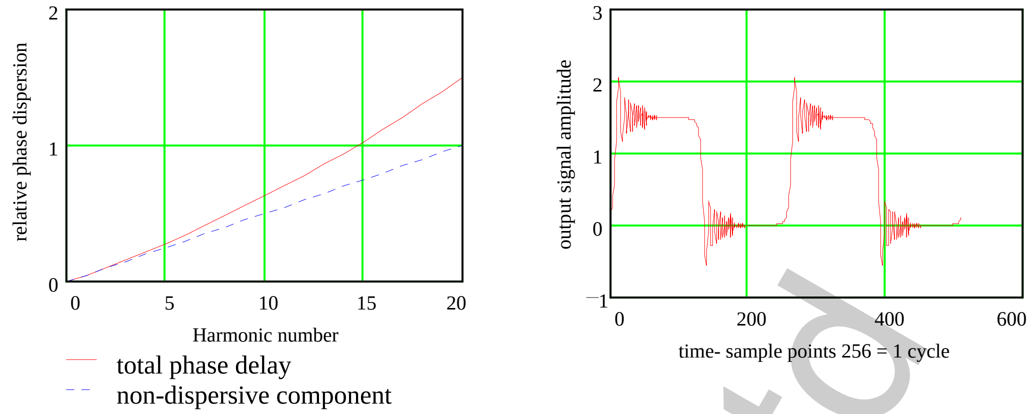


***Figure A12**: Pure phase dispersion and its impact on the input signal of Figure A11.*

Of course the level of phase dispersion which can be tolerated depends critically upon the system requirements. For most digital optical fibre transmission systems the total system bandwidth is of the order of the inverse of the bit length so that higher harmonics are severely attenuated. Indeed the pulse shape is chosen to ensure that this is the case. In some situations very broad fractional bandwidth signals are often required, for example, the bandwidth of most audio systems spans the three decades from 20 to 20,000 Hz and rapid transients are common. Fortunately though the ear is immune to the impact of these modifications to relative phase across the spectrum so the phase response of audio amplifiers is rarely if ever specified.

Phase dispersion of this type is common to any communication system. In contrast multipath dispersion which is prevalent in optical fibre communication systems is rarely encountered elsewhere. In this case we can model the effect of multipath dispersion by generalising the vector sum approach shown in Figure A3. The relative phases of the vectors in this sum are determined directly by the pulse dispersion and the amplitudes of these contributions are determined by the envelope of the impulse response. Figure A13 shows the impact of a Gaussian impulse response on a square wave signal including the comparison between the input (Figure A11) and output spectra. The total width of the Gaussian is truncated to two standard deviations either side of the mean and the mean dispersions is one half the period of the fundamental frequency of the input signal.

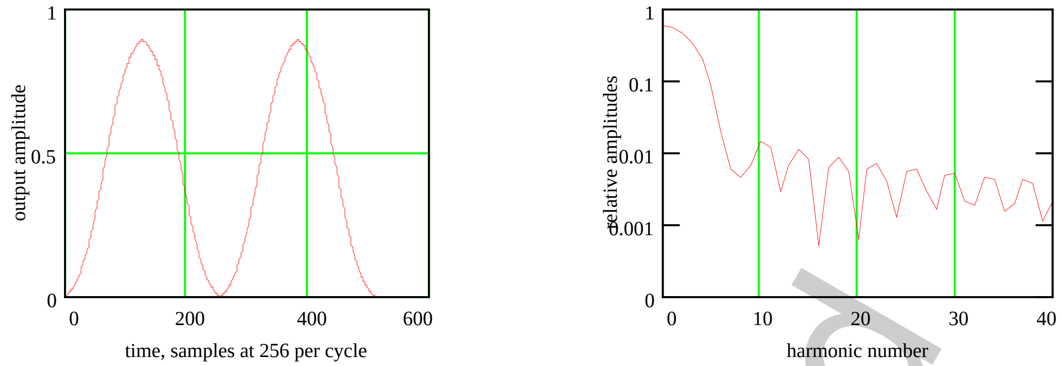


Figure A13: *The output waveform and corresponding spectrum for the input shown in Figure A11 after transmission through a Gaussian multipath channel with dispersion time equal to the pulse period.*

Whilst it is evident here that the pulse shape has been significantly affected it is also clear that the pulse can be readily recovered. However note the tendency of the pulse shape to spread out and in particular the fact that one pulse is beginning to overlap with the next one. This overlapping phenomenon gives rise to the generic criterion for digital systems that the pulse dispersion should be less than the pulse period.

APPENDIX B: EQUATING AN AMPLITUDE DIVIDED SIGNAL TRAVERSING TWO DIFFERENT PATHS

Consider the sinusoidal signal from the waveform generator which has been split into two signals of equal amplitude (*A*). One signal passes straight to the oscilloscope (Φ_1) while the second modulates the Laser Diode, is transmitted via the optical link, detected by the photoreceiver and is then displayed on the oscilloscope (Φ_2). These signals can be represented as follows:

$$\Phi_1 = A \, Sin\,(\omega t - kx) \qquad \text{(B1)}$$

$$\Phi_2 = A \, Sin\,(\omega(t+\Delta t) - k(x+\Delta x)) \qquad \text{(B2)}$$

where the terms in brackets represent the phase of the two signals.

ω is the angular frequency (i.e. $\omega = 2\pi\nu$ where ν is the signal frequency)
t is time and Δt is the additional time taken to pass through the fibre
k is the propagation constant ($k = 2\pi/\lambda$ where λ is the signal wavelength)
x is the distance and Δx is additional distance travelled by the signal in the fibre (i.e. the optical path length).

It is obvious from equations B1 and B2 that Φ_1 and Φ_2 will only be equal when the phases are matched, i.e. when

$$\omega\Delta t = k\Delta x \qquad \text{(B3)}$$

or correspondingly $\lambda\nu\,\Delta t = \Delta x$.

Since $\lambda\nu = c$, the velocity of light in vacuum (3×10^8 m/s), and Δx is the optical path length and thus equals nL, where n is the fibre refractive index and L is the fibre length, then L is given by

$$L = \frac{c.\Delta t}{n} \qquad \text{(B4)}$$

As the expression in B4 is independent of the signal frequency, the position (in time) at which the phase matched condition occurs will remain constant for all sinewave frequencies. Thus by measuring the time delay, between the initial trigger point (i.e. the zero delay position) and the static point (phase matched position) on waveform Φ_2, from the oscilloscope screen, the optical fibre length can be determined.

APPENDIX C: FIBRE LINK LENGTH MEASUREMENT USING BER(COM)

*If the **BER(COM)** extension module to ED-COM is available in the laboratory, alternative (easier and more accurate) methods of estimating the length of the fibre reels, compared to the method employed in Section 8.2.3 of the ED-COM student manual, are described here.*

C.1 Theory

In these experiments, you will estimate the length of the fibre reel, by measuring the time taken for a short pulse of light to travel through it.

The fibre length is determined from the following. The optical path length in the fibre, $\Delta x = nL$, where n is the fibre refractive index (effective fibre group refractive index = 1.497) and L is the fibre length. Since $\Delta x = c\Delta t$, where c is the velocity of light in vacuum (3×10^8 m/s), and Δt is the time taken for the light to pass through the fibre, then L is given by

$$L = \frac{c.\Delta t}{n} \qquad \text{(C1)}$$

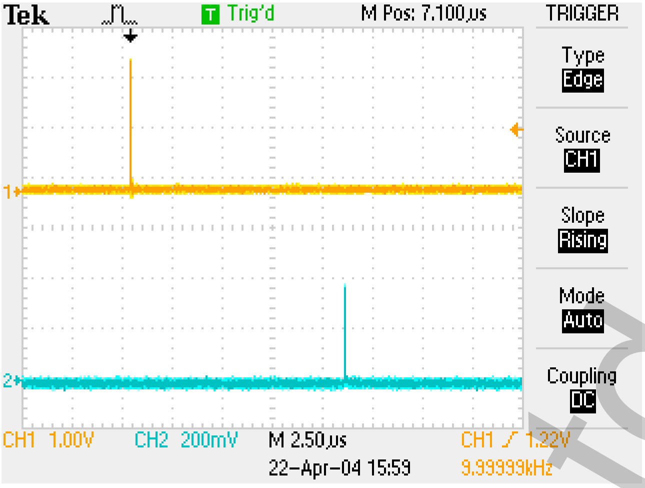
C.2 Measurement of Fibre Length with BER(COM) – Method 1

***N.B.** Before connecting the impulse signal to the modulation input of either ED-COM optical transmitter, ensure that each transmitter is biased at its operational position (see Section 7.4 of the ED-COM manual).*

Power up the BER(COM) unit and then the ED-COM unit and bias each optical source at its operational position.

Connect a BNC T-piece to Channel 1 of the oscilloscope and attach a 1m BNC lead from one end of the T-piece to the BER(COM) IMPULSE (COM) output and the remaining end of the T-piece to ED-COM's laser transmitter RF input. Connect the ED-COM receiver output to Channel 2 of the oscilloscope via another 1m BNC lead.

Using fibre reel #1 make the optical connections from the Laser Diode to the photoreceiver. Set the BER(COM) output rate to "00.010000" Mbit/s (push in and turn the rotary control knob to access the right-hand digits). For fibre reel #1 set the oscilloscope timebase to 1µs/div. Set the trigger source to Channel 1, and display both channels. Adjust the Channel 1 sensitivity to 1V/div and the Channel 2 sensitivity as required. The oscilloscope shows the transmitted signal on Channel 1 (top trace in Figure C.1(a)) and the received signal on Channel 2 (bottom trace).



(a)

Figure C.1(a): *Example display from oscilloscope for fibre reel #2.*

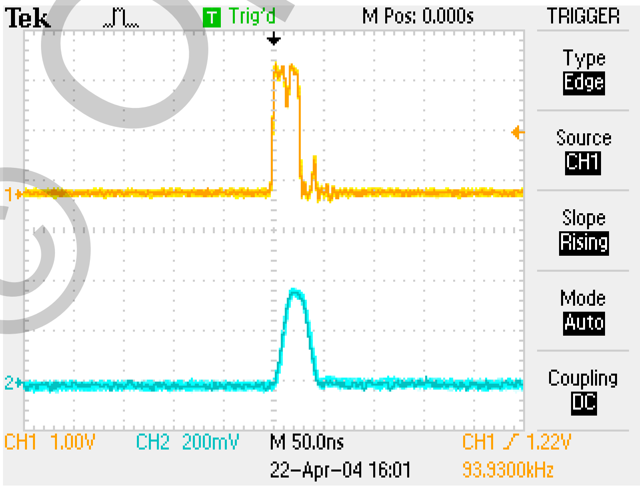
The time difference between the two signals is the time taken for the pulse to travel through the fibre. Read off the time difference from the oscilloscope, using the cursor function (if available). Repeat the measurement for fibre reel #2 (the time base will need to be set at 2.5 µs/div for this measurement).

From the results determine the length of each optical fibre reel.

C.3 Measurement of Fibre Length with BER(COM) – Method 2

In this section, the fibre length is determined again with BER(COM) but using a different method.

Using fibre reel #1 and the same setup as employed previously, increase the BER(COM) output rate until the received pulses line up with the transmitted ones on the oscillopscope screen (see Figure C.2). Zoom in by decreasing the oscilloscope timebase to make sure that you have lined up the rising edge of each pulse accurately.



(a)

Figure C.2(a): *Aligning the received and transmitted pulses.*

> ***Practical Note:*** *Since the BER(COM) unit produces one impulse for every bit sent then, 1 Mbit/s = 1MHz. Consequently, when the received pulses are aligned with the transmitted ones, the bit rate displayed on the BER(COM) screen will be equal to 1 / (transit time through the fibre reel).*

Calculate the length of fibre reel #1 from the bit rate shown on the BER(COM) LCD display and repeat the measurement for fibre reel #2. Which method is more accurate for determining the fibre length?

***Optional*:** With the set-up as above (Method 2) for determining the length of fibre reel #2 add a 1m patchcord in series with fibre reel #2. Can you detect the extra length of fibre? Repeat the experiment with Method 1 commenting on the results.

C.4 Calculation of the Fibre Attenuation per km for the Optical Sources

Using the fibre length measurements determine the attenuation per km of the optical fibre (take an average value for both reels) for the respective transmitter using the attenuation results previously obtained in Section 8.2.2 of the ED-COM manual.

APPENDIX WOF: WORKING WITH OPTICAL FIBRES

1. General

Although optical fibres are light and flexible they are made of glass hence a degree of care must be applied during their handling.

The principal requirements for handling fibres are

1. the end faces of the fibres are clean when in use (to achieve optimum transmission of light), and protected with their individual dust caps when not in use (to avoid scratching the fibre end face which would reduce the coupling efficiency of light into the fibre).
2. the fibres should not be subject to a tight bend radius. The general recommendation is that under normal operation the fibre should form a loop not less than 50mm in diameter. Note that tight loops and kinks in the fibre may occur by trapping the fibre against an edge or bending the fibre sharply at the end of the strain relief boot used on fibre patchcord connectors.
3. when making and breaking connections using optical patchcords care should be taken to grip the main connector body, not the strain relief boot or the cable itself. A fuller description of Optical Connector styles and their use is given below.

If a degradation in optical performance of the fibre optic cables (patchcords) is experienced during the experimentation please notify your instructor.

2. Use of Optical Connectors

All optical connections necessary in OptoSci educator kits are made using external fibre patchcords fitted with industry standard optical connectors (ST, FC, SC etc.).

When using any type of 'keyed' connector (e.g. ST, FC, SC etc.) it is essential that the key on the connector is correctly aligned with the slot in the uniter.

Figure WOF1 shows the relevant features and alignment of the FC style connector. Ensure that the ferrule fits into the central section of the uniter and the key is aligned to the slot. The outer body of the connector may then be screwed into place ensuring that the key has not moved. ***Do not overtighten*** this style of connector as this may damage the endfaces and result in higher losses. Removal is simply by unscrewing the outer body.

Figure WOF2 shows the SC style of connector – this is similar to the FC style but uses a push-fit. Firstly ensure that the key and slot are aligned then by holding the main body of the connector (not the strain relief boot) push the connector firmly until a positive click is felt. When fully mated the connection should be as shown on the right of Figure WOF2 with the key positioned at the rear of the slot. For removal, again holding the connector body (not the strain relief boot) pull back firmly until the connection is separated.

Figure WOF3 shows the ST style of connector – this is similar to the FC style but uses a bayonet style fitting. Firstly ensure that the key and slot are aligned then by holding the main body of the connector (not the strain relief boot) push the connector into place and lock with a clockwise half turn of the barrel. For removal, turn the barrel a half turn counter-clockwise and pull the connector body back until the connection is separated.

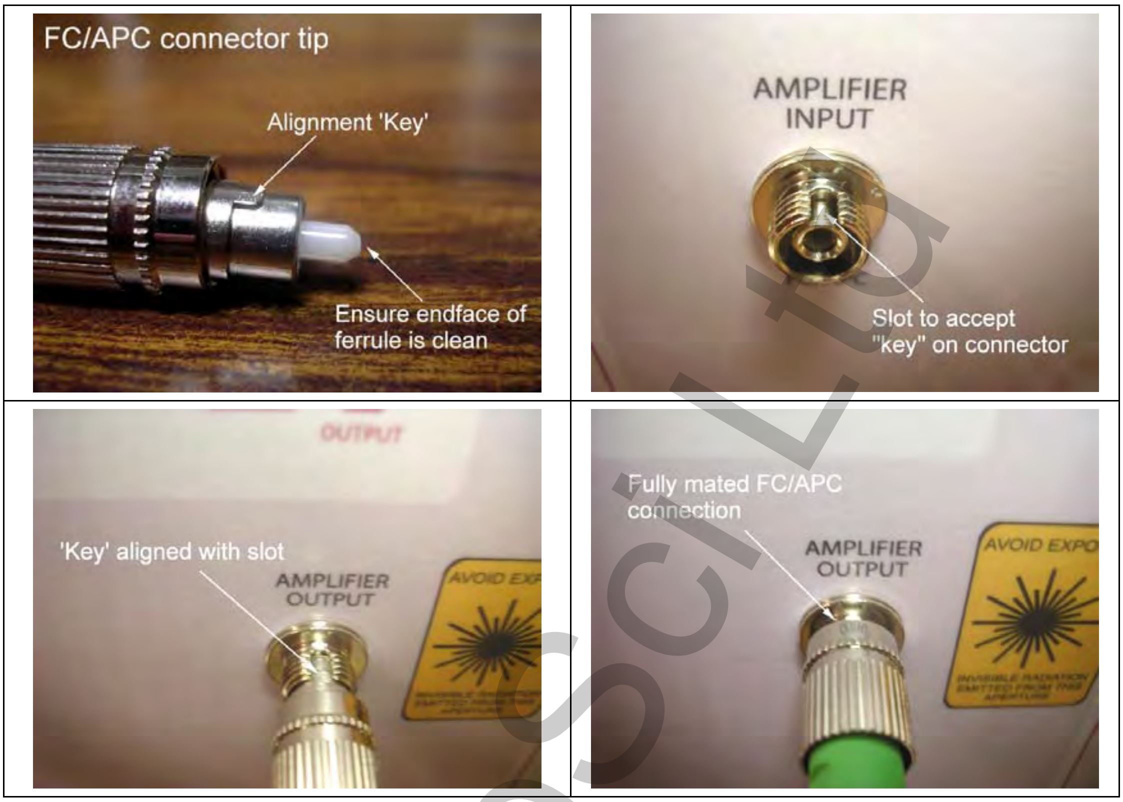


Figure WOF1: *Features and alignment of FC/APC style fibre connectors*

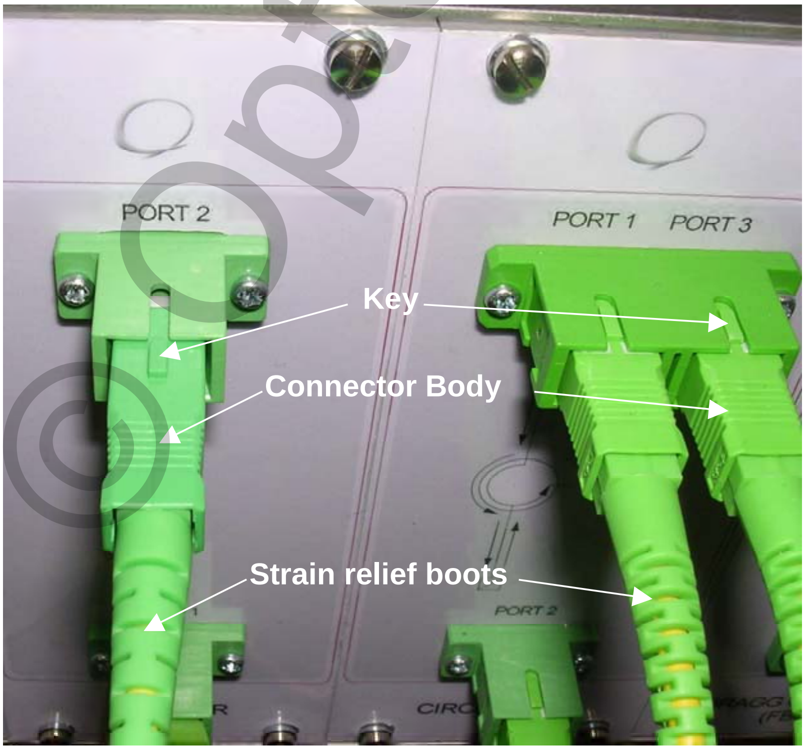


Figure WOF2: *Aligned (left) and fully mated (right) SC/APC connectors*

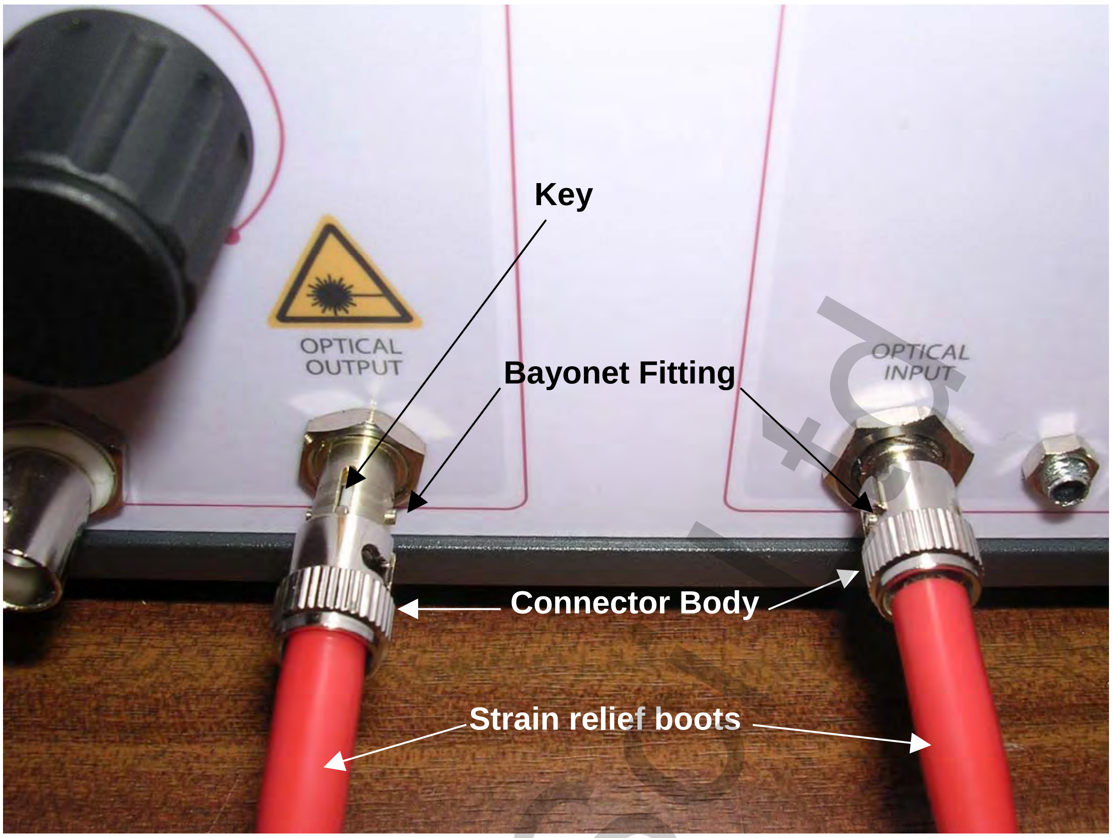


Figure WOF3: *Aligned (left) and fully mated (right) ST connectors*