## Chapter 1

# The Evolution of Optical Fibre Communication Systems

### 1.1 Introduction

The demand for high-capacity long-haul telecommunication systems is increasing at a steady rate, and is expected to accelerate in the next decade [1]. At the same time, communication networks which cover long distances and serve large areas with a large information capacity are also in increasing demand [2]. To satisfy the requirements on long distances, the communication channel must have a very low loss. On the other hand, a large information capacity can only be achieved with a wide system bandwidth which can support a high data bit rate ($>$ Gbit/s) [3]. Reducing the loss whilst increasing the bandwidth of the communication channels is therefore essential for future telecommunications systems.

Of the many different types of communication channels available, optical fibres have proved to be the most promising [4, 5]. The first advantage of an optical fibre is its low attenuation. Typical values of attenuation factor in Modified Chemical Vapour Deposition (MCVD) optical fibres are plotted against wavelength of the electromagnetic carrier in Fig. 1.1 [6]. At present, optical fibres with loss coefficients of less than 0.25 dB/km around emission wavelengths of 1.55 $\mu$m are available [7]. This remarkable progress in fibre manufacturing technology has led to wide applications of long distance optical fibre communications in recent years. Furthermore, optical fibres can also transmit signals over a wide bandwidth because the electromagnetic carrier in optical fibres has a frequency in the optical frequency region ($\approx 10^{14}$ Hz). Hence, optical fibres can also carry many baseband channels, each with a bandwidth of the order of GHz using wavelength division

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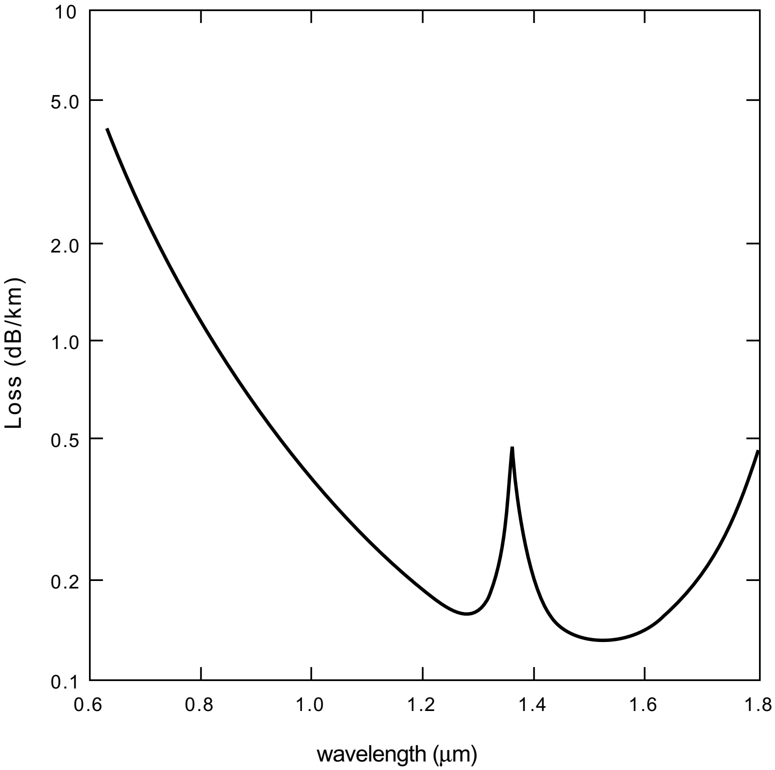

Fig. 1.1. Attenuation coeffiecient of MCVD optical fibres as a function of emission wavelength.

multiplexing (WDM) [8, 9]. For these reasons, optical fibre communication systems have attracted a lot of attention in recent years, and much research has been carried out to optimise their performance.

Figures 1.2(a) to (d), respectively, show the properties of various elements used in optical fibre communication systems, namely, the main materials and wavelengths used for different light sources, optical detectors, and optical amplifiers where there have been rapid recent advances. With semiconductor optical amplifiers, by changing the crystal composition the wavelength band (i.e. amplifiable waveband) can be selected as required from short to long wavelengths (see Fig. 1.2(c)). Furthermore, if a travelling wave device is used, broad band operation over 10 THz or so is possible. Rare-earth-doped optical fibre amplifiers, on the other hand, have an amplifiable waveband which is essentially determined by the dopant material,

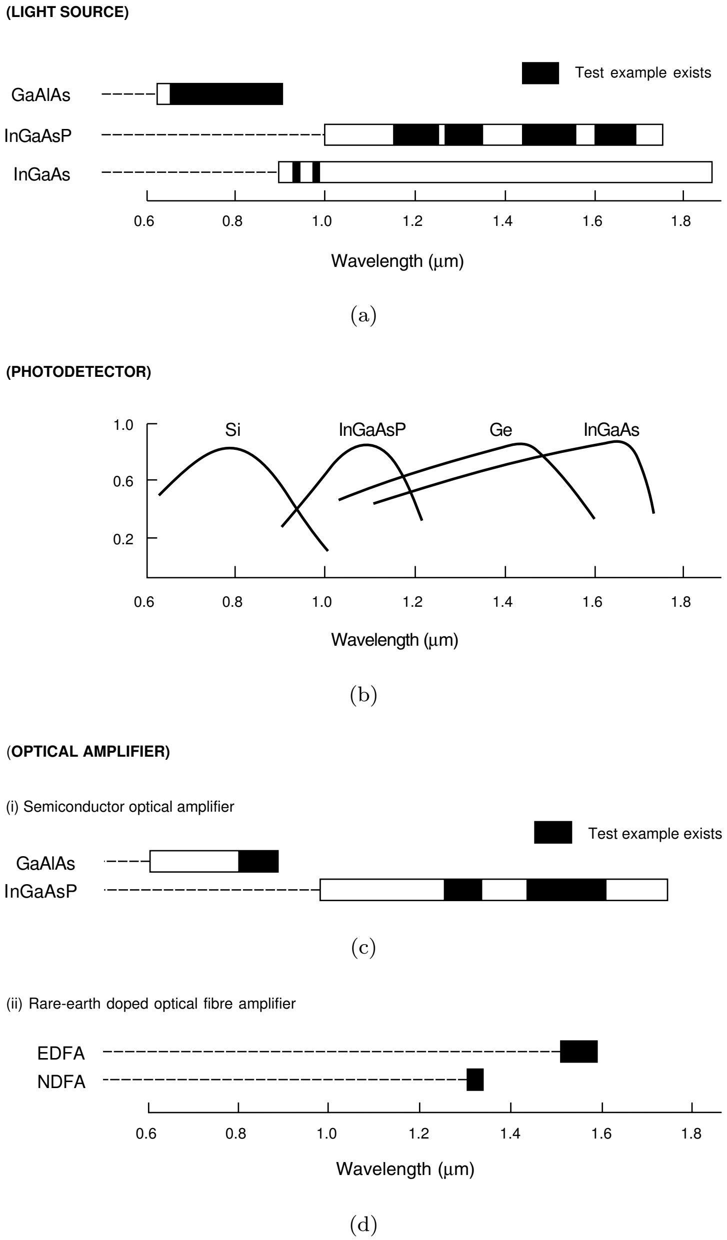

Fig. 1.2. Wavebands of components used in optical fibre communication systems. (after [28]).

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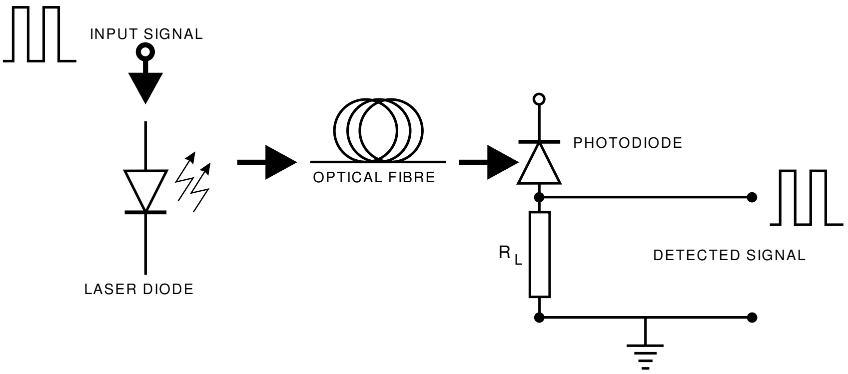

Fig. 1.3. Configuration for an optical fibre communication system employing direct detection.

and in the 1.55 $\mu$m band this is limited to erbium. Erbium doping is therefore of great practical value, since it allows fabrication of a fibre amplifier suitable for operation at 1.55 $\mu$m, which is the waveband of lowest loss in silica optical fibres.

A typical configuration for an optical fibre communication system is shown in Fig. 1.3. The optical fibre acts as a low loss, wide bandwidth transmission channel. A light source is required to emit light signals, which are modulated by the signal data. To enhance the performance of the system, a spectrally pure light source is required. Advances in semiconductor laser technology, especially after the invention of double heterostructures (DH), resulted in stable, efficient, small-sized and compact semiconductor laser diodes (SLDs) [10–12]. Using such coherent light sources increases the bandwidth of the signal which can be transmitted in a simple intensity modulated (IM) system [13]. Other modulation methods, such as phase-shift keying (PSK) and frequency-shift keying (FSK), can also be used [4, 14]. These can be achieved either by directly modulating the injection current to the SLD or by using an external electro or acousto-optic modulator [11, 15].

The modulated light signals can be detected in two ways. A direct detection system as shown in Fig. 1.3 employs a single photo-detector [13, 16] which acts as a square law detector, as in envelope detection in conventional communication systems [3]. Although such detection schemes have the inherent advantage of simplicity, the sensitivity of the receiver is limited [17]. In order to detect data transmitted across the optical fibre with a

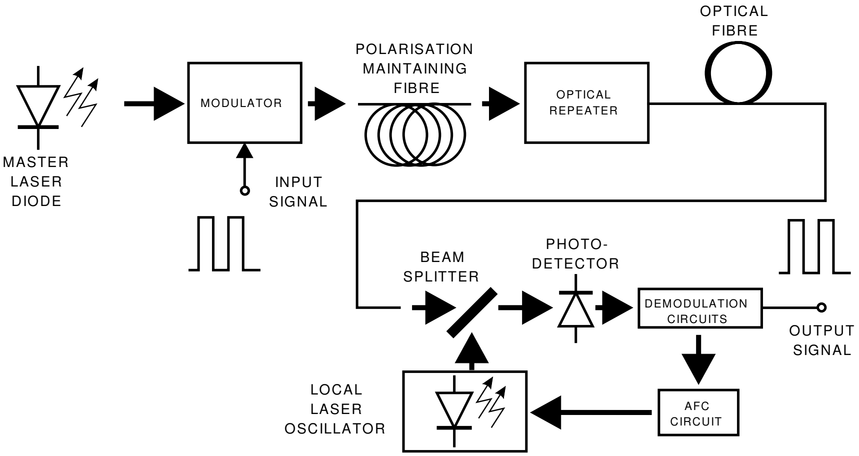

Fig. 1.4. Configuration for a coherent heterodyne optical fibre communication system.

higher bit-rate, the signal-to-noise ratio at the input to the receiver must be made as high as possible. In a system without repeaters, this will limit the maximum transmission span of the system [1]. An alternative detection method is to use coherent detection [4, 18] as shown in Fig. 1.4. By mixing the signal with a local oscillator at the input to the detector, it can be shown that a higher sensitivity can be achieved if the receiver is designed properly [5]. The principle is similar to that in a heterodyne radio [3]. In this system, one can easily, detect WDM transmission by tuning the local oscillator wavelength, as in a heterodyne radio system. In practice, however, because of the finite spectral width of the master and/or local oscillators which are usually SLDs, the limited tunability in SLDs and the extreme sensitivity of the receiver to the states of polarisation of the light signal will severely limit the performance of such complicated receivers [4]. Some of the recent field trials employing coherent detection are shown in Table 1.1 [5, 19–23].

Although coherent detection theoretically seems to offer a better performance for optical communications over direct detection, receivers employing this technique are very much at the research stage and their performance has yet to be improved [5]. On the other hand, many existing practical optical communication systems employ direct detection with intensity modulation. In order to use them for transmission of data with a higher data rate in the future, it is more economical if one can simply improve the input signal-to-noise ratio of the optical receiver instead of replacing or upgrading

Table 1.1. Recent coherent optical heterodyne transmission field experiments.

| Laboratory | Transmission Speed | Modulation Scheme | Route | Year |
|---|---|---|---|---|
| KDD | 565 Mb/s | FSK | Submarine Cable | 1988 |
| BTRL | 565 Mb/s | DPSK | Cambridge-Bedford | 1988 |
| AT & T | 1.7 Gb/s | FSK | Roaring Creek-Sunbury | 1989 |
| BTRL | 622 Mb/s | FSK, DPSK | Edinburgh-Newcastle | 1989 |
| BTRL | 620 Mb/s | DPSK | U.K.-Guernsey | 1989 |
| NTT | 2.5 Gb/s | FSK | Matsuyama-Ohita-Kure | 1990 |
| Japan | 32 × 1.244 Gb/s | CP-FSK | 121 km SMF | 1991 |
| BTRL | 4 Gb/s | CP-FSK | 100 km SMF | 1991 |
| Denmark | Up to 5 Gb/s | CP-FSK | In Lab | 1993 |
| U.S.A. | 26 GHz |  | Receiver | 1995 |
| Japan | 60 GHz | 64QAM | In Lab | 2001 |

existing components in the systems like using new optical fibres or replacing the entire receiver using coherent detection with a new modulation scheme. In addition, the problem of retrieving WDM signals using direct detection has been overcome by using tunable optical filters, which are cheaper than tunable SLDs at the input of the receiver [1]. Hence, it appears that, if the input signal-to-noise ratio of the receivers can be improved, existing direct detection systems with intensity modulation can be used for transmissions with an even higher data rate.

The weak signal at the receiver in many optical communication systems arises because of the accumulation of losses along the optical fibres [1]. Although the loss can be as low as 0.2 dB/km for optical fibres operating around 1.55 $\mu$m, for a long transmission span this can build up to a significant loss, which will degrade signal power and hence the overall system performance [24]. Two ways of improving the signal-to-noise ratio of an optical receiver are possible. One can either boost the optical signal power along the transmission path using in-line repeaters [25], or boost the optical signal power at the input of the receiver by a pre-amplifier [26]. For many applications, both methods must be used to improve the system performance. In-line repeaters can be constructed using electronic circuits, which consist of photodetectors, electronic circuits for demodulation of the signals, amplification circuits for loss compensation, and laser diode driving circuits for regeneration. These conventional electronic repeaters are known commonly as regenerative repeaters. With them, the signal-to-noise ratio at the input of the receiver can indeed be improved. However, since the specification and subsequent design and configuration of this type of regenerator depends heavily on the modulation format, data bit-rate, multiplexing scheme and, in the case of optical networks, the number of branches emerging from a node, they are uneconomical because of their poor flexibility [27].

To solve the flexibility problem for in-line repeaters and to provide a pre-amplifier for optical receivers, one must be able to amplify light signals directly. Direct optical amplification avoids regeneration circuits in the in-line repeaters, so they can be used for any modulation format of the signal [28] and provides a maximum flexibility for applications in systems [27]. Repeaters employing such techniques are commonly known as non-regenerative repeaters, and the devices which perform such tasks are called optical amplifiers, or quantum amplifiers [29]. These optical amplifiers are usually called laser amplifiers because stimulated emissions are involved in the amplification process, which is also responsible for oscillations in lasers. These optical amplifiers can also be used as pre-amplifiers to receivers to enhance their sensitivities further [30]. Improvement in system performance by using optical fiber and laser diode amplifiers as in-line repeaters and/or pre-amplifiers to optical receivers has been reported in numerous experiments, some of which are tabulated in Tables 1.2 and 1.3 [1, 22–49].

The future prospects of long distance optical communication systems thus depend heavily on the availability of low-cost optical amplifiers which can compensate for the build-up of losses in optical fibre cables over long distances [2, 4]. Two types of optical amplifier exist: semiconductor laser amplifiers (SLAs) and fibre amplifiers (FAs). SLAs are essentially laser diodes operating in the linear amplification region below oscillation threshold [28, 5–51], whereas FAs are optical fibres doped with Erbium ions ($Er^{+3}$) to provide optical gain [24]. SLAs have the inherent advantage of compactness and the possibility of integration with other opto-electronic components, whereas FAs have the advantages of easy and efficient coupling with optical fibres. The design and analysis of both these types of optical amplifiers are therefore crucial for future development in optical fibre communication systems.

In this book, the principles and applications of semiconductor laser amplifiers in optical communications will be explored. In Chapter 2, the fundamentals and important performance characteristics of optical amplifiers will be outlined. An introduction to optical amplification in semiconductor lasers will be described in Chapter 3. A formal treatment of the analysis of semiconductor laser amplifiers will be given in Chapters 4

Table 1.2. Recent transmission experiments with erbium doped fibre amplifiers (EDFAs).

| Year | Laboratory | Bit Rate (Gbit/s) | Distance (km) | Comments |
|---|---|---|---|---|
| 1989 | NTT | 1.8 | 212 | Booster + pre-amplifier used |
| 1989 | BTRL | 0.565 | — | DPSK system |
| 1989 | KDD | 1.2 | 267 | Two amplifiers used |
| 1989 | NTT | 20 | — | Soliton transmission |
| 1989 | Bell Core | 11 | 260 | Two amplifiers used |
| 1989 | Fujitsu | 12 | 100 | — |
| 1989 | KDD | 1.2 | 904 | 12 amplifiers used |
| 1990 | NTT | 2.5 | 2223 | 25 amplifiers used |
| 1991 | BTRL | 2.5 | $10^4$ | Recirculating loop |
| 1991 | NTT | 10 | $10^6$ | Soliton transmission, 12 amplifiers used |
| 1991 | NTT | 20 | 500 | Soliton transmission |
| 1992 | NTT | 2.4 | 309 | 4 Repeaters + pre-amplifier |
| 1992 | NTT | 10 | 309 | 4 repeaters + pre-amplifier |
| 1993 | BELL | 10 | 309 | EDFA + Dispersion Compensation |
| 1994 | BELL | 16 × 2.5 | 1420 | 14 amplifiers |
| 1995 | BELL | 2.5 | 374 | 1 local EDFA + 1 remotely-pumped EDFA + pre-amplifier |
| 1997 | BELL | 32 × 10 | 640 | 9 Gain-flattened broadband EDFA with 35 nm Bandwidth (Total Gain 140 dB and total gain ununiformity 4.9 dB between 32 channels spaced by 100 GHz) |
| 1998 | Alcatel | 32 × 10 | 500 | 4 EDFA + pre-amplifier (with 125 km amplifier spacing) |
| 2000 | KDD | 50 × 10.66 | 4000 | EDFA + low-dispersion slope fiber (40 km span) |
| 2000 | BELL | 100 × 10 (25 GHz spacing) | 400 | 4 EDFA + 4 Raman Amplifier |

to 6, where the waveguiding properties, and the basic performance characteristics such as gain, gain saturation and noise will be studied. A new technique for analysing SLAs using an equivalent circuit model will also be introduced. Implications for system performance will also be discussed. In Chapter 7, the accuracy and limitations of this model will be investigated by comparing theoretical predictions with the results of experimental measurements on actual devices. In Chapter 8 we introduce a new

Table 1.3. Recent transmission experiments with semiconductor laser amplifiers.

| Year | Laboratory | Bit Rate (Gbit/s) | Distance (km) | Comments |
|---|---|---|---|---|
| 1986 | BTRL | 0.14 | 206 | 2 amplifiers used |
| 1988 | AT & T | 1 | 313 | 4 amplifiers used |
| 1988 | AT & T | 0.4 | 372 | 4 amplifiers + FSK |
| 1988 | Bell Core | — | — | 20 Channels transmission |
| 1989 | BTRL | 0.565 | 400 | 5 amplifiers + DPSK |
| 1989 | KDD | 2.4 | 516 | 10 amplifiers used |
| 1991 | KDD | 0.14 | 546 | 10 amplifiers used |
| 1993 | Japan | 4 × 10 | 40 | 2 SOA preamplified receiver receiver with bandwidth of 40 nm |
| 1994 | PPT | 10 | 89 | 2 SOA preamplified receiver |
| 1995 | PTT | 2 × 10 | 63.5 | 2 SOA preamplified receiver |
| 1997 | BT | 40 | 1406 | 2 mm-long SOA for dispersion compensation |
| 1996 | | 10 | 420 | 38 km interval |
| 1997 | Germany | 10 | 550 | 34 km interval |
| 1998 | Germany | 40 | 434 | SOA for dispersion compensation + 3 EDFA |
| 1998 | Germany | 10 | 1500 | 38 km interval |
| 1999 | Germany | 80 | 106 | SOA for dispersion compensation |
| 2000 | Germany | 10 | 5000 | 25 km interval |
| 2000 | USA | 32 × 10 | 160 | 4 SOA (40 km interval) + 1 EDFA |
| 2000 | AT & T | 8 × 20 | 160 | 4 SOA (40 km interval) |
| 2001 | BELL | 10 (WDM) | 500 | 50 km interval |

semiconductor laser diode amplifier structure. Chapter 9 deals with amplification characteristics of pico-second Gaussian pulses in various amplifier structures. Chapter 10 studies the sub-pico-second gain dynamic in a highly index-guided tapered-waveguide laser diode amplifier. In Chapter 11 we introduce a novel approximate analytical expression for saturation intensity of tapered travelling-wave semiconductor laser amplifier structures. Wavelength conversion using cross-gain modulation in linear tapered-waveguide semiconductor laser amplifiers is studied in Chapter 12. The main theme of the work presented in Chapters 13 to 17 is microwave circuit principles applied to semiconductor laser modelling. The advantages and additional insight provided by circuit models that have been used for analytical analysis of laser diodes have long been acknowledged.

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In these chapters, we concentrate on the derivation, implementation, and application of numerical circuit-based models of semiconductor laser devices.

In Chapter 13 first, a short historical background and the relevant physics behind the semiconductor laser will be given. Chapter 14 introduces the transmission-line matrix (TLM) method that provides the basic microwave circuit concepts used to construct the time-domain semiconductor laser model known as the transmission-line laser model (TLLM). We then proceed to compare two categories of equivalent circuit models, i.e. lumped-element and distributed-element, of the semiconductor laser in Chapter 15. In the same chapter, a comprehensive laser diode transmitter model is developed for microwave optoelectronic simulation. The microwave optoelectronic model is based on the transmission-line modelling technique, which allows propagation of optical waves as well as lumped electrical circuit elements to be simulated. In Chapter 16, the transmission-line modelling technique is applied to a new time-domain model of the tapered waveguide semiconductor laser amplifier, useful for investigating short pulse generation and amplification when finite internal reflectivity is present. The new dynamic model is based on the strongly index-guided laser structure, and quasi-adiabatic propagation is assumed. Chapter 17 demonstrates the usefulness of the microwave circuit modelling techniques that have been presented in this thesis through a design study of a novel mode-locked laser device. The novel device is a multisegment monolithically integrated laser employing distributed Bragg gratings and a tapered waveguide amplifier for high power ultrashort pulse generation. Finally, Chapter 18 is devoted to some concluding remarks suggestions and comments.

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