619

Optical fibres, lasers, and amplifiers

W. A. Gambling

Initially, the only operation that could be performed in optical fibre communication was transmitting optical information from one point to another, necessitating complex auxiliary electronic circuitry. In recent years, however, a range of fibre components has been developed which promise to become as ubiquitous and indispensable as the transistor is in electronics.

Very few types of information can be transmitted in their raw form over distances of more than a few tens of metres: consider, for example, shouting and picture projection in a cinema! In order to be used in an effective way raw information has to be 'carried' on a suitable 'carrier'. Thus in the telephone the human voice (signal) is carried by an electric current (carrier), the amplitude of which is made to vary with the amplitude and frequency of sound waves striking the microphone in the telephone handset. The modulated electric current – that is, the modulated carrier – is then transmitted to a distant receiver over a copper wire. The fluctuations in electric current are then changed into corresponding fluctuations in air pressure (sound waves) by the loudspeaker in the receiving hand-set. Increasingly in modern systems the analogue-modulated current is coded in digital form before transmission. However, the general principles are the same for both analogue and digital modulation. The highest frequency of the human voice carried over the telephone system is 4 kHz and when coded into 'bits' (binary digits) a frequency of 4 kHz corrsponds to a bit rate of 64000 bit/s. Accurate transmission of the music from a symphony orchestra requires a bit rate of 1000000 bit/s, while the transmission of colour pictures by television involves a bit rate of 140000000 bit/s.

There is a limit to the rate at which any carrier wave can be modulated and this upper rate is comparable with the frequency of the carrier wave itself, although in practice one is hard pushed to modulate at a rate much more than 10 per cent of the carrier frequency. Thus audio information can be transmitted by relatively low-frequency radio waves; in technical terms, medium frequency and high frequency transmissions in the region of 1–10 MHz. For video transmission it is necessary to go to the much higher frequencies in the VHF and UHF ranges, in the region of 100 MHz, but even then only one video channel can be carried on a single carrier. The highest 'electrical' frequencies in use today are in the microwave region of 4 to 6GHz and this includes satellite communication and broadcasting. Great excitement was generated in the 1960s by the concept of optical fibre transmission because the frequency of an optical wave is 100000 times greater than that of microwaves and thus there was the potential that optical waves could be made to carry much more information than electrical waves.

Optical communication is not new. For example, in Britain the arrival of the Armada in 1588 was signalled by the lighting of a series of bonfires between Cornwall and London. Since each bonfire had to be allowed to burn out, then be relaid and lit, the rate of information transmission was of the order of 1 bit per day. The heliograph, using the sun and a flashing mirror, increased the bit rate to about 1 bit/s but this was very far from the 140 megabits per second required for television or the 10^{13} bits per second potentially possible with light.

The first major development was that of the laser providing, for the first time, a coherent optical source which potentially could be modulated. The second problem was how to guide that light in an efficient way over long distances, and this was solved by introducing the optical fibre. An optical fibre typically consists of a cylindrical glass structure with an inner core and a surrounding cladding. In a single-mode fibre the core is of the order of 5–10μm in diameter and the overall diameter of the fibre is about 120μm. By far the most efficient fibres known at the present time are those based on certain silicate glasses. Because of their small diameter these fibres are very flexible and can be curved to bend radii of about 1 cm without damage and without interfering with the propagating optical signal. The fibre is immune to electromagnetic interference and can be made with such a high degree of purity that absorption is reduced to a minute degree at wavelengths in the region of 1μm and the attenuation is largely determined by Rayleigh scattering.

Optical fibres have been developed to a high degree of sophistication for long-distance transmission [1]. Compared with coaxial cables which have a bandwidth of 20MHz or so over distances of 3 to 5km, optical fibres can have almost infinite bandwidth at repeater spacings of several hundred kilometres. They are also small, light in weight, flexible, and free from electromagnetic interference. It is not surprising, therefore, that optical fibres have already revolutionized telephone and data networks and are being rapidly installed in most countries of the world. Nevertheless, in normal communications terms optical fibre communication is still in a very primitive stage of development. The only operation that can be performed is that of transmitting optical information from one point to another. In order to process the information it must be converted back to electrical form and operated on in complex electronic circuits. The information then has to be reconverted to the optical wavelength. Such methods of signal amplification and processing are complex and expensive.

The next stage of optical fibre communication will require fibre components in both passive and active form. Passive components such as couplers, switches, and isolators are now becoming available commercially and research leading to active fibre devices is showing considerable promise.

Fibre lasers

The first major active fibre device was the fibre laser. Laser action is produced by introducing suitable rare-earth ions into the core of a single-mode fibre [2, 3]. When these ions are pumped by an optical source in an absorption band, relaxation occurs rapidly and the ions

W. Alex Gambling Ph.D., D.Sc., F.R.S., F.Eng., Hon. F.I.E.E.

After graduating in the University of Bristol he held appointments in the University of Liverpool before moving in 1957 to the University of Southampton, where he is now Professor of Optical Communication. His main research interests have been in plasmas, microwaves, quantum electronics, and optical fibres. He launched the University Optical Fibre Research Group in 1966, and is now Director of the SERC Interdisciplinary Optoelectronics Research Centre there.

Endeavour, New Series, Volume 16, No. 1, 1992.
0160–9327/92 $5.00 + 0.00.

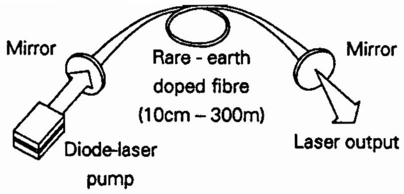


Figure 1 Schematic diagram of an optical fibre laser.

fall to a metastable energy state. They are then capable of amplifying spontaneous emission which arises from that state [4].

Laser action may be obtained by placing mirrors at each end of the fibre, as shown in figure 1. The considerable advantages of the fibre configuration arise from the fact that the pump radiation travels along the axis of the fibre and is guided by the core, as is the lasing radiation. There is, therefore, very efficient coupling between the pump radiation and the ions, while the pump intensity is very high because of the small core diameter. Pumping efficiencies approaching 100 per cent become possible and slope efficiencies exceeding 60 per cent have been measured, as have threshold pump powers of a few hundred microwatts.

Fibre lasers are small, robust, flexible, and give easy access to the laser cavity, thus enabling the operations of Q-switching, mode-locking and line-narrowing to be carried out. Because of the large fluorescent linewidths large tuning ranges have been reported – over 70nm in erbium, 150nm in ytterbium, and 300nm in thulium. These tuning ranges are enormous. New lasing wavelengths in the visible region of the spectrum at 651nm have been obtained with samarium [5], as well as at 491nm, 520nm, 605nm, and 635nm in a praseodymium upconversion laser [6] and others are likely to follow. Figure 2 indicates some of the various wavelengths, ions, and fibres so far reported.

Developments in fibre lasers are occurring rapidly and likely performance achievements over the next five years are listed in Table 1. Considering that the new methods of doping the cores of optical fibres with rare-earth and transition-metal irons were developed only six years ago these are remarkable achievements. Fibre lasers have many advantages over diode lasers, as indicated in Table 2, and may well exceed them in performance in all but one aspect: diode lasers can be directly modulated by an electrical signal whereas the fibre laser requires an external modulator. On the other hand, this situation will change as the requirement for higher modulation rates emerges, when the laser diode also will require an external modulator. The balance of advantage will then shift even more strongly to the fibre laser.

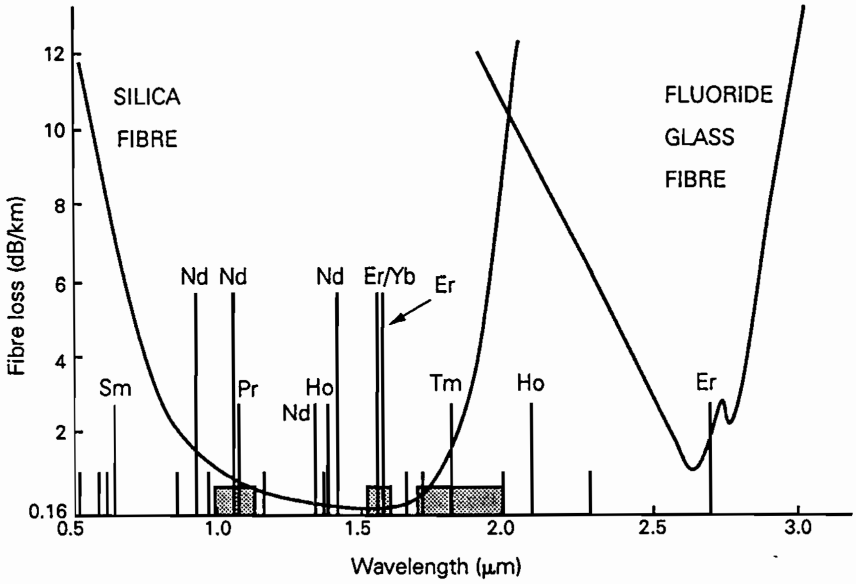


Figure 2 Selected fibre laser emission lines superimposed on the attenuation curves of silica-based fibres and fluoride fibres. The shorter lines are unlabelled to avoid confusion on the diagram. The shaded regions denote the tuning ranges described in the text.

An example of the flexibility in cavity design available in the fibre laser is given in figure 3 where a metal strip is placed alongside the core [7] to provide a high loss to one of the polarisation directions with little loss to the other. Preferred polarisation directions are created by the elliptical core. The output of this laser is linearly polarised. Switching between the two polarisation eigenmodes has also been demonstrated [8].

TABLE 1 RARE-EARTH-DOPED GUIDED-WAVE LASERS

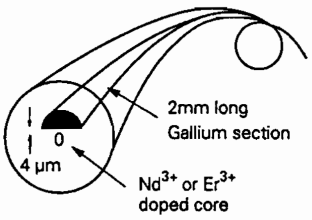
The Future

- Tunable CW output > 1W
- Q-switched output > 10kW
- Mode-locked pulse duration << 1ps, power > 10kW
- 470nm frequency-doubled output > 100mW
- Intra-cavity non-linear effects in fibres
- Wavelengths 0.9μm to 4μm diode-pumped
- Upconverters into the visible and UV
- New transitions

TABLE 2 SOLID-STATE LASERS VS DIODE-LASERS

- Visible emission possible
- Peak powers > 1kW
- Easy resonator access and complex cavities
- Distributed devices
- Polarisation independent
- Quieter, more stable
- Shorter pulses

Because of the broad fluorescence width of the laser ions, fibre lasers operate on many longitudinal modes and emit over a range of wavelengths. However, the ease of access to the cavity allows great flexibility in laser design. Thus the evanescent field of the core can be accessed by polishing away the cladding glass to allow a diffraction grating to be deposited [9] by photolithographic techniques, close to the core of the fibre. In this way the output can be limited to only a single longitudinal mode, thus reducing the linewidth to as little as 1MHz. In a travelling-wave ring configuration [10] the linewidth has been reduced to 10kHz. Alternatively, a grating can be produced by creating a periodic series of defects by optical interferometric techniques. In principle, a distributed feedback fibre laser can be constructed at a



	Polarised Output	Extinction ratio
Nd^{3+} (1.09 μm)	20mW	35dB
Er^{3+} (1.55 μm)	1.2mW	22dB

Figure 3 Fibre laser with an elliptical core and an integral metal polariser.

localised position in a longer length of fibre without the need for splicing – a truly integrated component.

The ease of resonator design has led to many novel configurations. Thus a loop of fibre connected to the lasing fibre via a coupler produces a loop mirror having interesting properties. A further development incorporates a fibre amplifier into one end of such a fibre loop mirror, producing a very low threshold Sagnac switch of very high switching speed. In one version the loop length was 336m and contained an erbium fibre amplifier with a gain of 46dB at a wavelength of 1.536μm. The switching power of 0.2mW is 5000 times smaller than previously reported values. The switching time of less than 1ns was not optimised [11].

An additional major advance in the application of such non-linear amplifying loop mirrors results in a figure-of-eight fibre configuration with an isolator in one loop and an amplifying section of fibre in the other. The two loops are connected by a 50:50 coupler. In one mode of operation the system behaves as a self-starting, passively mode-locked, laser. A typical output consisted of 150ps pulses at a rate of 16MHz. Input pumping powers were tens of milliwatts [12].

Perhaps the most exciting mode of operation is where the system generates a regular train of soliton pulses. Pulses as short as 320 femtoseconds at pulse rates of 10GHz have been reported [13] and it is expected that by using the full 35nm bandwidth of the erbium fibre amplifier the pulse width should be reduced to 80fs. This fibre laser configuration is an extremely attractive soliton source for future communication systems.

Fibre amplifiers

Probably the most immediate application of rare-earth-doped (RED) fibres will be as fibre amplifiers [14], which consist of only a short length of RED fibre with optical pumping radiation coupled into the core via a dichroic coupler (figure 4). The coupler has a high coupling ratio at the pump wavelength but prevents loss of the signal power. The pump source can be a diode laser of simple construction. It can be seen that the fibre amplifier comprises only three basic components – fibre, coupler, and diode laser – so that it is highly reliable, small (10cm to a few metres in length), highly efficient and should eventually be cheap compared with an electronic repeater.

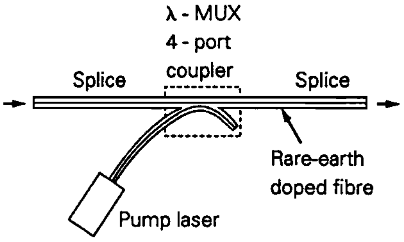


Figure 4 Schematic diagram of a fibre amplifier.

Erbium-doped fibre amplifiers

The erbium-doped fibre amplifier (EDFA) has recently attracted very considerable attention in optical fibre communications [15]. The EDFA conveniently operates in the preferred telecommunications spectral window located at a wavelength of 1.55μm. In this wavelength region the ordinary, undoped, optical fibre based on silica (typically a germano-silicate core with a boro-fluoro-silicate cladding) has a transmission loss of 0.15dB/km, nearly 100 times lower than a high-frequency copper coaxial cable. It is also possible at these wavelengths to balance the glass material dispersion with that of the waveguide dispersion to produce enormously wide bandwidths [16]. No wonder this is the preferred wavelength of operation in practical systems! It is a most fortuitous coincidence that erbium-doped fibre lasers and amplifiers also operate at this frequency. In addition, the EDFA has been shown to have high polarisation-insensitive gain (>40dB); low-crosstalk between signals at different wavelengths; good saturation output power (>0dBm); and a noise figure close to the fundamental quantum-limit (~3dB). The excellent noise characteristics potentially allow hundreds of amplifiers to be incorporated along the length of a fibre telecommunication link, which could then span more than 10000km. Compared with the alternative of a transmission link using electronic repeaters, an all-optical link has the merit that it is transparent to the transmission code format and bit rate. It can thus be uprated by changing only the transmitter and receiver, and not the repeaters.

Although Stark-splitting of the ground and metastable levels in erbium-doped glass generates a wide spectral bandwidth in an EDFA, its gain spectrum is typically irregular compared with that of its diode-amplifier rival, having a sharp peak 3.5nm wide at 1.53μm. While the amplifier can be operated at wavelengths away from the peak gain, disadvantages occur due to increased spontaneous × spontaneous beat noise and possible laser action at the wavelength of maximum gain.

TABLE 3 WHY ERBIUM FIBRE AMPLIFIERS?

- 1.5μm
- Broadband
- High gain (> 30dB)
- Fibre compatible
- Low noise
- Power- or pre-amplifier
- Diode laser pumping

However, by incorporating an optical filter within the length of an EDFA, the overall gain spectrum and gain characteristics can be modified to be nearly uniform over the entire 1.53–1.56μm range [17]. An optical notch filter located at the centre of the amplifier and tuned to suppress the gain spectrum at the peak wavelength, produces a broadband amplifier with a 3dB bandwidth of 33nm at a gain of 27dB. Locating the filter within the amplifier length has considerable advantages, particularly with regard to pump efficiency, since amplified spontaneous emission is suppressed before it has risen to a significant value.

Table 3 summarizes the properties of the erbium fibre amplifier. High efficiency is achieved by adjusting the combination of length and doping concentration so that all of the pump power entering the core is absorbed in the amplifying region of the fibre. Optical amplifiers are analogue devices and cannot perform digital regeneration but the noise performance is such that they can be concatenated whilst still preserving low distortion/error rates at high bandwidth.

As with other amplifiers the doped fibre amplifier (Table 4) can be operated as a line amplifier, a power amplifier, or as a pre-amplifier. Its properties as a line, or signal, amplifier are discussed above. As a power amplifier it is capable of CW output powers approaching 1W and one of its first applications could well be to amplify the output of a modulated diode laser to form a powerful transmitter. If the diode output is amplified by, say, 20dB then the permitted transmission distance is increased by 100km. Similarly, when placed immediately prior to a detector the receiver sensitivity can be

TABLE 4 APPLICATIONS OF OPTICAL AMPLIFIERS

Power Amplifier	Line Amplifier	Pre-Amplifier
● Boosts source power Telecoms Non-linear switching PS pulses	● Low Noise Telecoms repeaters	● Low Noise Improved detection High bit-rates

increased by an even greater amount, giving rise to another increase in transmission distance.

Unlike a diode amplifier, the erbium-doped fibre amplifier has a saturation output power which increases with pump power, as well as an ability to operate deep in saturation without signal distortion and interchannel crosstalk. The latter is a consequence of having slow gain dynamics which are quite different from those of the diode-amplifier. As a consequence of these two attributes, when EDFAs are employed as power amplifiers, where the input signal is large and the amplifier heavily saturated, near quantum-limited differential pump/signal conversion efficiencies are possible. Thus highly-saturated EDFAs are efficient power amplifiers with a maximum absolute pump/signal power conversion efficiency as high as 47 per cent. The slope efficiency is near quantum-limited at 53 per cent. It is also noteworthy that power amplifiers operating in the highly-saturated mode have virtually flat spectral-gain characteristics, owing to their largely homogeneously-broadened behaviour.

The erbium fibre amplifier is very stable because the pumping power is stored in a metastable energy level which acts as a form of reservoir from which energy can be drawn when required. Thus the gain is largely independent of both the wavelength and magnitude of the pumping diode over quite large ranges, and when saturation begins to occur the gain falls by only 5dB for an increase in signal power from 100μm to 2mW.

The fibre amplifier is an important new active device that will have applications in many different situations, such as long-distance transmission, local-area networks, sensors, non-linear optics, and novel optical circuits. There are some spectacular examples of the use of the optical fibre amplifier in communications. Thus a transatlantic cable is planned for 1995 powered completely by optical amplifiers, and a similar cable across the Pacific Ocean will be laid in 1996. More experimentally, transmission of 45ps solitons at 10Gbit/s through 1000km of dispersion-shifted single-mode fibre has been demonstrated with 22 EDFAs separated by 50km. In a related experiment multiple transmission around a 500km loop with amplifiers again spaced by 50km resulted in soliton propagation over a total length of 1000000km at 10Gbit/s [18]. By incorporating a novel pulse-shaping and retiming technique the output pulse shapes and pulse trains were indistinguishable from those at the input. This is a remarkable result. A distance of 1000000 km corresponds with a round trip from the Earth to the Moon and back again, and obviously there is no practical requirement for such a system. Nevertheless, the experiment shows that terrestrial optical fibre transmission can now take place over unlimited distances with almost unlimited bandwidths. Even more importantly, the pulse-shaping and retiming technique reduces pulse and timing distortions to what was hitherto an unbelievable level.

Long-distance transmission is only one of the potential applications for the fibre amplifier which, in fact, will become the basic building block of all optical signalling systems. It will become a component as common, ubiquitous and indispensable as a transistor is to electronics. Following long-distance transmission the second key application will be to video and data distribution in local-area networks. Thus an optical fibre carrying signals from a sub-station to a distribution point will be fed directly into an optical amplifier before the signal is split into several hundred lines for distribution to individual houses and buildings. The power supply for the whole operation can remain in the sub-station.

The extremely high efficiency and output power of the fibre amplifier has already begun to simulate a major new interest in non-linear optics and the creation of new fibre devices based on non-linear interactions. Some of these have already been described. There will be further developments in harmonic generation providing new and shorter wavelengths with appreciable power whilst the large line widths will give rise to powerful tunable coherent sources covering a wide wavelength range.

The optical fibre amplifier was first demonstrated at the University of Southampton Optical Fibre Group in 1987 [14] and rapidly stimulated worldwide interest (figure 5). Its importance may be judged from the fact that since the first paper and accompanying patent over 600 papers have appeared in the literature and, in 1989, only AIDS, cold fusion, and superconductors generated more interest in the scientific community.

Conclusions

The revolution in telecommunications brought about by the advent of conventional single-mode optical fibres is only the first stage in their exploitation. The second stage, namely their application to passive components and optical sensors, is proceeding steadily but not very rapidly. The third stage, involving the creation of a new range of active devices, is upon us and is advancing very rapidly indeed. Some predictions of performances likely to be achieved within the next five years are contained in Table 5. Compared with what was thought possible only two years ago these are remarkable indeed.

The developments described here have been brought about purely through the creation of optical fibres incorporating new materials. Progress

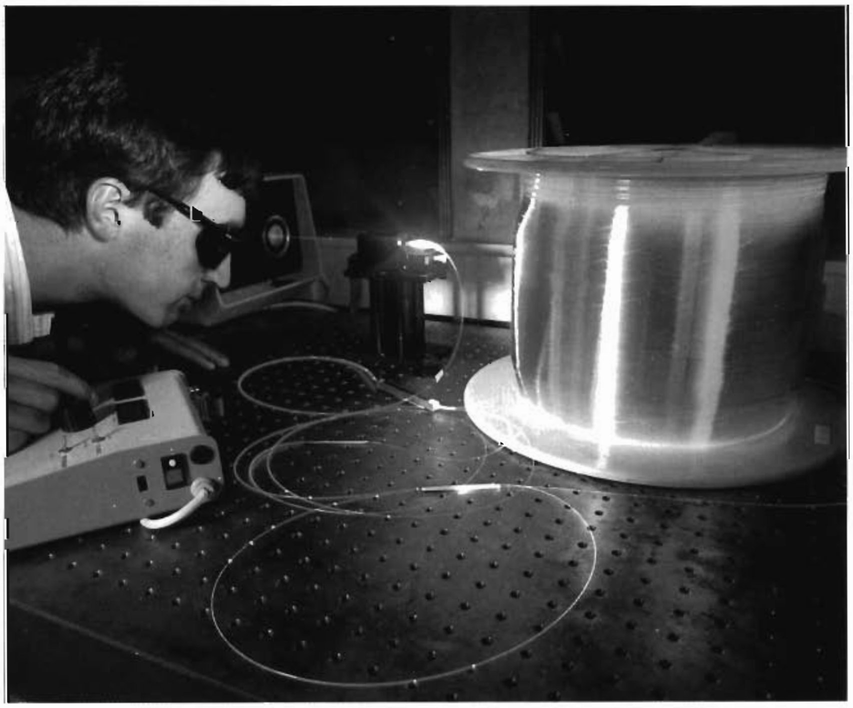


Figure 5 Work being carried out on the Er^{3+}-doped optical fibre amplifier developed at Southampton University. Using this revolutionary device, it is now possible to exploit the extremely large bandwidth provided by the optical fibre over long-haul and inter-continental telecommunication networks. Trans-Atlantic and trans-Pacific links using the Er^{3+}-amplifier are planned for the mid-1990s.

Figure 6 Conventional telecommunication fibre has exceptionally high transmission for near infrared light, but heavily attenuates in the blue region of the spectrum. A special fibre capable of transmitting high power blue light has been developed by Southampton University, aimed at the ever-expanding fibre sensor market. The first use of the fibre has been to carry out remote laser Doppler velocimetry using a high power Ar$^+$-ion laser operating at 488nm.

has also been made in designing new types of fibre structure which will increase the versatility of fibre applications still further. It is not possible to treat these in detail here and only one will be mentioned. Thus fibres have been produced [19] with metal structures parallel to, and very near the core. By applying modest voltages to the metal components the electric field across the core can be as high as 800 V/μm (800 megavolts per metre). Such a large field is sufficient to distort the electron shells of the core atoms and a wide range of interesting and applicable effects have been observed.

Active fibre devices can be designed and fabricated for specific applications and wavelengths. Many new devices, sources, and sensors are now possible and it is expected that the range will be extended by the introduction of new fibres based on new materials, some of which perhaps can be created only in fibre form. There will be parallel developments in planar optical devices as fibre fabrication techniques are adapted to planar technology. The drive towards creating new devices, particularly those involving non-linear optical effects, will also shed light on many fundamental optical and materials properties. The next few years will be very fruitful.

The remarkable developments in optical fibre materials and structures have produced a revolution in optical signal processing for communications. The interplay between applied and basic research as exemplified by the programme at the Optoelectronics Research Centre is fascinating (figure 6). The perceived requirement for a new device or application requires appropriate basic research to evaluate the materials or fabrication possibilities. Having determined likely approaches a good deal of applied research follows which, in turn, sheds light on the underlying science and suggests new avenues for fundamental research. Often the only difference between applied and fundamental research is not what is being done but why it is being done.

TABLE 5 APPLICATIONS OF ACTIVE FIBRES

- Tunable, fs-pulse, all-guided-wave laser emitting > 10kW peak power at 1.55μm
- High-power diode-pumped solid-state guided-wave sources emitting > 1W c.w.
- Tunable up-converter guided-wave lasers emitting in the visible and blue regions. Output power > 100mW
- Low-noise c.w. and fs-pulse amplifiers for pre-, line and power amplification. Output power > 1W c.w.
- All-optical switching and new non-linear effects
- Distributed acoustic, intruder, radiation and temperature sensors

References

[1] Gambling, W. A. Glass, light, and the information revolution. *Glass Technology*, Vol. 27, No. 6, pp. 179–187, 1986.

[2] Poole, S. B., Payne, D. N. and Fermann, M. E. Fabrication of low-loss optical fibres containing rare-earth ions. *Electronics Letters*, Vol. 21, No. 17, pp. 737–738, 1985.

[3] Townsend, J. E., Poole, S. B. and Payne, D. N. Solution-doping technique for fabrication of rare-earth-doped optical fibres. *Electronics Letters*, Vol. 23, No. 7, pp. 329–331, 1987.

[4] Orazio, Svelto. 'Principles of Lasers' (Trans. David C. Hanna), Plenum Press, New York, 1976.

[5] Farries, M. C., Morkel, P. R. and Townsend, J. E. Samarium^{3+}-doped glass laser operating at 651nm. *Electronics Letters*, Vol. 24, No. 11, pp. 709–711, 1988.

[6] Smart, R. G., Hanna, D. C., Tropper, A. C., Davey, S. T., Carter, S. F. and Szebesta, D. CW room temperature upconversion lasing at blue, green and red wavelengths in infrared-pumped Pr^{3+}-doped fluoride fibre. *Electronics Letters*, Vol. 27, No. 14, pp. 1307–1309, 1991.

[7] Li, L., Birch, R. D. and Payne, D. N. High-performance composite metal/glass fibre polarisers. Proc. European Conference on Optical Communication, Barcelona, pp. 137–140, September 1986.

[8] Lin, J. T., Wells, P. J., Minelly, J. D. and Payne, D. N. Photon-injection polarisation-switching in fibre lasers. Proc. 16th European Conference on Optical Communication, Vol. 1, Paper WeB4.1, pp. 563–566, Amsterdam, 16–20 September 1990.

[9] Jauncey, I. M., Reekie, L., Mears, R. J., Payne, D. N., Rowe, C. J., Reid, D. C. J., Bennion, I. and Edge, C. (Plessey Caswell) Narrow-linewidth fibre laser with integral fibre grating. *Electronics Letters*, Vol. 22, No. 19, pp. 987–988, 1986.

[10] Morkel, P. R., Cowle, G. and Payne, D. N. A travelling-wave erbium fibre ring laser with 60kHz linewidth. *Electronics Letters*, Vol. 26, No. 10, pp. 632–634, 1990.

[11] Richardson, D. J., Laming, R. I. and Payne, D. N. Very low threshold Sagnac switch incorporating an erbium-doped fibre amplifier. *Electronics Letters*, Vol. 26, No. 21, pp. 1779–1781, 1990.

[12] Richardson, D. J., Laming, R. I., Payne, D. N., Matsas, V. and Phillips, M. W. Self-starting, passively mode-locked erbium fibre ring laser based on the amplifying Sagnac switch. *Electronics Letters*, Vol. 27, No. 6, pp. 542–544, 1991.

[13] Richardson, D. J., Laming, R. I., Payne, D. N., Phillips, M. W. and Matsas, V. J., 320fs soliton generation with passively mode-locked erbium fibre laser. *Electronics Letters*, Vol. 27, No. 9, pp. 730–732, 1991.

[14] Mears, R. J., Reekie, L., Jauncey, I. M. and Payne, D. N. High-gain rare-earth-doped fibre amplifier at 1.54μm. *Technical Digest*, IOOC/OFC, Reno, Nevada, Paper W12, January 1987.

[15] Welter, R., Laming, R. I., Vodhanel, R. S., Sessa, W. B., Maeda, M. W. and Wagner, R. E. Performance of an erbium-doped fiber amplifier in a 16-channel coherent broadcast network experiment. Proc. CLEO, Baltimore (Postdeadline Paper) April 1989.

[16] Gambling, W. A., Matsumura, H. and Ragdale, C. M. Mode dispersion, material dispersion and profile dispersion in graded-index single-mode fibres. *Microwaves, Optics and Acoustics*, Vol. 3, (6), pp. 239–246, November 1979.

[17] Tachibana, M., Laming, R. I., Morkel, P. R. and Payne, D. N. Erbium-doped fibre amplifier with flattened gain spectrum. *Photonics Technology Letters*, Vol. 3, No. 2, pp. 118–120, 1991.

[18] Nakazawa, M., Yamada, E., Kubota, H. and Suzuki, K. 10Gbit/s soliton data transmission over one million kilometres. *Electronics Letters*, Vol. 27, No. 14, pp. 1270–1272, 1991.

[19] Li, L., Wells, P. J., Taylor, E. R. and Payne, D. N. Electric-field induced permanent second-order susceptibility for second-harmonic generation in optical fibres. Proc. XVII International Conference on Quantum Electronics (IQEC'90), Vol. 8, Paper QTH06, pp. 274–275, Anaheim, California, 21–25 May 1990.