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Optical fibres in telecommunications

An update on optical fibres, especially the active fibre, in telecommunications.

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In recent years, the field of telecommunications has undergone a major revolution with the introduction of optical fibre as a replacement for coaxial cable on major trunk routes. Fibre offers significant advantages over coaxial cable in terms of cost, convenience and, most especially, performance. It is now possible to link major cities within the UK by using unrepeatered lengths of high bandwidth, low loss single-mode optical fibre. There is, however, a need for signal boosters on the long haul, land-based and submarine links now being installed. These repeaters are spaced at intervals of approximately fifty kilometres and, for submarine links such as the transatlantic cable, TAT-8, must be extremely reliable and maintenance-free.

Current repeater technology relies on a hybrid technique whereby the optical signal is taken from the fibre and amplified by means of conventional electronics. The signal is then relayed to the next station. Not only is this technique cumbersome and expensive, but it may not be able to cope with the demands of future systems handling many gigabits per second. The logical solution is to amplify the optical signal directly, either within the fibre or externally, and several different techniques have been adopted.

All installed optical fibre links use either semiconductor diode lasers or light emitting diodes (LEDs) as the signal source. The former device is favoured for long distance applications due to its higher power and greater coherence, or spectral purity. Since a laser is merely an optical amplifier to which feedback has been applied by means of a pair of mirrors, it is possible to process the semiconductor laser in such a way that it behaves purely as an optical amplifier.[1] Research has been carried out on these devices since the mid-1960s, with renewed activity in recent years due to the need for an all optical repeater.

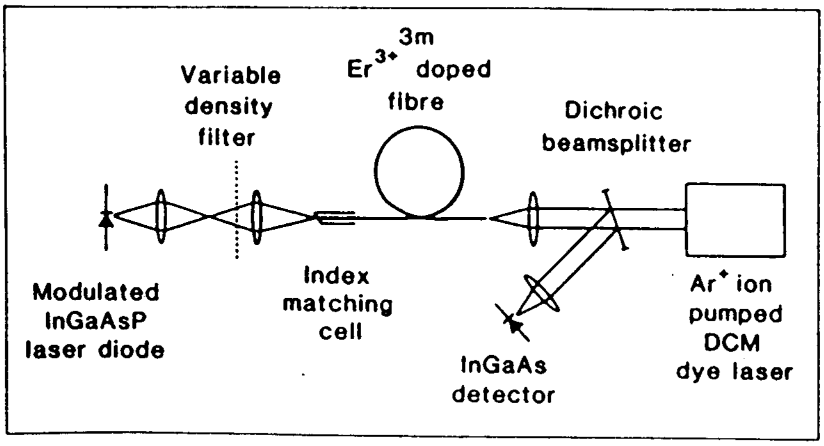
Optical amplification using this technique is by no means easy. Typical devices are no larger than a pinhead, the mirrors being formed by cleaving the crystalline facets of the laser itself. The facet reflectivity is suppressed by applying dielectric anti-reflection coatings, a painstaking process which must be done carefully if the full benefits are to be realised. There is also the problem of coupling light from the fibre into the semiconductor laser/amplifier and back into the receiving fibre with minimum loss, made more difficult by the waveguide mismatch between fibre core and laser. In spite of these difficulties, respectable results have been achieved, and British Telecom are now carrying out field trials.

Keeping it in the fibre

A far more satisfactory approach is to amplify the optical signal without removing it from the fibre. This eliminates the problem of coupling light from the input to the output fibre, leading to a more efficient and rugged device. Light is launched from a pump laser into the fibre and somehow coupled to the signal in such a way that amplification is achieved. Normally, the coupling is carried out via some non-linear interaction such as Raman or Brillouin scattering, placing stringent requirements on the type of pump laser which may be used.

The traditional role of the optical fibre has been as a passive carrier of light, and the ultra low loss silica/germania fibres now in use have been designed not to interact with the signal that they carry. As such, telecommunications-grade optical fibre is not the ideal medium in which to carry out non-linear interactions. Until

Figure 1: Experimental doped fibre amplifier



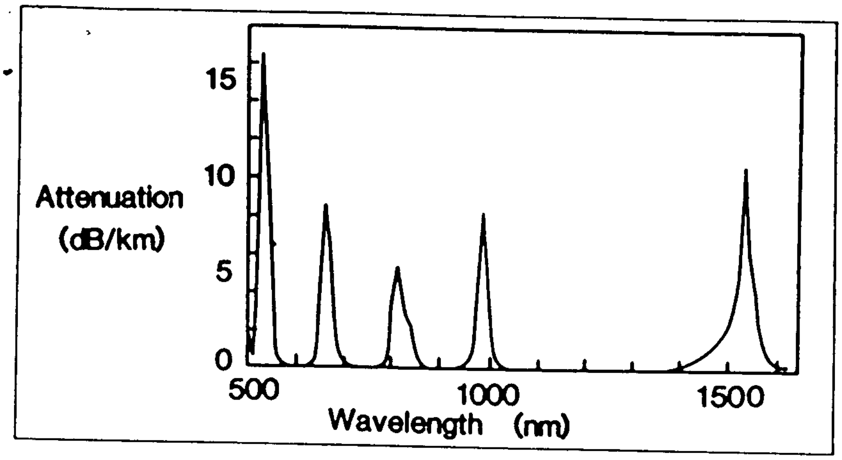


Figure 2: Attenuation of Er^{3+} doped fibre

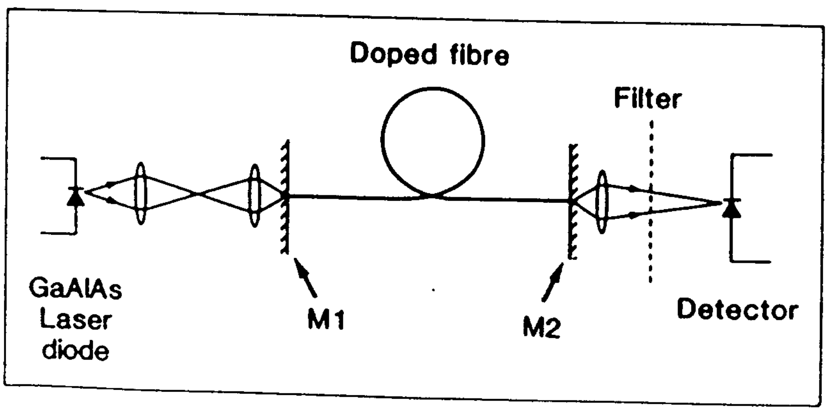
recently, Raman amplification involved relatively large, high power lasers as the pump source, restricting their use to laboratory demonstrations. Using specially designed semiconductor lasers, it has been shown recently that diode laser pumped operation of such a fibre amplifier can be achieved.[2] A fibre-to-fibre gain of 5dB has been recorded in early trials. Much work remains to be done, however, before a practical system based on this technique can be demonstrated.

The technique of Brillouin scattering as a means of optical amplification places even more stringent requirements on the pump and signal lasers.[3] The wavelength of operation and the spectral purity of the pump laser must be accurately controlled with respect to that of the signal. Furthermore, the gain/bandwidth product of the amplifier is significantly less than that of the other amplifiers already mentioned, and the difference places severe restrictions on the applicability of this technique for high bit-rate communication systems.

Using rare-earth lasers

The most recent and perhaps most promising newcomer in the field is the rare-earth doped optical fibre. Researchers in the Optical Fibre Group at the University of Southampton have shown that single-mode optical fibres, similar to those used in telecommunications, can be doped with rare-earth ions such as neodymium (Nd^{3+}) and erbium (Er^{3+}) without incurring the large optical losses which are normally associated with doped glasses.[4,5]

Figure 3: Semiconductor laser pumped single-mode fibre laser



Doped fibres can now be fabricated with losses in excess of 50dB/m in the visible and near infrared regions of the spectrum in the absorption bands associated with the rare-earths, whilst maintaining the low losses (typically ~1dB/km) at other frequencies found in telecommunication grade fibre. It has become possible therefore to adapt the techniques used in bulk rare-earth doped glass lasers and amplifiers for use with optical fibres.

Fibre lasers and amplifiers are by no means a new development; much of the seminal work was carried out in the early 1960s using large core (multimode) fibres fabricated from samples of bulk doped glass. The work of the Southampton group has simply brought the technology into the 1980s so that it is compatible with currently available single-mode optical fibres. Rare-earth ions possess the desirable property of absorbing light in the visible and near infrared bands ($<1\mu m$) as has been mentioned, and re-emitting in the infrared region between $1\mu m$ and $3\mu m$ with good efficiency.

If an optical signal that is resonant with such an emission (ie, of the same wavelength) is launched into the fibre, then it will be amplified. The most common dopants to have been studied to date are those already mentioned, Nd^{3+} and Er^{3+}. Of these, Er^{3+} is best suited to telecommunication applications. Er^{3+}-ions in glass fluoresce predominantly in the region of $1.54\mu m$, which coincides with the region of lowest loss in silica/germania optical fibres, the so-called 'third window' of optical communications.

The absorption spectrum of an Er^{3+}-doped fibre consists of several prominent bands at 530nm, 650nm, 810nm and 980nm. The most important is the 810nm band, which coincides rather well with the emission of cheap, readily available GaAlAs diode lasers. It provides a route to diode laser pumping of an Er^{3+}-doped fibre amplifier.

It should be noted that there is a strong absorption band around $1.54\mu m$, coincident with the fluorescence of the Er^{3+}-ions. This is characteristic of the three-level nature of the Er^{3+}-transition. Fluorescence occurs to the ground state of the Er^{3+}-ion, and it is necessary to 'bleach' this absorption before amplification can be obtained. In bulk glass form, bleaching would require at least several hundred watts of optical power, rendering it useless for practical purposes because of the power requirements and thermal loading. However, due to the small size of the core in a single-mode optical fibre, typically $<10\mu m$, the necessary high intensities can be attained by using only a few milliwatts of optical power, such as may be provided by a diode laser.

Preliminary work has been carried out using a dye laser as the power source for the amplifier. This laser can be conveniently 'tuned' on to the peak of the absorption band, thus optimising the amplifier's performance. Diode laser pumping of the amplifier is also underway. Even at this early stage, impressive results have been obtained, rivalling those of the more established technologies. Using a three metre length of Er^{3+}-doped single-mode optical fibre, a substantial gain of 28dB has been obtained at a rate of 140Mbit/s.[6]

The amplifer's noise and saturation characteristics also compare favourably with other methods of amplification. The wide fluorescence linewidth of the Er^{3+}-ion in glass allows for the simultaneous amplification of many signals separated by a small wavelength difference, a technique known as wavelength division multiplexing.

This broad linewidth will also lend itself to the amplification of picosecond pulses, allowing transmission rates in excess of 100Gbit/s, which are well beyond the capabilities and needs of current, and indeed future telecommunication systems. It is interesting to note that this work has triggered a major research effort in many of the world's major telecommunication research laboratories into the properties of this type of fibre.

The use of doped fibre is not restricted to solving the problems of optical amplification in telecommunications. If optical feedback is applied using suitable mirrors, then the fibre can be made to lase in a variety of ways. The beauty of the single-mode optical fibre as a lasing medium is that a highly intense and well-controlled beam of light can be confined over long distances at both the pump and lasing wavelengths. In its simplest configuration, the laser cavity is formed by cleaving or polishing the ends of the doped fibre and then butting against suitable mirrors. It is possible of course to coat the mirrors directly on to the end of the fibre.

Battery-powered lasers

The power requirements of such a device are exceedingly low, and a Nd^{3+}-doped fibre laser has exhibited a threshold of $<100\mu W$. It is possible therefore to use an inexpensive, commercially available diode laser as the power source. The concept of a compact, battery powered laser may be used in a variety of applications. At first sight, there would appear to be little advantage in using a diode laser as the pump source for another laser, when the diode laser itself may be capable of being used in a particular application. It should be noted, however, that the fibre laser possesses markedly different properties from the diode laser which make it the laser of choice for many applications.

The linewidth of the rare-earth ions which, as has been mentioned, is substantially broadened in glass, allows the laser to be tuned over a large range of wavelengths. A wavelength selective element, such as a prism or diffraction grating, is inserted into the cavity. A tuning range of 50nm to 100nm is usually obtainable. It is possible therefore to fix the wavelength of the laser in order to suit a specific application, or to scan the wavelength continuously over a given range.

The latter ability is particularly attractive when considering the laser as a source for optical fibre sensors, a relatively new type of device which is finding widespread use due to its inherent safety and immunity from ambient electrical noise in an industrial environment. The Nd^{3+}-doped fibre laser is particularly versatile, in that it can be tuned over two separate bands, centred at 938nm and 1088nm. Operation on the 938nm line has the advantage that inexpensive silicon photodiodes can be used to detect the laser output, lowering the overall cost of the system.

It is possible to generate short, intense pulses of light using a technique known as Q-switching. An optical switch, typically an acousto-optic modulator, is inserted into the cavity in such a way that it introduces a substantal loss, preventing the onset of lasing. This allows a relatively large population inversion to build up which, when the optical switch is toggled, is released as a short, intense pulse of light.

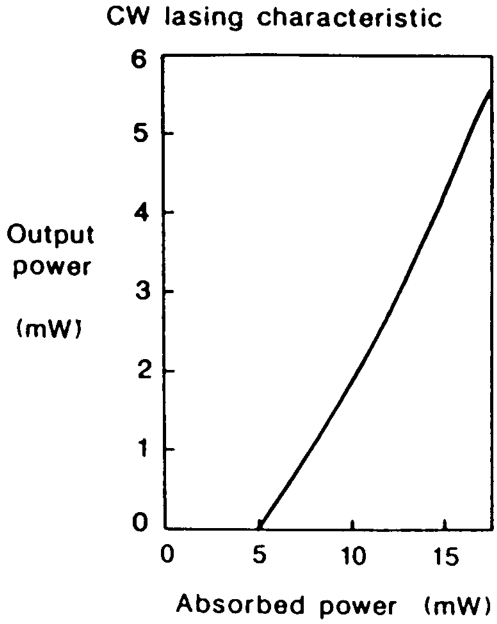


Figure 4: Diode-pumped Nd^{3+} fibre laser

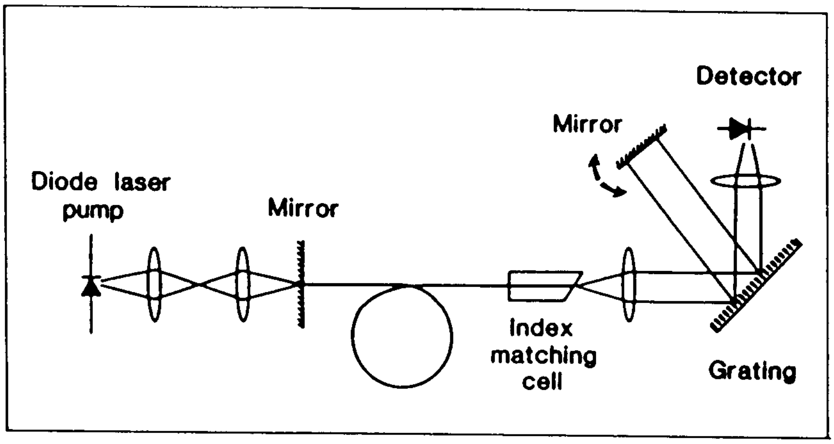


Figure 5: Tunable fibre laser

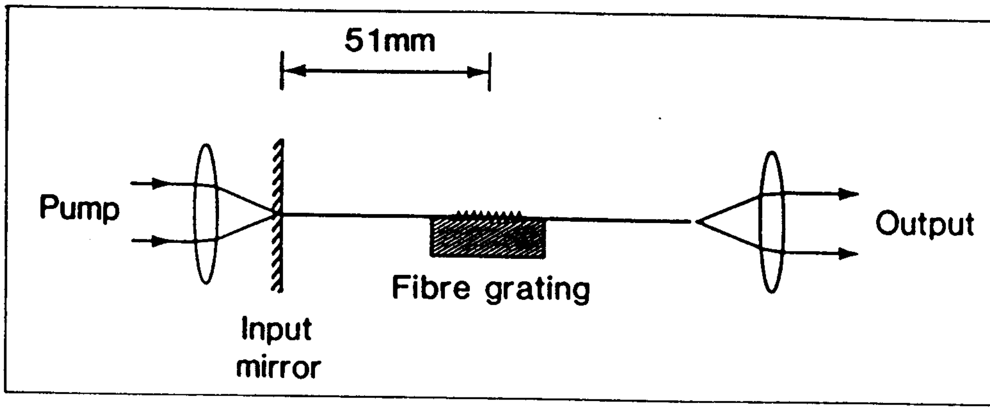


Figure 6: Experimental configuration of single longitudinal mode fibre laser

Using a diode laser pumped Nd^{3+}-doped fibre laser, it is possible to generate pulses with a peak power in excess of ten watts and a pulse duration of approximately 100ns at a rate of several hundred pulses per second.[7] This high peak power is obtained for an optical input power of less than twenty milliwatts from a diode laser, and is a graphic example of a fibre laser operating in a regime which is impossible for diode lasers. This device is expected to find widespread use as a source for optical time domain reflectometry (OTDR), a technique in which pulses are launched into a fibre and the Rayleigh backscattered light is measured in order to detect breaks or bend losses in the cable.

The high peak power obtainable will allow longer lengths of fibre to be interrogated than was previously possible. Alternatively, results that could once be obtained only by averaging a large number of weaker pulses from a diode laser will now be obtainable in real time. This means that any additional cost incurred by incorporating a fibre laser instead of a diode laser will be offset by the savings obtained through using simpler signal processing electronics.

The Q-switched fibre laser is particularly suitable as a source for optical fibre sensors, several of which rely on the OTDR technique. The simultaneous tuning of such lasers allows remote wavelength selective sensors to be used; for instance, a position-sensitive encoder. It will also be possible to wavelength-division multiplex several sensors using one laser as the power source.

Exploiting the linewidth

The usefulness of a broadband, tunable source has already been outlined. It is also possible to exploit the large fluorescence linewidth of the laser in another way. By means of an anti-reflection coating, or by polishing the output end of the fibre at an angle in order to suppress optical feedback, it is possible to obtain substantial amounts (~100μW) of spontaneous emission over a broad spectral range. This source is useful in applications that require relatively large amounts of coherent emission such as would normally be obtained from a LED, but at significantly higher power levels. It is of course possible to couple this light efficiently into other single-mode fibre systems. The sensitivity of the spontaneous emission to temperature drift is also negligible compared to that of a LED, an important consideration in many applications such as the optical fibre gyroscope, a device which requires a stable source of incoherent radiation.

At the other end of the scale, narrow linewidth, single longitudinal mode operation of a fibre laser has been realised by incorporating a specially designed fibre narrowband reflector into the cavity.[8] A stable, narrow linewidth laser is required as a source for future coherent transmission systems, a technique which is expected to show improved performance over the direct detection systems used today. Even at this early stage, a linewidth of 1.3MHz has been demonstrated, a result which compares most favourably with the distributed feedback diode lasers now in use, and further improvements are expected in the future.

Much has been achieved in the field of rare-earth doped single-mode fibres in a short space of time and, with other laboratories now joining the field, many new devices are expected to emerge in the near future. The future looks bright indeed for the active fibre.

References

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