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Optical Amplifiers - A Telecommunications Revolution

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In the early 1960's it was widely recognised by telecommunications engineers that existing electrical transmission technologies (twisted-pair, coaxial cables) would be inadequate for the rapidly-developing telecommunications industry. The needs of wideband distribution networks to carry video and digital data, as well as the burgeoning telephone traffic, could not be met by foreseeable advances in electrical transmission. Consequently research focussed on the huge bandwidth offered by optical transmission, initially in free space but later in guided-wave form, to provide the wideband services of the future. In 1966 Dr Charles K Kao (a previous C&C Award Winner) demonstrated the feasibility of using glass optical fibres as a transmission conduit - the optical equivalent of the coaxial cable.

The concept of optical communications is a simple one. The information to be conveyed is modulated onto a light beam which is transmitted down a glass fibre to an optical receiver where it is reconverted into electrical signals. The losses of optical fibres are now as low as 0.2dB/km, enabling transmission distances of up to 100km before the light becomes so weak that amplification is required. The bandwidth of optical fibres is quite phenomenal. There are two main transmission windows, one located at a wavelength of 1.3μm where 35,000GHz is available and the other at 1.55μm where an additional 25,000GHz can be accessed.

The 1980's saw extensive deployment of optical fibre throughout the world's trunk networks. The relatively-simple amplification requirements of point-to-point trunk transmission operating at below a GHz could be readily met by using electrical regenerators. In these, the incoming signal is detected and converted to an electrical signal, whereupon it is amplified, retimed and reshaped, before being reconverted to an optical signal using a semiconductor laser. However, as optical technology advanced and bandwidth requirements increased apace, it became obvious that inserting electrical repeaters periodically along an optical transmission system was a major bottleneck to exploiting the full transmission capacity of the fibre. Electronic signal regeneration becomes increasingly difficult above 10Gbit/s and, moreover, constrains the fibre to operate at a given line-code and bit-rate. Furthermore, if multiple wavelength channels are present, an electrical repeater for each wavelength must be used. It thus became increasingly clear that if the 60,000GHz potential capacity of the fibre was to be fully exploited, a means to eliminate the repeater bottlenecks was needed.

The answer to the problem was to use an all-optical amplifier, thus avoiding the need to reconvert the light periodically to electrical signals for amplification. The history of fibre optical amplifier development goes back to 1964 when Koester and Snitzer [1] at the American Optical Co. demonstrated a flash-pumped, neodymium-doped, multimode fibre laser at a wavelength of 1.06μm. These workers recognised the high-gain characteristics of rare-earth-doped fibres and were thus able to demonstrate the first ever glass laser. The idea lay dormant until it surfaced briefly again in 1974 when Stone and Burrus working at Bell Laboratories revisited fibre lasers and reported a 1cm-long, multimode, neodymium-doped fibre laser, again operating at 1.06μm. It was not until 1985 that Payne, Poole, Mears, Reekie and Fermann working at Southampton University developed a rare-earth-doping process for silica telecommunications fibres which did not significantly affect their remarkably-low background losses [2]. This key development allowed the authors to make Er^{3+}-doped single-mode fibres and demonstrate lasers with lengths as long as several kilometres. They prophesied at that time [3]:

> "The broad fluorescence linewidth of rare-earth ions in glass allows the construction of broadband amplifiers for use in wavelength-division multiplexing. It should also be possible to use distributed amplification as a means of overcoming losses in soliton propagation".

There followed a phase of considerable activity at Southampton on rare-earth-doped fibre lasers at various wavelengths using different dopant ions. The work focussed on erbium-doped fibre lasers because their operating wavelength of 1.55μm corresponded to the telecommunications operating window with lowest fibre loss. Progressing naturally from lasers to amplifiers, in January 1987 the Southampton group reported the first erbium-doped fibre amplifier (EDFA) at the Optical Fibre Communications Conference in the USA [4]. The amplifier had a gain of 26dB, operated at 1536nm and gave an output power of 13dB, a performance which was remarkable at that time. Following this discovery, several laboratories immediately started work on EDFA's, most notably British Telecom, AT&T Bell Laboratories, NTT and KDD. In 1988 wavelengths of 980nm (Southampton) and 1480nm (Snitzer et al) were identified as the two most desirable amplifier pump wavelengths and in January 1989 NTT reported [5] the key result which demonstrated the practicality of the fibre amplifier, namely laser-diode pumping at 1.48μm. Since that time hundreds of publications have emerged from numerous laboratories, dealing with pump efficiency, interchannel crosstalk, noise characteristics and all the other parameters required to fully specify a practical amplifier. The EDFA has become available commercially from as many as 20 companies worldwide and is currently set for deployment in a range of terrestrial and undersea applications, perhaps the best known being the 9,000km trans-Pacific link due to be installed in 1996 in a joint venture between AT&T (USA) and KDD (Japan).

So why are EDFA's so attractive? It has emerged over the six intervening years of research since its first announcement in 1987 that the EDFA is remarkably close to a perfect optical amplifier. It is extremely pump efficient, requiring only tens of milliwatts of power at the most efficient pump wavelength of 980nm and can exhibit a gain as high as 54dB [6]. Results for pumping at 1480nm are almost as good. The gain is independent of the input polarisation-state of the signal, which is essential in a fibre telecommunications system where the polarisation state is both unknown and time-variable. The EDFA has a virtually quantum-limited noise figure of 3dB and is completely fibre compatible, which means it can be spliced into fibre links with extremely-small insertion loss (essential to maintain its low-noise characteristics). It is also able to generate high signal output powers, since unlike many optical amplifiers, its output increases proportionally with pump power. It is thus ideally suited for use in large optical distribution networks to millions of subscribers where it can compensate the splitting losses. In addition, the EDFA gain dynamics are slow, thus minimising the crosstalk which might otherwise occur between optical channels at different wavelengths. In quantum-physics terms, these attributes are the result of a long excited-state lifetime (10ms), the lack of any intermediate energy levels between excited-state and ground-state energy levels, and the almost complete absence of excited-state absorption which plagues most solid-state laser systems. Thus nature has been generous in providing not only an unusually-perfect optical amplifier, but also siting it at the ideal wavelength for telecommunications (1.55μm).

The applications of EDFA's are as (i) power amplifiers when they can boost the transmitter signal to compensate branching losses in multi-terminal networks, (ii) as line-amplifiers when they reduce or eliminate the number of regenerators required and thus allow "transparent" transmission, ie independent of digital format or bit rate, even allowing mixed analogue and digitial transmission, and (iii) as pre-amplifiers when they are able to considerably improve the signal-to-noise ratio in high bit-rate direction-detection systems.

The EDFA has effectively eliminated loss as a barrier to the capacity of an optical fibre transmission system. Periodic insertion of line-amplifiers whenever the signal becomes weak allows the signal to be transmitted over thousands of kilometres with only a small degradation in signal-to-noise ratio. However, as commonly happens, the removal of one technological barrier allows progress until the next hurdle is encountered, in this case **signal dispersion**. The old-style electrical repeaters had the sole advantage that they reshaped and retimed the digital signal pulses every 50km or so and thus dispersion in the fibre was periodically reset to zero. With the capability to transmit over thousands of kilometres afforded by the EDFA, dispersion accumulates and pulse spreading limits the capacity to around 10,000 $(\text{Gbit/s})^2/\text{km}$, even using the most finely-tuned, dispersion-shifted fibre. Nonetheless, each successive year has brought reports of yet higher bit-rates and yet greater distances using tens of EDFAs placed at intervals of around 50km along the fibre. Perhaps the most spectacular recent demonstration has been that by a group led by M Nakazawa at NTT [7] who has used EDFAs in a recirculating loop experiment to show that many millions of kilometres can be traversed if dispersion is compensated by the use of solitons, pulses which finely balance the dispersion in the fibre with non-linear self-phase-modulation. These magnificent experiments forcibly demonstrate the liberating effect on system design offered by the EDFA. In retrospect, it is difficult to imagine how optical fibre telecommunications could progress as far as it has without a viable optical amplifier. The technology would undoubtedly have been limited to a relatively-low transmission capacity and distribution networks to a small number of subscribers.

Although the progress in EDFA technology has been remarkably rapid, its arrival has been too late to fully exploit the bandwidth of the 40M kilometres of installed fibre already in the ground in the advanced nations. The great challenge of today is therefore retrospectively to apply the new fibre-amplifier technology to uprate this buried goldmine of transmission capacity. Unfortunately, the vast majority of this installed fibre base operates at a wavelength of 1.3μm where currently no viable fibre amplifier exists. There is presently a worldwide search for such an amplifier, and there have been demonstrations of a praseodymium-doped fibre amplifier using a special fluoride glass composition [8]. Most engineers regard the reported pump efficiency of 4% as too low for practical use and although research continues, interest has now turned to uprating the installed fibre base by operating it at a wavelength of 1.55μm, where the EDFA can be used. The strategy of operating at 1.55μm in the existing standard (high-dispersion) fibre, rather than the dispersion-minimised fibre normally employed at this wavelength, regrettably results in a large pulse dispersion and hence bandwidth penalty. Uprating in this way therefore limits the transmission span to around 60km at 10Gbit/s, unless a way can be found to compensate the large link dispersion. Put another way, to increase the capacity of the installed fibre network involves the choice between developing a viable 1.3μm amplifier (if this is possible), or employing the EDFA and developing dispersion-compensation. Many transmission engineers believe that a limited time-window now exists to develop the 1.3μm fibre amplifier, before a heavy and irreversible commitment is made to the EDFA approach.

There are numerous ways in which dispersion-compensation can be achieved. Passive techniques involve the addition of a (usually long) length of fibre having opposite dispersion to that of the link such that the net dispersion is zero. Non-linear techniques being investigated employ solitons or mid-point spectral-inversion. The latter is a powerful technique first suggested by Yariv in 1979 [9] which has the ability to eliminate completely almost any degree of dispersion with the aid of a single-phase conjugator placed at the mid-point of the transmission link. The conjugator uses four-wave mixing in a semiconductor laser or optical fibre to invert the optical spectrum, whereupon the dispersion accumulated in the first half of the link is reversed within the latter half, thus banishing dispersion as a limitation to system capacity. This powerful process in combination with the EDFA could finally result in the transmission engineer's dream - a transmission medium in which neither loss nor dispersion is a limitation to transmission capacity, thus liberating the full 25,000GHz bandwidth of the 1.55μm fibre transmission window.

In conclusion, the EDFA provides near-perfect gain and noise performance, coupled with a high output power capability. The amplifier has revolutionised optical telecommunications design, allowing 10,000km trans-oceanic spans at Gbit rates, huge subscriber distribution networks, as well as previously unheard of terrestrial inter-nodal spans. The future will bring extensive deployment of the EDFA to wideband subscriber networks, contributing greatly to the current worldwide focus on fibre-to-the-home networks. And all this from a simple erbium-doped strand of glass.

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