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Unleashing the Full Capacity of the Installed Fibre Base

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Introduction

There are some 20 million kilometres of installed fibre transmission links throughout the world, the great majority of which operate at a wavelength of 1.3μm. These links are limited in capacity by a combination of fibre loss and the bandwidth of their electronic repeaters, both of which limitations can be removed by the use of optical amplifiers. It is therefore highly attractive to consider uprating the world's installed fibre base by the simple installation of optical amplifiers. In the absence at present of a suitable commercially-available 1.3μm amplifier, it has been proposed to change the operating wavelength from 1.3μm to 1.55μm of those fibre links which have been specified for dual-window operation, thus enabling the erbium-doped fibre amplifier (EDFA) to be employed. The penalty of this approach is that the chromatic dispersion of the fibres is high (17ps/nm.km) at 1.55μm and must be compensated if a reasonable transmission capacity is to be achieved. Thus upgrading existing installed 1.3μm links involves either developing a viable 1.3μm amplifier or operating at 1.55μm using EDFAs and dispersion compensation.

Fibre Amplifiers at 1.3μm

There is currently considerable interest in Pr^{3+}- and Nd^{3+}-doped fibre amplifiers which operate in the 1.3μm region. Extensive development of Pr^{3+}-doped fluoride-glass fibre amplifiers[1] in Japan has resulted in 20dB gain from ~100mW of pump power at 1.02μm, and diode-pumped modules have been demonstrated. However, the quantum efficiency of the Pr^{3+}-doped ZBLAN fibre amplifier is low (typically 3-4%) as a result of non-radiative, multi-phonon decay from the $^1G_4$ level to the underlying $^5F_4$ level, which competes with the radiative emission at 1.3μm and reduces the observed lifetime to 110μs. Although this performance is perhaps adequate as a power (ie post) amplifier, significant further improvements are unlikely without development of alternative hosts with lower phonon-energy, such as mixed-halide or chalcogenide glasses. This approach is being actively pursued in a number of laboratories, but is presently in its infancy. Significant problems relating to the chemical durability of the glasses have yet to be overcome, although the predicted efficiency (>60%) of Ga-La-S glasses is particularly tantalising.[2]

Dispersion Compensation

Dispersion-compensation (ie optical equalisation) techniques can be sub-divided into linear or non-linear techniques.

Linear dispersion compensation includes the concatenation of a specially-manufactured high-dispersion fibre (such as two-mode fibre)[3] having equal and opposite dispersion to that of the fibre span in order to reduce the net link dispersion. This option is wideband, but is expensive and adds attenuation, since the required fibre length is around 15% of the total link length. A further option is some form of optical filter which has a high dispersion, although this is generally obtained at the expense of being narrowband, so that the filter must be servoed to the channel wavelength.

The shortest possible dispersion compensator using an optical fibre consists of a long chirped fibre grating, which could in principle be made using the photorefractive writing process. At present fibre gratings are made by exposing a short section (<20mm) to crossed coherent beams from a UV laser. To compensate 100km of fibre having a dispersion of 17ps/nm.km over a spectral band of 10nm requires a grating length of around 2m, which far exceeds current writing capabilities. Thus the long length of gratings for dispersion compensation precludes their fabrication by conventional single-step procedures. Nonetheless, this is an attractive proposal and is being pursued in some laboratories. A recent report which demonstrates that photorefractive fibre gratings can be written during the fibre draw[4] considerably expands the possibilities for this technology.

Non-Linear Dispersion Compensation There are two non-linear dispersion-compensation techniques. Non-linear dispersion-compensation using solitons compensates the dispersion through non-linear transmission. Although well known at 1.55μm in dispersion-shifted fibre where the dispersion is small, this is a new proposal in high-dispersion fibre and theoretical investigations are underway, some of which will be reported at this conference. The main problem to be overcome is the effect of the short soliton period compared to the amplifier spacing and the increased timing jitter.

The second non-linear technique uses spectral-inversion of the data spectrum at the midpoint of the transmission link. The pulse disperses in the first half of the link, at which point its spectrum is inverted so that the dispersion in the second half acts in the opposite sense and recompresses the pulse. Non-degenerate four-wave mixing (FWM) in both a semiconductor amplifier[5] and a dispersion-shifted fibre[6] (to obtain phase matching) have been employed to provide the required spectral inversion. With the latter technique, the transmission of 10Gbits^{-1} NRZ data over 360km of standard fibre has been demonstrated[7].

Mid-point spectral inversion (MPSI) is a particularly powerful technique to banish dispersion from fibre links. For example, we have demonstrated[8] linear transmission, spectral inversion and retransmission of 6.2ps pulse pairs (mark-space ratio in the range 2-5) over a total distance of 50km of standard fibre. A minimum pulse broadening of $\sim$10% was observed, limited primarily by spectral shaping in the optical filters. In addition, no pulse-to-pulse jitter was found and thus the results confirm the applicability of the technique to bit rates greater than 100Gbit^{-1}. Note that without MPSI the pulses broadened to 400ps and were unusable for data transmission.

The MPSI technique eliminates first-order dispersion, leaving only higher-order dispersion uncompensated. We estimate that 50Gbits^{-1} higher-order dispersion will limit transmission distances to $\sim$2000km in standard ($D \approx 17$ps/nm.km) fibre. It is interesting to speculate therefore whether MPSI would allow standard high-dispersion fibre to be used in undersea links, where it might permit higher bit-rates and longer amplifier spacings than presently envisaged because of the lower loss and higher non-linear threshold. However many issues, such as the polarisation sensitivity, efficiency and length of the spectral invertor, still remain before this ultimate potential can be exploited.

Conclusions

Dispersion is perhaps the last barrier to exploiting the full capacity of fibre transmission systems. The incentive provided by the prospect of upgrading the installed fibre base to operate at 1.55μm and obtain far-higher bit-rates has spurred research into dispersion compensation, with possible spin-off into sub-sea systems. A number of interesting options both linear and non-linear, are available and it is not at present clear which is the most commercially viable. Developments in these areas could well define a time window before interest in 1.3μm fibre amplifiers wanes.

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