Optical Amplifiers and their Applications [and Discussion]

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Optical amplifiers and their applications

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In the past few years research into all-optical amplification has been intensified. The performance expectations of both semiconductor and fibre amplifiers are becoming better understood and the number of possible applications is rapidly increasing. The particular attraction of linear optical amplifiers is that in most cases they offer very wide bandwidths, up to 5 THz, which is attractive for many of the wideband signalling schemes proposed for future networks. Thus it is hoped that optical amplifiers will allow the direct amplification of wavelength- and frequency-division multiplexing and other wideband schemes such as subcarrier modulation. There is still considerable work to be done, however, in evaluating the amplifier performance in certain cases, for example in the presence of a large number of closely spaced channels.

This paper discusses the characteristics of semiconductor and fibre amplifiers and considers their performance expectations in a number of applications relating to wideband networks.

1. INTRODUCTION

Optical amplifiers will play an important role in future optical transmission systems and in all-optical processing. Currently, most research is concerned with amplifiers based on semiconductor laser structures or optical fibre. These two classes of amplifiers can provide high gain with wide bandwidth, characteristics that makes them suitable for future systems and networks.

Optical amplifiers can be used in both linear and nonlinear modes of operation, although the latter is still mainly restricted to semiconductor laser amplifiers. The first use in real systems will be to provide linear amplification. Some possible applications follow.

1. As an optical gain block to compensate for losses in splitting networks, for example to provide fan-out capability for future all-optical networks.

2. An an optical linear repeater in a long-haul transmission system (Yamamoto 1980; Simon 1983). In optical transmission systems using single longitudinal mode lasers the effects of fibre dispersion may be small and the main limitation on repeater spacing is the signal attenuation as a result of fibre loss. Such systems do not require a complete regeneration of the signal at each repeater and linear amplification of the signal is sufficient. Thus linear optical amplifiers can be used as repeaters.

3. As a preamplifier to boost the weak optical signal before detection. Use of a semiconductor laser amplifier to linearly amplify the optical signal before the photodetector can increase the detection sensitivity. The improvement can be particularly significant for bit rate in excess of 1 Gbit s^{1}.

This paper discusses the characteristics and performance of semiconductor laser amplifiers and Raman fibre amplifiers as these are the most developed and well understood. Rare-earthdoped fibre amplifiers (Mears *et al.* 1987) are also an important area of current research, but their capabilities have yet to be fully determined. Brillouin amplifiers (Tkach *et al.* 1988) have a more specialized application and are not discussed here.

2. Optical amplifiers

Amplifier description

Figure 1 shows the schematic diagrams of a semiconductor laser amplifier and a fibre amplifier. The laser amplifier is based on the normal semiconductor laser structure. Population inversion is achieved by electrical pumping, by using the injected bias current. In operation the device is biased below the normal lasing threshold current and light entering one facet appears amplified at the other facet together with noise. In practice the amplifier chip is bonded into a package with monomode fibre tails used to guide light to and from the laser.

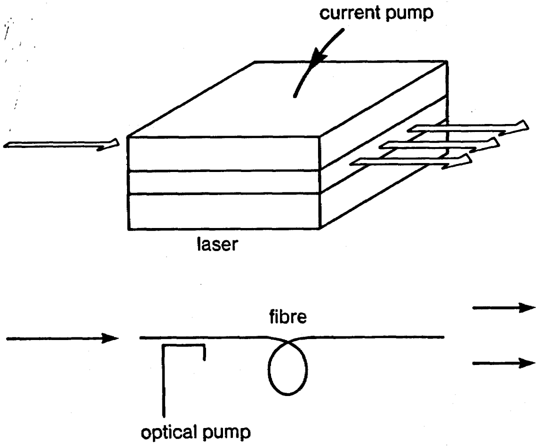

Figure 1. Schematic diagrams of semiconductor laser amplifier and optical fibre amplifier.

The Raman fibre amplifier relies on the phenomenon of Raman scattering to provide the optical gain (Nakazawa *et al.* 1985). The amplifier itself comprises a length of fibre and population inversion is achieved by optical pumping; the optical pump and signal are normally combined by using a fibre coupler. Because of the mechanism involved, the pump wavelength is lower than the signal wavelength, for example amplification of a 1.55 μm signal requires a pump wavelength of the order of 1.46 μm. The main problem hindering the use of Raman amplifiers is the requirement for a high-power optical pump; however, with the continuous improvement in semiconductor laser technology this may well be overcome in the near future. The main advantage of the fibre amplifier is its high output saturation power.

The single-pass gains through semiconductor and Raman fibre amplifiers have the same form, $G_s = e^{gL}$, where g is the net gain coefficient per unit length and L is the amplifier length. The net gain coefficient depends on the material gain and loss coefficients and the pump intensity. In the fibre amplifier the pump intensity, for a given pump power, is increased by decreasing the optical spot size. For this reason Raman amplifiers use fibre which is suitably doped (for example by Germania) to provide a small spot size.

The characteristics of semiconductor amplifiers can be significantly affected by the Fabry–Perot resonances associated with the laser facet reflectivities. For this reason most semiconductor amplifiers facets have anti-reflection coatings. These have the effect of increasing the amplifier bandwidth and make the transmission characteristic less dependent on fluctuations in bias current, temperature and input signal polarization.

The general equation for the gain of a laser amplifier is

$$G = \frac{(1-R_1)(1-R_2)\,G_s}{(1-\sqrt{R_1}\,\sqrt{R_2}\,G_s)^2 + 4\sqrt{R_1}\,\sqrt{R_2}\,G_s\sin^2\phi}, \tag{1}$$

where R_1 and R_2 are the input and output facet reflectivities, respectively, and where G_s and ϕ represent the single-pass gain and phase shift through the device. This equation shows that the passband comprises peaks and troughs whose relative amplitudes are determined by the facet reflectivities and the single-pass gain (and hence the applied bias current). For wideband operation the gain ripple should be small; in a true travelling-wave amplifier the ripple would be zero. For convenience a near travelling-wave amplifier is defined as one in which the gain ripple is less than or equal to 3 dB. An amplifer whose gain ripple considerably exceeds 3 dB is usually termed a Fabry–Perot amplifier, because of the large Fabry–Perot resonances in the passband.

For low facet reflectivities and a gain ripple of 3 dB one can show that the peak gain is related to the mean facet reflectivity R by the relationship $G = 0.25/R$. For wideband applications, therefore, the available gain is determined by the quality of the anti-reflection coatings. Currently, the state of technology is such that residual reflectivities of the order of 0.1% are now regularly obtained, giving facet-to-facet gains in the region of 24 dB.

The single-pass amplifier gain can be shown to depend on the optical intensity within the amplifier (Mukai *et al.* 1982). This is an important feature as the effects of gain saturation can be quite significant in many applications. The maximum possible output signal power demonstrated by a laser amplifier is less than 10 mW, thus a semiconductor laser amplifier is not suitable as a power amplifier. For higher output signal powers fibre amplifiers are required. Future systems, therefore, may well use a combination of semiconductor and fibre amplifiers, the type used depending on the particular application.

Amplifier measurements

Figure 2 shows the measured internal gain of a semiconductor laser amplifier as a function of injected current for orthogonal polarizations of the input signal. This amplifier was based on a double channel planar buried heterostructure laser of length 500 μm with a lasing threshold

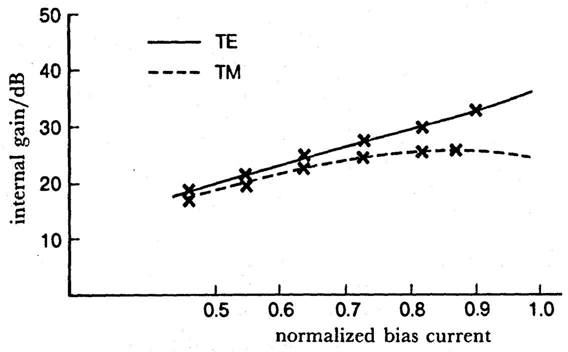

FIGURE 2. Laser amplifier internal gain as a function of normalized bias current for TE and TM signal polarizations. Current normalized to lasing threshold current after anti-reflection coating (55 mA).

current of 12 mA. The residual facet reflectivities were approximately 0.1 %. After the coatings were applied the new lasing threshold current was approximately 55 mA. The word 'internal' is used to denote that coupling losses are not included and the bias current has been normalized to the lasing threshold current after anti-reflection coating. The important features of this characteristic are as follows.

1. The striking linearity between bias current and gain (in decibels) for the TE polarization mode. This characteristic is typical of a near travelling-wave amplifier as the net gain per unit length (g) is proportional to the carrier density and hence bias current to a first approximation.

2. The difference between gains for orthogonal polarizations, approximately 2.5 dB at a gain of 25 dB.

3. Gains of the order of 35 dB can be obtained when operating close to threshold.

Figure 3 shows the variation of laser amplifier gain with input signal power. The graph shows the internal gain plotted against input power for two values of bias current. At 70 % of threshold current the gain has fallen by 3 dB when the input power has increased to approximately −28 dBm, corresponding to an output power of −6 dBm. Although this result is not the best that can be achieved it illustrates one of the limitations of laser amplifiers.

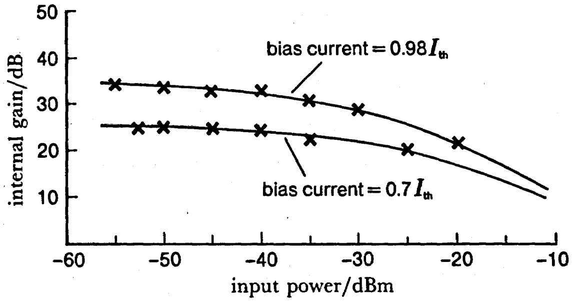

FIGURE 3. Laser amplifier internal gain as a function of mean signal input power at bias currents corresponding to 70 % and 98 % of lasing threshold current.

Figure 4 shows the theoretical transfer characteristic for a Raman amplifier. These results show that gains of the order of 30 dB are possible with a pump power of 500 mW and that maximum output powers of the order of 100 mW are achievable. Such a device could be used as an optical power amplifier.

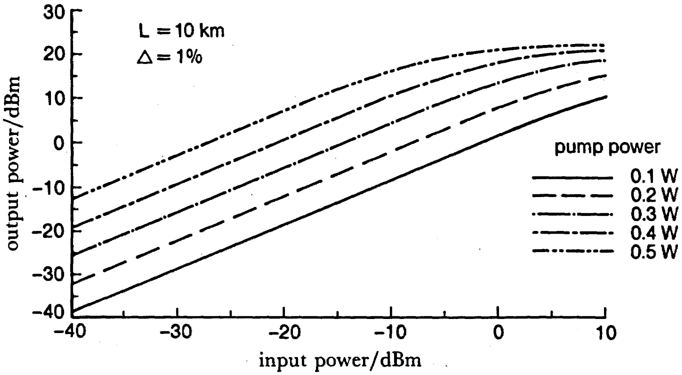

FIGURE 4. Theoretical transfer characteristic of Germania doped Raman amplifier. Fibre length is 10 km with 5 μm core diameter and 1 % refractive index difference between core and cladding.

The attraction of linear amplifiers is the possibility of their use with wideband signals, for example with wavelength- or frequency-division multiplexing (WDM or FDM). The passband characteristic is therefore of great importance. Figure 5 shows the gain against wavelength characteristic of the semiconductor amplifier, with an input signal power of approximately −45 dBm. The solid curves represent the passband gain envelopes. As shown on the lower gain curve, with the amplifier operating at 70% of threshold current the amplifier gain peak occurs at a wavelength of approximately 1.508 μm, and the envelope bandwidth is approximately 50 nm. The inset figure shows the passband detail which comprises a gain ripple of approximately 3 dB peak–trough at maximum; this is caused by the residual Fabry–Perot resonances. In frequency terms the near travelling-wave amplifier has a bandwidth of the order of approximately 5 THz with a gain of 25 dB and this illustrates the potential for future wideband optical system application.

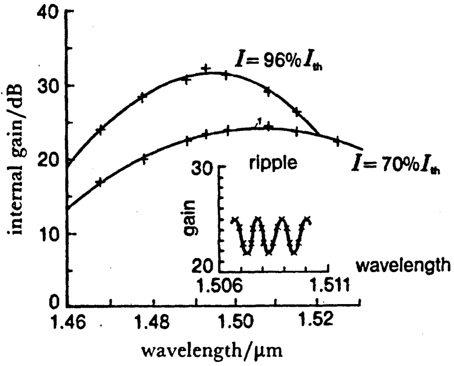

FIGURE 5. Laser amplifier passband characteristic for bias currents corresponding to 70% and 96% of lasing threshold current. Inset shows gain ripple under 70% envelope resulting from residual Fabry–Perot resonances.

Figure 6 shows the corresponding measured characteristic for a Raman amplifier. The abscissa is marked in wavenumbers, and the 3 dB bandwidth, at 1.5 μm is almost exactly 50 nm. Thus the semiconductor and Raman fibre amplifiers have similar bandwidths and this is an attractive feature of the combination.

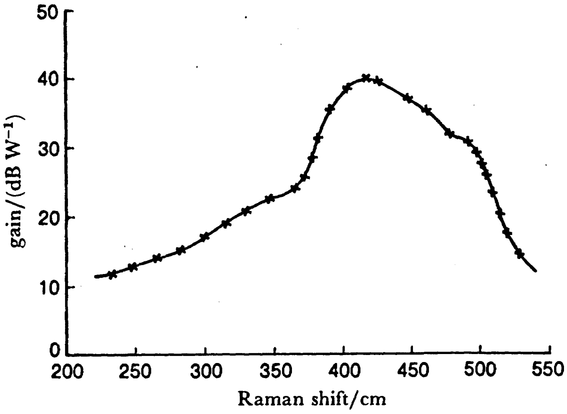

FIGURE 6. Measured passband of Raman amplifier using standard silica fibre.

Amplifier noise

The noise performance of optical amplifiers is a critical parameter in terms of their application. One means of evaluating the noise has been to determine the signal-to-noise ratio (SNR) at the output of an ideal photodetector coupled to the amplifier output (Mukai *et al.* 1982). The SNR of a travelling-wave semiconductor amplifier has the form:

$$SNR = \frac{4c_1^2 c_2^2 P^2 G^2 \eta^2 \cdot 2T/E^2}{c_2 \eta[2Pc_1 G/E + 2(G-1)\gamma\Delta f] + c_2^2 \eta^2 [2G(G-1)\gamma P/E c_1 + (G-1)^2 \gamma^2 \Delta f] + \frac{1}{50}(F-1)k\theta/e^2}, \tag{2}$$

where P is the mean power in the input fibre; G is the amplifier gain; γ the population inversion parameter; T the bit duration; η the photodiode quantum efficiency; c_1 and c_2 represent the input coupling efficiency between fibre and input facet and the coupling efficiency between the output facet and the photodetector, respectively; Δf is the optical bandwidth; F is the noise factor of the electronic amplifier (assumed to be a 50 Ω amplifier); k and θ represent the Boltzmann constant and temperature, respectively; E is the photon energy and e the electron charge.

The first two terms in the denominator of the SNR represent the shot noise associated with the amplified signal and spontaneous emission components. The second two terms represent beat noise between signal and spontaneous photons; and spontaneous–spontaneous photons respectively. The fifth component is the noise contributed by the electronic amplifier. Because of the dependence of the SNR on the input and output coefficients, c_1 and c_2, the SNR and the relation between the various noise components depends on the application, for example whether it is used as a preamplifier or as a repeater. The SNR equation also shows that, unlike an electronic amplifier, the output noise is a function of signal intensity.

The Raman amplifier has a similar expression but with an equivalent population inversion parameter of unity. Thus the fibre amplifier is less noisy than the semiconductor amplifier and represents ideal optical amplification.

3. FUTURE SYSTEM APPLICATIONS

Linear repeater

The use of a laser amplifier as a linear amplifier repeater in an optical transmission system has many attractions and a number of experiments have been reported using both intensity and coherent modulation (Marshall *et al.* 1986; Olsson 1985; O'Mahony *et al.* 1986). The particular advantages of a linear amplifier repeater are

(1) reduced complexity in comparison with conventional electro-optic repeaters and reduced power requirements;

(2) bit rate transparency, allowing the upgrading of system capacity by increasing the bit rate without repeater modification;

(3) wide bandwidth allowing WDM or FDM.

There are also problems. For example,

(1) the system is inherently analogue and hence noise accumulates along a chain of repeaters limiting the number that can be cascaded;

(2) backward travelling waves in laser amplifiers (O'Mahony 1985) can cause the system to be unstable. These difficulties should not arise in fibre amplifiers.

The following discussion considers some of the more recent repeater experiments, which illustrate many of the points outlined above and show the performance that can be expected from such systems.

So far there have been many experiments demonstrating an optical system with a single linear repeater. A typical example would be a 100+100 km system operating at 2 Gbit s^{-1}, with intensity modulation. Because of the improvement in optical coating technology near travelling-wave amplifiers are now a reality, allowing the use of DFB sources despite their large dynamic bandwidths. The use of tapered fibre lenses for coupling the light to and from the amplifier allows high coupling efficiencies (up to 65%) and allows net repeater gains in the range of 15–20 dB to be achieved. For single repeaters, system penalties due to amplifier noise are generally small, typically less than 1 dB. As the amplifier noise is a function of the gain, it should be possible to operate at higher gains (achieved for example by a further reduction in facet reflectivity) without a significant increase in this penalty. At present single amplifier systems operate in a gain-limited rather than noise-limited régime.

Several single-repeater experiments have also shown the WDM capability of laser optical amplifiers; and three-channel WDM has been demonstrated in a system using a semiconductor pumped Raman amplifier (Edagawa *et al.* 1987). Because of the importance of WDM in future optical networks, a significant area of current research is concerned with the theoretical and experimental evaluation of crosstalk in amplifiers (Grosskopf *et al.* 1986; Agrawal 1987; Darcie & Jopson 1988). Crosstalk occurs because of gain saturation by the total optical intensity and carrier density modulation when the wavelengths are closely spaced. Gain saturation at relatively low output power levels (milliwatts régime) is a particular problem for semiconductor amplifiers. As the maximum output power is limited, the power per channel in a WDM system decreases as the number of channels increases. At the current state of techology this implies that only small numbers of channels could be used in long haul systems. Fibre amplifiers, with their high saturation powers, may be the means of overcoming this problem.

The available bandwidth of optical amplifiers should allow the transmission of subcarrier multiplexed signals (Olshansky & Lanzisera 1988) although as yet there are no reported experiments. Laboratory measurements have indicated that amplifier dynamic bandwidths of up to 50 GHz are available, which should support the subcarrier schemes currently being proposed.

System experiments have also been reported using several amplifier repeaters in cascade (the record at present stands at four) both for direct detection and coherent systems. The main distinguishing features of multiamplifier experiments are

(1) amplifier gain saturation by spontaneous emission from other amplifiers;
(2) SNR degradation along the amplifier chain;
(3) interaction between amplifiers as a result of backward travelling waves.

It has been shown (O'Mahony 1985) that (1) and (2) above limit the number of repeaters that can be cascaded to about ten. However, this number can be increased significantly by the use of optical filters to reduce the spontaneous emission. Recent experiments by Olsson (1988*a*, *b*), for example, have demonstrated intensity modulation and coherent transmission over four laser amplifiers at 1 Gbit s^{-1} (313 km) and 400 Mbit s^{-1} (372 km) respectively.

Linear amplifier repeater systems are attractive because of their simplicity and such systems show many of the advantages of a repeaterless system, e.g. bit rate independence, can support multiplex operation, etc. Because of the limitation on the number of amplifiers that may be cascaded, the first all-optical repeater system will probably have a total length in the range of

300–1000 km. There are still many problems to be solved, however, before these systems become a practical reality. Steps have been taken in this direction at British Telecom with the development of a control circuit that operates on the voltage developed across the amplifier junction when a signal is present. This control acts as an AGC circuit and removes the effects of polarization sensitivity, gain variation with temperatures, etc.

Optical preamplifiers

Laser amplifiers can be used as optical preamplifiers to increase the sensitivity of optical receivers (Marshall & O'Mahony 1987). By providing optical gain before the receiver, the signal is amplified above the receiver noise level. The detected signal to noise ratio is then dominated by the optical amplifier and at best is slightly worse than the quantum limit. Optical preamplifiers, therefore, offer the advantage of eliminating the effects of receiver noise, which is a similar function to that provided by coherent detection. The particular advantage of preamplifier receivers in comparison with conventional receivers is that offer a high sensitivity with a very wide bandwidth, a combination vital for future system development.

The ratio given by equation (2) can be used to show that in this application the dominant noise terms are the beat noise components and the electronic amplifier noise. If the amplifier gain is high and a sufficiently narrow-band optical filter is used between amplifier and detector the laser amplifier gain can be adjusted such that the SNR is dominated by the signal–spontaneous beat noise. Under these conditions the SNR is within a factor c_1/γ of the quantum limit, where c_1 and γ are the input coupling loss and the population inversion parameter respectively. In the BTRL experiments this factor has been estimated as approximately 0.42, thus in theory the preamplifier can attain a sensitivity within 3.8 dB of ideal direct detection.

In a practical realization of the preamplifier receiver a bandwidth of 10 GHz has been achieved, equivalent to a bit rate capability of 15 Gbit s^{-1} (Marshall & O'Mahony 1987). The sensitivity based on noise measurements was estimated as -27 dBm, which is about 10 dB better than the equivalent conventional receiver. At lower bit rates a record sensitivity of -51 dBm at 140 Mbit s^{-1} has been demonstrated, but this required the use of optical filters to limit the broadband amplifier noise.

It should also be noted that although preamplifier receivers offer significant advantages for the improvement of future wideband direct detection systems, they may also have an important role in future high bit rate coherent systems, which rely on a wide-bandwidth low-noise receiver for efficient operation.

Nonlinear amplifiers

Semiconductor laser amplifiers can be operated in a nonlinear mode by a suitable choice of operating parameters. Dispersive nonlinearity and hysteresis have been observed experimentally (Adams *et al.* 1985). One application of a nonlinear amplifier is as a pulse-shaping element in an all-optical regenerative repeater (O'Mahony 1987). Regenerative repeaters are necessary in many applications (such as long-haul systems) to remove pulse distortion and jitter. Ideally such a repeater would produce a reshaped, retimed amplified pulse without optical to electrical conversion. This would allow each repeater section to be independent and cater for the assembly of systems of any desired length or configuration. Nonlinear amplifiers can also be used to provide wavelength translation, a function which may be important in future all-optical passive networks using wavelength routing.

Recent work at BTRL has concentrated on the use of multicontact lasers as nonlinear amplifiers and wavelength translators. Multicontact lasers comprising amplifier–absorber combinations (figure 7) have been studied by a number of authors and in recent years have become known as bistable lasers (Kawaguchi 1987). The bistable laser is in effect a triggerable laser which can also provide the wavelength translation function. The input signal can have a wavelength anywhere in a 50 nm band, whereas the output signal is fixed for a particular device. Amplifier–absorber devices can also be operated below the lasing threshold as nonlinear or bistable amplifiers and they have many advantages over the single contact amplifier, for example a larger bandwidth. Nonlinear switching powers as low as −51 dBm have been observed.

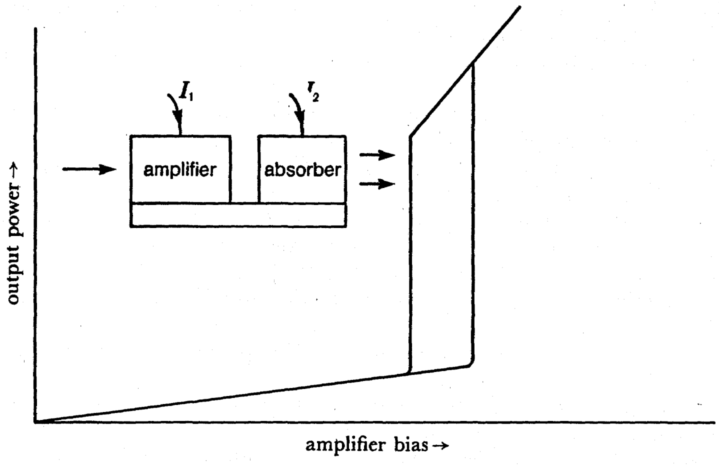

FIGURE 7. Schematic of multicontact amplifier or laser.

4. CONCLUSIONS

Optical amplifiers are an important component for future optical systems and networks. They are an essential component for many of the proposed future networks and hence research and development in this area will accelerate in the future. The first commercial introduction of amplifiers will be as linear repeaters in long-haul fibre systems, because such systems can be readily upgraded, for example by using WDM, without disturbing buried plant. For this reason these systems are very attractive to planners. Although optical amplifiers have been shown to be useful and essential components a great deal of research and innovation is still required to overcome many of the practical problems associated with their application, for example crosstalk and limited saturation power.

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Discussion

I. Darwazeh (*UMIST, Manchester, U.K.*). What is the sensitivity of the 'electrical' amplifier following the optical preamplifier mentioned (140 Mbit s^{-1}, -51 dBm sensitivity)?

M. J. O'Mahony. The receiver comprised a laser preamplifier, an optical filter and a photodiode followed by a low-noise electrical amplifier. The optical filter bandwidth was approximately 1.5 nm and the sensitivity of the photodiode low-noise amplifier combination was -38 dBm at 140 Mbit s^{-1}. This implies that the equivalent input noise of the electrical amplifier was approximately 15 pA $Hz^{-\frac{1}{2}}$.