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Second-generation fibre amplifiers for advanced optical networks.

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I. Introduction

The erbium-doped fibre amplifier[1] (EDFA) has seen rapid development and is now established as a key component in future optical networks. To date, EDFA development has been driven by specific requirements, primarily the single-channel, point-to-point fibre links. There are, however, many more applications which may require, for example, either broadband or narrowband amplifiers and signal-processing functions. In addition, non-telecommunication applications can benefit enormously by the use of EDFAs. Second generation EDFAs either novel designs or incorporating additional components, are now under investigation to modify appropriately and optimise amplifier characteristics for a given application.

A composite EDFA is described in Section II where it is shown that an integral isolator allows high gains to be achieved at relatively low pump power[2,3] without compromising the near quantum-limited noise figure (NF). In section III, a novel configuration of an optical limiting amplifier is presented which exhibits a input-signal dynamic range in excess of 30dB[4]. In section IV, an optical equalising amplifier is demonstrated which is based on a novel optical fibre, the erbium-doped twin-core fibre. This fibre geometry shows wavelength-dependent spatial (longitudinal) hole burning thus increasing the effective inhomogeneous broadening in the amplifier and provides enhanced output-signal equalisation in a multichannel system.

The potential of the EDFA as a compact source of high-peak power and high-energy pulses, for medical and military applications, is discussed in Section V. Finally, progress in all-optical amplification for 1.3μm networks is outlined in Section VI with particular reference to the 1.3μm Pr^{3+} fibre amplifier and 1.5μm dispersion compensating techniques.

II. Composite EDFA

A composite-EDFA configuration incorporating an optical isolator has been studied both theoretically[2] and experimentally[3]. It has been demonstrated that appropriate positioning of the isolator within the EDFA suppresses the build-up of backward-ASE and results in a near quantum limited NF. The typical configuration is shown in figure 1. A high gain efficiency Er doped germano-silicate fibre is employed for maximum small signal gain with the optimum isolator position found to be 1/3 of the distance from the front end. Reverse isolation of ~30dB is achieved and forward isolator insertion losses are of order 1dB at the signal but substantially higher at the pump wavelength (980nm) so WDM couplers are used as pump by-pass for this stage.

Typical gain and NF data are presented in Figure 2. Gains as high as 54dB with a corresponding NF of 3.1dB can be easily obtained. By comparison with the conventional EDFA, for 45mW of pump power a 75m standard EDFA gives a high gain of 46.6dB and NF of 4.85dB and to reduce the NF to about 3.36dB requires a sub-optimal length of 30m, resulting in a moderate gain of 25.2dB and correspondingly, reduced gain-efficiency. However, for the same pump power the composite EDFA achieves a combination of 51dB gain and 3.1dB NF, which represents a very significant improvement. The solid lines in Fig. 2 correspond to the calculated gain and NF of the composite EDFA. Using this composite amplifier as a preamplifier in an optical receiver configuration resulted in a record sensitivity of 102 photons/bit at a transmission rate of 10 Gbits/s[5].

III. Optical limiting amplifier

A novel configuration of an erbium-doped-fibre optical limiting amplifier (OLA) has been realised simply by introducing a differential localised-loss between the signal and the pump power at a particular point along the fibre. The differential loss between the signal and the pump power can, for example, be introduced by bending the erbium-doped fibre tightly at a particular point along its length. The optical isolator with the two pump-bypassing WDMs used in the composite EDFA (Section II) can also be utilised to provide the differential loss. The OLA exhibits an input-power dynamic range in excess of 35dB and the capacity to control optically the level of the constant-output signal.

The underlying principle of operation of the proposed OLA is explained with reference to Figure 3 where the pump and signal evolution along the normalised fibre length are shown for two extreme input signal powers of -25dBm and 0dBm. The pumping is uni-directional with a pump power of 20mW. The loss for the signal, forward and backward ASE is 2dB while for the pump it is 0.5dB The limiting action is achieved by the balance between the pump and amplified-signal power in the 1st and 2nd stages, before and after the lump-loss position, respectively. In the 1st stage, both signals are amplified, with the low-input-power (-25dBm) signal attaining lower levels than the high-input-power (0dBm) one, as expected. However, the pump power is depleted at a slow rate by the low-input-power signal and there is sufficient remnant pump power available in the 2nd stage to amplify the attenuated low-input signal to the same level as the high-input signal. On the other hand, although the high-input-power signal attains a higher level throughout the 1st stage, it heavily depletes the pump power which drops below threshold towards the end of the 2nd stage and, as a consequence, the signal is slightly attenuated to level-off with the low-input-power one. The signals of intermediate input power evolve in an analogous manner and converge to the same output level.

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In Figure 4, the calculated input/output response and noise figure of an OLA (solid line) are plotted for typical device parameters. The lump-loss is introduced through the insertion of an optical isolator placed at the optimum position[4] (~3.5m from the input end) an EDF length of 8.2m. The isolator extinction ratio is 30dB and the signal and pump loss are 2dB and 0.5dB, respectively and an input pump power of 20mW is employed. In addition to the differential loss between the pump and signal there is introduced a 30dB differential lump-loss between the forward and backward ASE which results in higher amplifier gain within the low-input-signal regime and extends the dynamic range of the OLA. The broken line corresponds to the no-loss case. With the isolator at optimum position, the OLA exhibits a dynamic range in excess of 30dB. The NF of the OLA in this case remains close to 3dB for most of the dynamic range.

To confirm these trends experimentally the configuration described in Section II has been employed to construct an OLA and preliminary data are shown in Figure 5 and compared with results for an optimised conventional EDFA employing a 60m length of the same doped fibre.

IV. Channel equalising optical ampliifer

A novel EDFA configuration is proposed which provides automatic channel equalization in WDM networks[6]. The device relies on the effective increase in the inhomogeneous broadening in an EDFA by spatial hole burning. The concept is shown schematically in figure 6.

The gain medium comprises a twincore fibre in which both cores are Er^{3+}-doped. The amplifier is configured such that the signal and pump light couple periodically between the two cores along the fibre length (with period approximately proportional to λ^{-3}). One signal exhibits a certain periodic spatial intensity distribution and thus accesses a subset of ions, whilst a different signal wavelength will access a different subset of ions. The gain at the two signal wavelengths is spatially (longitudinally) decoupled and thus for the case when one signal is larger than the others, spatial hole-burning will preferentially decrease its gain resulting in spectral channel equalization.

The concept has been confirmed experimentally by splicing a 10m length of doped twincore onto 14m of conventional amplifier fibre. The twincore was fabricated such that both cores were nominally identical with an index difference Δn of 0.0258 and core radius and separation of 1.43μm and 4.5μm respectively. The resulting coupling length is wavelength dependent and estimated to be 1.26mm (1.2575mm) at a wavelength of 1.55μm (1.551μm). The absorption at the signal wavelength was ~1dB/m. The output from two signal lasers was employed to probe the amplifier gain simultaneously at two closely-spaced wavelengths in order to investigate spectral gain equalization. Small sinusoidal modulations at 49 and 51kHz were superimposed on the cw output of the lasers allowing lock in techniques to discriminate their amplified outputs.

Amplifier saturation characteristics are shown in figure 7 for the two channels in the new amplifier. Here the pump power is ~50mW at 978nm and channel A input power is held constant whilst channel B input power is increased. The wavelength separation of the lasers is 1nm, close to the gain peak at 1531.2nm. The characteristics are compared with those of a conventional amplifier employing 18m of the initial fibre and ~30mW of pump power. In both cases it can be seen that when channel B input is lower than that of channel A, relatively its gain is increased, whilst when larger its gain is reduced. This effect in the conventional amplifier is caused by spectral hole burning (due to inhomogeneous broadening) whilst for the twincore amplifier the compensation is approximately doubled owing to the combined effects of spectral and spatial hole-burning.

Using this device, channel equalisation rates up to 0.11dB per dB difference between input signal levels have been demonstrated. This should increase the effective bandwidth of cascaded amplifier networks as shown schematically in figure 8, as well as reducing the tolerance in wavelength add-drop networks. Further with improved fibre designs channel equalization rate up to 0.3dB/dB are predicted[7].

V. High-power pulse amplification

The generation of high peak power pulses by amplification of the output from a DFB diode laser is an attractive alternative to Q-switched lasers which may find medical, sensing and military applications. 111KW pulse generation has been demonstrated by using a cascade of three erbium-doped fibre amplifiers (EDFAs) separated by an acousto-optic gate[8]. The optimised amplifier chain comprises two efficient, high-gain single-mode EDFAs pumped at 980nm, followed by a multi-mode EDFA pumped at 978nm. The multi-mode EDFA is designed to store energy and allow large pulse powers and energies to be extracted.

The configuration is shown in figure 9. The first two EDFA's (EDFA 1 and 2) correspond to the two segments of the composite EDFA studied in section II. The third EDFA (EDFA3) acts as a power amplifier and had a geometry optimised for an input pulse of energy $\approx 10^{-7}$J. To obtain mJ pulses it is obviously necessary to store energy in the amplifier of this order and this requirement determines the core volume for a given Er^{3+} concentration. The stored energy was achieved in our case by employing a multimode fibre in order to increase the core area. In addition, the NA was reduced to minimise the number of fibre modes and thus the ASE. We employed a germano-alumino-silica erbium-doped multimode fibre of length 1.7m with an erbium concentration of 1450ppm, numerical aperture of 0.12 and core diameter of 25μm which supported ~20 modes at both pump and signal wavelengths. EDFA3 was pumped with 1.5W at 978nm from a Ti:Sapphire laser. Since the fibre is multimode, in principle one of the new multi-stripe 980nm diode lasers could be employed. The signal source was a DFB laser diode operating at 1.534μm and allowed 5-500ns pulses with a maximum peak power of 1.53mW to be launched into EDFA1. The signal and pump source were copropagated in EDFAs 1 and 2 and counterpropagated in EDFA3.

An acousto-optic modulator (AOM) was employed between EDFA2 and EDFA3 to gate the optical signal. The output beam from EDFA2 was collimated through the AOM and the first-order defracted beam launched into EDFA3. The transmission loss was 3.4dB and the extinction ratio of 41dB effectively prevented any significant ASE power coupling from one amplifier to the other when the AOM was in the off state. The rise time of the optical gate was 300ns.

The maximum output power obtained was 111kW using a 10ns quasi-square input pulse of peak power 1.53mW at a repetition frequency of 400Hz. However, because of the high peak powers in EDFA3 the output power decreased with time, (Figure 10) showing clearly that the pulse was significantly depleting the population inversion. The average output pulse power over its 10ns duration was 34.5kW, giving a pulse energy of 0.35mJ. Slightly higher pulse output energies (0.5mJ) were achieved for longer duration input pulses (500ns).

VI Upgrade of installed 1.3μm fibre cable

Praseodymium doped-fibre amplifier

The EDFA allows systems to operate at 1.5μm, however, the majority of the world's installed fibre cable is designed to operate around 1.3μm, having minimum dispersion at this wavelength. Thus there is currently a large interest in Pr^{3+} doped fibre amplifiers which operate in this region. Extensive development of Pr^{3+}-doped fluoride amplifiers has resulted in 20dB gain from ~ 100mW of pump power[9] at 1.02μm, and diode-pumped modules have been demonstrated[10]. 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 reducing the observed life time to 110μs. Significant improvements in the performance of this particular device are unlikely without development of alternative hosts.

Thus there currently is a significant effort directed towards development of novel glasses which offer lower maximum phonon energies and hence higher efficiencies than conventional fluorozirconate glasses. A range of alternative glasses have been investigated and the two most promising candidates appear to be the mixed halides[11,12] (eg CdF_2 - NaCl - $BaCl_2$) and the chalcogenides[13,14] (Ga_2S_3-La_2S_3). Extended fluorescence lifetimes of 315μs and 300μs have been observed in these hosts leading to improved quantum efficiencies of 12% and 60% respectively. Although offering a significant potential improvement, the major task of producing low-loss fibre from these glasses remains.

Dispersion compensation

An alternative to designing an amplifier which operates at the dispersion minimum is to compensate the dispersion of the fibre at 1.5μm. Compensation has been demonstrated by employing either dispersion equalizing fibre[15] or optical phase-conjugation[16] of the data signal at the midpoint of the link. The second technique has allowed 10Gbits^{-1} transmission over 360km of standard transmission fibre. Further, recent results[17] report the successful, transmission of ~6ps pulses over 50km of standard fibre, again employing optical phase conjugation to compensate the dispersion. These techniques may obviate the requirement for 1.3μm amplifiers.

VII. Conclusions

Second-generation EDFAs have been developed by incorporating additional optical components into an ordinary EDFA so that the amplifier response is altered to achieve special functions.

Addition of an optical isolator within the erbium-doped fibre prevents the build-up of backward ASE and results in a composite EDFA which exhibits high gains (>50dB) accompanied by near-quantum-limited NF (~3.1dB) at relatively low pump powers (~50mW). Such a device can used as preamplifier and enhance the sensitivity of optical receivers.

Incorporation of a localised differential loss between signal and pump results in an efficient optical limiting amplifier with input-signal dynamic range in excess of 30dB. The constant output of the limiter can be easily adjusted by varying the input pump power. Such a device is useful in cascaded-amplifier links. It can stabilise the signal power against slow, unwanted variations, thus increasing the dynamic range of subsequent optical and electronic devices.

Using a twin-core erbium-doped fibre, i.e. incorporating an additional core into the standard fibre design, results in an amplifier with passive, automatic gain equalisation. Such a device can increase the useful bandwidth of cascaded amplifiers. Gain equalisation rates of 0.11dB per dB difference between input-signal levels have been demonstrated.

A cascade of three EDFAs has been used as a compact source of high-peak power, high-energy pulses. 111 kW output pulses at a repetition frequency of 400Hz have been produced by using 10ns quasi-square input pulses of peak power 1.53mW. This is comparable to the performance of a diode-pumped, Q-switched Nd:YAG laser although at the more favourable wavelength of 1.5μm and can be used in medical, sensing and military applications.

Finally progress in alternative techniques to allow the upgrade of installed fibre cable, designed to operate at 1.3μm, have been discussed.

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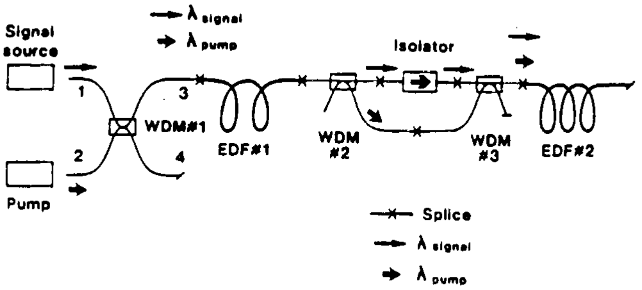

Figure 1: Composite-EDFA configuration.

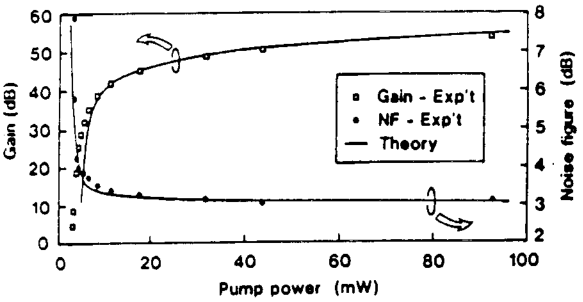

Figure 2: Gain and NF measurements for the composite EDFA.

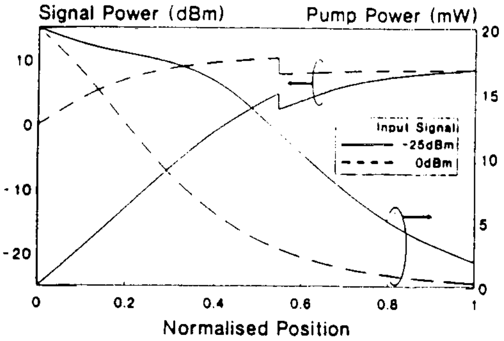

Figure 3: Pump- and signal-power evolution along the OLA for input-signal powers of -25dBm (solid) and 0dBm (dashed).

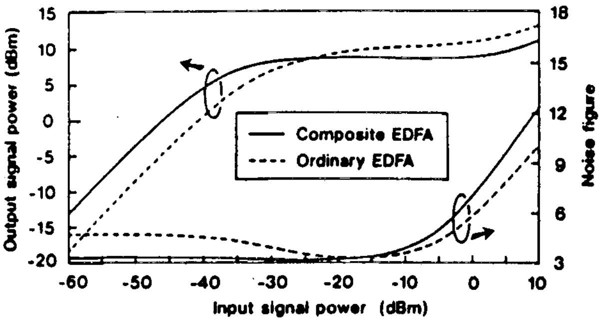

Figure 4: Input-output characteristics of the proposed OLA (solid) and conventional EDFA (dashed).

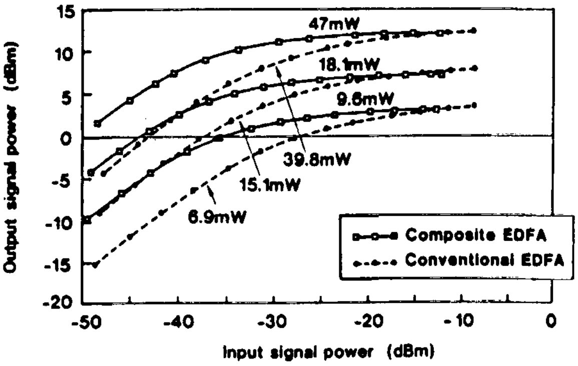

Figure 5: Experimental results of an OLA compared with the conventional EDFA.

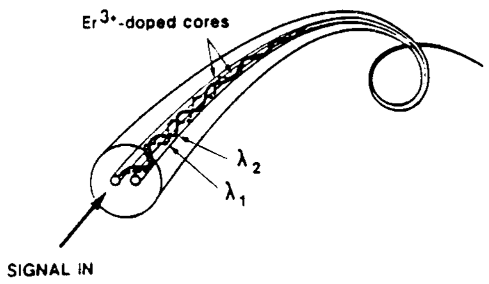

Figure 6: Schematic of twin core EDFA.

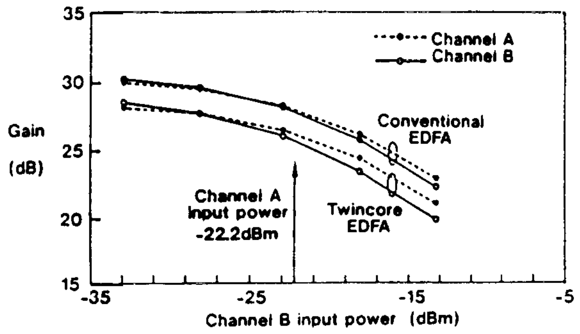

Figure 7: Comparison of two-channel gain saturation characteristics for twin-core EDFA and conventional EDFA.

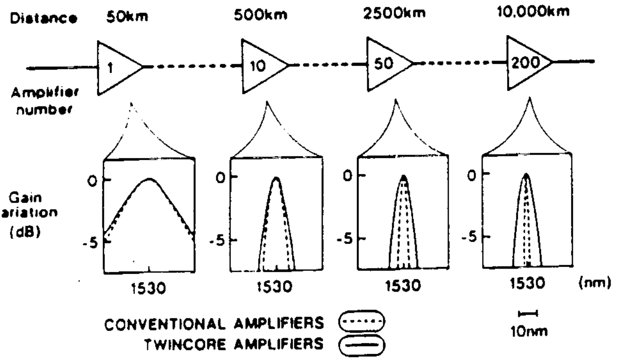

Figure 8: Effective bandwidth of a cascade of either conventional or the new twincore-EDFA.

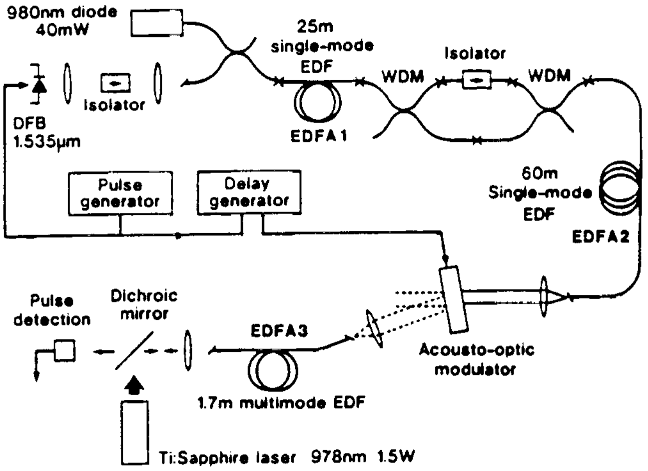

Figure 9: Experimental set-up of a three-stage amplifier for pulse amplification.

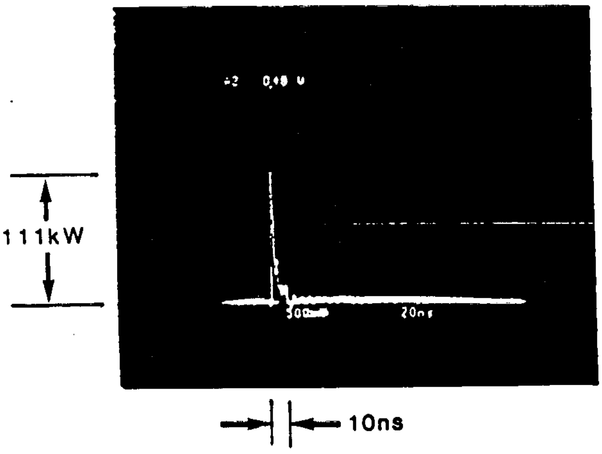

Figure 10: 10ns amplified pulse of 111kW peak power (0.34mJ).