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SECOND-GENERATION ERBIUM-DOPED FIBRE AMPLIFIERS FOR ADVANCED OPTICAL COMMUNICATIONS

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I. INTRODUCTION

The erbium-doped fibre amplifier (EDFA) [1] 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.

We are currently investigating second-generation EDFAs which incorporate additional components within the amplifier, as well as new amplifier designs. The aim of this work is to modify appropriately and optimise the amplifier characteristics for a given application. In section II, we discuss the performance of a composite EDFA with an integral isolator. It is shown that this configuration exhibits high gains and quantum-limited noise figure (NF) at relatively low pump powers [2,3]. 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 an 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. Finally, in section V, the potential of the EDFA as a compact source of high-peak power and high-energy pulses, for medical and military applications, has also been explored.

II. COMPOSITE EDFA

A composite-EDFA configuration which incorporates an optical isolator has been investigated theoretically and experimentally. The isolator prevents the build-up of the backward-ASE and results in an amplifier with high gain and near-quantum-limited noise figure (NF). The optimum position of the isolator has been calculated as a function of the pump power so that minimum NF and maximum gain are achieved simultaneously. It is shown that under practical pump power at 980nm, the optimised composite EDFA exhibits a gain improvement of about 5dB and a NF reduction in excess of 1.5dB when compared with an optimised conventional EDFA. It is also shown that with further optimisation the composite EDFA can be employed in a practical fibre link as a pre-amplifier without the use of an input isolator. Finally, a high-gain composite EDFA has been experimentally demonstrated which exhibits a gain of 51dB and NF of 3.1dB for only 45mW of pump power at 980nm.

The proposed amplifier configuration is shown in Figure 1. A commercially-available fibre isolator is incorporated into the erbium-doped segment of the EDFA. The active length now comprises two erbium-doped fibre lengths (EDF#1 and EDF#2) with the isolator spliced in between. A wavelength-division-multiplexing (WDM) coupler is used to launch both the pump and signal into the input section (EDF#1), whereupon it is transmitted via the isolator to EDF#2. The amplifier is pumped in the forward direction, i.e. the pump and signal co-propagate. The isolator is designed to transmit the signal, forward ASE and pump wavelengths with low loss (typical values : pump loss < 0.5dB, signal loss < 2.0dB). Two low-loss WDM fibre couplers (typical loss < 0.1 dB) are utilised to extract the residual pump power at point A and re-launch it into the erbium-doped fibre at point B.

An erbium-doped germano-silicate fibre was used having an NA of 0.24, cutoff wavelength of ~920nm and erbium absorption of 0.95dB/m at 1.536μm. The composite EDFA comprised two fibre lengths of 25m and 60m, respectively, which were separated by a polarisation-independent isolator to suppress the backward-travelling ASE. The isolator insertion loss at the signal wavelength was 1dB. Since the isolator has a very high loss at the pump wavelength of 980nm, two WDM couplers with insertion losses at the pump/signal wavelengths of 0.11dB/0.31dB and 0.16dB/0.31dB were incorporated to provide a low-loss by-pass for the pump. The total forward insertion losses between the two sections of amplifier fibre were ~0.6dB and ~2.1dB at the pump and signal wavelengths, respectively. The isolation in the reverse direction was greater than 30dB over a 50nm bandwidth centred at 1540nm.

Figure 2 shows gain and NF measurements for the composite EDFA. It is shown that gains as high as 54dB with a corresponding NF of 3.1dB can be easily obtained. Comparing with the conventional EDFA, we found that for 45mW of pump power a 75m length conventional EDFA gives a high gain of 46.6dB and NF of 4.85dB whilst to reduce the NF to about 3.36dB requires a sub-optimal length of 30m resulting in a moderate gain of 25.2dB and corresponding gain-efficiency reduction. On the other hand, 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 [7].

III. OPTICAL LIMITING AMPLIFIER

A novel configuration of an erbium-doped-fibre optical limiting amplifier (OLA) is presented which is realised by simply introducing a differential lump-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 simply bending tightly the erbium-doped fibre at a particular point along its length. The optical isolator with the two pump-bypassing WDMs used in the composite EDFA (section II) can be also 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 the 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 stages I and II, before and after the lump-loss position, respectively. In stage I, 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 stage II 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 stage I, it heavily depletes the pump power which drops below threshold towards the end of stage II 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.

In Figure 4, the calculated input/output response and noise figure of an OLA (solid line) are plotted in which the lump-loss is introduced through the insertion of an optical isolator placed at the optimum position (~3.5m from the input end) [4]. The input pump power is 20mW and the EDF length is 8.2m. The isolator extinction ratio is 30dB and the signal and pump loss are 2dB and 0.5dB, respectively. In this case, 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 [4] 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.

An important feature of the proposed OLA is the possibility of controlling the output signal power optically by varying the input pump power. By increasing the input pump power from 20mW to 60mW, the signal output of the OLA increases from ~8dBm to ~14dBm and is accompanied by an ~20% increase in the dynamic range of the OLA.

An OLA was constructed by incorporating an optical isolator inside an Er-doped fibre to induce the pump/signal differential loss (see section II). The various parameters are the same as in section II. Preliminary results demonstrating the limiting action and the output control of the proposed OLA are shown in Figure 5 and compared with results for an optimised conventional EDFA employing a 60m length of the same doped fibre.

IV. EQUALISING OPTICAL AMPLIFIER

A novel EDFA configuration is proposed which provides automatic spectral gain equalization. The device relies on the effective increase in the inhomogeneous broadening in an EDFA by spatial hole burning. The gain medium is 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 gain equalization.

An equalising optical amplifier was built and tested. The amplifier consisted of two sections of EDF. The first was a 14m length of germano-alumino-silica doped fibre with NA of 0.2, λ_{cutoff} of ~930nm and absorption at the signal wavelength of ~3dB/m and was used to boost input signal levels. The output was spliced to one core of a 10m length of doped twincore 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 lockin techniques to discriminate their amplified outputs.

Figure 6 shows the amplifier saturation characteristics 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, gain equalisation rates up to 0.11dB per dB difference between input signal levels have been demonstrated and should increase the useful bandwidth of cascaded amplifiers.

V. HIGH-POWER PULSE AMPLIFICATION

The generation of high peak power pulses by amplification of the output from a DFB diode laser is demonstrated using a cascade of three erbium-doped fibre amplifiers (EDFAs) separated by an acousto-optic gate. The optimised amplifier chain consisted of two high efficiency single-mode EDFAs pumped at 980nm, followed by a multi-mode EDFA pumped at 978nm.

The experimental configuration is shown in Figure 7. The first two EDFAs (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 ≈ 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. This output corresponds to a net amplifier gain of 78.6dB. The launched pump powers in this case were 40mW and 1.5W for EDFA1/2 and EDFA3 respectively. The amplification was split such that the output peak power from EDFA2 was 88W, corresponding to 47.6dB gain in these two sections. The AOM was driven with a gate width of 300ns. Owing to the coupling loss between the two EDFAs, the resultant input pulse to EDFA3 had 40W peak power and the peak gain of EDFA2 was 34.4dB. However, because of the high peak powers in EDFA3 the output power decreased with time, (Figure 8) 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. The peak output power measured was limited by the 2ns risetime of the 10ns pulse. However, it is clear that significantly higher output powers should be possible for a shorter duration pulse, particularly if the small mismatch in spectral gain peak noted earlier could be eliminated.

VI. 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 building-up of the 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 lump 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.

Finally, 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 and military applications.

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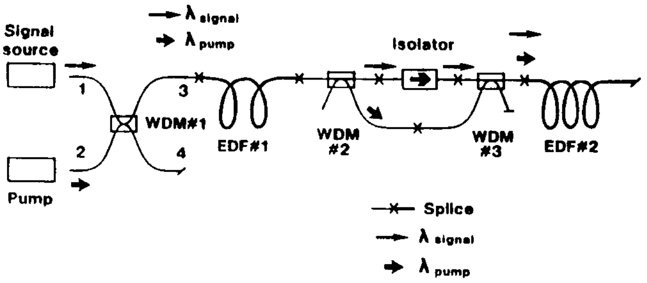

Figure 1: Composite-EDFA configuration.

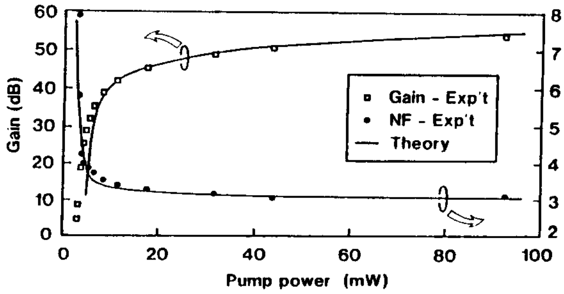

Figure 2: Gain and NF measurements for the composite EDFA.

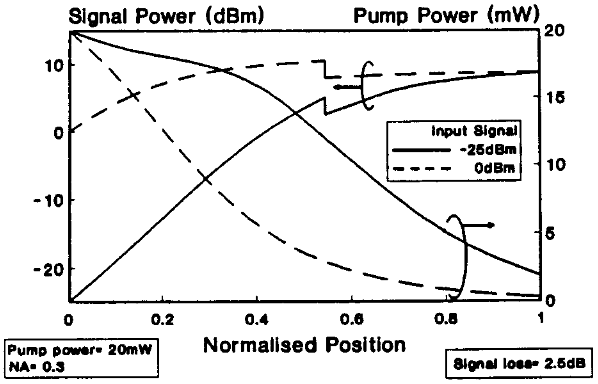

Figure 3: Pump- and signal-power evolution along the OLA for input-signal powers of -25dBm (solid) and 0dBm (dashed).

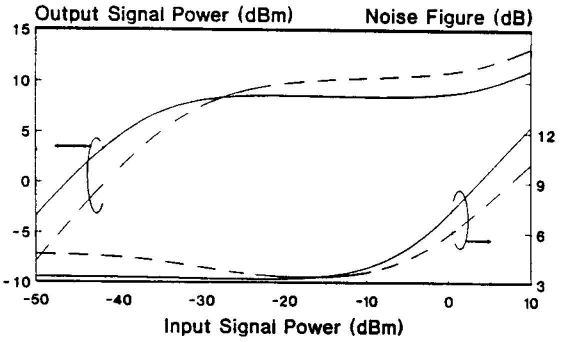

Figure 4: Input-output characteristics of the proposed OLA (solid) and conventional EDFA (dashed).

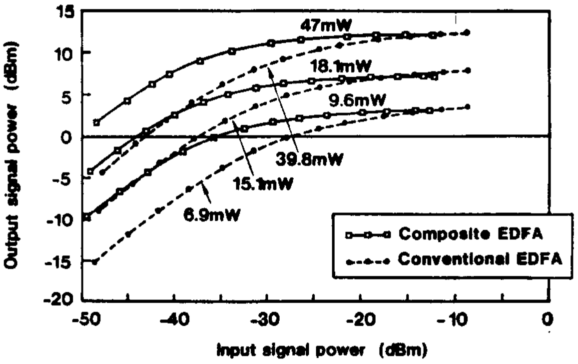

Figure 5: Experimental results of an OLA compared with the conventional EDFA.

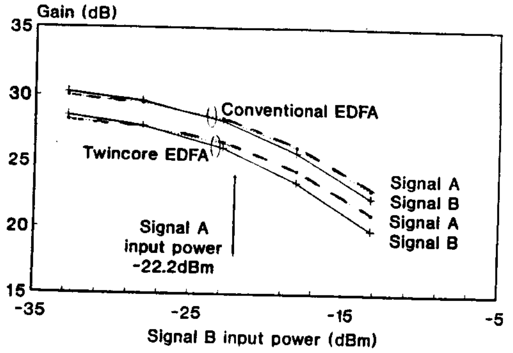

Figure 6: Comparison of two-channel gain saturation characteristics for twin-core EDFA and conventional EDFA.

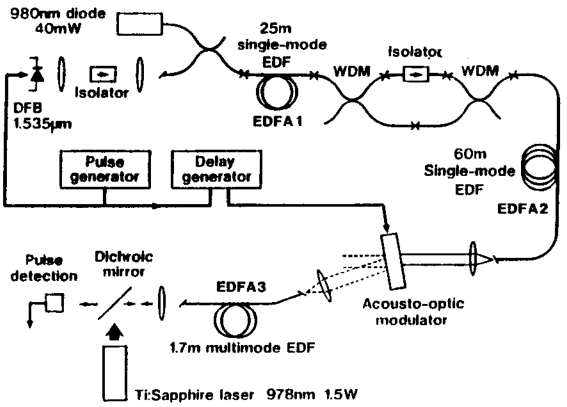

Figure 7: Experimental set-up of a three-stage amplifier for pulse amplification.

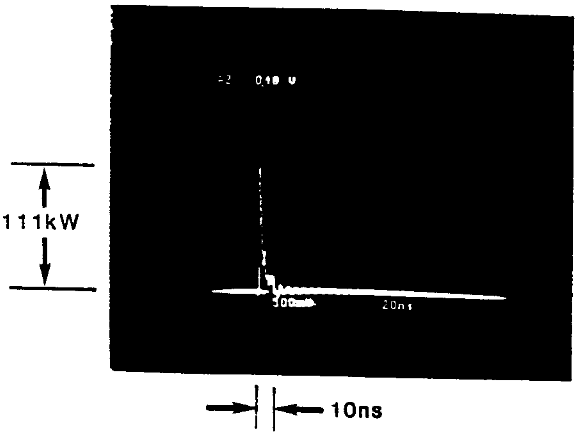

Figure 8: 10ns amplified pulse of 111kW peak power (0.34mJ).