TWINCORE ERBIUM-DOPED FIBRE AMPLIFIER WITH PASSIVE SPECTRAL GAIN EQUALISATION

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Indexing terms: Fibre lasers, Equalisers, Lasers

Automatic spectral gain equalisation is demonstrated using controlled spatial hole-burning in an erbium-doped twincore fibre. Gain equalisation rates up to 0·11 dB difference between input signal levels are demonstrated and should increase the useful bandwidth of cascaded amplifiers.

The erbium-doped fibre amplifier (EDFA) is attractive for wavelength-division-multiplexing (WDM) networks owing to its high gain, low noise and low interchannel crosstalk. The 3 dB gain bandwidth of EDFAs is typically 3–8 nm but can be increased to ~30 nm with appropriate techniques [1]. However, in these cases the gain band is not flat and exhibits a small ripple (~ ±1 dB). When combined with wavelength dependent losses in the transmission fibre and optical components in the link, such variations limit the number of amplifiers that can be cascaded before a significant difference in signal level develops between channels. Ideally the signal levels should be actively [2] or passively compensated after each amplifier to equalise all channels.

The gain available in EDFAs saturates with increasing total input signal and provides a self-limiting mechanism for the amplifier. However, Er^{3+} in silica-based optical fibre is predominantly homogeneously broadened [3, 4], which means that the gain spectrum decreases relatively uniformly even if one input signal is substantially larger than the others and no significant spectral gain compensation occurs. Alternatively, if the amplifier were predominantly inhomogeneously broadened the gain saturation of each channel would be independent and spectral gain compensation would be observed [5–7].

In this Letter we demonstrate an 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 [8] approximately proportional to λ^{-3}. One signal exhibits a certain periodic spatial intensity distribution and thus accesses a subset of ions, whereas a different signal wavelength will access a different subset of ions. This practically decouples the gain at the two signal wavelengths 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 equalisation.

The experimental configuration is shown in Fig. 1. The amplifier consisted of two sections of EDF. The first was a 14 m length of germano-alumino-silica doped fibre with NA of 0·2, λ_{cutoff} of ~930 nm and absorption at the signal wavelength of ~3 dB/m and was used to boost input signal levels. The output was spliced to one core of a 10 m 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 1·43 and 4·5 μm, respectively. The resulting coupling length is wavelength dependent and estimated to be 1·26 mm (1·2575 mm) at a wavelength of 1·55 μm (1·551 μm) The absorption at the signal wavelength was ~1 dB/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 equalisation. Small sinusoidal modulations at 49 and 51 kHz were superimposed on the CW output of the lasers allowing lock-in techniques to discriminate their amplified outputs.

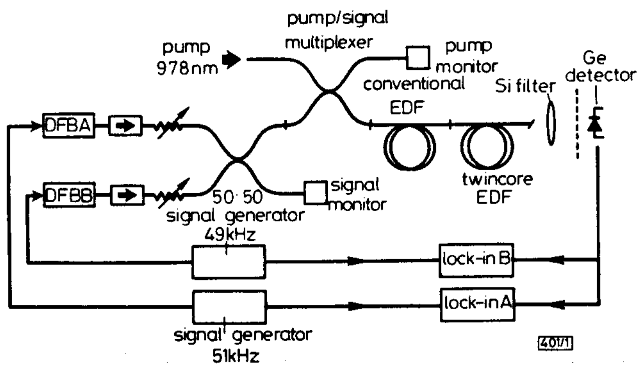

Fig. 1 *Experimental configuration*

Fig. 2 shows the amplifier saturation characteristics for the two channels in the new amplifier. Here the pump power is

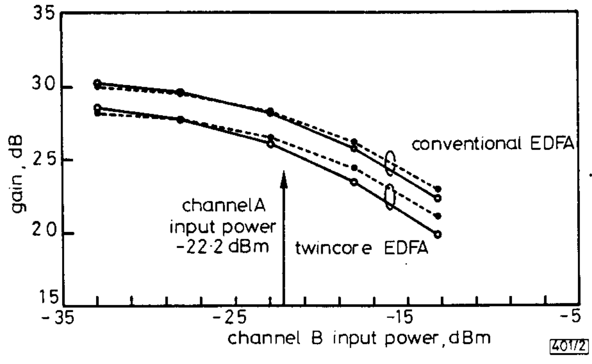

Fig. 2 *Comparison of two channel gain saturation characteristics for twincore EDFA and conventional EDFA*

Pump power is 30 and 50 mW at 978 nm for the conventional and twincore EDFAs respectively. The wavelengths of channels A and B are 1531·7 and 1530·7 nm, respectively
--●-- channel A
—○— channel B

~50 mW at 978 nm and channel A input power is held constant while channel B input power is increased. The wavelength separation of the lasers is 1 nm, close to the gain peak at 1531·2 nm. The characteristics are compared with those of a conventional amplifier employing 18 m of the initial fibre and ~30 mW 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, whereas when larger its gain is reduced. This effect in the conventional amplifier is caused by spectral hole burning (due to inhomogeneous broadening) whereas for the twincore amplifier the compensation is approximately doubled owing to the combined effects of spectral and spatial hole burning.

Compensation was investigated as a function of wavelength separation and the results are shown in Fig. 3*a* and *b*, respectively, for the conventional and twincore amplifier. Compensation in the conventional amplifier exhibited a dependence on wavelength separation characteristic of spectral hole burning with a gain compensation per relative input signal change (maximum slope of Fig. 3*a*) of ~0·046 dB/dB observed for a 0·4 nm channel separation. In the twincore amplifier the compensation for larger wavelength separations is largely independent of separation with a maximum value of 0·11 dB/dB observed. Although this compensation is slightly reduced for smaller channel separations (0·2 nm) the observed compensation, 0·055 dB/dB, still exceeds that of the conventional amplifier.

At the output of the twincore amplifier the power is split arbitrarily between the two cores because the total fibre length cannot be an exact integer number of coupling lengths for all possible signal wavelengths. The distribution of power between the two cores of a twincore fibre is a result of the superposition of an even and odd eigenmode which have equal power irrespective of wavelength [9]. These two modes travel at different velocities and thus result in the observed exchange of power between the two cores. For small core to core separations tapering the twincore fibre at the output to approximately 1/2 its original diameter should result in the cutoff of the odd (second) mode. The even mode which then approximates well to a Gaussian can then be coupled without significant loss into a singlemode fibre. As stated the key advantage of this technique is that the power in the even mode is independent of the precise amplifier length. Thus the periodic coupling of the light between the two cores as it propagates provides automatic gain compensation, and tapering at the output will remove any wavelength sensitivity due

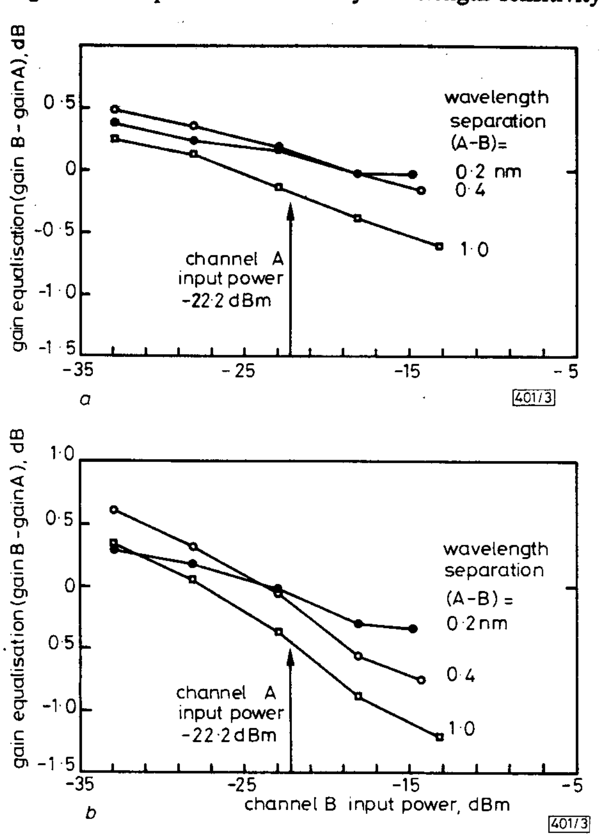

Fig. 3 *Gain compensation for conventional and twincore EDFA for three different signal wavelength separations*

Pump power is 30 and 50 mW at 978 nm for the conventional and twincore EDFAs respectively. The wavelength of channel A is 1531·7 nm
a Conventional
b Twincore

to the exact power distribution in the two cores with only a 3 dB output penalty. Other types of mode transformer such as the Y-junction [10] could also be used to the same effect at the amplifier output.

In conclusion, we have demonstrated automatic spectral gain equalisation due to spatial hole burning in an erbium-doped twincore fibre. Gain equalisation rates up to 0·11 dB per dB of relative input signal level are observed and should increase the useful bandwidth of cascaded amplifiers. As an example, if all received signals were required to be within 5 dB in a WDM network with 100 cascaded conventional EDFAs, then the useful bandwidth of each EDFA would be defined for only a 0·05 dB gain variation. However, this tolerance is relaxed to 0·5 dB for the new amplifier because, although the imbalance between signal levels in initial amplifiers would build, signals would be stabilised in subsequent amplifiers due to the proportional nature of the gain compensation. Future improvements in amplifier design should enhance this effect further.

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METHOD FOR ERROR RECOVERY OF LINE SPECTRAL FREQUENCIES

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Indexing terms: Speech coding, Codes and coding

Corruption of line spectral frequencies results in significant degradation of the speech quality. Usually, FEC is used to protect the LSFs, especially in very noisy channels. The Letter describes an effective error recovery scheme which relies only on the inherent and natural structure of the LSFs.

Introduction: Line spectral frequencies (LSFs) are used for coding and transmission of the short term predictor (STP) coefficients in many LPC-based low bit rate speech coders. Ensuring the integrity of the LSF vectors through noisy channels usually involves forward error correction (FEC) coding, which, unfortunately, incurs more redundancy for performance at higher bit error rates (BERs). It is thus desirable to perform error control on LSFs with less or no reliance on FEC.

In the method described here, scalar quantisation of the LSFs [1] is used. At the receiver, we use a search procedure to match an LSF vector to an entry in a trained codebook. Errors in the received vector are then identified through discrepancies with the codebook vector, thus enabling error correction. In addition, we also exploit frame to frame correlation characteristics of LSFs to aid the error recovery process.

Use of LSF properties: An LSF vector will cause instability in the LPC synthesis filter if its monotonicity is violated:

$$L_n(i) < L_n(j) \qquad 0 \le i < j \le N-1 \quad (1)$$

where N is the order of the LPC analysis, and n is the speech frame index. This is known as crossover of the LSFs and can cause annoying artefacts unless they are located and replaced with suitable values. To locate the offending LSFs when crossovers occur, deviations of the elements of the received LSF