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Passive WDM channel equaliser using a twin-core erbium-doped fibre amplifier

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ABSTRACT

A passive WDM channel equaliser using a twin-core EDFA is studied in detail. Gain saturation limits the range of input signal powers from ~-20dBm to ~0dBm. Channel equalisation rates as high as 0.35dB/dB are predicted.

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I. Introduction: Erbium-doped fibre amplifiers (EDFAs) show high gain and low noise over a wide signal bandwidth. Depending on the host glass and pump wavelength, the 3dB gain bandwidth is typically 3-8nm and can increased to about 30nm with suitable gain-shaping techniques [1]. Even in the latter case, the gain profile is not flat, exhibiting a small ripple of about ±1dB. In wavelength-division-multiplexed (WDM) systems, involving several amplifiers, such gain variations can result in large differences in signal levels and, when combined with wavelength-dependent losses in the transmission line, will eventually limit the number of EDFAs that can be cascaded. To overcome these problems, various channel equalisation schemes have been proposed which provide active power compensation for the individual WDM channels [2,3].

Recently, a passive, all-optical, channel equalising amplifier has been demonstrated using an erbium-doped twin-core fibre which is able to provide equalisation up to 0.11dB per dB of channel amplitude difference [4]. Obviously, a perfect channel-equalising amplifier would provide 1dB/dB of channel amplitude difference. In this communication, an in-depth theoretical investigation of the device is presented. The channel-equalising performance is affected by the twin-core fibre length and numerical aperture, as well as the input power of the various channels. We consider those factors in detail and propose optimum design criteria. The limitations imposed by the saturation of the device are also discussed. It is shown that the twin-core EDFA can provide channel equalisation as high as 0.35dB/dB for two channels.

II. Device description - Principle of operation: The gain spectrum of erbium ions in silica-based optical fibres is predominantly *homogeneously* broadened and, consequently, the spectrum saturates relatively uniformly even when only one WDM input channel increases significantly in comparison with the other channels. Therefore, conventional EDFAs provide <u>no</u> significant passive channel compensation. Alternatively, if the erbium ions were predominantly *inhomogeneously* broadened, the gain saturation of wavelengths separated by more than the homogeneous linewidth would be independent and the EDFA would provide some degree of passive channel equalisation, ie the channels would emerge from the amplifier having less amplitude variation than at the input.

We have previously described a method [4] which enhances the effective inhomogeneous broadening of the EDFA (regardless of its original degree of inherent inhomogeneous broadening) and results in a degree of passive WDM channel equalisation. The method uses a twin-core EDFA in which both cores are Er^{3+}-doped in order to spatially separate the amplifying regions available for different wavelength channels.

All channels and pump are initially launched into one of the fibre cores. The signals are periodically coupled between the two doped cores, with period roughly proportional to λ^{-3} [5]. Thus, the cross-coupling for individual channels moves periodically in- and out-of-phase as the signals propagate along the twin-core fibre and, therefore, the signals decouple spatially to some degree. As a consequence, one channel (λ_1) accesses and predominantly saturates a subset of erbium ions, while another channel (λ_2) predominantly saturates the complimentary subset of ions. In this way, the gain of the two signal wavelengths is *spatially (longitudinally)* decoupled and in the case when one signal increases with respect to the other, its gain can preferentially saturate resulting in spectral equalisation. The technique can be regarded as a form of spatial hole-burning which is well known to occur in laser resonators and which provides differential gain to the various oscillating wavelengths.

III. Theoretical model: The performance of the twin-core amplifier was investigated by means of a theoretical model in order to establish the effect on the degree of channel equalisation of various parameters, such as input channel power and channel separation, fibre length and NA. The model uses the coupled-mode theory formulation to describe the evolution and cross-coupling of the signal and pump power in a twin core fibre with distributed gain/loss [6]. A standard EDFA model [7] is used to analyse the distributed gain/loss and its variation along each fibre core. The model takes no account of any coupling non-linearities caused by anomalous dispersion as the various Er^{3+} transitions are pumped/saturated. This assumption is fully justified, since the pump is at 980nm and the signals around 1530nm (the first gain-spectrum peak) where the non-linear refractive index changes are approximately zero [8]. The EDFA model accounts for the homogeneous broadening only and, therefore, any degree of equalisation is entirely due to spatial hole-burning. The various other parameters are pertinent to GeO_2-Al_2O_3-SiO_2 and GeO_2-SiO_2 fibres [9]. The dopant concentration was taken to be 10^{24} m^{-3}. The forward and backward ASE has been neglected since the signal levels we considered were relatively high.

IV. Theoretical & Experimental Results: The degree of channel equalisation [gain difference (G#2-G#1)] was calculated and compared with experimental results for the case of two copropagating WDM channels #1 and #2. The wavelength and input power of channel#1 was kept constant while channel#2 was varied. The degree of channel equalisation of the passive channel-equalising amplifier was also compared with the ideal in which the gain difference (in dB) is equal and opposite, ie is linearly dependent with slope= -1, to the input channel power difference (in dB).

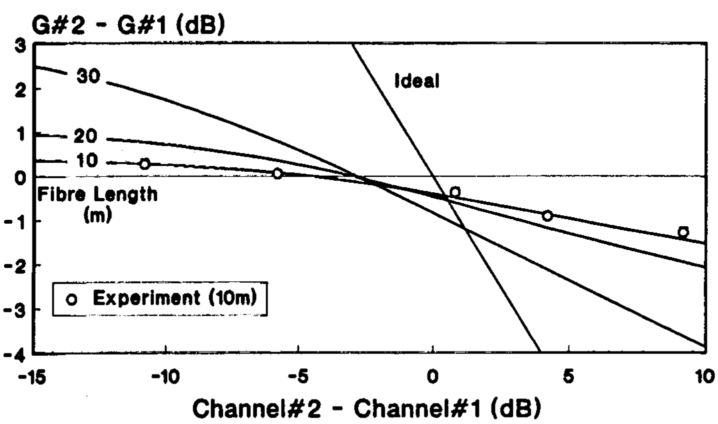

FIGURE 1: Channel equalisation against channel power imbalance for fibre lengths of 10m, 20m and 30m and pump power of 30mW, 30mW and 300mW, respectively. The input power of channel#1 is -5dBm. The fibre NA is 0.27 and the core separation is 4.5μm. Dots correspond to experimental data obtained with 10m of twin core fibre [4].

Figure 1 shows the effect of the twin-core fibre length on the channel equalisation which is given by the slope of the curve. The wavelength and input power of channel#1 is 1532nm and -5dBm, respectively, while the wavelength of channel#2 is 1531nm and its input power varies between -20dBm and +5dBm. The NA and radius of each core is 0.27 and 1.35μm, respectively, and the core separation is 4.5μm. The input pump power is 30mW (10m, 20m) and 300mW (30m). The dots correspond to experimental data [4] obtained with a 10m long twin-core GeO_2-Al_2O_3-SiO_2 fibre having parameters similar to the ones used in the computation and show very good agreement. It is also clear that, under the same pumping conditions, increasing the fibre length from 10m to 20m, results in an quasi-proportional increase of the degree in channel equalisation. However, by increasing the length and pump power still further, the effect is enhanced dramatically, resulting in a channel equalisation of ~0.35dB per dB of input signal level difference.

In Figure 2, the effect of the fibre NA on the degree of channel equalisation is investigated. The fibre parameters refer to GeO_2-SiO_2 host [9]. The wavelength and input power of channel#1 is 1530nm and -5dBm, respectively. The wavelength of channel#2 is 1531nm and its input power varies between -15dBm and +5dBm. The input pump power is 30mW, the fibre length is 10m and the core separation 4.5μm. For very low NAs, the gain equalisation is negligible, since the degree of gain saturation is very small. However, at higher fibre NAs the gain saturation is stronger and this results in an increased degree of channel equalisation (~0.15dB/dB).

The dependence of channel equalisation on the saturation of the device is also evident for each fibre NA as the input power of channel#2 is increased. In all cases, the gain equalisation curves exhibit two distinct slopes. For input signal level differences less than ~-5dB, the slope is close to zero and the corresponding rate of equalisation is negligible (~0.06dB/dB). However, for signal differences greater than ~-5dB, the curve slope increases, corresponding to a substantial (threefold) increase of the equalisation (~0.15dB/dB).

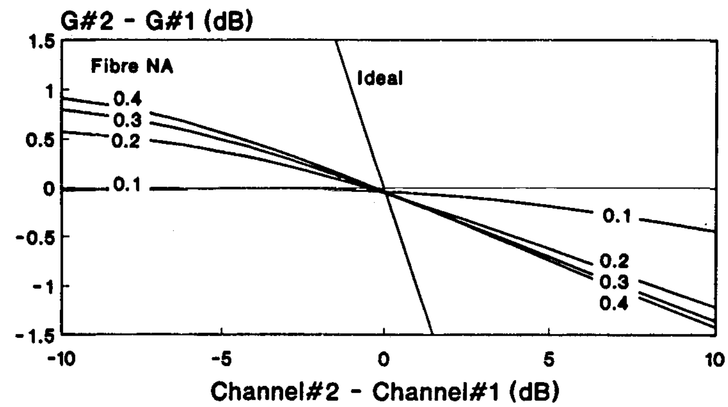

FIGURE 2: Channel equalisation against channel power imbalance for fibre NAs of 0.1 to 0.4. The fibre length is 10m, the pump power is 30mW and the channel#1 input power is -5dBm. The channel separation is 1nm and the core separation 4.5μm.

The effect of gain saturation on the degree of channel equalisation was further investigated by also varying the input power of channel#1. Here, the fibre characteristics are fixed so that the spatial (longitudinal) wavelength decoupling is constant and any difference in the response is entirely due to the different degrees of saturation. The results are summarised in Figure 3 for which the fibre NA is 0.3 and the core separation 9.5μm. The rest of the parameters are the same as in Figure 2. At channel#1 input powers less than ~-30dBm, the device provides no equalisation owing to negligible gain saturation. The gain remains constant to ~12.4dB for both signals over the entire dynamic range. Increasing the input power of channel#1 from -20dBm to 0dBm results in a considerable increase in channel equalisation (~0.15dB/dB) as the gain saturation increases progressively. An interesting effect occurs if the input power of channel#1 is further increased to +5dBm. Although the channel equalisation further improves in the case where channel#2 is smaller than channel#1, the response of the device degrades considerably as channel#2 exceeds channel#1. This is due to the heavy saturation of the gain medium. In this case, gain#1 and gain#2 drop to ~4.5dB-1.8dB and 6dB-1dB, respectively. It is evident from the results that the twin-core EDFA provides substantial channel equalisation for input channel powers in the range of -20dBm to 0dBm. However, the operation of the device can be extended into lower input channel powers by combining it with an optical pre-amplifier to increase the power and drive the channel-equalising amplifier well into saturation [4].

V. Discussion - Conclusions: An inhomogeneously broadened amplifying medium can provide some degree of passive channel equalisation. However, in a conventional EDFA the channel spacing should be greater than the homogeneous linewidth, which varies between ~4nm and ~12nm [10]. However, with the twin-core EDFA, the channel equalisation relies on the longitudinal dephasing and separation of the two signal wavelengths and relies on the spatial hole-burning effect which can be achieved even in totally homogeneously-broadened media and for very small channel separation. We have found that for a given fibre geometry, the signal decoupling and channel equalisation increases rapidly with the channel separation and oscillates slightly around a constant value which depends mainly on the geometry. For a fibre NA of 0.27, length of 10m and core separation of 4.5μm, the maximum decoupling and, hence, channel equalisation is achieved for channel separation of 5.8GHz (~0.15dB/dB) and oscillates around ~0.13dB/dB for channel spacings up to 10nm.

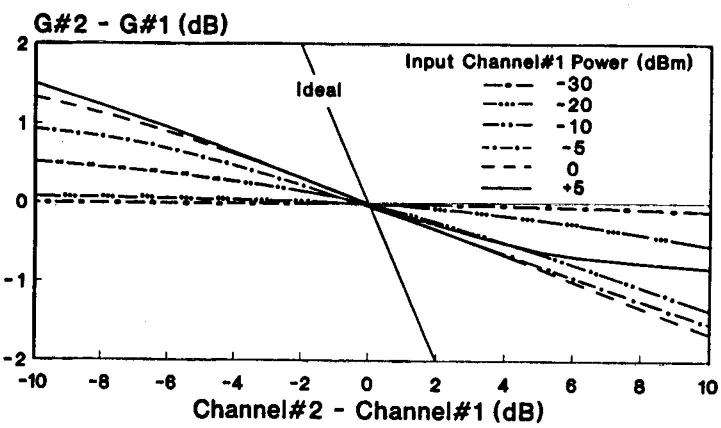

FIGURE 3: Channel equalisation against channel power imbalance for channel#1 input powers of -30dBm to +5dBm. The fibre length and NA are 10m and 0.3, respectively, pump power is 30mW and the channel separation 1nm. The core separation is 9.5μm.

In conclusion, the performance of an twin-core fibre passive channel-equalising amplifier has been studied in detail. The channel equalisation depends predominantly on the fibre geometry and saturation characteristics. A value as high as 0.35dB of differential (compensating) gain per dB of channel amplitude imbalance can be achieved, which will substantially correct and minimise the build up of channel amplitude errors in WDM systems.

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