markedly lower than values found for conventional laser structures.[7]

A similarly marked reduction of the linewidth-power product to a value of 5 MHz mW has also been achieved by optimisation of the structure of a long-wavelength InP-based QW distributed feedback laser.[8]

The low measured value of the linewidth-power product can be related to correspondingly low values of both β_{sp} and α. From distortion analysis of the audio-frequency modulated laser output, the spontaneous emission coefficient β_{sp} is measured to be $(3{\cdot}7 \pm 1) \times 10^{-6}$, compared to values of about 10^{-5} for conventional index-guided lasers.[9] Using the measured values of Δf_{rms} and $\tau_{ph} \simeq 2{\cdot}3$ ps calculated from the internal losses ($\alpha_i \simeq 30\,\text{cm}^{-1}$), the reflection coefficients and the laser length (see above), eqn. 2 yields a linewidth enhancement factor of $\alpha \simeq 1{\cdot}2 \pm 0{\cdot}5$.

Additionally, α can be determined directly from the spectral dependence of Δf^2_{rms} on f_m,[10] as

$$\frac{\Delta f^2_{rms}(0)}{\Delta f^2_{rms}(\infty)} = 1 + \alpha^2 \qquad (3)$$

Measurements of Δf^2_{rms} at 0·1 and 3 GHz yield $\alpha \simeq 1{\cdot}3$, which is in good agreement with the value obtained above. In conventional AlGaAs DH laser structures, α is typically about 4.[11]

In conclusion, the linewidth-power product of GaAs/AlGaAs GRINSCH-SQW flared waveguide lasers has been determined from FM noise measurements. $\Delta\nu P$ has been found to be as low as 4 MHz mW, which can be related to correspondingly low values of both β_{sp} and α. Considering that $\alpha \sim (\partial n_r/\partial N)/(\partial g/\partial N)$, where n_r is the real part of the refractive index, g is the gain and N the carrier density, these results support the prediction of α reduced by a factor of two in quantum-well structures.[12]

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LASER DIODE PUMPED OPERATION OF Er^{3+}-DOPED FIBRE AMPLIFIER

Indexing terms: Optical fibres, Optical communications, Semiconductor lasers

Semiconductor laser-diode pumped operation of an erbium-doped fibre amplifier, exhibiting 6 dB gain and operating at 1536 nm, is reported. The amplifier was optically pumped at 807 nm using a self-injection-locked semiconductor laser diode array.

Introduction: The potential of rare-earth-doped, single-mode fibre to provide optical amplifiers[1] and lasers[2] for telecommunications purposes has recently been demonstrated. Interest has centred around Er^{3+}-doped fibres as they exhibit optical amplification around 1536 nm when longitudinally pumped using a variety of laser sources. The bandwidth and noise characteristics of these amplifiers look promising,[3] while their inherent fibre compatibility and polarisation-independent gain[4] are attractive to system designers.

High single-pass gains have been reported when Er^{3+}-doped fibres are pumped at 514 nm[5] or 655 nm,[1] and more recently efficient operation has been achieved through pumping an erbium-doped fibre at 980 nm using a dye laser.[6] Unfortunately, practical pump sources at the above wavelengths are not readily available or cannot be reasonably implemented, although future pump-laser device development may change this situation. At present one of the most realistic pump sources for a practical fibre amplifier is a high-power semiconductor AlGaAs laser diode, operating in the region of 800 nm. It is known that useful gains are possible when an erbium-doped fibre is pumped at 807 nm,[7] a wavelength which lies within the $^4I_{15/2}$–$^4I_{9/2}$ absorption band of erbium. In this letter we report the results of gain measurements carried out on an Er^{3+}-doped fibre amplifier optically pumped at 807 nm using a commercially available semiconductor laser diode array. The diode array was self-injection-locked to improve coupling of the pump into the doped fibre.

Experiment: Small-signal gain measurements were carried out using the contradirectionally pumped system depicted in Fig. 1*a*. The gain medium was investigated using the −30 dBm output of a GaInAsP external cavity semiconductor laser. The input signal was tuned to the peak of the amplifier gain at 1536 nm and modulated at 3 kHz such that lock-in detection techniques could be used. This signal was coupled into the doped fibre via a fused fibre coupler, the free legs of which enabled convenient monitoring of remnant pump and input power. The GeO_2/P_2O_5 silica-based fibre, which had a numerical aperture of 0·3 and a cutoff wavelength of 1100 nm, was doped to a few hundred ppm with Er^{3+} ions using a variation of standard MCVD techniques.[8] The active fibre was contradirectionally pumped at 807 nm using a Spectra Diode Labs (SDL-2432) semiconductor laser diode array. The output signal was extracted by means of a dielectric mirror

highly reflecting at 1536 nm and highly transmitting at 807 nm and detected by a germanium photodiode. The length of the doped fibre was 8 m which was gain-optimised for a launched

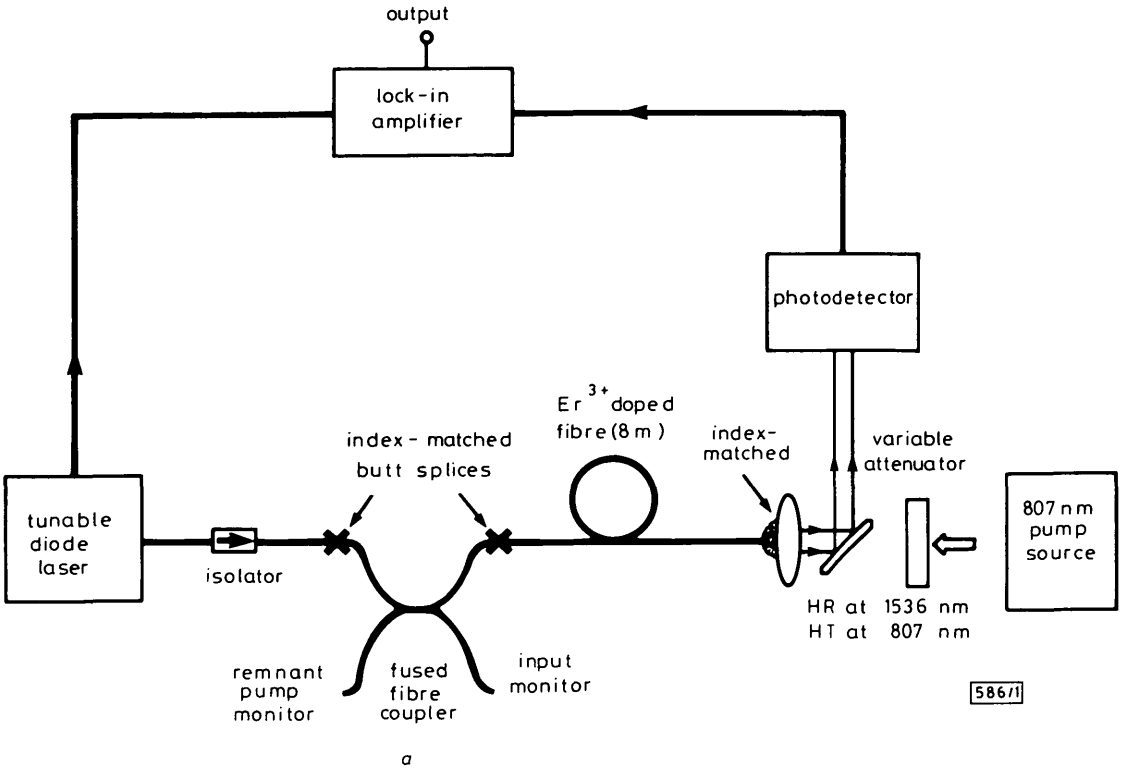


Fig. 1

a Experimental configuration used for gain measurements
b Schematic representation of self-injection-locked AlGaAs laser diode array
DA = SDL(2432) semiconductor laser diode array, L_1 = spherical lens, L_2 = cylindrical lens, M_1 = output mirror, M_2 = feedback mirror, SF = spatial filter

pump power of 50 mW at 807 nm. Gain values were obtained from a simple ratio by measuring the input signal from the coupler and the output signal from the amplifier, using the same optics and detector.

To improve pump coupling efficiency into the doped fibre, the diode array was self-injection-locked using a reflection feedback technique.[9,10] In this technique a proportion of the radiation field is spatially filtered and then reflected back into the array, thus injection-locking the device and improving the output beam quality. The injection locking scheme of Fig. 1*b* consists of a mirror (M_2) and a spatial filter (SF) positioned at the beam waist formed by lenses L_1 and L_2. The cylindrical lens (L_2) corrects for the astigmatism in the output of the laser diode array, ensuring that both planes of emission waist at the same position. The principle of operation is as follows. The diode array produces a twin-lobed output in the far field; one of these lobes is spatially filtered and then reflected back into the array. This reflected beam may be regarded as an injection-locking input into a reflective amplifier, and as such drives most of the array output into the other, near-diffraction-limited, lobe. This now dominant lobe may be selected using mirror M_1 and more efficiently coupled into the doped fibre. To date, up to 15 mW of pump power has been launched into the doped fibre.

Results: Using a variable attenuator to adjust the launched pump power, the evolution of gain at 1536 nm with launched pump power at 807 nm was investigated. The results plotted in Fig. 2 indicate that the unpumped absorption of the fibre was 24 dB and that 9 mW of launched pump power is required to bleach this 8 m length of fibre. A maximum gain of 6 dB is observed for a launched pump power of 15 mW from the laser diode array. This modest gain was limited by the launched pump power available when using the diode array. However, experiments using a Styryl 9 dye laser, the improved beam quality of which enabled much better pump launch efficiency, indicate that for high pump powers the gain approaches a maximum of 15 dB. This information forms the basis of extrapolating the results shown in Fig. 2 to higher pump powers. Fig. 2 thus indicates that around 30 mW of launched

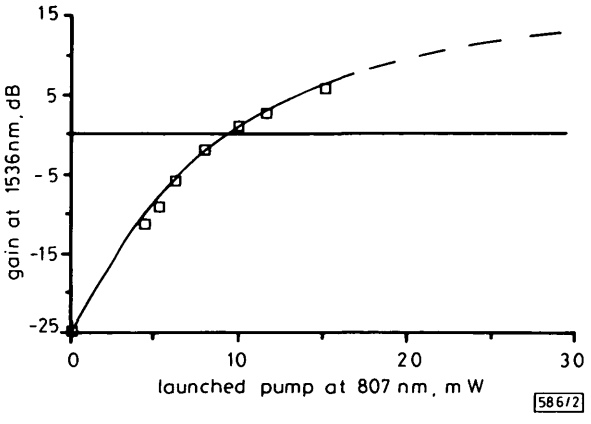


Fig. 2 *Evolution of gain at 1536 nm with launched pump power at 807 nm*

For explanation of broken-line extrapolation see text

pump power would be necessary to achieve a gain of 13 dB. Wyatt[10] has demonstrated that up to 50 mW of 807 nm wavelength radiation can be launched into a doped fibre using the type of self-injection-locking scheme detailed in Fig. 1*b*. It is thus expected that, with optimisation of the pumping scheme, diode-pumped gains in excess of 13 dB will be possible. Furthermore, compact diode-pumped fibre amplifiers could be envisaged using miniaturised injection-locking schemes similar to that of Reference 11.

Conclusions: An erbium-doped fibre amplifier has exhibited 6 dB single-pass gain at 1536 nm when pumped at 807 nm

using a self-injection-locked semiconductor laser diode array. Furthermore, for launched pump powers of around 50 mW, gains of 15 dB are predicted.

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APPLICATION OF MLSE TO GMSK SIGNAL RECEPTION USING FREQUENCY DEMODULATOR

Indexing terms: Telecommunications, Mobile radio systems, Radiocommunication

The applicability of the maximum likelihood sequential estimator (MLSE) to 16 kbit/s GMSK signal reception using a frequency demodulator is investigated. The experimental results for GMSK with a premodulation filter bandwidth-bit duration product of $B_bT = 0{\cdot}25$ show that the bit error rate performance with MLSE approaches that of MSK, with a loss of about 2·5 dB in the signal energy per bit/noise power spectral density ratio and about 3·5 dB in the desired signal/cochannel interference ratio. The experimental block error rates are also reported.

Introduction: Narrowband digital FM schemes such as GTFM[1] and GMSK[2] are promising for mobile radio because of their narrowband power spectra and constant envelope property. As a demodulation scheme in mobile radio systems, a frequency demodulator (FD) is of much interest because fast fading makes the use of a coherent demodulator difficult. Another reason for this interest is that the carrier frequency drift caused by the relatively instable frequency oscillators used in mobile units precludes application of the differential demodulator. However, the bit error rate (BER) performance using the FD is severely affected by the increased intersymbol interference (ISI) due to premodulation filtering. Chung[1] examined the eye patterns of frequency demodulated GTFM signals and proposed the maximum likelihood sequential estimator (MLSE) for improving the BER. This MLSE can also be applied to GMSK signal reception using the FD.[3] In this letter, the experimental results of 16 kbit/s GMSK signal reception using the FD-MLSE will be presented.

Application of MLSE: A frequency demodulated GMSK signal can be represented as

$$v(t) = \frac{\pi}{2T} \sum_{n=-\infty}^{\infty} a_n G(t - nT) + \text{noise} \quad (1)$$

where a_n ($= \pm 1$) is the nth binary data, $G(t)$ is the baseband pulse response of the GMSK channel including the transmitter and receiver filters, and T is the bit duration. $G(t)$ can be assumed to have symmetrical response centred at $t = 0$. When $B_bT = 0{\cdot}25$ (typical for mobile radio use), $G(t)$ spreads over several bits and causes ISI. Hence, a simple binary decision based on the eye sampled at $t_s = nT$ provides very poor BER performance.

If the sampling is taken at $t_s = (n - 1/2)T$, the FD output can be represented as

$$v_n \approx \frac{\pi}{2T} [(a_{n-1} + a_n)G(0{\cdot}5T) + (a_{n-2} + a_{n+1})G(1{\cdot}5T)] \quad (2)$$

when noise is absent. $G(1{\cdot}5T)$ is much smaller than $G(0{\cdot}5T)$ for $B_bT \geq 0{\cdot}25$ (assuming there is no ISI caused by a predetection filter, then $G(1{\cdot}5T)/G(0{\cdot}5T) < 0{\cdot}11$ when a 1-bit integrate & dump (I & D) filter is used as a postdetection filter). This output has, therefore, three-level eyes and has eye openings larger than that obtained by sampling at $t_s = nT$. The eye level depends on the past and present bits. This correlative property can be effectively used to improve the BER performance. In this letter, we apply Chung's MLSE proposed for FD reception of GTFM signals.[1] Chung's MLSE is based on the assumption of white Gaussian noise at the FD output. However the FD output is characterised by non-Gaussian noise such as clicks. Thus, this MLSE is not a real one in the strict sense. However, as shown in Reference 3, it may improve the BER performance of GMSK. For detailed operation principles of MLSE, see Reference 1. In the following, the transmission performance of GMSK signal reception using the FD-MLSE will be experimentally investigated.

Experiments: A 16 kbit/s 511-bit pseudonoise (PN) sequence was used as the transmitted data. A 900 MHz GMSK signal with $B_bT = 0{\cdot}25$ was generated. The receiver had a predetection filter (ceramic) with BT (3 dB bandwidth-bit duration product) = 1 and the FD (limiter-discriminator). The FD was followed by a timing recovery circuit and a 1 bit I & D filter. The demodulator output was sampled and quantised by using an 8 bit A/D convertor. The sampled output was stored in the memory for later processing. The software for the MLSE was developed for implementation in a microcomputer. The two output shift registers of the MLSE were 16 bits each.

The BER performance measured in an additive white Gaussian noise (AWGN) channel is shown in Fig. 1 as a function of the signal energy per bit/noise power spectral density ratio (E_b/N_0). Performance similar to that predicted by Kalet *et al.* was obtained. For comparison, the BER performance of a three-level eye decision[4] is shown in the Figure. An improvement of about 2 dB at a BER of 10^{-2} is achieved by using the MLSE. Also, the results for MSK reception are plotted in the Figure for reference. Performance with the MLSE, approaches that of MSK (with the 1 bit I & D filter and simple binary decision) with a loss of about 2·5 dB in the E_b/N_0 at a BER of 10^{-2}.