This activation energy is somewhat lower than the value reported in the literature; i.e. 0·5 eV in Reference 4 and 0·7 eV in Reference 5. The reason for this discrepancy is not well understood at this moment.

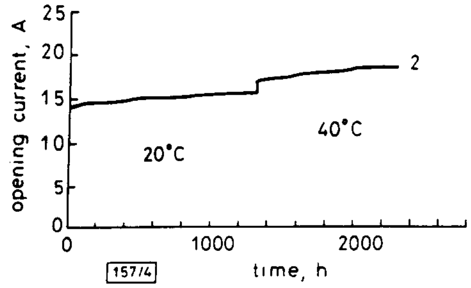

Fig. 4 *Constant power lifetest result at 10 W CW on array 2*

In conclusion, we have characterised 20% packing density 1 cm wide monolithic AlGaAs laser arrays. CW operation up to 16 W has been achieved at a heatsink temperature as high as 70°C. One array has been lifetested for over 3000 h and has a projected lifetime in excess of 17 000 h at 20°C. Temperature dependence of the degradation rate has been characterised and an activation energy of 0·2 eV has been obtained.

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SPECTRAL BROADENING DUE TO FIBRE AMPLIFIER PHASE NOISE

Indexing terms: Optical fibres, Spectral analysis, Noise, Amplifiers

We report, for the first time, measurements of signal spectral broadening caused by phase noise in an erbium-doped fibre amplifier. The spectral broadening was found to be less than 20 kHz. Thus it will not limit the performance of phase or frequency modulated coherent systems employing fibre amplifiers.

Introduction: Erbium-doped fibre amplifiers (EDFA) operating in the 1·5 μm[1,2] wavelength region will play an important role in future optical communication systems. Such devices offer large, polarisation-independent gain, low noise and high efficiency.[3] Advanced coherent communication systems employing optical amplifiers in combination with phase or frequency modulation will allow a greatly increased system capacity and are therefore of considerable interest. Recent results[4] have demonstrated the possibility of using many amplifiers in series to achieve coherent transmission over long distances. Coherent systems may suffer from spectral broadening caused by phase noise introduced by the optical amplifiers. This may limit the number of amplifiers which can be concatenated in an optical link. To quantify the effect, we have measured the spectral broadening caused by an Er^{3+}-doped fibre amplifier operating at 1·535 μm, and have found the amount of broadening to be less than 20 kHz for an amplifier operating with 17 dB gain.

Phase noise in a fibre amplifier arises because of various effects. It is thought to be dominated by the addition of randomly-phased spontaneous photons to the signal field. These phase variations add to the intrinsic phase fluctuations of the signal, causing the signal line to be broadened.

Experiment: Spectral broadening in an EDFA was measured using a Mach–Zehnder interferometer containing the amplifier in one arm, as shown in Fig. 1. The experiment was modelled by assuming that the signal from the DFB is of the form $E(t) = e^{j[\omega t - \phi_f(t)]}$, where ω is the laser frequency and $\phi_f(t)$ is the time-varying phase of the laser field. Provided the optical paths in the interferometer are matched in length so that the propagation time difference, τ_d, between the light passing through the two arms from the DFB to the detector is much less than the coherence time of the DFB laser source, τ_c, then the measured power spectral density at the detector in the limit $\tau_d \ll \tau_c$ is:

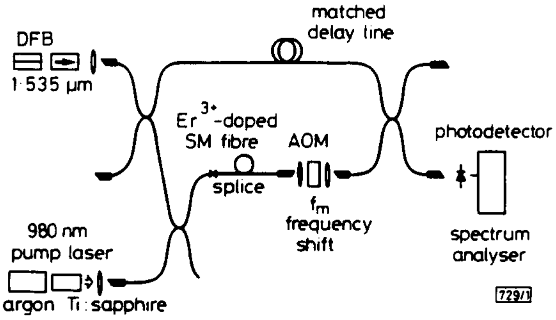

Fig. 1 *Matched-path Mach–Zehnder interferometer*

$$PSD = \mathscr{F}\{\langle e^{j[\phi_a(0) - \phi_a(t)]}\rangle\} \qquad (1)$$

where $\phi_a(t)$ is the time-varying phase shift introduced by the fibre amplifier alone. The technique effectively deconvolves the DFB laser spectrum from the amplifier spectral broadening and provides an output which consists solely of the amplifier spectral broadening response to a spectrum passing through the amplifier.

When a signal passes through the amplifier, the signal shape at the output of the amplifier is the convolution of the input signal shape with the spectral broadening term determined by eqn. 1.

The measured power spectral density of the amplifier spectral broadening response is shown in Fig. 2. The delta function spectrum which resulted when the amplifier was replaced by an equivalent length of undoped fibre [$\phi_a(t) = 0$] is also illustrated for comparison. This indicates that the path lengths were accurately matched. The amplifier was an 11 m length of Er^{3+}-doped single-mode optical fibre, pumped through a dichroic coupler by a Ti : sapphire laser operating at 980 nm. The DFB laser had a linewidth of ~30 MHz at a wavelength of 1·535 μm. At a pump power of 20 mW and signal input power of 50 μW, the amplifier had a gain of 17 dB. The spectral broadening gave rise to a PSD with an approximately Lorentzian line shape (Fig. 2), and a half-power width of less than 20 kHz. This corresponds to an increase in spectral width which is negligible compared to typical DFB linewidths of a few tens of megahertz. The result indicates the efficiency with which the measurement is able to deconvolve the narrow response of the amplifier spectral broadening from that of the broad linewidth diode laser signal source.

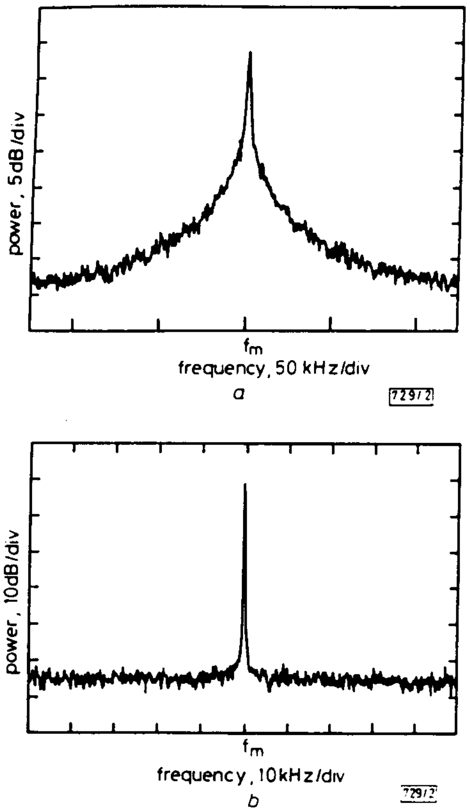

Fig. 2 *Power spectral density*
a Doped fibre
b Undoped fibre

The degree of spectral broadening in the amplifier was observed to change with input signal power as shown in Fig. 3. The signal power was varied by introducing attenuation and maintaining the DFB drive conditions at a constant. The spectral broadening introduced by the amplifier decreases with increasing signal power as expected. This brings an increase in the ratio of signal to amplified spontaneous emission (ASE). The effect was verified by varying the pump power into the fibre amplifier, keeping the signal power constant. No change in the spectral broadening was observed, since the ratio of signal to ASE was unchanged.

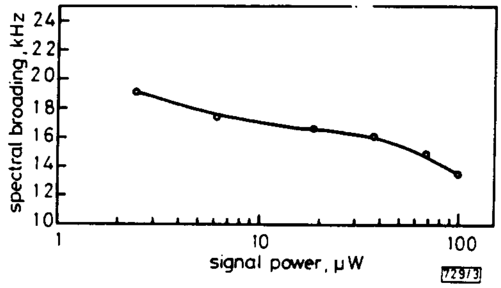

Fig. 3 *Variation of spectral broadening with signal power*

Conclusions: EDFAs operating in the 1·5 µm region introduce additional phase noise to a signal passing through the amplifier. The magnitude of the broadening is, however, less than 20 kHz for an amplifier with 17 dB gain. The implications for these results in coherent systems are that Er^{3+}-doped fibre amplifiers will introduce a negligible penalty as far as phase noise and spectral broadening are concerned, even in chained-amplifier systems. If only spectral broadening in the amplifier is considered, over 100 amplifiers could be employed before a signal having a 20 MHz linewidth was significantly broadened.

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MONTE CARLO COMPARISON OF HETEROJUNCTION CATHODE GUNN OSCILLATORS

Indexing terms: Modelling, Monte Carlo methods, Gunn devices, Oscillators

We have performed Monte Carlo simulations to investigate the physics of heterojunction cathode Gunn oscillators. We show that a simple heterojunction cathode does not improve the device performance because the Gunn domain matures too quickly. The inclusion of a thin n^+ layer at the heterojunction allows the Gunn domain to grow throughout the length of the device. This yields improved performance as was recently experimentally observed.

Recent experimental results[1,2] have shown that heterojunction cathode Gunn oscillators, which include a thin n^+ layer at the heterointerface, may yield higher power and efficiency compared with conventional notch oscillators. Theoretical results[3] have shown that heterojunction cathodes have the potential to improve the performance of the Gunn oscillators.

We have implemented a full time-dependent self-consistent ensemble Monte Carlo (SEMC) code to study the physics of heterojunction cathode Gunn oscillators. The Monte Carlo model includes a full three valley (Γ–L–X) nonparabolic band model[4] which uses a modified constant time technique (MCTT) for the random time of flight calculation.[5,6] This allows a particularly efficient implementation of the SEMC algorithm and a good degree of vectorisation on supercomputers, because of the preservation of particle synchronicity. The external tank circuit (Fig. 1*a*) is included as shown for instance by Tully,[7] and the displacement current is accounted for by using the cold capacitance procedure.[8]

We have considered a model device structure as shown in Fig. 1*b*. The regions I and III are n^+ contacts with $N_D = 10^{17}\,\text{cm}^{-3}$ and the drift region (II) is doped with $N_D = 10^{16}\,\text{cm}^{-3}$. The first structure investigated is a conventional one with GaAs in region I and a notch in doping in the drift region to help nucleate the domains. We have then considered a second structure with a heterojunction cathode (HC), with $Al_{0\cdot3}Ga_{0\cdot7}As$ in region I and a uniform doping density in region II. Finally, we have stimulated a third structure (HCS), basically identical to the second one, but with the inclusion of an n^+ spike doping ($N_D = 10^{18}\,\text{cm}^{-3}$) in a layer 125 Å wide close to the heterointerface. In our simulations, we used an