1·1 μm and 1·8 μm, as already reported by Ohishi *et al.*[3,4] In addition to these absorptions, Fe^{2+} has an absorption peak at 5 μm, extending its tail to the minimum loss region. These features were not influenced by the addition of NH_4HF_2. On the other hand, as can clearly be seen in spectra (*b*) and (*c*), the three absorption bands due to Fe^{2+} disappeared by preparing the glasses in NF_3, and alternatively a few peaks, most likely caused by Fe^{3+}, were observed in the 0·2 to 0·7 μm range.

The oxidation of the ferrous to the ferric state by NF_3 processing was also confirmed by the loss measurement for the fibres. Fig. 2 shows the loss spectra of the two fluoride-

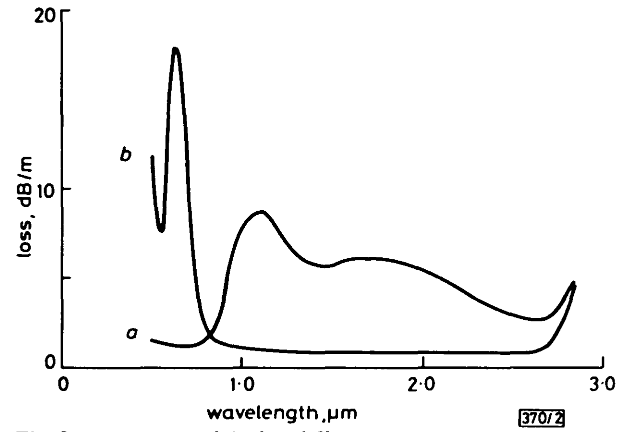

Fig. 2 *Loss spectra of Fe-doped fibres*

a 50 parts in 10^6 Fe in Ar
b 5000 parts in 10^6 Fe in NF_3

iron-doped fibres; (*a*) and (*b*) were obtained from the 50 parts in 10^6 Fe-doped glass prepared in Ar at 800°C and the 5000 parts in 10^6 Fe-doped glass prepared in NF_3 at 650°C, respectively. Fibre (*a*) exhibits the similar absorption characteristics to that found in Fig. 1*a*, and no absorptions due to Fe^{3+} were observed. On the other hand, by preparing the glass in NF_3, the Fe^{2+} absorptions were completely eliminated, as is clear in spectrum (*b*), and there is an alternative peak due to Fe^{3+} at 0·63 μm.

The influence of the iron ions on the absorption loss in the minimum loss region is estimated on the assumption that the absorption coefficient is independent of the iron concentration and that a Gaussian fit is valid. The absorption losses at 2·5 μm and 3·5 μm due to Fe^{2+} were obtained from the spectrum in Fig. 1*a*, taking the three absorption bands at 1·1, 1·8 and 5 μm into account. The estimated results are listed in

Table 2 ESTIMATED ABSORPTION LOSS DUE TO IRON IONS AT 2·5 μm AND 3·5 μm

	Loss, dB/km/10^6	
State	2·5 μm	3·5 μm
Fe^{2+}	33·3	19·5
Fe^{3+}	$<10^{-3}$	$<10^{-3}$

Table 2. The contribution due to Fe^{3+}, calculated from the absorption peak in Fig. 2*b*, is expected to be less than 10^{-3} dB/km/10^6 both at 2·5 μm and 3·5 μm.

In conclusion, the absorption loss due to the ferrous ions in fluoride glasses has been eliminated by oxidising them to the ferric ions. The oxidation has been carried out by preparing the glasses under NF_3 atmosphere. The absorption loss due to iron ions in the 2·5–3·5 μm range will be less than 10^{-3} dB/km by keeping the iron content below 1 part in 10^6.

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CONTRIBUTION OF SPONTANEOUS EMISSION TO THE LINEWIDTH OF AN INJECTION-LOCKED SEMICONDUCTOR LASER

Indexing terms: Optics, Semiconductor lasers

We show that the spontaneous emission inside an injection-locked semiconductor laser does not alter the lasing field. For injection at the free-running frequency, the linewidth is only governed by the injected-field phase noise and may no longer follow the Schawlow–Townes dependence on emitted optical power.

Introduction: Injection locking of semiconductor lasers has been largely considered previously with the aim of increasing their dynamic coherence properties.[1,2] Optical feedback, i.e. self-injection-locking, is well known to allow an important reduction of the CW linewidth.[3–5] Linewidth reduction is here possible through coherent interaction between the lasing field and an injected, correlated, time-delayed image of itself.[6] Similar linewidth reduction has been recently observed for cleaved-coupled-cavity (i.e. mutually injection-locked) semiconductor lasers.[7] The problem is quite different for a slave laser injection-locked with an independent master laser through a perfect isolator. Our purpose in this letter is to show by an analysis including phase-amplitude coupling effects that the injected laser resists the phase diffusion imposed by its own spontaneous emission. For injection at the free-running frequency, the slave field follows only the master phase noise fluctuations and, as is well known for microwave oscillators, exhibits the master linewidth for any output power. An experiment using two GaAlAs CSP semiconductor lasers is reported and shows, for various output power levels, an injected slave laser linewidth closely equal to the master linewidth.

Theory: The starting point of our analysis is the generalised rate equations for the total photon number P in the slave, the phase ϕ of the lasing field[5,8] and the usual equation for the carrier number N:

$$\dot{P} = \left[G - \frac{1}{\tau_p} + \frac{c}{n_g L}\left(\frac{P_i}{P}\right)^{1/2} \cos\theta\right]P + F_p(t) \quad (1)$$

$$\dot{N} = \frac{I}{e} - GP - \frac{N}{\tau_e} + F_N(t) \quad (2)$$

$$\dot{\phi} = (\omega_{m0} - \omega_0) + \frac{c}{2n_g L}\left(\frac{P_i}{P}\right)^{1/2} \sin\theta + \frac{\alpha}{2}\left(G - \frac{1}{\tau_p}\right) + F_\phi(t) \quad (3)$$

where G is the optical gain, τ_p is the photon lifetime, n_g is the group index, P_i is the injected photon number, L is the cavity length, $\theta = \phi_i - \phi$ is the phase difference between lasing and injected fields, ω_{m0} is the mth resonance frequency of the unperturbed cavity, ω_0 is the lasing frequency, α is the ratio between carrier-induced changes in index and gain,[9] I is the injected current and τ_e is the carrier lifetime.

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We account for spontaneous emission with the Langevin noise sources F_P, F_N and F_ϕ.[9]

Assuming a stable locked single-mode operation,[8] the standard procedure for solving eqns. 1–3 is to linearise them in terms of small deviations $\delta P = P - \bar{P}$, and δN, $\delta\phi$, δP_i, $\delta\phi_i$ and $\delta\theta$ defined similarly. In the usual gain approximation we note A the differential gain and Γ the filling factor.

Introducing the parameters $\omega_{RO} = (\Gamma A\bar{P}/\tau_p)^{1/2}$ and $\tau_R = 2[\Gamma A\bar{P} + (1/\tau_e)]^{-1}$, which are the relaxation frequency and associated damping time of the uninjected laser, respectively, and defining $(c/2Ln_g)(\bar{P}_i/\bar{P})^{1/2} = \rho$ the normalised injection rate, one obtains after a Fourier transform,

$$\begin{bmatrix} j\omega + \rho\cos\bar{\theta}, & -\omega_{RO}^2\tau_p, & -\rho\sin\bar{\theta} \\ \frac{1}{\tau_p} - 2\rho\cos\bar{\theta}, & j\omega + \frac{2}{\tau_R}, & 0 \\ \rho\sin\bar{\theta}, & -\alpha\omega_{RO}^2\tau_p, & j\omega + \rho\cos\bar{\theta} \end{bmatrix} \begin{bmatrix} \delta\tilde{P}(\omega) \\ \delta\tilde{N}(\omega) \\ 2\bar{P}\,\delta\tilde{\phi}(\omega) \end{bmatrix} = \begin{bmatrix} \tilde{F}_P + \rho\cos\bar{\theta}\,\frac{\bar{P}}{\bar{P}_i}\,\delta\tilde{P}_i - \rho\sin\bar{\theta}\,2\bar{P}\,\delta\tilde{\phi}_i \\ \tilde{F}_N \\ 2\bar{P}\left[\tilde{F}_\phi + \rho\cos\bar{\theta}\,\delta\tilde{\phi}_i + \frac{\rho}{2}\sin\bar{\theta}\,\frac{\delta\tilde{P}_i}{\bar{P}_i}\right] \end{bmatrix} \quad (4)$$

Solving eqns. 4 is quite tedious, but great simplifications occur when we ignore transient solutions since their contribution to the linewidth is negligible. This can be done through the adiabatic approximation $\omega \ll 2/\tau_R$. Assuming injection at the free-running frequency ($\omega_{m0} = \omega_0$), $\delta\tilde{\phi}(\omega)$ is found to have no dependence on the carrier noise $\tilde{F}_N$ and on the intensity noise of the injected field $\delta\tilde{P}_i$:

$$\delta\tilde{\phi} = \delta\tilde{\phi}_i + \frac{1}{\Delta\omega_l}\left[\tilde{F}_\phi - \frac{\alpha}{2\bar{P}}\tilde{F}_P\right] \quad (5)$$

where $\Delta\omega_l = \rho(1 + \alpha^2)^{1/2}$ is the modal half-locking bandwidth.[8] That $\delta\tilde{\phi}$ is independent of $\delta\tilde{N}$ has only a formal significance, but the lack of $\delta\tilde{P}_i$ dependence is of great importance since it can be a strong source of line broadening. Because there is no correlation between $\delta\phi_i(t)$ and $F_N(t)$ or $F_\phi(t)$ the injected laser phase noise power spectrum is found to be[9,10]

$$S_\phi(\omega) = S_{\phi_i}(\omega) + \frac{\omega^2}{\Delta\omega_l^2}S_{\phi_0}(\omega) \quad (6)$$

where $S_{\phi_i}(\omega)$ and $S_{\phi_0}(\omega)$ are the phase noise power spectrum of the free-running laser and injected field, respectively. The calculation of the linewidth $\Delta\nu$ is then straightforward by using

$$\Delta\nu = \frac{1}{2\pi}\lim_{\tau\to\infty}\frac{1}{\tau}\langle\Delta\phi^2(\tau)\rangle \quad (7)$$

where the mean-square phase jitter $\langle\Delta\phi^2(\tau)\rangle$ is related to the $\delta\phi$ power spectrum by

$$\langle\Delta\phi^2(\tau)\rangle = \frac{2}{\pi}\int_{-\infty}^{+\infty} S_\phi(\omega)\sin^2\left(\frac{\omega\tau}{2}\right)d\omega \quad (8)$$

It is to be noted that, by contour integration of eqn. 8, only the double pole $\omega = 0$ in $S_\phi(\omega)$ leads to a mean-square phase jitter increasing linearly with τ and so contributes to the linewidth as given by eqn. 7. Because this pole only exists in the first term of eqn. 6 the locked state linewidth is only given by the injected field. High linewidth reduction by the injection-locking technique is therefore only possible by using a low noise master (e.g. gas) laser.[11]

Experiment: The linewidth measurement of a GaAlAs CSP Hitachi HPL 1400 semiconductor laser has been performed by the delayed self-heterodyne method[12,6] both in the free-running and injection-locked states. An optical isolator has been inserted between the two lasers to avoid undesirable coupling in the injection-locked case. Both the temperature

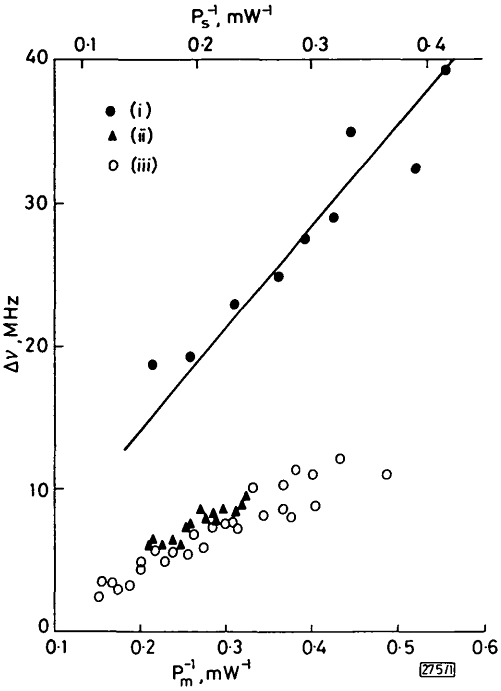

Fig. 1 *Free-running and injection-locked linewidths against reciprocal output power*

(i) Free-running slave linewidth against its reciprocal output power P_S^{-1}
(ii) Master linewidth against its reciprocal output power P_M^{-1}
(iii) Injected slave linewidth against P_M^{-1} (or P_S^{-1} which, in this case, is proportional)

and injection current of the master are tuned to achieve resonant injection and constant injection rate ρ for various values of the injected current in the slave. Fig. 1 shows the measured linewidth against the laser's reciprocal output power both in (i) the free-running and (ii, iii) injection-locked states. In the latter case we observe that, in good agreement with the model, the slave linewidth remains closely equal to that of the master. Its remaining linear dependence on reciprocal slave power output P_S^{-1} arises because the experiment was performed at a fixed injection rate ρ which required tuning the master power to maintain a constant $\bar{P}_i/\bar{P}$ and resonant injection. The low master linewidth can be explained by imperfect master isolation.[7]

Conclusions: As is well known for microwave oscillators both analysis and experiment indicate that the CW linewidth of an injection-locked semiconductor laser is the same as the master linewidth. The injection-locking technique can only lead to strong linewidth reduction by using a low noise master.

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BIDIRECTIONAL TRANSMISSION OVER 11 km OF SINGLE-MODE OPTICAL FIBRE AT 34 Mbit/s USING 1·3 μm LEDs AND DIRECTIONAL COUPLERS

Indexing terms: Optical communication, Optical transmission

Results of a laboratory trial are reported in which bidirectional transmission at 34 Mbit/s over 11 km of single-mode fibre was demonstrated using 1·3 μm ELEDs, single-mode fused biconical tapered couplers and GaInAs PINFET receivers.

Introduction: Optical fibre transmission systems using edge-emitting LEDs at modest bit rates in the telecommunications junction network are attractive because of their low cost and high reliability. Additionally, the use of single-mode fibre in these links is attractive to allow for future upgrading to exploit the bandwidth available.[1] In this letter we describe a 34 Mbit/s bidirectional system which yields a further cost reduction since only one fibre is necessary. Using the same wavelengths for each direction of transmission, the only observable system penalty was the ≃6 dB excess loss due to the optical couplers.

System description: The system configuration is shown in Fig. 1. The light sources are edge-emitting LEDs launching ≃20 μW (−17 dBm) peak power into a multimode pigtail (50/125 μm). The nominal peak wavelength of the devices was 1300 nm, and the halfpower bandwidth was ≃120 nm. In the system as implemented, one ELED actually produced 22·4 μW (−16·5 dBm) measured in the fibre with the cladding modes stripped, and had a centre wavelength of 1260 nm. The other ELED supplied 20·0 μW (−17·0 dBm), and had a centre wavelength of 1280 nm. The mean power when transmitting random data is 3 dB down on these values.

The two single-mode, four-port couplers used in the system were produced in BTRL and employ a fused biconical taper structure.[2,3] These gave a 3 dB power split at 1300 nm; however, the splitting ratio was significantly wavelength-dependent. Fig. 2*a* shows the measured splitting ratio

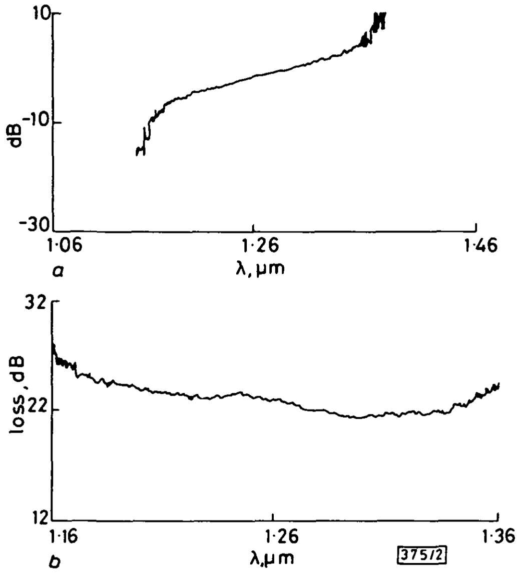

Fig. 2

a Power splitting ratio (dB) against wavelength for one-directional coupler

b Fibre loss measured over the range of wavelengths of interest

(difference in power in one output arm compared to the other in decibels) as a function of wavelength. This shows that at 1280 nm the splitting ratio is ≃1·0 dB and at 1260 nm it is

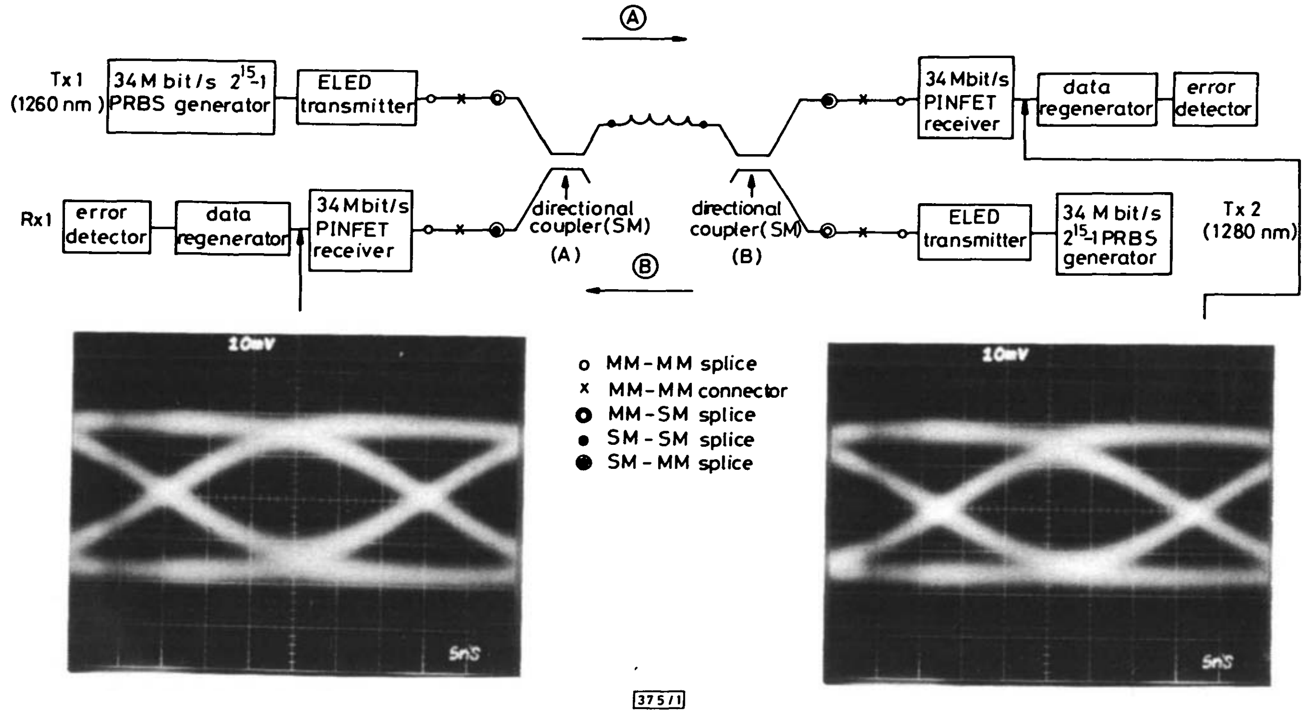

Fig. 1 *System configuration*

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