the 30mA drive (labelled '7ns') is initially almost uniform, indicating that this power level causes little SHB. When the current is increased to 70mA ('17ns'), the SHB increases. After the mode change ('30ns') the carrier density is highly asymmetric, with a large build-up of carriers at the rear facet. Further simulations showed that the time between the second transient and the onset of the mode change decreases when the drive current is increased, possibly due to the higher rate of SHB at high powers.

Conclusion: Our analysis has shown that modal instabilities can occur in complex-coupled DFB lasers even though the initial side-mode suppression is very high. Time-domain simulations using an independently derived model confirm the analytical prediction of unstable modes, and show that these instabilities are associated with SHB. Unfortunately, the coupling ratios leading to instabilities coincide with the antiphase design, which has previously been shown to give the maximum modulation bandwidth and the lowest chirp. The instabilities are associated with a large chirp, which could cause detrimental pulse spreading in long-haul communications systems. Furthermore, the mode distribution exhibits a random asymmetry, resulting in a huge uncertainty in the laser output power after turn-on.

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Mutual injection locking of a fibre laser and a DFB semiconductor laser

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Indexing terms: Distributed feedback lasers, Fibre lasers, Injection locked lasers

A fibre laser and a distributed feedback (DFB) laser are coupled through a 50:50 fibre coupler in such a way that the two lasers mutually injection-lock. The DFB laser forces the fibre laser to oscillate in a nearly single longitudinal mode. At the same time, the linewidth of the DFB laser is reduced to below 1.5MHz because of mutual injection-locking.

Erbium-doped fibre lasers are of interest for optical fibre communications because they operate around 1.55μm, the wavelength region where the loss of silica fibres is minimum. The narrow linewidth of fibre lasers (~10kHz) [1] is particularly attractive for coherent optical communication systems. However, fibre lasers tend to operate simultaneously in multiple longitudinal modes because of a relatively large (~30nm) gain bandwidth. Single-longitudinal-mode operation has been achieved by using many techniques such as the feedback from a fibre grating and injection locking by using an external-cavity diode laser [2]. However, it is generally difficult to tune the lasing wavelength when a fibre grating is used to select a single longitudinal mode. In this Letter we report the experimental results of injecting the output of a distributed-feedback (DFB) semiconductor laser into an erbium-doped fibre laser through a 50:50 fibre coupler. Because an optical isolator is not used, the two lasers are mutually injection-locked when the injected power exceeds a certain value. The output of this system is characterised and shown to exhibit beneficial effects for each laser. This scheme also permits tuning of the fibre laser by changing the DFB wavelength through temperature tuning.

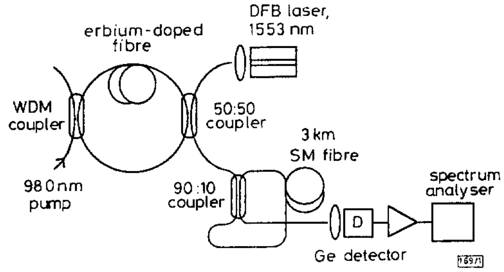

Fig. 1 *Experimental arrangement*

The experimental configuration is shown in Fig. 1. The fibre laser is pumped by a 980nm laser with a pigtail that is spliced onto a wavelength-division-multiplexer (WDM) coupler. Because an isolator was not used between the pump laser and the WDM coupler, it was necessary to modulate the pump current at a frequency of 300kHz to reduce the impact of undesirable reflections. The total length of the ring cavity is ~27m, corresponding to an axial mode spacing of 7.5MHz. 10m of the fibre was doped with erbium at a concentration of 600ppm. The output of a DFB laser (λ = 1553nm) was coupled into the fibre through a 50:50 output coupler. By introducing bending losses in the cavity, the fibre laser was forced to oscillate close to the wavelength of the DFB laser. Coarse spectra of the output of the coupled laser were measured with a monochromator, and high-resolution spectra were measured through a self-homodyne scheme (see Fig. 1).

A monochromator was first used to observe the spectral output of the fibre laser operating independently (DFB current turned off). The spectrum exhibited many lines over a range of ~4nm, indicating multiple-mode operation of the fibre laser. When the DFB laser was operated above threshold, the spectrum narrowed to a single line whose width was resolution-limited (< 0.1nm). To achieve better resolution, a delayed self-homodyne interferometer [3] was used to determine the linewidth and the beat signal resulting from beating among the longitudinal modes. The delay line was 3km long, which corresponds to a 67kHz resolution limit. The output was detected by a fast germanium photodiode, sent through a 30dB electronic amplifier, and finally displayed on an RF spectrum analyser with a resolution bandwidth of 100kHz and a sweep time of 50ms.

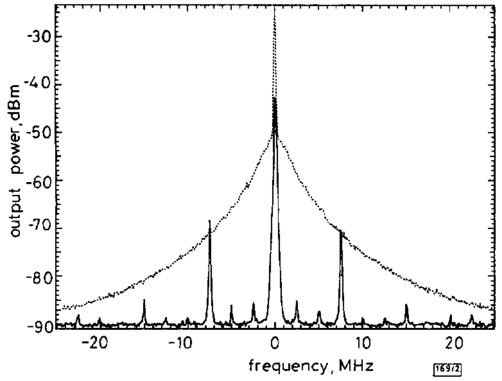

Fig. 2 *RF spectra of delayed self-homodyne measurements for a DFB laser operating alone and for a fibre laser operating alone*

· · · · · DFB laser
——— fibre laser

Before studying the behaviour of the coupled lasers, it is important to observe each laser independently. The dotted curve in Fig. 2 shows the RF spectrum of the DFB laser when 58μW of power was coupled into the 50:50 coupler while the 980nm pump laser was turned off. The narrow central structure should be ignored for these homodyne measurements. The spectrum is nearly Lorentzian, corresponding to an optical linewidth of about 1.5MHz which is much narrower than that expected for typical PFB lasers (> 10 MHz at ~1mW power). We attribute this line narrowing to the backreflections into the laser from the optics used to couple the light into the fibre, as feedback is known to reduce the linewidth of semiconductor lasers [4].

The solid curve in Fig. 2 shows the RF signal when the 980nm pump laser is operating at 25mW while the DFB laser is off. The fibre laser output is less than 1mW under such conditions. The linewidth of the fibre laser is still beyond the resolution limit. However, the intermodal beat signal seen at 7.5MHz and its multiples is due to the multimode operation of the fibre laser. The origin of the other weak peaks is not well understood. A likely cause may be reflections from the fibre splices. Indeed, the relative location of these peaks changed when additional lengths of fibre were added to the cavity.

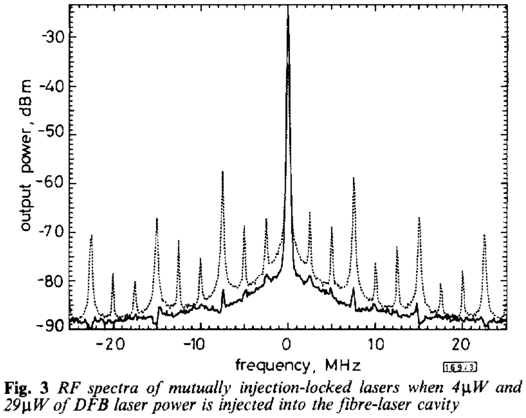

Fig. 3 *RF spectra of mutually injection-locked lasers when 4μW and 29μW of DFB laser power is injected into the fibre-laser cavity*

………… 4μW
——— 29μW

Fig. 3 shows the RF spectra of the mutually coupled lasers at two different DFB laser output powers. For both cases, the pumping level of the fibre laser is held constant, but the DFB laser output is increased from slightly above threshold (dotted curve), corresponding to an injected power of 4μW into the branch of the 50:50 coupler that is part of the laser cavity, to far above threshold (solid curve), corresponding to 29μW of injected power. In the case of low-power injection, the amplitude of the 7.5MHz sidemodes increases more than 10dB, indicating that the sidemodes have become even more dominant. However, the RF sidebands are dramatically reduced in the case of a higher injected power (> 25μW in our experiments) from the PFB laser. In addition, the phase-noise of the combined output (resulting in continuous spectral background) is reduced from that of the PFB laser operating alone (see Fig. 2). Finally, the system is considered to be mutually injection-locked because when the same interferometric RF measurements were pertormed under identical operating conditions on the light emitted from the rear facet of the DFB laser, the same characteristics as those of Figs. 2 and 3 were observed.

We have also made measurements of the intensity noise for both the isolated and coupled lasers. The intensity-noise spectrum of the fibre laser alone (DFB turned off) exhibited a relaxation-oscillation peak at 16kHz and another peak at 7.5MHz with little power in between. For the coupled lasers, the 7.5MHz frequency peak was seen to be reduced by 26dB when the injected DFB power was large enough to mutually injection-lock the two lasers.

In conclusion, we have shown that the mutual injection-locking of a fibre laser and a DFB laser results in output characteristics that are likely to be useful in practice. The DFB laser forced the coupled system to operate in a nearly single longitudinal mode, while the linewidth of the combined system was narrowed beyond that of a typical DFB laser, although not as narrow as the linewidth of a fibre laser operating independently. The usefulness of this coupled laser system remains to be determined based on detailed temporal measurements of the output, both for the CW and pulsed modes of operation.

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