the fundamental (HE_{11}) modes, and the second-order (TE_{01}, HE_{21} and TM_{01}) modes. The dips migrate toward shorter wavelengths as the strain increases, but the quality of the resonances is maintained.

Analysis of the mode fields and the perturbation induced by the flexural acoustic wave shows that coupling to the azimuthally symmetric modes (TE_{01} and TM_{01}) is polarisation dependent, whereas coupling to the degenerate pair of HE_{21} modes is not [6]. This feature is confirmed in Fig. 2, where the attenuation level of the TE_{01} and TM_{01} peaks is in all cases ~3dB whereas attenuations as high as 18dB are obtained for the HE_{21} peak.

Fig. 3 gives the centre wavelength of the three peaks as a function of the mass, for three different frequencies. A shift over a 500nm range is shown. This shows how strain can be used as a tuning parameter as well as to compensate for changes in frequency. For small strain values, the slope is ~75 nm/mε, decreasing slightly as the operating frequency increases.

Theoretical calculations of the resonance wavelengths using exact electromagnetic theory are included in Fig. 3, and excellent agreement with experimental data is confirmed. The calculations take into account the L_b and Λ dependence upon strain, as well as the non-Hookean behaviour of fused silica [8]. One result where no dependence of Young's modulus upon strain is assumed is also shown in Fig. 3. An increasing deviation from the experimental data is observed as the mass increases, highlighting the significance of the non-Hookean behavior of fused silica.

Conclusions: In this Letter, a systematic study of strain effect on tapered fibre acousto-optic filters has been reported. High strain sensitivity (75nm/mε) and wideband (> 500nm) strain induced tunability have been demonstrated.

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Mode-partition noise in fibre lasers

Z.M. Liao and G.P. Agrawal

The presence of mode-partition noise in an erbium-doped fibre laser has been experimentally demonstrated. A numerical model has been developed using the Langevin rate equations. Its predictions are in qualitative agreement with the experimental data.

Introduction: Mode-partition noise has been observed in a variety of lasers including semiconductor lasers [1 – 3], gas lasers [4], and dye lasers [5]. In semiconductor lasers, mode-partition noise arises from competition among multiple longitudinal modes. Mode-partition noise can also occur when the cavity design forces counter-propagating modes to compete for the same gain. In particular, bidirectional-ring dye lasers have been found to exhibit random on-off switching between the two counter-propagating modes of the cavity such that whenever one mode turns on, the other turns off completely [5]. This phenomenon is attributed to the strong mode coupling that can occur in a homogeneously broadened gain medium [6]. Fibre lasers are made using silica fibres the cores of which are doped with rare-earth ions, together with other codopants such as aluminium and germanium. Depending on the proportion of codopants, the gain spectrum of fibre lasers can be dominated by homogeneous or inhomogeneous broadening [7]. In this Letter, we present experimental evidence for mode-partition noise in fibre lasers. We have also developed a theoretical model, based on the Langevin rate equations, the predictions of which agree well with our experimental results.

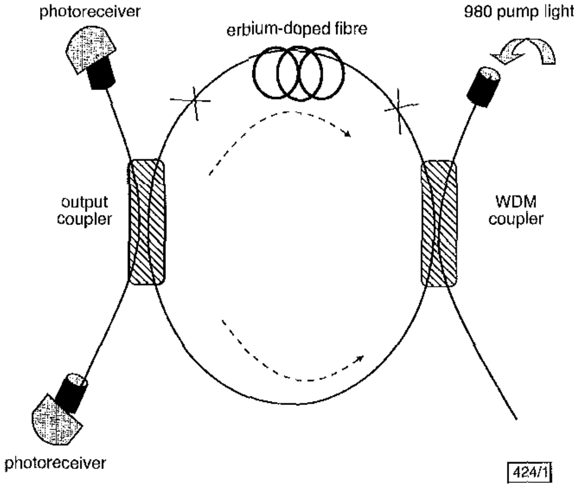

Fig. 1 *Experimental setup used to observe mode-partition noise*

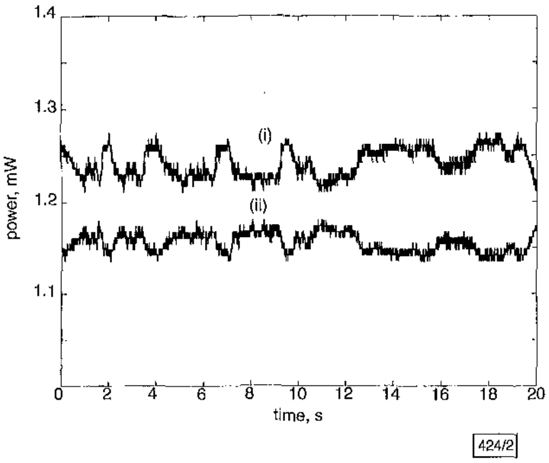

Fig. 2 *Output powers in clockwise and counter-clockwise directions*
(i) clockwise
(ii) counter-clockwise

Experiment: The ring-cavity of our fibre laser (see Fig. 1) consisted of ~7.2m of erbium-doped fibre and 11.1m of standard fibre, resulting in a total cavity length of ~18.3m [8]. A 980nm pump laser (Lasertron QLM9S470) injected light through a 980/1550nm WDM coupler; it coupled ~95% of the pump light into the cavity. The output coupler transmitted ~10% of the bidirectional circulating powers per round trip. Each end of the output coupler was connected to a large-area germanium photoreceiver (New Focus Model 2033). Temporal evolution of the photoreceiver signals was monitored using an oscilloscope. Since we did not use an intracavity isolator, the laser emitted light in both the clockwise and counter-clockwise directions.

Fig. 2 shows the output powers for the two directions when the laser was pumped 3.6 times above its threshold. The two modes were found to be almost perfectly anticorrelated; an increase in the power of the one mode corresponded to a decrease in the other. The sum of the powers remained nearly constant, except for small fluctuations occurring at the relaxation oscillation frequency (≃ 29kHz). The individual powers on the other hand fluctuated on a rather slow time scale (~0.1s). These fluctuations are due to mode-partition noise induced by cross-gain saturation. This interpretation is confirmed by the following theoretical model.

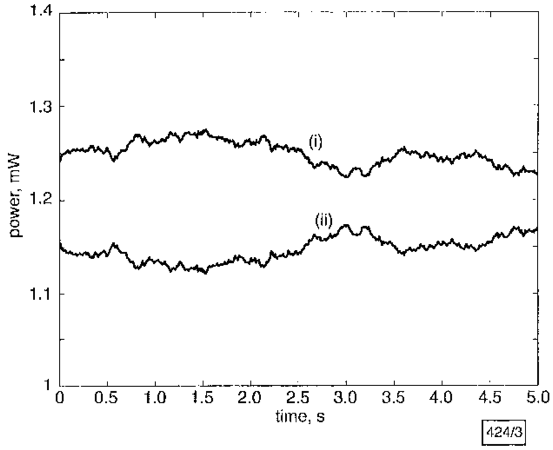

Fig. 3 *Numerical simulation of output powers in clockwise and counter-clockwise directions*

(i) clockwise
(ii) counter-clockwise

Theory: We use the standard three-level rate-equation model but simplify it by assuming rapid transfer of the pumped population to the excited state. The resulting rate equations with added Langevin noise terms can be written as [9]

$$\dot{P}_1 = (BN - \gamma)P_1 + R_{sp} + F_1(t) \qquad (1)$$

$$\dot{P}_2 = (BN - \gamma)P_2 + R_{sp} + F_2(t) \qquad (2)$$

$$\dot{N} = W_p(N_T - N) - 2(P_1 + P_2)BN - (N + N_T)/T_1 \quad (3)$$

where P_1 and P_2 are the number of photons in the co- and counter-propagating modes, respectively, and N represents the population-inversion level. The cavity-decay rate γ is related to the photon lifetime τ_p as $\gamma = 1/\tau_p$. The rate of spontaneous emission is taken to be $R_{sp} = n_{sp}BN$, where n_{sp} is the inversion parameter, and B is related to the rate of stimulated emission. In eqn. 3, W_p is the pump rate, N_T is the total number of dopants, and T_1 is the fluorescence time. The coupling between P_1 and P_2 is solely due to cross-gain saturation resulting from gain sharing.

The Langevin noise sources $F_1(t)$ and $F_2(t)$ are responsible for fluctuations in P_1 and P_2, respectively. They vanish on average ($\langle F_i(t)\rangle = 0$). Assuming noise to be Markoffian (white noise), we use [9]

$$\langle F_i(t)F_j(t')\rangle = 2D_{ij}\delta(t - t') \qquad (4)$$

where $i, j = 1, 2$. The diffusion coefficient is related to the rate of spontaneous emission as follows:

$$D_{11} = R_{sp}\bar{P}_1 \qquad D_{22} = R_{sp}\bar{P}_2 \qquad D_{12} = 0 \qquad (5)$$

where $\bar{P}_1$ and $\bar{P}_2$ are the average steady-state values.

The stochastic rate equations, eqns. 1 – 3, are solved numerically using parameter values appropriate to our fibre laser (a noise figure of 3.4dB corresponding to n_{sp} = 1.1 is assumed). Fig. 3 shows a 5s section of the time series simulated numerically. Comparing Figs. 2 and 3, we see that our model reproduces all qualitative features of the mode-partition noise observed experimentally. This agreement confirms that the anticorrelation seen in Fig. 2 has its origin in cross-gain saturation.

Discussion: We have experimentally observed mode-partition noise in a fibre laser. We have developed a rate-equation model that is capable of reproducing the experimentally observed behaviour. We did not observe complete on-off switching similar to that observed in dye lasers [5]. We believe that the inhomogeneous broadening of the gain spectrum in our fibre laser leads to weak mode coupling. It is well known that codopants such as aluminium can make the gain spectrum nearly homogeneously broadened. Such fibre lasers may exhibit complete on-off switching.

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Real-time optical spectrum analyser based on chirped fibre Bragg gratings

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A real-time fibre optic spectrum analyser for optical pulses is realised. It is based on a chirped fibre Bragg grating and the formation of a time domain analogue of the Fraunhofer diffraction regime. The spectrum of a modelocked diode laser was measured, with a resolution of 0.3nm, which can be easily improved to 0.06nm.

Introduction: We demonstrate a fibre optic spectrum analyser which is based on a chirped fibre grating, and the formation of a time domain analogue of the Fraunhofer diffraction regime, where a light pulse is transformed, in real time, into its Fourier image.