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.

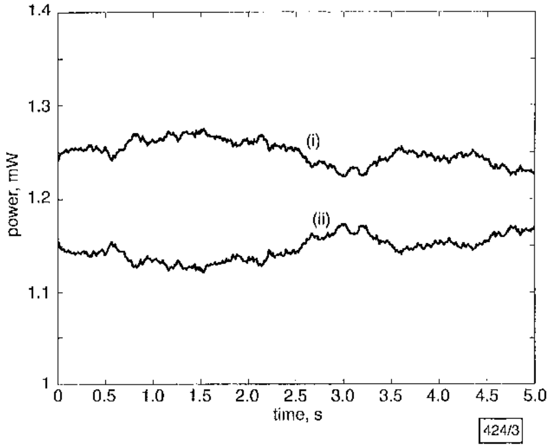

Fig. 3 *Numerical simulation of output powers in clockwise and counter-clockwise directions*

(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.

Acknowledgments: This research is supported by the US National Science Foundation. The authors thank Corning Lasertron for donating the 980nm pump laser. We also thank T. Lakoba for helpful discussions.

13 April 2000
Electronics Letters Online No: 20000862
DOI: 10.1049/el:20000862

Z.M. Liao and G.P. Agrawal (*The Institute of Optics and Rochester Theory Center for Optical Sciences and Engineering, University of Rochester, Rochester, New York 14627, USA*)

E-mail: zman@optics.rochester.edu

References

1 AGRAWAL, G.P., and DUTTA, N.K.: 'Semiconductor lasers' (Van Nostrand Reinhold, New York, 1993), 2nd edn.
2 WU, H., and CHANG, H.: 'Mode partition in semiconductor lasers with optical feedback', *IEEE J. Quantum Electron.*, 1993, **29**, (7), pp. 2154–2162
3 LAW, J., and AGRAWAL, G.P.: 'Mode-partition noise in vertical-cavity surface-emitting lasers', *IEEE Photonics Technol Lett.*, 1997, **9**, (4), pp. 437–439
4 VALLE, A., MECOZZI, A., PESQUERA, L., RODRIGUEZ, MA., and SPANO, P.: 'Transient statistics for two-mode gas ring lasers', *Phys. Rev. A*, 1993, **48**, (3), pp. 2426–2432
5 MANDEL, L., and WOLF, E.: 'Optical coherence and quantum optics' (Cambridge University Press, New York, 1995)
6 SARGENT, M., SCULLY, M., and LAMB, W.: 'Laser physics' (Addison-Wesley Publishing Company, Reading, 1974)
7 BECKER, P.C., OLSSON, N.A., and SIMPSON, J.R.: 'Erbium-doped fiber amplifiers: fundamentals and technology' (Academic Press, San Diego, 1999)
8 LIOU, L.: 'Temporal, spectral, and noise characteristics of erbium-doped fiber amplifiers and lasers'. PhD Thesis, University of Rochester, Rochester, NY, 1995
9 AGRAWAL, G.P.: 'Mode-partition noise and intensity correlation in a two-mode semiconductor laser', *Phy. Rev. A*, 1988, **37**, (7), pp. 2488–2494

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

N.K. Berger, B. Levit, A. Bekker and B. Fischer

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.

Such a compact fibre device may be of use for various applications in optics and fibre optic WDM networks.

The first real-time Fourier-transform processors were developed in the RF region for radar, sonar, and communication systems [1]. Surface acoustic wave (SAW) filters, providing chirped Bragg gratings, were used as the dispersive delay lines. In the optical region, real-time spectral analysis was obtained with SAW dispersive delay lines [2] by shifting the laser pulse spectrum to low frequencies. More recently, such an operation was demonstrated using a dispersive fibre [3, 4]. This has drawbacks due to the limitations in the fibre dispersion parameters. Fibre gratings, by contrast, can offer better performance and more flexibility. Chirped fibre Bragg gratings are successfully used for other purposes, such as chromatic dispersion compensation of pulses in fibre optic communication systems [5], and they allow electrical tuning of their wavelength and their dispersion magnitude [6]. A simulation of chirped fibre gratings used for real-time Fourier transform is given in [7].

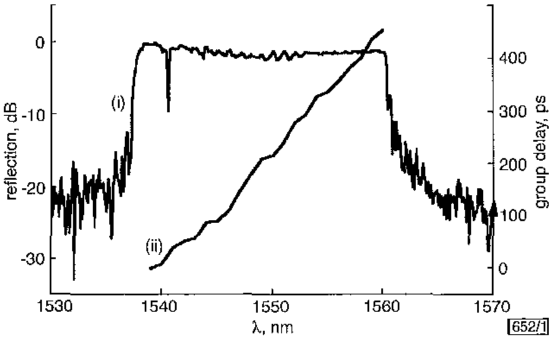

Fig. 1 *Experimental results of the wavelength dependence of the reflection and group delay for one of the chirped Bragg gratings*

(i) reflection
(ii) group delay

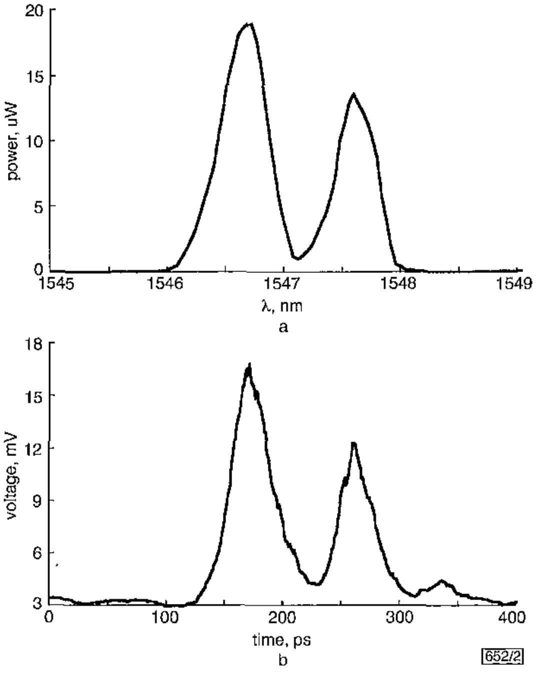

Fig. 2 *Pulse spectrum*

a Measured using conventional spectrum analyser
b Measured using real-time fibre spectrum analyser (oscilloscope trace)

Operation principle: The operation principle can be simply explained using the well-known analogy between the propagation of optical pulses in dispersive media and the propagation of beams in free space with diffraction in the paraxial approximation [8, 9]. In the diffraction case, a Fourier transform of a field envelope is obtained, in the Fresnel regime, at the back focal plane of a lens or in the Fraunhofer regime. The realisation of a time lens for pulse propagation can be obtained by a special element that provides a quadratic time-dependent phase modulation for the pulse. This can be used for the Fourier transform operation. However, a simpler method could be obtained by realisation of the Fraunhofer diffraction equivalent in the time domain case. Time domain Fraunhofer mapping occurs for sufficiently long propagation distances

$$L \gg \tau_p^2/4\pi|\beta_2|$$

where τ_p is the pulse duration, $\beta_2 = d^2\beta/d\omega^2$ is the group velocity dispersion, and ω and β are the optical frequency and propagation constant, respectively. Implementation of such Fourier transform operation necessitates, however, media with high group velocity dispersion. In this Letter, we demonstrate such a realisation using a chirped in-fibre grating.

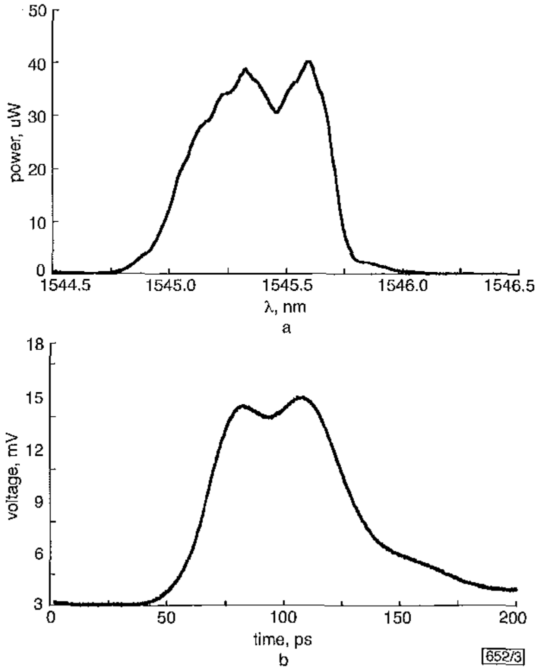

Fig. 3 *Pulse spectrum*

a Measured using conventional spectrum analyser
b Measured using real-time fibre spectrum analyser (oscilloscope trace)

Grating design and experimental results: The experiment was carried out using chirped gratings, produced by UV illumination (λ = 244nm) of a hydrogen-loaded singlemode fibre. The grating pattern was obtained using a special technique with a step-chirp phase mask [10], where the waves from different sections interfere. Fig. 1 shows the wavelength dependence against the reflectivity and group delay of one of the gratings, measured using a tunable diode laser.

The spectrum analysis was performed for laser pulses from an actively modelocked, cavity-extended diode laser with a fibre Bragg reflector. The laser gave short pulses with the multi-wavelength spectrum shown in Fig. 2. The pulse duration was of the order of 25ps and the repetition rate was 2.2GHz. As mentioned above, the Fraunhofer regime imposes the following condition on the pulse duration;

$$\tau_p^2 \ll 2\lambda^2|D|L/c$$

where $D = -2\pi c\beta_2/\lambda^2$, λ is the wavelength and c is the speed of light. The spectral resolution is given by [2]

$$\delta\lambda \simeq \lambda/(cDL)^{1/2}$$

Therefore, for currently achievable dispersion levels of chirped gratings, $DL \simeq$ 2000ps/nm [11], a resolution of the order of $\delta\lambda \simeq$ 0.06nm can be obtained. In our gratings, the DL product was lower. Therefore, we used two chirped gratings, giving an overall

DL = 100ps/nm, and thus a theoretical resolution of $\delta\lambda \simeq$ 0.27nm.

The measured spectra are given in Figs. 2 and 3, and show good agreement between the spectrum obtained directly using the optical spectrum analyser, and that obtained using time domain Fraunhofer mapping via the reflection from the chirped gratings (recorded using a sampling oscilloscope). The resolution is better than 0.3nm, matching the theoretical value given above.

Conclusion: A real-time optical spectrum analyser based on a chirped fibre Bragg grating has been realised. There are several advantages of using this fibre spectrum analyser, besides its simplicity and compatibility with fibre optic systems. It can be used to observe the dynamics of measured light, such as the time-dependent competition between two spectral lines, including changes from pulse to pulse. This cannot be achieved using a conventional analyser, which smears the structure because of its averaging effect. In addition, pulses embedded in slowly varying (compared to the above mentioned upper limit of the pulse duration) background noise can be analysed using the fibre device, but not by using a conventional analyser. Another feature is the preservation of the amplitude and phase spectrum in the transformed wave, allowing further processing, such as inverse Fourier transforms using a conventional analyser, and the analysis of an ultra-short pulse [12].

Acknowledgment: This work was partially supported by the Division for Research Funds of the Israel Ministry of Science, the Consortium of Broadband Communication administrated by the Israel Ministry of Commerce and Industry and by the European Community in the 5th framework of the METEOR Project.

4 May 2000
Electronics Letters Online No: 20000858
DOI: 10.1049/el:20000858

N.K. Berger, B. Levit, A. Bekker and B. Fischer (*Department of Electrical Engineering, Technion - Israel Institute of Technology, Technion City, Haifa 32000, Israel*)

E-mail: fischer@ee.technion.ac.il

References

1 JACK, M.A., GRANT, P.M., and COLLINS, J.H.: 'The theory, design, and applications of surface acoustic wave Fourier-transform processors', *Proc. IEEE*, 1980, **68**, (4), pp. 450–468

2 FEFFERMAN, H.R., TANNENWALD, P.E., PARKER, C.D., MELNGAILIS, J., WILLIAMSON, R.C., WOSKOBOINIKOW, P., PRADDAUDE, H.C., and MULLIGAN, W.J.: 'Real-time spectral analysis of far-infrared laser pulses using a SAW dispersive delay line', *Appl. Phys. Lett.*, 1979, **34**, (2), pp. 123–125

3 TONG, Y.C., CHAN, L.Y., and TSANG, H.K.: 'Fibre dispersion or pulse spectrum measurement using sampling oscilloscope', *Electron. Lett.*, 1997, **33**, (11), pp. 983–985

4 KELKAR, P.V., COPPINGER, F., BHUSHAN, A.S., and JALALI, B.: 'Time-domain optical sensing', *Electron. Lett.*, 1999, **35**, (19), pp. 1661–1662

5 OUELLETTE, F., CLICHE, J.-F., and GAGNON, S.: 'All-fiber devices for chromatic dispersion compensation based on chirped distributed resonant coupling', *J. Lightwave Technol.*, 1994, **12**, (10), pp. 1728–1738

6 FENG, K.-M., CAI, J.-X., GRUBSKY, V., STARODUBOV, D.S., HAYEE, M.I., LEE, S., JIANG, X., WILLNER, A.E., and FEINBERG, J.: 'Dynamic dispersion compensation in a 10Gb/s optical system using a novel voltage tuned nonlinearly chirped fiber Bragg grating', *IEEE Photonics Technol. Lett.*, 1999, **11**, (3), pp. 373–375

7 MURIEL, M.A., AZAÑA, J., and CARBALLAR, A.: 'Real-time Fourier transformer based on fiber gratings', *Opt. Lett.*, 1999, **24**, (1), pp. 1–3

8 PAPOULIS, A.: 'Pulse compression, fiber communications, and diffraction: a unified approach', *J. Opt. Soc. Am. A*, 1994, **11**, (1), pp. 3–13

9 KOLNER, B.H.: 'Space-time duality and the theory of temporal imaging', *IEEE J. Quantum Electron.*, 1994, **QE-30**, (8), pp. 1951–1963

10 KASHYAP, R., MCKEE, P.F., CAMPBELL, R.J., and WILLIAMS, D.L.: 'Novel method of producing all fibre photoinduced chirped gratings', *Electron. Lett.*, 1994, **30**, (12), pp. 996–998

11 DURKIN, M., IBSEN, M., COLE, M.J., and LAMING, R.I.: '1 m long continuously-written fibre Bragg gratings for combined second- and third-order dispersion compensation', *Electron. Lett.*, 1997, **33**, (22), pp. 1891–1893

12 KAUFFMAN, M.T., BANYAI, W.C., GODIL, A.A., and BLOOM, D.M.: 'Time-to-frequency converter for measuring picosecond optical pulses', *Appl. Phys. Lett.*, 1994, **64**, (3), pp. 270–272

Sensitive, multipoint gas detection using TDM and wavelength modulation spectroscopy

H.L. Ho, W. Jin and M.S. Demokan

The authors report on the use of time division multiplexing coupled with wavelength modulation of an external cavity laser for sensitive, multipoint gas detection. A three-sensor ladder-topology acetylene system is experimentally demonstrated with a detection sensitivity of 150ppm (25mm gas cells) for a time constant of 300ms and –30dB crosstalk between the sensors.

Optical fibre gas sensors based on the absorption of light at near-IR wavelengths (1–1.8μm) have attracted considerable attention over the past ten years [1]. The advantages of fibre sensors include their remote detection capability, safety in hazardous environments and immunity to electromagnetic fields. The use of high spectral density distributed feedback/external cavity lasers coupled with wavelength modulation spectroscopy (WMS) [2] has allowed the demonstration of high sensitivity gas detection with relatively simple micro-optic gas cells [3]. However, a single sensor system is not cost-effective due to the high cost of the laser sources. Sensor multiplexing must be implemented in order to reduce the cost-per-sensing-point where some expensive optical components can be shared by a number of sensors. Spatial division multiplexing (SDM) has been applied for multiplexing fibre optic gas sensors [4]. The SDM system performs in a similar manner to that of a single-cell system, but a number of receivers need to be used. An alternative is to apply a time division multiplexing (TDM) technique to gas sensor networks [5]. A TDM system uses a single source and receiver unit and is thus potentially cheaper. However, the limited extinction ratio of the optical switch used in a TDM system results in crosstalk and affects the system performance. A detailed theoretical investigation of the potential and limitations of TDM systems has already been carried out [5]. However, no experimental investigation into the performance of TDM gas sensor networks has been reported to the authors' knowledge. In this Letter, we report such an experimental investigation.

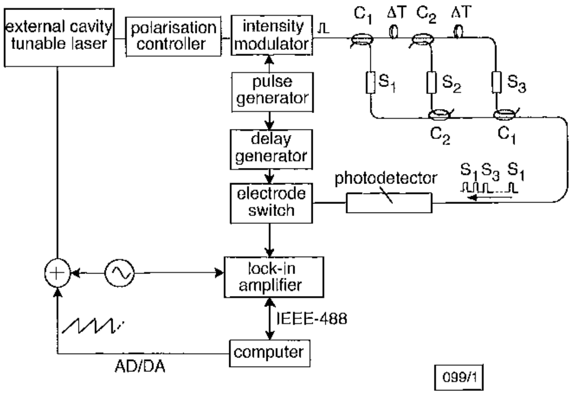

Fig. 1 *Experimental setup*

Fig. 1 shows the experimental setup. The sensor network reported here is the same as that described in a previous paper [5] with a sensor number of N = 3. The light source used was a new focus model external-cavity tunable laser (ECTL) with a wavelength tunable from 1520 to 1580nm. During the experiments, the wavelength of the tunable laser was tuned to one of the absorption lines of acetylene around 1530.2nm. Light from the laser was