was recorded over 180° using a hemicylindrical screen of photosensitive paper (Kodak Panalure) with the capillary at the centre. (i) and (ii) in Fig. 3 show the response of a water-filled, uncoated capillary under TE and TM illumination, adjusted to strike a broad range of angles and to highlight the region of the capillary response corresponding to reflections from the internal surface below the critical angle (30° to 90° in Fig. 3). As expected, TE reflectivity is greater in this region. The fringes (–30° to 30° in Fig. 3) result from the interference of rays that travel different optical paths through the capillary, but emerge at the same angle [4].

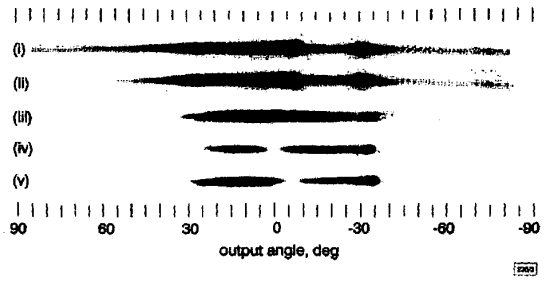

Fig. 3 *Capillary response, recorded photographically*

(iii) and (iv) in Fig. 3 show the response of a water-filled capillary which has been internally coated with Au. The illumination was adjusted to strike only the region above the critical angle, and so no fringes are seen. The TE response (Fig. 3(iii)) is uniform, while the TM response (Fig. 3(iv)) shows the dip characteristic of SPR. Fig. 3(v) shows the TM response when the capillary is filled with ethanol (n = 1.36 compared to n = 1.33 for water); as expected, the dip moves to a lower angle on the screen (corresponding to a higher angle on the internal surface of the capillary).

Conclusions: These results show that it is possible, with a simple optical setup, to implement SPR sensing in capillaries. To create a practical sensor, good stability and resolution must be achieved, and fabrication techniques must be improved. In particular, wet chemical deposition of Au [6] may be ideal for this application.

The capillary geometry is optically versatile and ideal for the handling of fluid analytes. We have presented the first theoretical and experimental work towards implementing SPR sensing in this configuration. Future work will aim to combine SPR with other capillary-based optical sensing techniques.

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References

1 WOLFBEIS, O.S.: 'Capillary waveguide sensors', *Trends Anal. Chem.*, 1996, **15**, pp. 225–232

2 STELLMAN, C.M., BUCHOLTZ, F., EWING, K.J., and AGGARWAL, I.D.: 'A fiber-optic pipette for rapid long-pathlength capillary spectroscopy', *Sens. Actuators B*, 1998, **46**, pp. 56–60

3 BORING, C.B., and DASGUPTA, P.K.: 'An affordable high-performance optical absorbance detector for capillary systems', *Analytica Chimica Acta*, 1997, **342**, pp. 123–132

4 TARIGAN, H.J., NEILL, P., KENMORE, C.K., and BORNHOP, D.J.: 'Capillary-scale refractive index detection by interferometric backscatter', *Anal. Chem.*, 1996, **68**, pp. 1762–1770

5 HOMOLA, J., YEE, S.S., and GAUGLITZ, G.: 'Surface plasmon resonance sensors: Review', *Sens. Actuators B*, 1999, **54**, pp. 3–15

6 LYON, L.A., MUSICK, M.D., SMITH, P.C., REISS, B.D., PEÑA, D.J., and NATAN, M.J.: 'Surface plasmon resonance of colloidal Au-modified gold films', *Sens Actuators B*, 1999, **54**, pp. 118–124

Time-domain optical sensing

P.V. Kelkar, F. Coppinger, A.S. Bhushan and B. Jalali

A chirped optical supercontinuum is used to map absorption spectra into temporal waveforms. Time-domain spectral measurement of acetylene is demonstrated using a modelocked fibre laser as the source of broadband radiation and a sampling oscilloscope for spectral measurement.

Supercontinuum sources, consisting of an erbium doped fibre laser followed by a nonlinear pulse compression stage, are being investigated as broadband sources in wavelength division multiplexing (WDM) networks [1]. Sources with bandwidths as large as 325nm centred around 1550nm have recently been reported [2]. Such a broadband source can be a powerful tool for the spectral analysis and sensing of a range of chemicals such as methane, carbon dioxide, and hydrogen sulphide. A single source can encompass a wide range of gases, eliminating the need for tunable lasers. Compared to light emitting diodes (LEDs) which are also broadband, supercontinuum sources deliver an order of magnitude greater power.

In this Letter we demonstrate a novel spectrometer that performs spectral measurement in the time domain. It uses a chirped supercontinuum pulse to map the spectral data into temporal waveforms which are then measured using an oscilloscope. Time-domain spectral measurement eliminates the need for an optical spectrometer [3]. The schematic diagram of the setup is shown in Fig. 1. Nearly-transform-limited pulses from the supercontinuum source are filtered to select the desired wavelength range and are dispersed through a long length of singlemode fibre. Different spectral components are separated as they travel through the fibre providing the wavelength-to-time mapping. Linearly chirped pulses are then passed through an acetylene gas cell. After photodetection, the output is recorded with either a sampling oscilloscope or an analogue-to-digital converter (ADC) depending on the temporal bandwidth of the resulting signal. The temporal bandwidth determines the spectral resolution of the system.

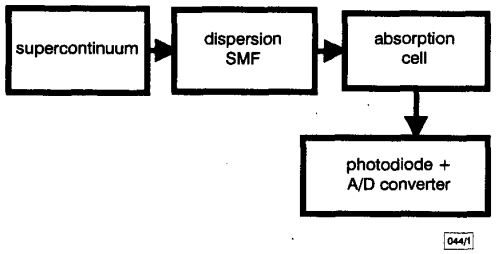

Fig. 1 *Schematic diagram of time-domain spectrum characterisation*

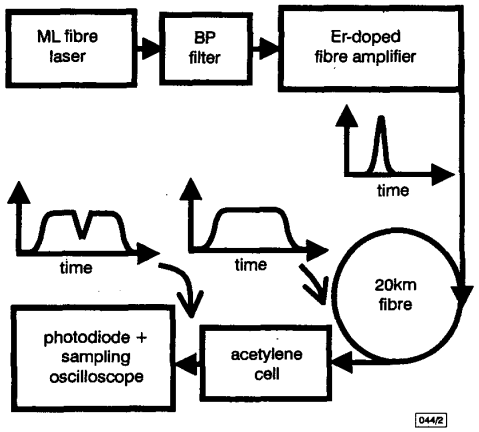

Fig. 2 *Experimental setup for time-domain spectrum characterisation*

The experimental setup is shown in Fig. 2. A passively modelocked erbium doped fibre laser with a pulse compression stage was used as the supercontinuum source. The source generates pulses with a 60nm bandwidth at a 40MHz repetition rate. A thin

film bandpass filter centred at 1522nm with a full-width-at-half-maximum (FWHM) of 10nm was used to select a desired portion of the laser spectrum. The peak intensity for the signal as well as the reference was obtained at 1529nm due to the shape of the laser spectrum. The autocorrelation trace of the filtered laser output showed an FWHM pulsewidth of 0.5ps and had a bandwidth of 10nm resulting in a time-bandwidth product of 0.64. The output after the bandpass filter was amplified by ~6dB in a low-dispersion erbium doped fiber amplifier (EDFA) and launched into 20.56km normal singlemode fibre (Corning SMF-28). This fibre has a dispersion coefficient of 17ps/km nm. Since the initial pulsewidth of 0.5ps is negligible compared to the pulsewidth after dispersion (~3.5ns), the pulse entering the gas cell can be assumed to be linearly chirped, in spite of the fact that the initial pulse was not exactly transform-limited. Acetylene has absorption peaks in the range 1515–1540nm. After passing through the gas cell, the signal was detected using a 60GHz photodiode and 40GHz sampling oscilloscope. A reference signal was obtained by replacing the acetylene cell with a singlemode fibre, which had the same length as the pigtail fibres of the absorption cell. The reference signal was used for normalisation. For comparison, direct spectrum measurements were performed with an HP70950B optical spectrum analyser (OSA).

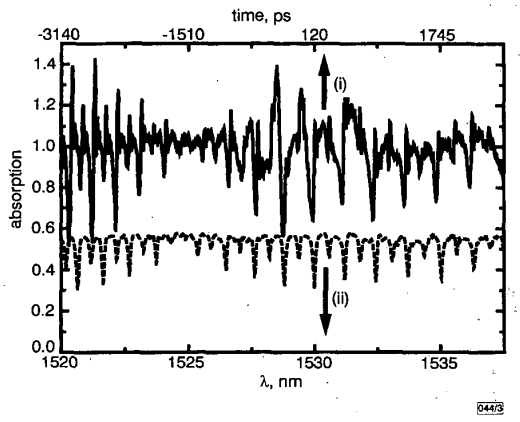

Fig. 3 *Time domain waveform and spectrum measured with spectrometer*

(i) time domain waveform (20 km fibre)
(ii) spectrum measured with OSA

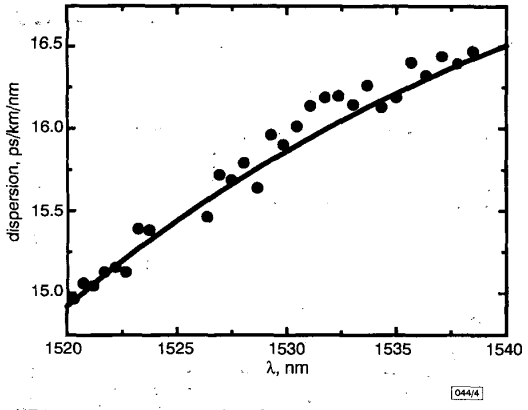

Fig. 4 *Dispersion against wavelength*

● experimental data
——— approximate fit to data

The resulting normalised time domain signal is shown in Fig. 3 along with the normalised spectrum measured using the OSA. The OSA was set to its highest resolution bandwidth of ~0.08nm. Absorption peaks are distinctly visible in the spectrum obtained by the OSA. The same resonances are also clearly visible in the temporal waveform measured by the oscilloscope. The resolution of the time domain data is comparable to the highest resolution of the OSA, i.e. 0.08nm. The peaks associated with each rising edge in the time-domain signal are due to ringing in the electrical circuitry and can be eliminated by impedance matching.

After dispersion through length L of fibre, a spectral separation ($\Delta\lambda$) will appear as a temporal separation ($\Delta\tau$) given by

$$\Delta\tau = DL\Delta\lambda + \frac{dD}{d\lambda}L(\Delta\lambda)^2 + \cdots$$

where D is the dispersion coefficient of the separation. Here we have neglected third and higher-order terms. The value of D can be obtained by comparing the position of resonances observed in the time-domain waveform and those observed in the spectral domain. The value obtained around 1529nm is $D = 15.8 \pm 0.3$ps/km/nm. Fig. 4 shows the value of D at different wavelengths. From this plot, we obtain a value for the second order dispersion, $dD/d\lambda$ of 0.075ps/km/nm^2. The extracted values for both D and $dD/d\lambda$ are in good agreement with the published results for SMF-28 [4]. Hence it can be inferred that the time-to-wavelength mapping can be accurately described by first and second-order dispersion of the fibre.

The pulsed nature of the technique allows single shot detection, which can be important in real time spectral analysis [5]. In principle, the dispersion can also be performed after the gas cell in Fig. 1. In this case, the peak power entering the cell would be extremely high causing undesired nonlinear interaction between the optical signal and the gas.

In summary we have demonstrated a simple yet effective optical spectrometer. It uses chirped supercontinuum pulses as a broadband source and a sampling oscilloscope or A/D converter for spectral analysis. Distinct advantages for this system include the absence of an optical spectrometer, the broad spectral bandwidth available from the supercontinuum source, and the possibility of real time spectral analysis.

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References

1 MORIOKA, T., KAWANISHI, S., MORI, K., and SARUWATARI, M.: 'Nearly penalty-free, < 4ps supercontinuum Gbit/s pulse generation over 1535-1560 nm', *Electron. Lett.*, 1994, **31**, pp. 816–817

2 SOTOBAYASHI, H., and KITAYAMA, K.: '325nm bandwidth supercontinuum generation at 10Gbit/s using dispersion-flattened and non-decreasing normal dispersion fibre with pulse compression technique', *Electron. Lett.*, 1998, **34**, pp. 1336–1337

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

4 JEUNHOMME, L.B.: 'Single mode fibre optics' (Marcel Dekker Inc., 1990)

5 FETTERMAN, H.R., TANNENWALD, P.E., PARKER, C.D., MELNGAILIS, J., and WILSON, R.C.: 'Real time spectral analysis of far-infrared laser pulses using a SAW dispersive delay line', *Appl. Phys. Lett.*, 1979, **34**, pp. 123–125

Effect of interdiffusion on dark current response of GaInP/GaAs quantum well infrared photodetectors

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The dark current response of interdiffused GaInP/GaAs quantum well intersubband infrared photodetectors is theoretically analysed for the case of group-III-only interdiffusion. The abrupt carrier confinement profile that is maintained after interdiffusion exhibits an increase in barrier height, and a significant reduction in the dark current of the interdiffused photodetector can be achieved.