implementation of the procedure described in [1 – 3]. Finally, the group delay was computed by differentiation of the retrieved phase characteristics.

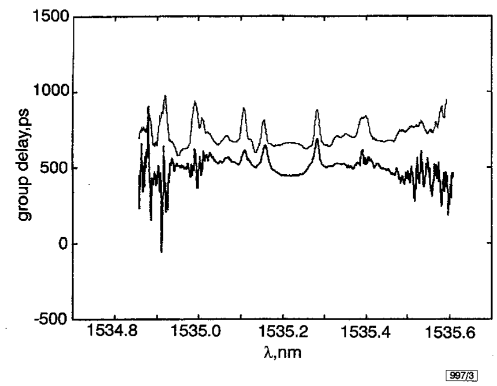

Fig. 3 *Measured and computed from modulus group delay of UFBG1*

Vertical offset intentionally added to make visual comparison easier; otherwise curves are one on top of the other
——— measured
·········· computed

Fig. 3 shows both the computed (broken line) and measured (solid line) group delay for the UFBG in the upper part of Fig. 2. Both curves are almost identical inside the grating stopband. Note that one curve has been displaced in time (i.e. in the direction of the vertical axis) for comparison. This time shift does not in fact exist, so both curves are very difficult to distinguish. Note also the fidelity in the reproduction of the peaks in the group delay curve due to the existence of secondary sidelobes in the modulus of the UFBG.

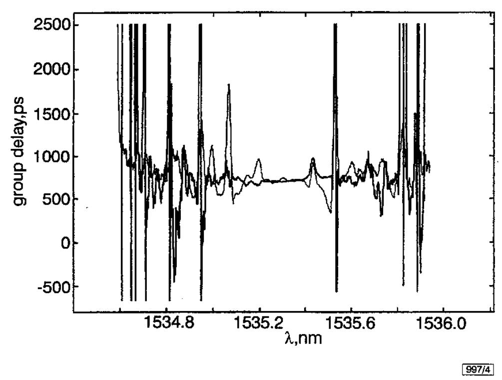

Fig. 4 *Measured and computed from modulus group delay of UFBG2*

No vertical offset added
——— measured
·········· computed

In Fig. 4 we plot identical results for the UFBG shown in the lower trace of Fig. 2. In this case the measured (solid line) and computed (broken line) results are shown as they stand; that is to say, no time shift has been applied. Again, almost perfect matching is obtained inside the grating stopband (reflection band). Also, although peaks in the group delay curve are reproduced as expected, it can be seen that the measured curve does not show a peak at the end of the stopband on the lower wavelength region. This is attributed to insufficient resolution of the measuring system, since the theory of UFBGs (and the retrieved group delay characteristic) show that it must be present.

Summary and conclusions: We have provided, to the best of our knowledge, the first full experimental demonstration of the applicability of the phase retrieval technique proposed in [1, 2] for uniform fibre gratings. Computed results of the group delay characteristic obtained by application of the Wiener-Lee transform to the fibre grating reflectivity have been compared to those directly obtained by measuring two UFBGs. The theoretical and experimental results are in excellent agreement, thus showing, as intended, the applicability of this technique.

24 April 1998
Electronics Letters Online No: 19980926

D. Pastor and J. Capmany (*Departamento de Comunicaciones, ETSI Telecomunicación, Camino de Vera s/n, 46017 Valencia, Spain*)

References

1 MURIEL, M.A., and CARBALLAR, A.: 'Phase reconstruction from reflectivity in uniform fibre Bragg gratings', *Opt. Lett.*, 1997, **22**, (2), pp. 93–95
2 CARBALLAR, A., and MURIEL, M.A.: 'Phase reconstruction from reflectivity in fibre Bragg gratings', *IEEE J. Lightwave Technol.*, 1997, **15**, (8), pp. 1314–1322
3 PAPOULIS, A.: 'The Fourier integral and its applications' (McGraw-Hill, New York, 1962)
4 PASTOR, D.: 'Fibre gratings for photonic signal processing'. PhD Dissertation, Universidad Politécnica de Valencia, 1996

Fibre coupled difference frequency generation utilising ytterbium-doped fibre amplifier and periodically poled $LiNbO_3$

D.G. Lancaster, L. Goldberg, J. Koplow, R.F. Curl and F.K. Tittel

A new mid-infrared tunable spectroscopic source based on fibre coupled difference frequency generation in bulk periodically-poled $LiNbO_3$ for trace gas detection is reported. The source mixes the outputs of a fibre coupled external cavity diode laser and a 1083nm seeded Yb-doped fibre amplifier. Powers up to 0.8μW are obtained in the 3.8–4.3μm range.

Recent developments in tunable diode laser technology and non-linear optical materials have led to the demonstration of difference frequency generation (DFG) in the 3–5μm spectral region for use in compact optical gas sensors. The characteristics of these sensors have been shown to be suitable for the sensitive, selective and real-time detection of numerous molecules with ro-vibrational spectra in the mid-infrared (mid-IR) fingerprint region. Since DFG with two single longitudinal mode laser diodes [1] results in low mid-IR powers (typically 10nW), high power semiconductor master oscillator power amplifiers (MOPAs) [2, 3], or a diode-pumped monolithic ring Nd:YAG laser [4] can be used. To realise the compactness and robust optical alignment of these sensors required for field applications, it is desirable to employ optical fibre technology wherever possible rather than bulk optical components. The first step in implementing such an optical design strategy is a partially fibre coupled DFG system using $AgGaSe_2$, producing light at 8.7 μm, which was reported by Petrov [5].

Here, we report a novel spectroscopic source generating up to 0.8μW from 3.85–4.3μm, based on DFG in bulk periodically poled $LiNbO_3$ (PPLN) pumped by a 1083nm diode laser seeded, Yb-doped double cladding fibre (DCF) amplifier [6] and an external cavity diode laser (ECDL) tunable from 845 to 865nm. Compared with other pump sources, the Yb-doped fibre amplifier offers the advantages of all-fibre construction, higher power, low cost, and a wide gain bandwidth. The mid-IR source reported here generated DFG output powers of up to 1μW and wavelength tunability of 450nm near 3.9μm with a sub-100MHz bandwidth for potential multi-species detection capability in this spectral region. The DFG source used fibres for beam delivery and combining, improving system robustness and ensuring automatic overlap and mode matching of the pump beams in the PPLN crystal.

In the DFG source configuration, shown in Fig. 1, the output of the Yb-doped DCF amplifier, operated in a single-pass counter-propagating geometry, was mixed with a 14mW tunable ECDL (SDL-8610-850). After collimation and passing through a Faraday isolator (~25dB) and an f = 30cm cylindrical lens, the ECDL emission was coupled into a singlemode APC terminated fibre using a free space coupler (OFR Inc) with an overall coupling efficiency of 50%. The Yb-doped fibre amplifier was seeded with a 50mW 1083nm distributed Bragg reflector (DBR) diode laser (SDL-6702). After collimation using a 3.1mm focal length aspheric lens, the laser light passed through a λ/2 plate to rotate the polarisation into the vertical plane, a 3× anamorphic prism pair (APP) to circularise the beam and a 30dB Faraday isolator, resulting in the launch of 23mW into the angle-cleaved input amplifier fibre.

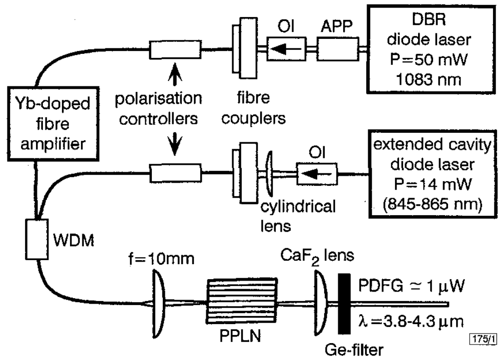

Fig 1 *Schematic diagram of mid-infrared DFG sensor*

APP: anamorphic prism pair
OI: Optical isolator

Fibre polarisation controllers were used to set the polarisation states for both input beams to be linear and vertical. The two fibre coupled pump sources were combined into a singlemode fibre using a 850/1080nm fibre wavelength division multiplexer (WDM), which had a transmission loss of < 5% at both wavelengths. Conveniently, ~0.5% of the pump light was available at the second output fibre of the WDM, and was directed to a wavemeter for optical frequency monitoring.

The fibre amplifier utilised a 7.2m long Yb-doped DCF double-cladding fibre (Lucent Tech.), with a polymer outer cladding, a nearly-hexagonal 131μm inner cladding, and a 6μm diameter core with a numerical aperture of 0.16. The fibre was side-pumped with a 975nm, 2W (at 3.0A) broad stripe diode (SLI Inc.) using a v-groove pump coupling technique [7], with the v-groove located near one end of the DCF gain fibre. The DCF ends were fusion spliced to conventional singlemode fibre (Flexcore 1060). Pump light from the 200μm wide broad stripe laser was collected and coupled into the fibre through the v-groove by a micro-lens, with an overall efficiency of ~65%. All amplifier components were packaged into a 9 × 11 × 2cm housing. When seeded with P_i = 23mW, the amplifier generated a maximum saturated output power of 780mW. The small signal gain was > 30dB in the 1030–1100nm range, reaching a maximum of 47dB at 1080vnm. Owing to the high small-signal gain, > 90% of the maximum saturated power could be extracted with a P_i of only 1mW. Fig. 2 shows the saturated Yb amplifier output power as a function of the pump diode current, with P_i = 23mW. The slight rollover of power near 3 A is due to spectral broadening of the pump laser resulting in a reduction in the absorbed pump power.

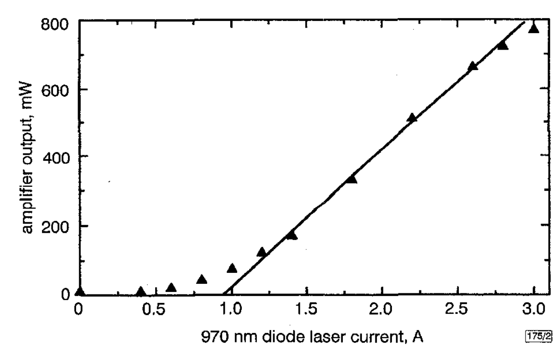

Fig 2 *Output power at 1.083μm from side-pumped ytterbium-doped fibre amplifier*

P_i (1083nm) = 23mW

A single AR coated achromatic 10mm focal length lens was used to image the beam spot from the output fibre end (cleaved at ~8°) onto the 19mm long PPLN crystal (Crystal Tech.) with a magnification of 7.5. No attempt was made to achieve optimal focusing. The PPLN crystal contained eight gratings with periods of 22.4 to 23.1μm in increments of 0.1μm. The crystal was temperature controlled to extend the spectral quasi-phasematching (QPM) range. For QPM, we calculate a grating period of 23.4μm at 23°C for 850/1083nm DFG. Hence, the crystal mount was heated to a temperature of 93°C to achieve QPM in the largest available period (23.1μm) grating channel. The entire tuning range of the DFG source could be phasematched from 845–865nm over a temperature range of 73–102°C.

The mid-IR DFG output was collimated by an uncoated 50mm focal length CaF_2 lens and the residual pump beams were blocked by an AR coated Ge filter and focused onto a calibrated thermoelectrically-cooled HgCdTe detector, with a 1mm² active area, using a 5cm focal-length off-axis parabolic mirror.

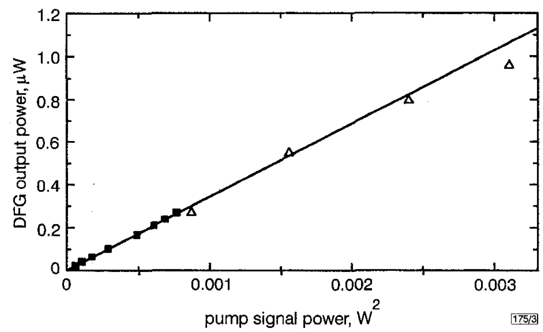

Fig. 3 *Output power (corrected for uncoated optics) of DFG source at 4μm against product of signal and pump powers*

■ signal power = 184mW
△ pump power = 4.84mW

The DFG radiation at 4μm was measured as 0.8μW, at an incident pump power of 5.1mW and a signal power of 740mW. The corrected DFG power was 1.0μW, taking into account Fresnel losses from the uncoated PPLN crystal and collimating CaF_2 lens. Fig. 3 shows the DFG power as a function of the corrected incident pump power product. In this experiment the signal power was set to 184mW and the DFG power was measured as a function of increasing (851nm) pump power. Then, with the maximum ECDL pump power of 4.84mW, the DFG power was measured for increasing 1083nm signal power. The resulting slope efficiency was 0.33mW/W², less then the theoretically predicted efficiency of 0.60mW/W² using the CW DFG theory of Chu and Broyer [8] and $d_{eff} = 2/\pi \cdot 27$pm/V. This discrepancy can be attributed to the non-optimised focusing condition of L/b = 0.02 (where L is the nonlinear crystal length and b is the beam confocal parameter) used in the experiment. The theoretically predicted optimum focusing condition is L/b = 1.3.

In conclusion, a potentially compact and robust fibre coupled DFG-based mid-IR spectroscopic source has been demonstrated that uses a tunable ECDL and a 1083nm SLM diode seeded Yb-doped fibre amplifier. The system is tunable from 3.85–4.3μm, and temperature phase-matched over this entire region using a 23.1μm grating period in PPLN. It is expected that by using a pigtailed ECDL, and optimising the focusing into the nonlinear optical crystal, the sensor should generate an order of magnitude higher power than the 0.8μW demonstrated. The system also lends itself to further power scaling through the use of higher power Yb-doped DCF amplifiers and recently reported optical waveguide structures with significantly increased conversion efficiencies [9].

28 April 1998
Electronics Letters Online No: 19980917

D.G. Lancaster, R.F. Curl and F.K. Tittel (*Rice Quantum Institute, Rice University, 6100 Main Street, Houston, TX 77005, USA*)

E-mail: davelanc@rice.edu

L. Goldberg, and J. Koplow (*Optical Sciences Division, Naval Research Laboratory, Washington, D.C. 20375-5672, USA*)

References

1 SIMON, U., MILLER, C.E., BRADLEY, C.C., HULET, R.G., CURL, R.F., and TITTEL, F.K.: 'Difference frequency generation in $AgGaS_2$ using single-mode diode laser pump sources', *Opt. Lett.*, 1993, **18**, pp. 1062–1064
2 BALAKRISHNAN, A., SANDERS, S., DEMARS, S., WEBJORN, J., NAM, D.W., LANG, R.J., MEHUYS, D.G., WAARTS, R.G., and WELCH, D.F.: 'Broadly tunable laser-diode-based mid-infrared source with up to 31mW of power at 4.3µm wavelength', *Opt. Lett.*, 1996, **21**, pp. 952–954
3 SIMON, U., TITTEL, F.K., and GOLDBERG, L.: 'Difference-frequency mixing in $AgGaS_2$ by use of a high-power GaAlAs tapered semiconductor amplifier at 860nm', *Opt. Lett.*, 1993, **18**, pp. 1931–1933
4 TÖPFER, T., PETROV, K.P., MINE, Y., JUNDT, D., CURL, R.F., and TITTEL, F.K.: 'Room-temperature mid-infrared laser sensor for trace gas detection', *Appl. Opt.*, 1997, **36**, pp. 8042–8049
5 PETROV, K.P., CURL, R.F., TITTEL, F.K., and GOLDBERG, L.: 'CW tunable 8.7mm spectroscopic source pumped by fibre-coupled communications lasers', *Opt. Lett.*, 1996, **21**, pp. 1451–1453
6 KOPLOW, J., GOLDBERG, L., and KLINER, D.A.V.: 'Compact 1W Yb-doped double cladding fiber amplifier using v-groove side-pumping', *Photonics Technol. Lett.*, 1998, **10**, (6), pp. 793–795
7 GOLDBERG, L., COLE, B., and SNITZER, E.: 'V-groove side-pumped 1.5µm fibre amplifier', *Electron. Lett.*, 1997, **33**, pp. 2127–2129
8 CHU, T.B., and BROYER, M.: 'Intracavity cw difference frequency generation by mixing three photons and using Gaussian laser beams', *J. Physique*, 1985, **46**, pp. 523–533
9 ARBORE, M.A., CHOU, M.H., and FEJER, M.M.: 'Difference frequency mixing in $LiNbO_3$ waveguides using an adiabatically tapered periodically-segmented coupling region'. CLEO Tech. Dig. Series, 1996, Vol. 9, pp. 120–121

Large mode area photonic crystal fibre

J.C. Knight, T.A. Birks, R.F. Cregan, P.St.J. Russell and J.-P. de Sandro

The authors report the realisation of a new design for a large mode area monomode optical fibre. This photonic crystal fibre will guide only a single mode, no matter how large the fibre diameter, provided the shape is kept constant. This is demonstrated with a fibre which has a core diameter equal to approximately 50 free-space wavelengths.

A photonic crystal fibre (PCF) is a glass fibre with a regular array of holes running down its length. A single missing hole in the array forms a region which effectively has a higher refractive index than the surrounding photonic crystal. This acts as a waveguide core in which light can become trapped, forming a guided mode [1]. We have previously reported that the PCF remains monomode even for very short wavelengths, and have explained this using an effective index model [2]. We now demonstrate that it remains monomode even for very large-scale fibres. Such large mode area fibres are useful for generating and propagating high optical powers without limitations due to the onset of intensity-dependent nonlinear effects. Monomode photonic crystal fibre can readily be made as large as desired because, unlike conventional optical fibres, the number of guided modes in a PCF is independent of the ratio of core radius ρ to optical wavelength λ (provided that the wavelength is sufficiently short). Instead, the number of modes depends only on the ratio of the air hole diameter d to the spacing between holes Λ [2]. One consequence of this is that no change in the refractive index profile is required to fabricate fibres with different core diameters, and a single preform can be used to fabricate monomode fibres with cores of any size.

An SEM micrograph of a portion of the cleaved face of the fibre reported here is shown in Fig. 1. It has a core of pure silica which is surrounded by an array of air holes in a silica matrix. The fibre shown is 180µm in diameter and is several metres long. The air holes run along the entire length. The core diameter (defined as the diameter of the ring formed by the innermost air holes) is $2\rho \simeq 22.5$µm, and the air holes (with diameters d = 1.2µm) are spaced by Λ = 9.7µm in the periodic region. The fibre was made by stacking a number of silica capillaries into the required hexagonal array, replacing a single one of them with a solid silica cane to form the fibre core, and drawing the stack down on a fibre drawing tower. The core diameter 2ρ is greater than twice the pitch Λ because the air holes in the original capillaries were relatively larger than in the final fibre: the holes are allowed to collapse in a controlled fashion during the fabrication process. It is worth emphasising that apart from being a very different size, the fibre shown in Fig. 1 is virtually identical to those fibres described previously [1] which were approximately five times smaller in diameter and which also guided only a single mode over the wavelength range to be described here.

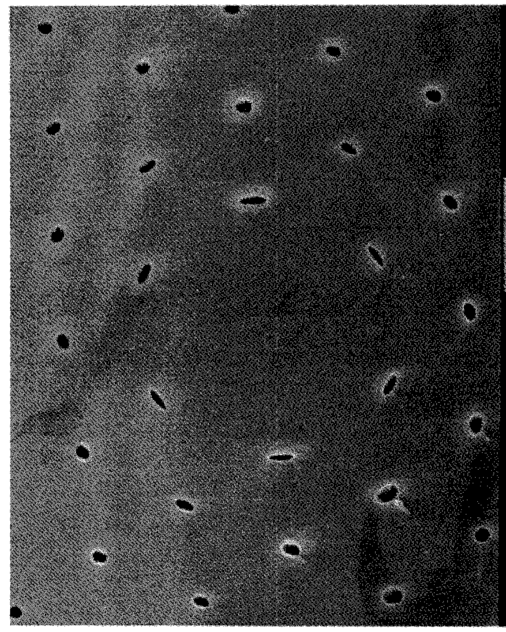

Fig. 1 *Scanning electron micrograph of cleaved end face of large mode area photonic crystal fibre*

Fibre shown has 22.5µm core diameter, relative air hole diameter d/Λ = 0.12, and is monomode at all wavelengths λ > 458nm at least

Fig. 2 *Contour map of near field intensity distribution for guided mode in fibre shown in Fig. 1 at wavelength* λ = *458nm*

Contours are plotted at 10% intervals in modal field intensity distribution

The fibre shown in Fig. 1 guides only a single mode at a wavelength of λ = 458nm (and at all longer wavelengths within the transparency window of silica). We know this because we have coupled light into one end of the fibre and have used index-matching oil to strip off light in cladding modes. We then find that the near and far field patterns of the light guided in the fibre core are independent of the input coupling conditions or of any bends or twists introduced into the fibre. This is strong evidence of mono-