To test the high speed performance of this GaAs oscilloscope probe, an experiment similar to the high speed sampling

Fig. 2 Micromachined GaAs IC which includes a two diode sampling bridge and an abrupt junction NIT pulser with the GaAs probe tip

system of Marsland *et al.*[7] was performed. The GaAs oscilloscope probe, which included the sampler and the local oscillator, was used to make contact to the output of a 60 diode NIT test pulser on a GaAs wafer. A 15:1 attenuator was located between sampler and DUT to prevent sampler saturation. An 880fs fall time was measured at the output of this 40 diode NIT test pulser as shown in Fig. 3. This 880fs system rise time is root-mean-squares convolution of the 40 diode NIT fall time, the sampling scope aperture time and the GaAs tip transition time. From this we estimate a probe rise time of ~600fs corresponding to a 3dB bandwidth of 500GHz.

Fig. 3 880fs fall time measured at the output of a 60 diode NIT test pulser by a 500 GHz bandwidth on-wafer oscilloscope probe

Summary: This is the first time all electronic on-wafer measurement has been extended to subpicosecond regime. A novel pulse sharpener with improved diode and transmission line losses was developed for subpicosecond output fall times and 100ps input fall times. By using this novel pulse sharpener, a subpicosecond oscilloscope probe was built for time domain on-wafer measurements.

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INTEGRATED GRATING DEMULTIPLEXER AND *pin* ARRAY FOR HIGH-DENSITY WAVELENGTH DIVISION MULTIPLEXED DETECTION AT 1.5µm

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Indexing terms: Diodes, Photodetectors, Integrated optoelectronics

An integrated wavelength demultiplexer and *pin* detector array is reported for high density WDM detection at 1.5µm. Signals spaced at 1nm over the 1.48-1.55µm wavelength range are separated and detected; channel passbands are 0.6-0.8nm. Grown on a semi-insulating substrate, and providing a pseudoplanar device surface, the HD-WDM detector array is suitable for monolithic integration with high-speed multichannel receiver circuitry.

Introduction: Wavelength division multiplexed (WDM) direct detection systems have potential application in telecommunications and computer networks, with 1-4nm channel-spaced systems being of particular interest. To date, receivers for such applications have employed bulk-optic demultiplexers to separate the signals, which are then directed to photodiodes in a 1-D array [1]. There is considerable advantage to be gained, however, if the demultiplexing and detection functions can be performed on a single chip: component count is reduced and optical alignment automatic. Assembly costs should thus be reduced and field reliability improved.

We report a monolithically integrated wavelength demultiplexer and detector array operating in the 1.5µm fibre band. The planar waveguide device integrates a curved diffraction grating and a *pin* waveguide detector array, and employs a high-efficiency waveguide/detector coupling scheme [2]. Grown on a semi-insulating InP substrate, and with separate contacts to each detector, it may be monolithically integrated with high-speed receiver electronics. A 42 channel, 4nm channel spacing, WDM detector array has been previously reported [3]; this Letter reports a device operating at the closer channel spacing of 1nm and is the first to employ independently-contacted high-speed diodes on a semi-insulating substrate as required for integration with high-speed array electronics. Preliminary results were reported in Reference 4.

Integrated HD-WDM detector arrays: The integrated high-density WDM detector array is based on a previously reported InP/InGaAsP/InP planar waveguide grating demultiplexer [5]. Light enters the planar region from a singlemode ridge waveguide, spreads out, and is diffracted by the vertically-walled grating into an array of output waveguides which feed into waveguide *pin* detectors. Fig. 1 shows a schematic diagram of the device; the geometry is similar to that reported in Reference 5, with output guides separated by ~20µm.

Fabrication: The HD-WDM detector was grown by low pressure (76 torr) organometallic chemical vapor deposition

Fig. 1 Schematic diagram of monolithic wavelength demultiplexer and detector array

(MOCVD) at 620°C. The layer structure and growth stages were identical to those described in Reference 2: first, the waveguide core (0.6 μm InGaAsP, $\lambda_g = 1.1 \mu\text{m}$) and detector layers (0.1 μm *n*-InP contact layer, 0.7 μm undoped InGaAs, surmounted by 0.4 μm *p*-InGaAsP, $\lambda_g = 1.3 \mu\text{m}$, and 0.1 μm *p*⁺-InGaAs *p*-contact layer) were grown, then the detector mesas were formed by etching to the waveguide core and the waveguide cladding layer (0.5 μm, undoped InP) regrown.

The grating wall (2.5 μm-deep, <3° to vertical) was formed by chemically assisted ion beam etching [6] through the waveguide core and then reflection-coated (70 Å Ti/2000 Å Au). The ridge guides were formed by wet-chemical etching: two 6 μm-wide input waveguides in the centre (only one is used) and output guides on either side tapering down from a 14 μm-wide opening to 6 μm at the photodiode. Detector fabrication was completed by etching the 'down-stream' half of each mesa to the *n*-InP layer and forming separate *p*- and *n*-contacts [2]. 92 detectors (25 μm long, by 15 μm wide) were fabricated, covering the free spectral range of the grating. Fig. 2 shows the central portion of the array; the contact metalisation is supported on a polyimide spacer layer.

Fig. 2 Central portion of detector array surrounding the (two) input waveguides

Results: The HD-WDM detector array was examined over ~1.48 μm–1.55 μm with an F-centre laser. The peak-detection wavelengths for the central 65 detector span are plotted in Fig. 3 for TE incident light; the gap at 1.513 μm–1.514 μm marks the position of the input guides. Reliable data for the peripheral diodes were not attainable because of the much lower incident laser power at these wavelengths and the decreasing collection efficiency of the output guides (see below).

Fig. 3 shows the high wavelength uniformity achievable with the grating-based device. The dispersion is highly linear, with a measured standard deviation of just 0.14 nm (see Fig. 4). The intrinsic linearity is actually higher than this, as the responses were obtained using discrete, 0.15 nm-step, wavelength scans. The 'error bars' drawn correspond to the typical FWHM response; one is illustrated in the inset to Fig. 3.

Nearest-neighbour (NN) crosstalk is ~ -7 dB, next-nearest-neighbour ~ -10 dB, thereafter decreasing rapidly to < -25 dB (the limit of measurement) for the more remote detectors. The modest near-neighbour isolation is believed to

be limited by radiative coupling between the tapered output guides; slight design modification is expected to yield >20 dB NN isolation without significant reduction of the channel

Fig. 3 Peak-response wavelengths for the central 65 detector span
Inset: typical response of central detector

Fig. 4 Measured deviation from linearity
 $\sigma = 0.14$; 'error bars' represent the FWHM of a typical channel passband: 0.7 nm

passband.* We have previously measured ~20 dB isolation in passive demultiplexers with straight output guides [5].

The efficiency of the waveguide detectors is known to be ~90% [2]. On-chip losses of the HD-WDM detector array were measured at -13 to -14 dB for the central detectors. The larger portion of this is believed to be diffraction loss (~9–10 dB, arising predominantly from uncorrected spherical aberration), the remainder being reflection loss at the grating and propagation losses in the waveguides. We note that the efficiency was uniform over a central ~20-detector span, but decreased to -3 dB for a width of ~30 detectors, and -6 dB for a width of 56 detectors. This drop is caused primarily by the reduced phase matching at the mouth of the output waveguide (with a small contribution from a reduced diffraction efficiency), but may be largely corrected for by tilting the output waveguides. Similar behaviour has been observed in passive grating demultiplexers [5].

The waveguide detectors had a low capacitance (~50 fF) and were capable of high speed operation (~3 dB bandwidth, ~15 GHz [2]). They are thus suitable front ends for a fast high-sensitivity receiver.

Summary: We have presented a monolithic HD-WDM detector array grown on semi-insulating InP. HD-WDM detection was demonstrated for 1 nm-spaced signals over the 1.48–1.55 μm wavelength range. The semi-insulating substrate and pseudoplanar surface permits the further electronic integration needed to provide a fully-monolithic high-speed wavelength-demultiplexing receiver array.

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METHANE AND CARBON DIOXIDE SENSING USING A DFB LASER DIODE OPERATING AT 1.64 μ m

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Indexing terms: Lasers, Semiconductor lasers, Gas sensors

Selective gas sensing of CH₄ and CO₂ using a single tunable 1.64 μ m DFB laser diode is demonstrated for the first time. By precise wavelength tuning of the diode to non-coincident absorptions of the two gases in their overlapping spectral region we can detect both using absorption spectroscopy.

Introduction: Recently it has been shown that the overtone absorptions of the strategically important methane gas in the 1.6 μ m region can be used for sensitive optical detection [1]. Specifically, sensitivities of 1 ppm have been achieved using tunable single frequency DFB lasers of the type developed for telecommunications [1–3]. It was pointed out that the excellent tuning accuracy and spectral resolution of DFB lasers could lead to high selectivity gas sensing [1]. Optical sensors using techniques such as pressure modulation [4] or active stabilisation of the laser wavelength [5] to reduce cross-sensitivity in gas detection by locking on to the absorption line of interest can achieve good gas selectivity. However, these systems based on the use of a reference cell filled with the target gas introduce extra complexity and limit detection to that particular gas. In this Letter we use a single InGaAsP DFB laser diode operating at 1.64 μ m and demonstrate an ability to detect two gases with overlapping absorption bands by accurately tuning to a position where individual absorption lines do not coincide. Specifically, we have targetted the rotational sideband of the 2 ν_3 overtone of methane and the 6 ν_2 + ν_3 combination band of carbon dioxide both of which absorb in the 1.64 μ m spectral region. To the best of our knowledge this is the first report of the detection of more than one gas with a single DFB laser diode.

Experimental setup: The experimental setup is basically the same as used in the work previously reported [1]. A single-mode InGaAsP/InP DFB laser diode with a typical linewidth of 30 MHz (HWHM) and a room temperature wavelength of 1.64 μ m was used. Temperature control and stabilisation of the laser was achieved in the usual way using a thermoelectric module and heatsink arrangement. Coarse and fine control of

the laser wavelength were carried out by temperature and injection current adjustment, respectively. Temperature and current tuning characteristics are 0.0918 nm/°C and 0.00276 nm/mA and a minimum current step of 0.05 mA provided a potential tuning accuracy of 1.38×10^{-4} nm. This is approximately a factor of 2 less than the HWHM laser linewidth of 30 MHz and so makes only a small contribution to the overall resolution. A wavelength tuning of 5.5 nm was achieved by adjustment of the laser temperature over a 0–60°C range. Detecting the gas in a multipass cell allowed open path absorption measurements to be made in a controlled way. Pressure, concentration and absorption length can be easily varied and controlled and also baseline information obtained by evacuation. A personal computer was used for system control and data acquisition. Strong absorption signals from high gas concentrations were measured using amplitude modulation with a chopper and synchronous detection, while for low concentrations (ppm) modulation of the laser current at a frequency F and synchronous detection at 2F (second harmonic detection) was used to achieve high sensitivities.

Results and discussion: Fig. 1 illustrates the absorption spectrum at CO₂ atmospheric pressure in the range 1640–1645 nm

Fig. 1 Absorption spectrum of carbon dioxide at atmospheric pressure in 1640–1645 nm region

obtained by temperature tuning the laser at a fixed current. A comb structure with a period of ~0.4 nm is clearly seen. Recent work [1] has shown that the R7 and R8 sideband absorption feature of the 2 ν_3 overtone of CH₄ overlaps this wavelength region. It is clear that the ability of any gas sensor to achieve selective detection will be significantly enhanced by high resolution and good tuning accuracy.

The integrated line intensity of the 6 ν_2 + ν_3 CO₂ absorption band is approximately three orders of magnitude less than that of the 2 ν_3 CH₄ overtone band [6]. With roughly a 2 to 1 difference in the number of lines, the line intensity is about 500 to 1 in favour of CH₄ assuming equal intensity distribution between lines. To ensure that the signal levels from CO₂ and CH₄ in the mixture were comparable the relative concentration was set at 360 to 1. A spectrum of a mixture of CO₂ and CH₄ at atmospheric pressure in the R8 rotational sideband region of CH₄ obtained by temperature tuning at a fixed current is shown in Fig. 2(i). Given the comb structure of CO₂ it is likely that a CO₂ absorption line is overlapping with the R8 feature of CH₄. To investigate this, a high resolution absorption spectrum obtained by current tuning was taken at a pressure of 10 mB to reduce pressure broadening and the results are shown in Fig. 2(ii). Fully resolved CO₂ and CH₄ lines separated by less than the pressure broadened linewidth are clearly seen. At low pressure the linewidths are dominated by Doppler broadening and hence are sufficiently narrow to allow complete resolution of the CH₄ and CO₂ lines which coincide at atmospheric pressure. Obviously a CH₄ sensor operating at atmospheric pressure targetting the R8 feature would produce spurious results in the presence of CO₂. However, the next rotational sideband feature of CH₄ (R7) is well within the tuning range of the same DFB laser. An absorption spectrum taken in this region at atmospheric pressure (Fig. 3) shows the R7 feature and the adjacent CO₂ lines clearly resolved.