Broadly tunable mid-IR radiation source based on difference frequency mixing of high power wavelength-tunable laser diodes in bulk periodically poled $LiNbO_3$

S. Sanders, R.J. Lang, L.E. Myers, M.M. Fejer and R.L. Byer

Indexing terms: Semiconductor junction lasers, Lithium niobate

Coherent mid-IR radiation throughout the 3.6 to 4.3μm wavelength range is generated by difference frequency mixing (DFM) of wavelength-tunable laser diodes in periodically-poled $LiNbO_3$ (PPLN). Mid-IR power levels up to 7.1μW and DFM conversion efficiencies up to 0.015%/Wcm are demonstrated.

Room-temperature, compact mid-IR (2–5μm) sources are essential to the development of gas-sensing instrumentation for application to environmental monitoring, industrial process control, biochemical analysis, and high resolution scientific instrumentation. Such sources can be based on difference frequency mixing (DFM) of high power near-IR laser diodes by noncritical birefringent phasematching in $AgGaS_2$ and $AgGaSe_2$ [1] or by quasi-phasematching (QPM) in periodically poled $LiNbO_3$ (PPLN). $LiNbO_3$ is a low cost, robust material, and periodic poling allows it to be tailored to non-critically phasematch any near-IR laser diode wavelengths for DFM, limited only by the $LiNbO_3$ absorption edge near 5μm. Both waveguide [2, 3] and bulk [4 – 7] interaction geometries in PPLN have been used to mix near-IR wavelengths to the mid-IR. While DFM conversion efficiencies are higher in waveguides, bulk materials can handle higher power levels, are easier to fabricate, are far less sensitive to beam alignment, and can be rotated for angle tuning. In this Letter, we describe the first broadly tunable mid-IR source based on laser diode DFM in bulk PPLN. By mixing two wavelength-tunable high power single-spatial-mode laser diodes [8], mid-IR radiation is generated over the 3.6 to 4.3μm wavelength range at power levels up to 7.1μW.

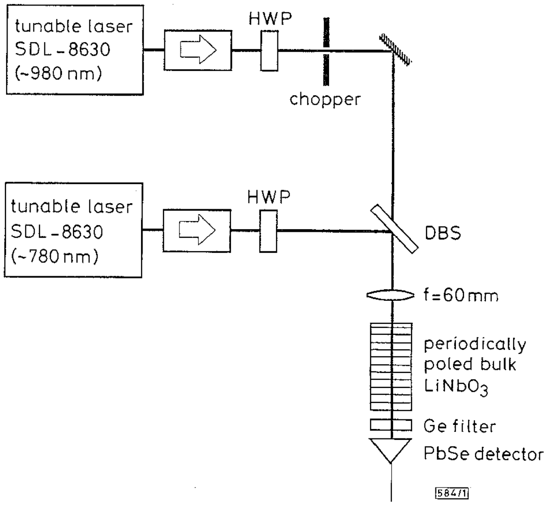

Fig. 1 *Schematic diagram of laser diode difference frequency mixing configuration*

HWP: half-wave plate
DBS: dichroic beamsplitter

A schematic diagram of the mid-IR DFM experimental configuration is shown in Fig. 1. The output from two wavelength-tunable near-IR 0.5W single-spatial-mode laser diodes (SDL-8630) is isolated and polarised parallel to the crystallographic *z*-axis of the PPLN sample. The PPLN sample is fabricated by electric field poling of a 0.5mm thick *z*-cut $LiNbO_3$ wafer and has ferroelectric domains modulated with a 40% duty cycle and 21μm period along its crystallographic *x*-axis. The circular laser diode beams are focused to a spot size of ~30μm in the PPLN crystal by an achromatic lens to obtain a nearly optimal beam size for DFM. At the crystal output, near-IR light is blocked by a germanium filter, and the generated mid-IR radiation is detected by a thermoelectrically cooled PbSe detector.

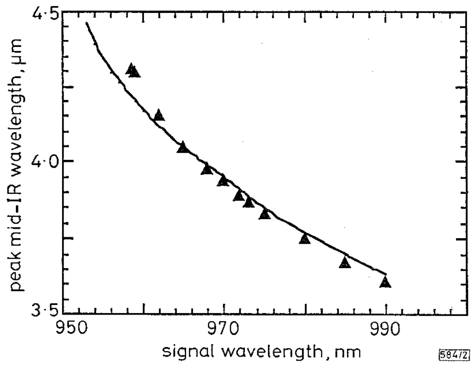

Fig. 2 *Peak mid-IR wavelength generated against signal wavelength for 21μm QPM period*

Pump wavelength is varied from 776 to 783nm to maintain phasematching
▲ experimental points
—— theoretical phasematching wavelength

As shown in Fig. 2, mid-IR radiation is generated over the 3.6 to 4.3μm wavelength range by tuning the signal wavelength between 958 and 990nm. To maintain phasematching, the pump laser diode wavelength is tuned between 776 and 783nm, and in the opposite direction of the signal wavelength tuning. The experimentally measured phasematching wavelengths are close to those theoretically predicted as shown by the solid line in Fig. 2. This line was calculated for the 21μm poling period at 25°C temperature using a Sellmeier equation for the extraordinary index of $LiNbO_3$. The fact that the pump and signal wavelengths tune in opposite directions for non-critical phasematching in PPLN, greatly decreases their required tuning ranges for covering a given portion of the mid-IR spectrum. In contrast, noncritical phasematching in $AgGaS_2$ requires the signal and pump wavelengths to tune in the same direction and therefore, over a much larger wavelength range to cover the same mid-IR wavelengths.

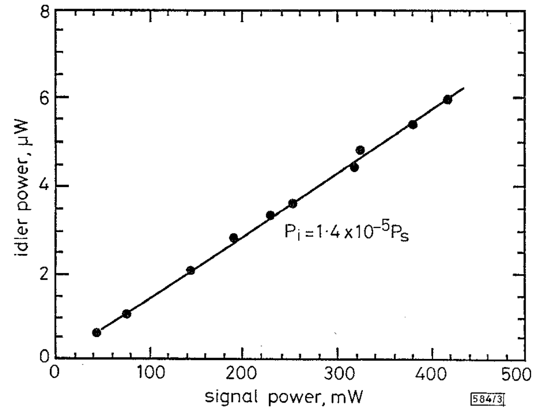

Fig. 3 *Generated idler power at 3.75μm wavelength against signal power*

Overall DFM conversion efficiency is 0.008%/W
λ_p = 777nm, λ_s = 980nm, λ_i = 3.75μm, P_p = 180mW

The dependence of the idler power at 3.75μm wavelength on the signal power is shown in Fig. 3. The pump power is fixed at 180mW, and the slope efficiency is 1.4×10^{-5}, which corresponds to an overall DFM conversion efficiency of 0.008%/Wcm. This value for this 7.8mm long crystal is comparable to results for laser diode DFM in $AgGaS_2$, where reported conversion efficiencies are 0.010%/W for a 45mm long sample [1]. The actual material DFM conversion efficiency for the PPLN is 0.015%/Wcm when corrected for Fresnel losses of 12–14% for the pump, signal and idler wavelengths at the uncoated $LiNbO_3$ to air interfaces. At a slightly longer wavelength of 3.89μm, up to 7.1μW of power is generated with the pump laser at 510mW, as shown in Fig. 4.

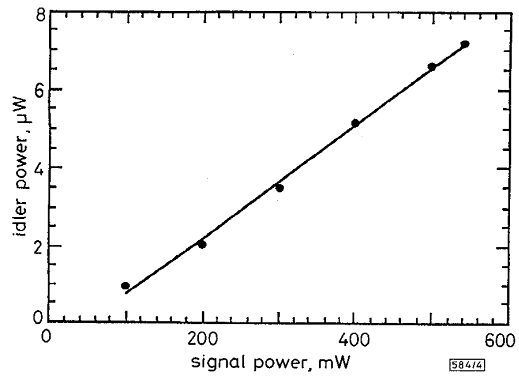

Fig. 4 *Generated idler power at 3.89μm wavelength against signal power*
λ_p = 777.7nm, λ_s = 972nm, λ_i = 389μm, P_p = 510mW

In summary, we have demonstrated a broadly tunable, laser diode based room temperature source of mid-IR radiation using bulk PPLN material for DFM. The broad tuning range and high conversion efficiency of PPLN devices make them excellent candidates for developing low cost, compact laser diode based mid-IR sources for gas sensing applications.

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Oxygen sensing using single frequency GaAs-AlGaAs DFB laser diodes and VCSELs

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Indexing terms: Gas sensors, Semiconductor junction lasers

Oxygen detection using a GaAs-AlGaAs distributed feedback laser diode emitting at a wavelength of 761nm is demonstrated for the first time. Using wavelength modulation spectroscopy with harmonic detection the authors have achieved a detection limit of 20ppm.m with a lock-in amplifier time constant of 33.3ms. The first results comparing the relative merits of VCSELs and DFB laser diodes for sensing applications are also shown.

Single frequency laser diodes with emission wavelength around the optical communications transmission windows at 1.3 and 1.55μm have shown excellent performance as light sources for near infrared, spectroscopic based, gas sensing [1 – 3]. Device availability has largely limited applications to sensing gases with overtone absorption features whose wavelengths are accessible with 1.3 and 1.55μm material systems. Recently however, there has been excellent progress with the development of single frequency distributed feedback (DFB) laser diodes and vertical cavity surface emitting lasers (VCSEL) emitting at other wavelengths, targeting oxygen, which has significant absorption features around λ = 761 nm, in particular. While O_2 sensing has been demonstrated over a very limited wavelength tuning range using standard Fabry-Perot laser diodes [4], and also over wide tuning ranges with devices tuned with a gratihg loaded external cavity [5, 6], it is widely recognised that deployable systems will require robust optical sources which must display excellent single frequency emission over wide temperature and current tuning ranges, i.e. DFB, DBR and VCSEL laser diodes. While the first visible (λ = 759nm) AlGaAs (DFB) laser diode operating continuous wave at room temperature was reported [7] in 1987, a significant step forward in the development of lasers for O_2 sensing occurred recently. This step forward was the development of GaAs-AlGaAs quantum well DFB laser diodes [8] exhibiting low threshold current, narrow linewidth and continuous single frequency emission over a 4 nm tuning range in the 761nm wavelength region. The devices also exhibit excellent linearity in their light output against drive current, which is an attribute essential for large signal to noise ratio when using sensitive signal recovery techniques such as wavelength modulation spectroscopy (WMS) and harmonic detection.

In this Letter we describe the first application of these now commercially available devices to oxygen sensing. We have targeted and observed the complete R rotational branch of the O_2 spin forbidden $b^1\Sigma_g^+(v' = 0) \leftarrow X^3\Sigma_g^-(v'' = 0)$ electronic transition which is centred at 762nm, and have estimated a detection limit of 20ppm.m by probing the strongest line (R7Q8) in the band. We also show initial results comparing GaAs-AlGaAs DFB laser diode performance with that of a commercially available vertical cavity surface emitting laser (VCSEL) operating in the same wavelength range.

The experimental setup is as reported previously [1, 2]. The DFB laser diode emits ~(λ) = 761nm in a single mode with a linewidth of 12MHz [8]. We have measured the device tuning rates to be 0.598Å/°C and 0.038Å/mA over a wide temperature and current tuning range. Operation over a temperature (T) range of –5°C ≤ T ≤ 60°C allows a tuning range of ~4nm.

In Fig. 1 the laser diode light current (L-I) curve taken with a source to detector separation of 32m in air at atmospheric pressure demonstrates the magnitude of atmospheric O_2 absorption around λ = 761nm. The (L-I) curve is taken at two laser heatsink temperatures to clearly demonstrate the effect. In both cases the (L-I) curve is clearly distorted by the laser emission line wavelength shift with changing current through the indicated O_2 absorption lines. In Fig. 2 we show an absorption spectrum of room air (20.9% oxygen) at a pressure P = 300mB over a path length of 36m, which was acquired by tuning the laser diode wavelength by temperature over the range –5°C ≤ T ≤ 60°C. This corresponds to a wavelength tuning range of 759.6nm ≤ λ ≤ 763.6nm. A commercial 5mm² silicon photodetector with an integral amplifier was used for measuring the transmitted laser light