

QMC3 Fig. 3. Electron density n_e vs distance d from the target as obtained by Stark broadening measurements for both YBCO and PZT (fluence of the ablating laser $I_t = 2.2 \text{ J/cm}^2$).

= 1 for $d \leq 2 \text{ mm}$ and $x \approx 1.7$ for $d > 2 \text{ mm}$, revealing a one-dimensional nature of the first-stage expansion for the free electron cloud.

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QMC4

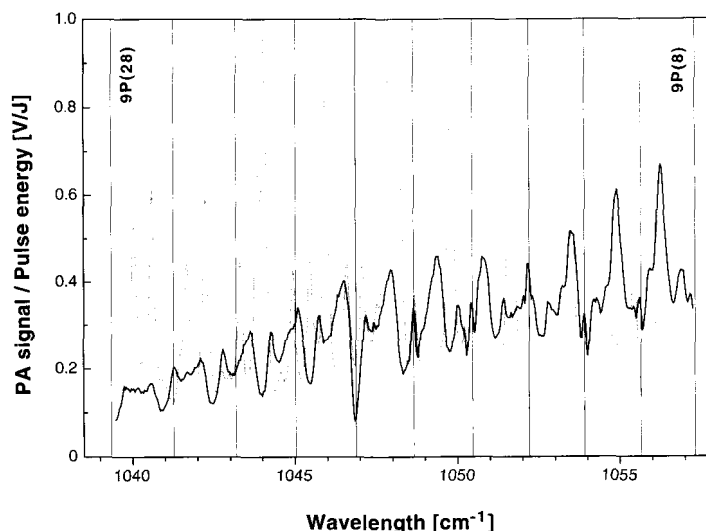
1015

Trace gas monitoring with CO_2 laser photoacoustic systems

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Atmospheric trace gas monitoring by tunable lasers combined with photoacoustic (PA) detection represents a valuable alternative to more common schemes. Laser photoacoustic spectroscopy meets the various requirements such as high-detection sensitivity and selectivity for relevant compounds, continuous monitoring with good time resolution, and portability for *in situ* measurements.¹

During the last few years we have pioneered the development of a mobile system based on a line-tunable sealed-off CO_2 laser and special resonant PA cell.² In the meantime, this system is fully computer-controlled and can be operated unattended for extended periods. Temporal concentration profiles of various compounds taken in different environments with ppb sensitivity and time resolution of minutes demonstrate the versatility of this system. An example is the simultaneous monitoring of five different compounds (organic and inorganic) in rural air.¹ Other examples concern urban air and stack emission. In certain cases, however, the detection selectivity is impaired by the discrete rather than continuous



QMC4 Fig. 1. Normalized photoacoustic spectrum of 101.8 ppm ethylene (C_2H_4 , light line) and 15.9 ppm methanol vapor (CH_3OH , dark line), both buffered in 1 bar of synthetic air. The vertical lines indicate the emission lines of conventional low-pressure CO_2 lasers.

tunability of the laser. Apart from other measures, such as the use of laser isotopes and of a photoacoustic Stark cell in the mobile system, we have thus recently implemented a home built high-pressure CO_2 laser into a laboratory PA system. The pulsed laser is operated at a total pressure of 11.5 bars and is continuously tunable in the 9P, 9P, 10R, and 10P branches over 19 cm^{-1} , 18 cm^{-1} , 16 cm^{-1} , and 21 cm^{-1} , respectively. The line width is $0.017 \pm 0.003 \text{ cm}^{-1}$. For the first time, calibration spectra of certified gases diluted in synthetic air (80% $\text{N}_2/20\% \text{ O}_2$) and on gas mixtures prepared with a gas-mixing device (MKS) have been taken with such a spectrometer. These spectra form the basis for the analysis of spectra on polluted air. A typical example is presented in Fig. 1 where the photoacoustic spectra for ethylene and methanol vapor are plotted for the 9P CO_2 laser branch. The figure also shows the regular-band absorptions of CO_2 corresponding to the laser transitions of a conventional CO_2 laser. The drastic gain in information and thus of detection selectivity between a discretely tunable system and the continuously tunable system are evident. Examples for other molecules will be presented that also demonstrate the excellent agreement of our photoacoustic spectra with calculated HITRAN data.³

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QMC5 (Invited)

1030

New tunable compact difference-frequency laser sources for high-resolution spectroscopy

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Recent advances in the development of nonlinear optical materials, such as AgGaS_2 and AgGaSe_2 , now offer a convenient technique of generating cw tunable infrared narrow-band coherent radiation over a wide wavelength range (3 to $18 \mu\text{m}$) by means of difference-frequency generation (DFG) at room temperature.¹ The use of semiconductor diode lasers as pump sources in the nonlinear DFG mixing process is particularly attractive, as their compact size and ease of operation allow the construction of a portable and robust mid-infrared laser source especially suitable for environmental remote sensing, pollution detection, chemical analysis, and medical research. In this paper we describe our recent progress towards the development of such a compact diode-laser based widely tunable cw DFG source with AgGaS_2 as the nonlinear optical material.

In a first step² a cw tunable $\text{Ti}:\text{Al}_2\text{O}_3$ ring laser (Coherent 899–29) operating in the wavelength range from 690 to 840 nm and a single-mode diode laser polarized for 90° type I ($e \rightarrow o + o$) phase-matching in AgGaS_2 were spatially overlapped with a polarizing beam splitter. The visible beams were focused into the 45-mm-long AgGaS_2 crystal to a beamwaist of about $40 \mu\text{m}$ by using a 10-cm-focal-length lens. The infrared radiation generated in the mixing crystal was collimated with a 5-cm-focal-length CaF_2 lens

and detected after the germanium filter with a liquid-N₂ cooled photoconductive HgCdTe detector.

The three diode lasers used in this experiment were unmodified commercial devices operating at 671 nm, 690 nm, and 808 nm. Each was operated in a single longitudinal mode. By varying the temperature and the current of the diodes, their emission wavelength could be tuned over about 2 nm. The collimated diode laser beam was converted to a beam dimension of approximately 5 mm by using an anamorphic prism pair. A3:1 telescope transformed the diode laser beam size to a dimension comparable to that of the Ti:Al₂O₃ laser. The diode laser output had a polarization ratio of ~100:1; the appropriate polarization direction for type I phase-matching was chosen by proper mounting of the diodes.

For a signal and pump wavelength of 808.3 nm (Ti:Al₂O₃ laser) and 690.3 nm (Toshiba TOLD 9140(s) diode laser), respectively, an idler wavelength of 4.73 μm was detected. For 1 W of Ti:Al₂O₃ laser power and 12.1 mW of diode laser power, a DFG power of up to 1.4 μW was measured. The phase-matching bandwidth of the diode/Ti:Al₂O₃ pump laser configuration was observed to be as large as 600 GHz. This is much larger than the phase-matching bandwidth of about 30 GHz observed for the dye/Ti:Al₂O₃ pump laser configuration.¹ The high-resolution capability of this novel spectroscopic source was demonstrated by obtaining a Doppler-limited CO absorption spectrum around 2119 cm⁻¹ using a 20-cm absorption cell and about 10 Torr of CO pressure. In this case the diode laser wavelength was fixed, and the infrared wavelength was varied by tuning the Ti:Al₂O₃ laser.

One way to increase the DFG output power to a level that is useful for spectroscopic applications is the use of optical semiconductor amplifiers to boost the power output of the single-mode diode lasers. Significant progress has been made in obtaining diffraction-limited coherent radiation from high-power broad-area diode amplifiers.

We demonstrated difference-frequency mixing of a high power GaAlAs tapered traveling-wave semiconductor amplifier³ with a cw Ti:Al₂O₃ laser in a 45-mm long AgGaS₂ crystal cut for type I noncritical phase-matching at room temperature. The master laser was an index-guided diode laser emitting up to 130 mW in a single-longitudinal mode around 860 nm with a less than 20-MHz linewidth. With 100 mW of master laser power incident on the amplifier, 38 mW was coupled into the amplifier. The pump wave was provided by a Ti:Al₂O₃ ring laser operated at 715 nm. Both beams were overlapped using a polarizing beam splitter and focused into the 45-mm-long AgGaS₂ crystal using a 30-cm-focal-length lens. The beam waists were set to ~33 μm in both vertical and horizontal planes, close to optimum focusing. Phase-matching was found to occur at a wavelength of 714.50 nm and 858.60 nm for pump and signal wave, respectively, corresponding to a generated difference-frequency wavelength of ~4.26 μm (2350 cm⁻¹). Tuning of the infrared wavelength was limited to ~25 cm⁻¹ by the limited

temperature tuning range of the master diode laser.

In conclusion, DFG in AgGaS₂ utilizing diode/Ti:Al₂O₃ and diode/diode laser input configurations has been demonstrated, producing tunable infrared radiation at a wavelength around 5 μm. As much as 47 μW of cw and 89 μW of pulsed infrared radiation around 4.3 μm have been generated by difference-frequency mixing the outputs of an injection-seeded GaAlAs tapered semiconductor amplifier and a Ti:Al₂O₃ laser in AgGaS₂ using type I noncritical phase-matching. It is anticipated that the use of an external enhancement cavity for the nonlinear mixing crystal will also result in significantly improved DFG performance. This compact mid-infrared source is promising for a wide range of applications, including chemical analysis, remote sensing, pollution detection, and medical research.

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Room L

Atom Optics

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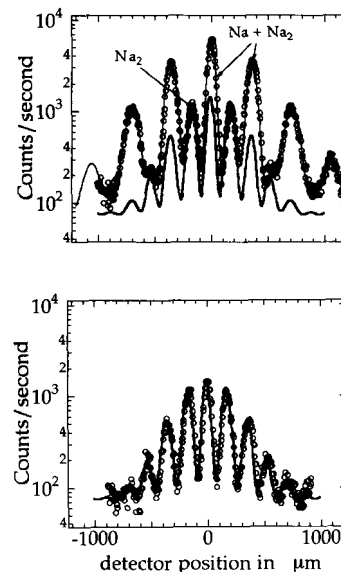
QMD1 (Invited)

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Interferometry with atoms and molecules

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Three 0.2 micron period diffraction gratings were used to realize an interferometer for atoms and molecules¹ that passes the interfering components of the deBroglie wave on opposite sides of a stretched metal foil positioned between two side plates. The foil was 10 cm long and 10 μm thick, and a gas sample of density ~2 × 10¹³ atoms/cm³ could be introduced on one side of the foil only. With this septum in place, we have observed atomic (molecular) fringes with 30% (7%) contrast and an interference amplitude of more than 3500 (50) counts/s. We can determine the phase of the interference pattern with a precision of 5(200) mrad in one minute.



QMD1 Fig. 1. The top graph shows diffraction of sodium atoms and sodium dimers by a 100 nm period diffraction grating. The fit indicates 16.5% of the intensity is molecules, which have half the diffraction angle of the sodium atoms. The bottom graph shows the diffraction pattern after the atoms have been removed from the beam with a deflecting laser beam. The fit is the same as in the top graph, indicating that the small orders in the top graph were entirely molecules.

We have observed both the attenuation and the phase shift of an atomic sodium matter wave when it is transmitted through both atomic (He, Ne, Ar, Kr, Xe) and molecular gases (N₂, CO₂, NH₃, and water vapor). From the perspective of wave optics, the passage of a wave through a medium is described in terms of an in-general complex index of refraction $n = 1 + 2\pi/k^2 N \cdot f(k, \theta)$ where N is the density of the medium and $f(k, \theta)$ is the scattering amplitude. The phase shift (attenuation) is proportional to the real (imaginary) part of the forward scattering amplitude, allowing us to determine both these quantities. Recently we have changed the velocity of the sodium (by changing the mass of the carrier gas in our seeded supersonic oven) so that we have been able to measure the dispersion of the index of refraction (i.e., its dependence on deBroglie wavelength).

This is the first time that $\text{Re}[f(\theta = 0)]$ has been measured for atom-atom scattering, and it is noteworthy that this quantity varies over more than an order of magnitude, in contrast to $\text{Im}[f(\theta = 0)]$, which varies by a factor of about two. If the collision is modeled as a hard sphere, the partial wave-scattering phase shifts are nearly random, and the ratio of the real to imaginary parts of the forward-scattering amplitude is predicted to be about 0.01 for He, in rough accord with