DFB laser diodes for sensing applications using photoacoustic spectroscopy

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Abstract. We present typical device characteristics of novel DFB laser diodes which are employed in various sensing applications including high resolution photoacoustic spectroscopy. The laser diodes discussed are based on a genuine fabrication technology which allows for the production of ultra stable devices within a broad spectral range from 760 nm up to 3000 nm wavelength. The devices exhibit narrow linewidths down to <1 MHz which makes them ideally suited for all photoacoustic sensing applications where a high spectral purity is required. As an example we will focus on a typical medical application where these diodes are used for breath analysis using photoacoustic spectroscopy.

1. Introduction

Strong interest in remote gas sensing systems has emerged in the last few years. Typical sensitivities of laser based detection systems lie the range of ppm to ppb [1]. However, there is an ever growing need for even higher sensitivities and at the same time increased spectral selectivity. Photoacoustic spectroscopy is a valuable tool to achieve both high sensitivities and at the same time keep the costs and size for sensing systems at a relatively low level.

The major key element of these modern gas sensing systems are distributed feedback laser diodes, which are used to excite rotational vibrational transitions of the gas species to be detected. Through a special technology based on lateral metal Bragg gratings incorporated in the laser structure [2] it is possible to fabricate semiconductor single mode emitting laser diodes in a broad spectral range starting from 760 nm wavelength (for e.g. oxygen sensing) up to wavelengths in the 3 µm range, where many industrially and ecologically relevant gas species exhibit strong absorption features.

As an example Fig. 1 shows the absorption of a some exemplary gases in the wavelength range mentioned above.
Fig. 1: Absorption spectra of some exemplary gases in the wavelength range between 760 nm and 3000 nm.

2. DFB laser diodes

The complex coupled DFB laser diodes described above work in cw operation at room temperature and exhibit output powers well above 20 mW, which make them ideally suited for photoacoustic sensing schemes. The laser diodes can be manufactured in such a way that the emission is close to energetic resonance with a prominent absorption line of the gas species under investigation. By applying a current ramp onto the DC laser current, one makes use of a current induced transient redshift of the laser wavelength. In this way the laser emission can be scanned across the spectral position of the absorption line to be detected. Alternatively, a well defined temperature change of the laser can be employed for coarse wavelength tuning.

The fact that the emission linewidth of such a laser device is below 3 MHz, one can even resolve the fine structure of single absorption lines which typically exhibit linewidths on the order of a few GHz at room temperature. Therefore this technique even enables to resolve different gas isotopes, e.g. a discrimination between $^{12}$CO$_2$ and $^{13}$CO$_2$ is possible which will be shown in the next chapter.

Fig. 2 shows the emission spectrum of a DFB laser diode emitting at 2043 nm wavelength. This emission wavelength is located right within the rotational-vibrational absorption band of CO$_2$ (see Fig. 1).

Fig. 2 (left): Emission spectrum of a DFB laser diode emitting around 2034 nm wavelength. (Right) Emission wavelength of the laser as a function of temperature.
As can be seen in Fig. 2, the emission spectrum of such a DBF laser diodes is characterized by a high side mode suppression ratio of > 35 dB which ensures a high spectral selectivity and guarantees cross interference free measurements.

3. Applications

One major application of these laser diodes is their use for medical diagnostics, in particular for non-invasive breath tests employing photoacoustic spectroscopy. Among this class of diagnostic test schemes, the $^{13}$C-Urea Breath Test (UBT) for the detection of Helicobacter pylori infections in humans is the most well-known. Helicobacter pylori is a bacterium which infects up to 50% of the human population [3]. Some strains of this bacterium are pathogenic to humans as it is strongly associated with peptic ulcers, chronic gastritis, duodentitis and stomach cancer. For the UBC test procedure the patient orally receives a small amount of urea which is isotope marked with the $^{13}$C isotope. If the patient suffers from an Helicobacter pylori infection this isotope-marked substrate will be split by the bacterium’s enzyme urease into isotope-marked $^{13}$CO$_2$ and ammonia. This gas then diffuses into the lungs of the patient via the bloodstream and can be identified in the patient’s breath via laser based photoacoustic sensors. The major advantage of this diagnostic test scheme is the fact that –in strong contrast to traditional methods which require surgery- it is non-invasive and free of side effects or risks for the patient. In the experiment the breath gas to be measured is guided into a gas cell and exposed to the tunable DFB laser source. Within the cell the laser light is absorbed by the molecules (12CO$_2$ and 13CO$_2$) and transferred into kinetic energy of the surrounding molecules via inelastic collisions. This in turn causes local pressure fluctuations within the sample cell, i.e. a sound wave is generated when the exciting laser source is modulated. This sound wave can be monitored using a microphone in combination with phase sensitive lock in detection schemes. For low modulation frequencies below 1 MHz, the photoacoustic signal is directly proportional to the absorption cross section of the molecular transition, the concentration of the absorbing molecules and the intensity of the laser source.

Fig. 3 displays measurements on two samples of CO$_2$ with different isotope concentration ratios. Sample 1 (dashed line) represents CO$_2$ in natural abundance (12CO$_2$: 98.42%; 13CO$_2$: 1.10%) while sample 2 (solid line) contains slightly more 13CO$_2$ (12CO$_2$: ca. 98.46%; 13CO$_2$: ca. 1.06%). Both measurements were performed under atmospheric conditions (1013 hPa, 20°C) using laser wavelength modulation with a modulation depth of +/-5%. The line strengths of the CO$_2$ transitions are approximately inversely proportional to the natural abundances of the corresponding isotopes. Therefore both isotopes yield comparable signals of the same order of magnitude. Since there are no strong water absorption lines in the spectral window under investigation cross-sensitivity with water is excluded. As can be seen in Fig. 3 a difference of the 12CO$_2$ signals for the chosen concentrations is not observable. This is well expected due to the major difference in abundance and hence the CO$_2$ lines can be used for normalization purposes. In contrast, the difference in 13CO$_2$ concentrations is clearly visible in the spectra. The ratio between the peak amplitudes of the 13CO$_2$ signal therefore serves as a sensitive measure for medical diagnostics.

With this test a maximum signal to noise ratio of S/N= 90 is achieved, which corresponds to a detection limit for 13CO$_2$ of about 5 ppm. Hence, variations of the 13CO$_2$ concentration of about 1% are detectable.
Fig. 3 Photoacoustic spectra of CO$_2$ in natural abundance and –0.4% enriched.

4. Summary
Complex coupled DFB laser diodes offer a large potential for sensing applications in such various fields as environmental monitoring, process control or medical analytics, where a high level of precision is required. The superb spectral brilliance of these devices even enables a discrimination between different gas isotopes, which exhibit slightly different vibrational transitions (e.g. different carbon monoxide isotopes for the helicobacter pylori bacteria identification in the medical field). This demonstrates the high potential of these laser diodes in a wide variety of remote gas sensing applications based on photoacoustic spectroscopy.

References

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