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# A Widely Tunable Three-Section DBR Lasers for Multi-Species Gas Detection

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**Abstract:** We demonstrate a widely tunable distributed Bragg reflector (DBR) laser operating at 1.8µm, in which the DBR section was butt-jointed InGaAsP ( $\lambda = 1.45 \mu$ m) material. Through current and temperature tuning, a widely tuning range of over 11 nm with a side mode suppression ratio (SMSR) higher than 30 dB is obtained. Utilizing this DBR laser, the water and methane detection experiment has been successfully implemented, which illustrates the potential capacity of such DBR laser as the light source used for multispecies gas sensing. The work also illustrates that the buttjoint active-passive integration technology developed for the InGaAsP quantum-wells (QWs) can be successfully applied in the InGaAs QWs.

Keywords: butt-jointed; DBR laser; multispecies gas sensing

## 1. Introduction

In recent years, multi-gas detection has important applications in many fields such as production process optimization, medical health and environmental protection [1–3]. Due to its reliable, rapid, non-contact features, and low spectral interference, tunable diode laser absorption spectroscopy (TDLAS) is very promising in many different techniques [4–6]. A highly precise TDLAS gas sensing system requires its laser source possessing several special properties such as single-longitudinal-mode (SLM) and continuous wave (CW) operation, continuous tuning, mode-hop-free, and narrow spectral linewidth. TDLAS system commonly use distributed feedback (DFB) lasers as the light sources because of its simple fabrication process and narrow linewidth. Since the tuning range of DFB lasers is relatively small (one or two nanometers), it need multiple lasers in the multiple gases sensing system [7], which make the system very complex. In application, costeffective monitoring, rapid measurement and equipment miniaturization is of great importance for an excellent gas sensing system, thus the widely tunable semiconductor lasers show their advantages when they are applied in such system [8,9]. At present, because of the rapid development of communications, the DBR lasers emitting at 1.5 and 1.3  $\mu$ m have been reported [10–14]. Furthermore, an arrayed waveguide based tunable quantum-dot (QD) laser with a ring structure, operating at around 1.6–1.8 µm has been developed by Tilmaet al. for optical coherence tomography systems [15–18]. However, the 1.6– 1.9 µm monolithic quantum-well DBR lasers have yet to be explored. The spectral range (1.6 to 1.9 µm) is consistent with the absorption spectrum of many gas species in environmental and industrial interest [19], such as water (H2O), methane (CH4), nitric oxide (NO), carbonic oxide (CO), hydrogen chloride (HCL), carbon dioxide (CO<sub>2</sub>), et al. So, this near-

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**Copyright:** by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). infrared wavelength range is important for spectroscopic and gas sensing applications. Although the 1.6–1.9  $\mu$ m wavelength band is in the overtone and combination absorption region whose absorption features is much weaker than that of the fundamental absorption region (2-20  $\mu$ m), however, it is completely enough to achieve a sub ppm detection accuracy based on the TDLAS detection schemes [20]. It can be seen from the above, a widely tunable DBR laser is an ideal light source in the multiple gas detection applications.

By simulation, the photoluminescence (PL) wavelength of the grating material is proportional to the wavelength tuning range of the laser [21]. In order to get a larger tuning range, the InGaAsP bulk materials with a PL wavelength of 1.45  $\mu$ m which has the big refractive index difference under a fixed injection current are adopted as the butt-joint material in DBR section. Through the design, we get a total tuning range of 11 nm. The lasing spectra can cover the absorption lines of multiple gases, (HCL, H<sub>2</sub>O, N<sub>2</sub>O, NO, CH<sub>4</sub>) which are extracted from the HITRAN (high-resolution transmission molecular absorption) database, as shown in Figure 1. Sensing of those gases is attractive in environmental and industrial applications. Furthermore, we also study its application for measuring two spectral features of molecular gases (water and methane). It demonstrates that the DBR lasers we fabricate are capable of accurate wavelength scanning and are applicable for gas sensor. To our knowledge, this is the first demonstration of 1.8  $\mu$ m wavelength monolithic tunable DBR quantum-well laser diode for multispecies gas detection.



**Figure 1.** Absorption spectrums of different gas species in the 1720-1840 nm wavelength range which are extracted from the HITRAN (high-resolution transmission molecular absorption) 2016 database.

## 2. Experimental Details

Figure 2a shows the DBR laser's photograph. It is composed of three segments. The epitaxial layers of the device were grown on an n-InP substrate by the low pressure metalorganic chemical vapor deposition (MOCVD) with a three-step procedure. The active region composed of four 1.2% compressive strained 7-nm InGaAs quantum wells and five 0.25% tensile strained 12-nm InGaAsP barriers embedded in the separate confinement heterostructure (SCH) was grown in the first step, exhibiting a 1.78 µm photoluminescence (PL) peak at room temperature (RT). After the first epitaxy, a 150-nm SiO<sub>2</sub> layer was deposited as the mask, the active layers in the phase and DBR sections were removed selectively by wet chemical etchings. We usually use the selective 311 etchant (H<sub>2</sub>SO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O = 3:1:1) to etch InGaAsP material, but the etching rate of 311 solutions is too fast for InGaAs materials. There is almost no report on the wet etching scheme of buttjoint integrated of InGaAs quantum-wells. According to the article [22], the less phosphors composition in InGaAsP, the faster the etch rate. After experimental exploration, we adopted optimized solutions (H2SO4:H2O2:H2O = 2:1:5) which can avoid severe undercut at the interface of the passive and active regions. In the second growth step, the 340-nm InGaAsP (PL peak at 1.45 µm) waveguide layer was butt-jointed with the MQWs (multiple-quantum wells) layers in the gain section. Figure 2b shows the SEM image of the buttjoint interface with no voids. The good butt-joint morphology is a key factor to device performance. Figure 2c shows the comparison of PL spectrum from the gain and passive waveguide section. The effective index change in the grating material strongly affects the tuning range [21]. A longer wavelength (smaller bandgap) of butt-joint grating material results in a larger index change in a fixed carrier injection, thus yielding a larger tuning range. Here, we used a 1.45-µm InGaAsP (1.45Q) as the butt-joint layer which has a 340 nm wavelength detuning compared to the wavelength at the gain section ( $\lambda_g = 1.78 \ \mu m$ ), ensuring both a sufficient low absorption loss and a large tuning range.



**Figure 2.** (a) Optical microscope image of the DBR (distributed Bragg reflector) laser. (b) Scanning electron microscope (SEM) image of the butt-joint interface. (c) Photoluminescence (PL) spectra of the butt-joint material and the active material [23].

After waveguide layer and the MQWs were butt-jointed by the MOCVD epitaxial growth, grating corrugations were fabricated in the 1.45Q of the DBR section using conventional holographic lithography and reactive ion etching (RIE), respectively. Afterwards, a p-InP cladding layer and a p+-InGaAs contact layer were implemented in the third step regrowth. When the whole layer structure was finished, a ridge waveguide with the width of 3  $\mu$ m was formed by photolithography and wet chemical etching. Then, a 50- $\mu$ m isolation gap between the three sections (DBR section, phase section, and gain section) was accomplished by moving the p+-InGaAs contact layer away. The following He<sup>+</sup> implantation was implemented to these gaps to increase the electrical insulation. To provide the lateral current confinement, a SiO<sub>2</sub> insulating layer was deposited with a 3- $\mu$ m-width current injection window opened above the ridge waveguide. A Ti-Au metal layer was

used for a P-contact metallization. AuGeNi/Au was evaporated on the bottom side of the wafer after thinning the substrate. The chips composed of a 350- $\mu$ m gain section, a 100- $\mu$ m phase section and a 200- $\mu$ m DBR section were cleaved with both sides uncoated (Figure 2a).

## 3. Results and Discussion

## 3.1. Characterization of the DBR Laser

First, the electro-optical characteristics of the device are measured at different temperature, as shown in Figure 3a, with a current of the DBR and phase section 0 mA. The optical power is measured from the gain section facet of the device by an integrating sphere. We can see that, with the temperature increasing from 15 to 35 °C, the threshold current of the device increases (20 to 30 mA) and the laser power decreases (9.9 to 6.9 mW). The data are analyzed in the empirical relation,  $Ith = Ioexp(T/T_0)$ , the characteristic temperature  $T_0$  is determined to be 53 K. The value of  $T_0$  obtained here is comparable to the conventional 1.65-µm DFB lasers. The laser's emission wavelength redshifts with the temperature. The temperature-tuning rate is 0.11 nm/°C when the gain current is maintained at 60 mA, as shown in Figure 3b. This indicates that in addition to the tuning of DBR and phase currents, the tuning range of the DBR laser can also be expanded effectively by changing the temperature. Meanwhile the SMSR properties of the device are not deteriorated.



**Figure 3.** (a) CW (continuous wave) L–I (Light-Current) characteristics of the DBR laser at the temperatures between 15 to  $35 \,$ °C. Inset shows the threshold current dependence on mount temperature. (b) Lasing spectrum of the DBR laser at different temperature at 60 mA gain current.

Then, the wavelength tuning character is investigate by varying the phase and DBR current. The lasing wavelength dependence on the DBR current at 25 °C in a fixed gain current of 60 mA is shown in Figure 4a. It can be seen from the figure, the lasing wavelength can be switched digitally over 11 consecutive channels for about a tuning range of 9 nm, when increasing the DBR current from 0 to 100 mA. The channel wavelength blue shifts when the DBR current increasing. From the tuning characteristics of DBR section, it indicates that the tuning physical mechanism is determined by the free-carrier (FC) injection effect. However, a tuning saturation takes place when the DBR current is increased to 63 mA. Actually, the tuning saturation which is caused by the self-heating effect can be improved by designing and selecting the coupling coefficient  $\kappa$  and the length of Bragg

grating carefully. The longer the PL wavelength of the grating material, the bigger effective refractive index change at the same density of the injected FC [21]. So, we can get a larger tuning range by selecting a narrower bandgap DBR material.



Figure 4. (a) Lasing wavelength dependence on DBR current. (b) Lasing wavelength dependence on Phase current [23].

By changing the current in the DBR section, the lasing wavelength of the laser can be tuned continuously in the separate channel and it is not continuous between channels. This can be compensated by tuning the phase current. Through the phase current adjusting, the wavelength shift can cover the gaps between two channels where the mode hopping happens, which is shown in Figure 4b. The emission wavelength sweeps 0.88 nm continuously as the phase current increasing from 1 to 8 mA. The single channel range realized by the phase current is larger than the 0.8-nm mode-spacing. Therefore, a continuous tuning range can be realized by combining injected current of DBR and phase area.

Combined with the temperature tuning (increasing the heat sink temperature from 15 to 35 °C), the tuning range of the device can be further increased from 9 to 11 nm, as shown in Figure 5a. For gas detection, the side mode suppression ratio (SMSR) is also a key parameter to DBR lasers. The SMSR of higher than 30 dB are obtained for all channels, as shown in Figure 5b.



Figure 5. (a) Lasing wavelength varies with DBR current and work temperature. (b) The SMSR (side mode suppression ratio) of DBR laser over the entire wavelength range [23].

In practical applications, the beam quality of the laser is also an aspect that needs to be considered. Generally, the far-field characteristics can be used as a parameter to evaluate the quality of the laser beam. We measured the far-field characteristics of the DBR laser in a 60 mA gain current at room temperature. The horizontal and vertical divergence angles are 14 ° and 36 °, respectively, which is comparable with the traditional DFB lasers for communication. Furthermore, we also tested the device's wavelength stability for seven hours when the temperature of the laser was controlled to 20 °C, as shown in Figure 6. It can be seen from the figure that the wavelength change of the laser is less than 0.05 nm which is the minimum resolution of the spectrometer.





It can be seen from the above test results that the DBR laser can achieve continuous wavelength tuning, single-mode output, and good wavelength stability, which meet the requirements of light source for gas detection.

#### 3.2. Experimental Setup of TDLAS

To demonstrate the DBR laser's possibilities in multi-gas detection, the experimental setup of the gas detection system based on TDLAS technology is schematically illustrated in Figure 7. For the convenience of gas sensing, an industry standard 14-pin butterfly packaging scheme of the DBR laser chip is adopted and the whole device is integrated with thermistor, thermo-electric cooler (TEC), optical isolator, and the photo-detector (PD).





Figure 7. TDLAS (tunable diode laser absorption spectroscopy) experimental setup for the gas detection.

Temperature control circuit ensures the DBR laser working at a proper temperature, stabilizing the output power, and locking laser emission peak to the absorption line of the target gas. The laser is modulated by two waveform generators. One is to generate a low frequency triangular wave providing a slow wavelength scan by a function generator. The other is to superimpose a high frequency sinusoidal modulation to the laser by a lock-in amplifier. The modulated light is guided to the gas cell which is filled with target gas and is detected by a photo-detector (PD) which transforms the optical signals to the electrical ones. Finally, the electrical signals are sent to another lock-in amplifier where such signals are demodulated, outputting the signals in a second harmonic type.

According to the spectra extracted from Hitran database, we choose absorption lines around 1781 nm which corresponds to that of methane and water for detection experiment, as shown in Figure 8. The peak emission wavelength of the DBR laser is 1781 nm with a SMSR of 40 dB when the gain current is 75 mA at 22 °C. For H<sub>2</sub>O detection, a 1 kHz triangular ramp (gain current varied from 62 to 86 mA) and a 10 kHz sinusoidal modulation (with the amplitude of 6.48 mA) are applied to the driving current in the gain section while the current in the DBR section is set to 0 mA. For methane detection, the applied signal in the gain section is the same with H<sub>2</sub>O applied except an additional 4 mA current in the DBR section.

The second harmonic curve (the "2f" curve) of H<sub>2</sub>O and CH<sub>4</sub> is shown in Figure 9. The current in the valley bottom of the "2f" curve is consistent with the driving current of the DBR laser in which the emitting wavelength corresponding to the sample gas absorption line. In other words, the "2f" curve contains a dip where the sample gas absorbed at the wavelength corresponding to that laser current. The current at the dip represents the driving current of the laser at the wavelength of interest.

The theoretical formula of TDLAS is based on the Beer–Lambert law. For a single frequency laser, the light intensity changes can be described as follows [24]:

$$I(\nu) = sI_0(\nu)exp[-\alpha(\nu)CL]$$
<sup>(1)</sup>

where *s* is the light collection efficiency, which is the ratio of laser power received by the photo-detector to the original optical power without gas absorption; I(v) and  $I_0(v)$  are the transmitted and incident laser intensities, respectively;  $\alpha(v)$  is the spectral absorption coefficient in unit length and unit concentration at the frequency of *v*; *C* is the concentration of sample gas; *L* is the length of optical path. The working principle is that, when a light beam at a specific wavelength which is modulated passes through the target gas at a path

length *L* and the transmitted laser power is measured by a PD. The amount of light intensity lost (absorbed by the sample gas) is proportional to the gas concentration in the path of light. Analyzing this second harmonic data extracted from the lock-in amplifier, the gas concentration value can be calculated.



**Figure 8.** The spectrum of DBR laser near the absorption lines of the measured gas. Inset is the selected absorption lines of methane and water in the gas detection experiment.



Figure 9. The second harmonic curve extracted from the lock-in amplifier (water-black, methane-red) [23].

## 4. Conclusions

Through butt-joint growth technology, a three-section InGaAs/InGaAsP DBR laser has been fabricated. The DBR section was realized by using butt-jointed InGaAsP ( $\lambda_{PL}$  = 1.45 µm) material. A total tuning range of 11 nm with a SMSR higher than 30 dB is obtained. Simultaneous detection of methane and water vapor experiments are implemented, which shows that such DBR lasers possess significant advantages for multiple gas species detection.

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