Bragg-grating-stabilised external cavity lasers in optical fiber and integrated planar silica-on-silicon circuits

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ABSTRACT

Conventional singlemode semiconductor DFB and VCSEL lasers used in high resolution spectroscopy are often required to operate at specific, custom wavelengths, such as those associated with gas absorption lines. We present the results of work to develop alternative sources in the 1550nm and 1650nm regions, the latter coinciding with an absorption line of methane. Custom wavelength Bragg gratings have been used to stabilize the output of external cavity lasers implemented in both optical fiber and planar silica-on-silicon integrated circuits, using commercially available semiconductor gain chips, to give laser output at 1648 and 1649 nm, respectively. Thermal expansion or mechanical strain of the Bragg grating offers a suitable wavelength tuning mechanism. Results are presented including the wavelength tuning range, output power, relative intensity noise (RIN), side-mode suppression and linewidth of devices for application in high resolution gas spectroscopy. The different methods of writing Bragg gratings in optical fiber and planar silica-on-silicon allow a high degree of flexibility in the choice of emission wavelength.

Keywords: External cavity diode laser, Bragg grating, optical fiber, planar silica-on-silicon, gas spectroscopy

1. INTRODUCTION

The widespread availability of monolithic, wavelength-tunable lasers has revolutionized optical gas sensing. In tunable diode laser spectroscopy (TDLS), the emission wavelength of a narrow linewidth laser diode is scanned across an individual gas absorption line at very high resolution [1,2]. A narrow linewidth (a few MHz) enables individual gas absorption lines (with typical linewidths of a few GHz at atmospheric pressure) to be fully resolved. The measurement is effectively self-referenced by comparing the central peak absorption to the zero level on either side of the line. Working at such high resolutions therefore gives the following advantages:

- High signal to noise ratios resulting from fully resolved gas lines and a narrow effective baseline.
- A high degree of specificity to the target gas.

Developments aimed at optical telecommunications have resulted in semiconductor laser diodes with high reliability and residual intensity noise (RIN) of typically -140 dB/Hz or lower[3]. Each must be custom made at a particular wavelength (the specific gas absorption line). Wavelength selection is required for mode-hop free singlemode operation; DFB lasers employ a grating structure, usually written above the active waveguide region, whereas VCSELs typically employ interference layers above and below the active layers. Custom lasers are required for any gases whose absorption lines do not overlap with the 1.3 or 1.55 µm telecommunications bands (these bands cover weak CO and CO_2 lines, H_2S and NH_3, but not the hydrocarbons, NO or stronger CO and CO_2 lines). Only a limited range of such wavelengths is routinely available, and these custom devices are often the most expensive component for industrial systems.

Conventional external cavity lasers have long offered narrow linewidth, singlemode operation with tuning over a wide range[4]. In external cavity diode lasers (ECDLs), a diode is used as the gain medium, often specifically engineered for

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use in an ECDL and referred to as a gain chip. The external cavity then typically incorporates a reflective grating as a wavelength-selective element, in the Littrow[5] or Littman–Metcalf[6] configurations. By rotating the grating, the wavelength can be tuned. Careful choice of the centre of rotation allows automatic compensation for phase changes that would otherwise be experienced at the gain chip. However, such ECDLs are large and require careful engineering to maintain alignment over a wide tuning range.

A number of attempts have therefore been made to develop an alternative. Multimode absorption spectroscopy (“MUMAS”) proposes the use of simpler, low cost multimode devices, allowing multiple emission modes to be absorbed by gas lines as they happen upon them. These have been realized using low cost, Fabry Perot devices[7] and more recently in pumped Er:Yb:glass[8]. MEMS based VCSELs are under development at the Technical University of Munich. By adding a MEMS-actuated mirror to the top of the VCSEL, the tuning range is increased to 20 nm[9]. Finally, work is in progress to develop Bragg grating stabilized lasers, whereby the wavelength-selective element consists of an optical fiber Bragg grating (FBG)[10]. In the latter, fabrication of the wavelength selective element is decoupled from that of the gain medium, potentially allowing greater flexibility in choice of wavelength and lowering the investment required for short runs of custom wavelength devices. Here, we present the results of two approaches to the development of Bragg grating stabilised external cavity lasers, the first implemented in optical fiber and the second in planar silica-on-silicon.

2. TUNABLE DIODE LASER SPECTROSCOPY

Optical gas detection using absorption spectroscopy is based on application of the Beer Lambert Law [11];

$$I = I_0 \, exp(-\alpha \ell) \tag{1}$$

Where I is the light transmitted through the gas cell, I_o is the light incident on the gas cell, α is the absorption coefficient of the sample (typically with units of cm^{-1}) and ℓ is the cell’s optical pathlength (typically with units of cm). α is the product of the gas concentration (for example in atm – the partial pressure in atmospheres) and the specific absorptivity of the gas ε (for example in $cm^{-1}atm^{-1}$).

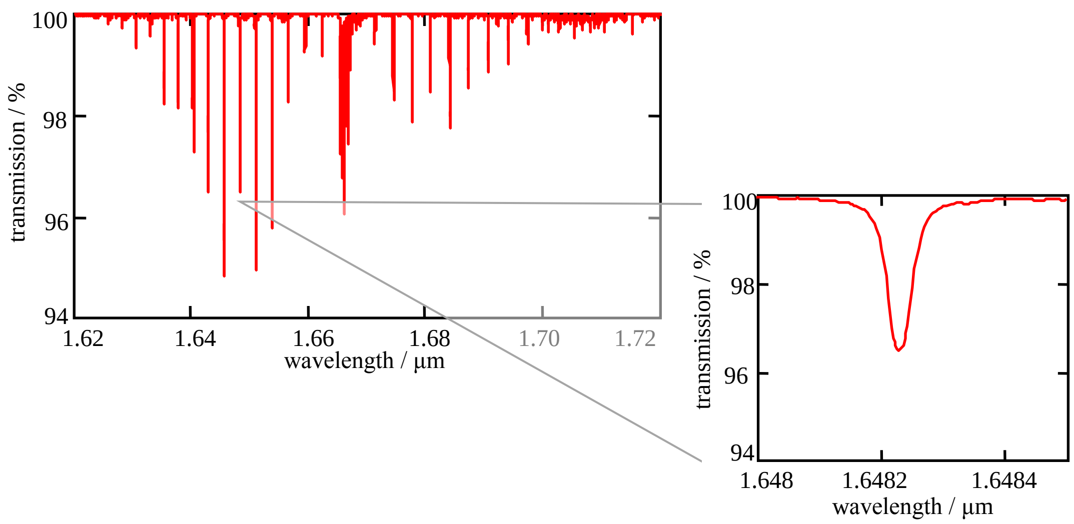


Figure 1 Example transmission spectrum of methane (1000 ppm, 1 m pathlength) showing the $2\nu_3$ band at 1.66 µm. Inset shows the R5 gas line at 1648 nm. Generated with data from the HITRAN database [12].

Tunable diode laser spectroscopy (TDLS) places high demands on laser design, notably in wavelength precision, wavelength modulation frequency and relative intensity noise (RIN). Ideally, wavelength tuning should enable the full gas line to be scanned (typically a few GHz at atmospheric pressure), plus an allowance for additional, slow tuning to compensate for thermal changes in the laser that alter its wavelength. In standard diode lasers, the precise emission wavelength is often determined by reference to the position of the gas line. (Indeed, gas lines are often used as wavelength standards in telecommunications [13]). For wavelength scanning, it is advantageous to be able to modulate the wavelength with a sufficiently high frequency to remove the effects of vibration or background light from the measurement. A small, sinusoidal wavelength modulation (often at kHz frequencies) is often applied simultaneously with a slow wavelength scan through the gas line, with 2f signal recovery giving a 2nd derivative of the lineshape[2].

3. OPTICAL FIBER IMPLEMENTATION

3.1. Design and experimental details

For implementation in optical fiber, our laser was built around an InP gain chip (Thorlabs: SAF1091H). This had an amplified spontaneous emission (ASE) bandwidth (FWHM) of 90nm, peak wavelength of 1650nm and typical operating current of 500 mA. A high back face reflectivity (> 90%) defined at one end of the laser cavity. The front face had a low reflectivity (< 0.01%) achieved by the combination of a dielectric coating and an angled facet (see Figure 2) helped to eliminate parasitic internal cavities in the laser. The output was coupled to a conical lensed fiber (Lase Optics, fabricated in SMF-28 fiber), designed to match the emission mode size as closely as possible, in order to maintain coupling efficiency for both emission and feedback directions. Special care was taken to minimize the length of the fiber section to maximize the free spectral range (FSR) of the cavity. The lensed fiber was cleaved to a length of ~12 mm, which was limited by the positions of the clamps on the fusion splicer. Onto this was spliced an FBG written at Cranfield using a custom phase mask, in hydrogen loaded SMF-28 fiber. This fiber has a tight refractive index tolerance, again helping to minimize any parasitic internal reflections that might arise from the splice junction.

Our FBG had a peak reflectivity of 50%, a bandwidth (3dB) of 0.5 nm and a center wavelength of approximately 1647nm. This was spliced to a lensed fiber tip (Oz Optics) and the FBG section attached at either end to a multilayer PZT actuator (PAC-266J, FACE) using cyanoacrylate adhesive. The actuator offers up to 11 µm displacement for a PZT applied voltage of 150 V, imposing a strain of 1100 µε (microstrain) to the attached FBG and giving a full DC tuning capability of around 1 nm. This tuning range covers the 1648.2nm absorption line of methane shown in Figure 1.

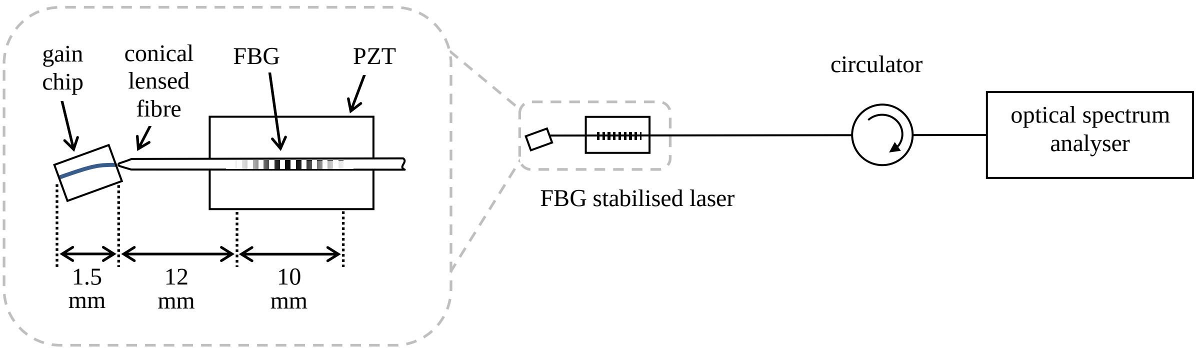
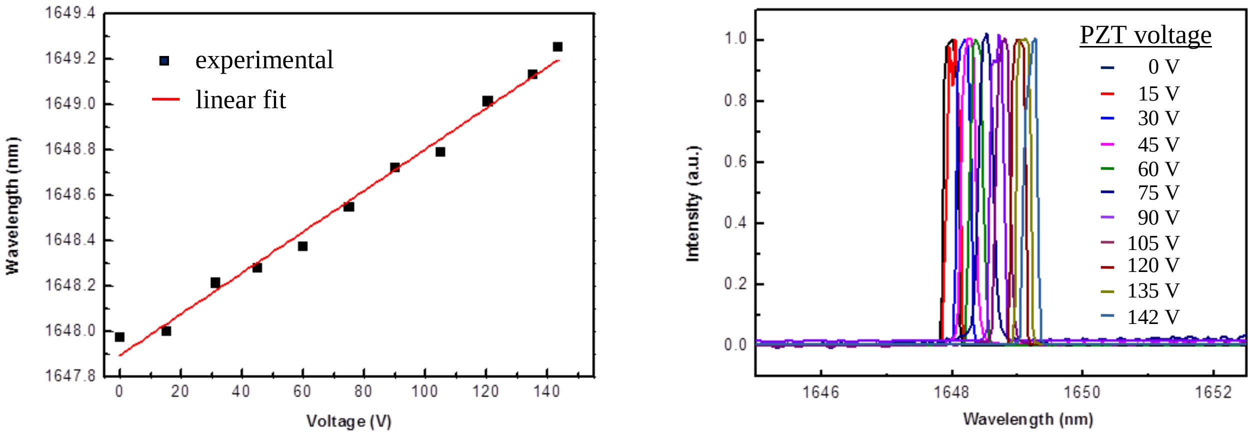


Figure 2. Configuration of FBG stabilised tunable laser, showing physical dimensions of the lasing cavity.

3.2. Results and analysis

The output from the fiber was coupled into an Optical Spectrum Analyzer (Yokogawa) and confocal Fabry-Perot interferometer (Toptica FPI 100-1500-1, 1GHz free spectral range) to analyze the resulting emission wavelength and mode structure. The results are shown in Figure 3. The total optical pathlength for our cavity was 60mm for a round trip, implying a mode spacing of 45 pm or 5 GHz. On this basis, we believe that there may still be several modes within the bandwidth of the FBG at the -40dB level.



(a) (b)

Figure 3. (a) Emission center wavelength versus voltage applied to the PZT, showing a 1.3nm tuning range for an applied DC voltage of up to 150V. (b) Corresponding normalized emission from optical spectrum analyzer.

4. IMPLEMENTATION IN PLANAR SILICA-ON-SILICON

The laser described in the previous uses a Bragg grating in fiber. An alternative platform for grating is planar silica-on-silicon waveguide which is compatible with UV exposed Bragg gratings. The planar format simplifies various features especially in allowing thermo-optic elements to be deposited using lithography. Further advantages include robustness and desirable polarization properties. Planar gratings have been reported previously, for example commercial devices produced by RIO [14] offer high stability operation. In the follow section we will describe a novel planar device target operation at ~1650 nm using directly laser written waveguide and gratings.

4.1. Design and experimental details

Like the previous implementation this device uses a similar InP gain chip as the gain section (Thorlabs: SAF1091H). Instead of a fiber Bragg grating a planar design is used, the overall layout of the device is shown in figure 4. The fiber pigtailed planar chip is simply butt coupled to the gain chip. The planar chip is a flame-hydrolysis-deposited (FHD) glass-on-silicon planar chip. The chip core refractive index and thickness was fabricated to maximize coupling to the gain chip in the vertical direction. The Bragg grating and waveguide are written simultaneously in the photosensitive core layer of the device using a UV writing technique different to the one previously described. This technique does not use a phase mask but instead interferes two beams of 244 nm light to form a fringe pattern that defines the Bragg pattern into the photosensitive portion of the chip. The fringes are controlled using an Electro-Optic Modulator in one beam path. Due to small writing spot used in the fabrication the grating spectra is software controlled, specifically the central wavelength can be tuned over hundreds of nanometers. A complete description of this technique can be found elsewhere [15]. The planar chip is then diced into an appropriate geometry to accommodate the heat sink supporting the gain chip and also to reduce parasitic back reflections forming unwanted cavities (Figure 4). Near optical quality finish was achieved using an optimized physical matching technique [16].

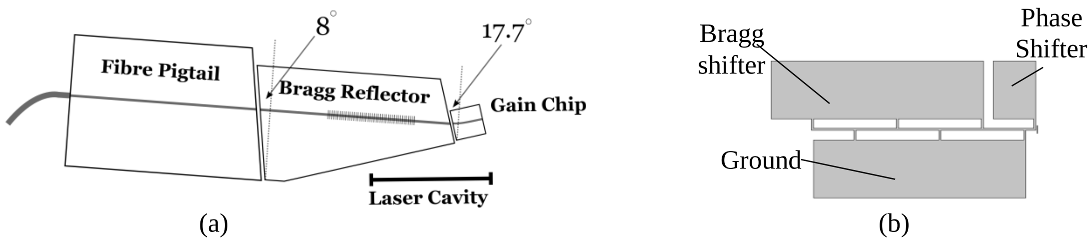


Figure 4. (a) Overall layout of gain chip coupled to Bragg reflector planar chip. Angles used to prevent parasitic back reflections are show. (b) Layout of heating elements, the large areas are contact pads, with the central strip acting as the heater.

Tuning is achieved by using nichrome heating elements deposited on top of the planar chip. The planar geometry lends itself well to photolithography and electron-beam deposition processing [17]. The heating elements consist of a phase heating and grating heating sections. The Bragg grating operating wavelength is sensitive to both the change in effective refractive index and the periodicity which are affected by the thermo-optic effect and thermal expansion. The phase heating section allows precision control of FSR fringes, when operating in single mode operation this will allow continuous mode-hop free modulation of the central frequency for TDLS albeit for a limited spectral range.

4.2. Results and analysis

Using the planar chip and shorter (5mm) grating allowed for a shorter cavity length that yields a larger FSR in addition to the narrow Bragg spectrum (FWHM 0.21 nm) facilitating single mode operation at 1649 nm. The spectrum of the laser was measured by an optical spectrum analyzer (OSA) and is shown in Figure 5.(a). The resolution was limited to 10 pm bandwidth (implying linewidth < 1.1GHz). The output of the laser of the system was connected to a 16 GHz photoreceiver and the relative-intensity-noise (RIN) measured (Figure 5.b), no beat frequency was observed at < 2 GHz confirming single mode operation. The side mode suppression of these devices are consistently high with all devices display >55dB suppression. The RIN was compared to the output of a commercial tunable diode-laser. The measured free spectral range was 16 GHz, indicating a roundtrip cavity optical path length of 20 mm.

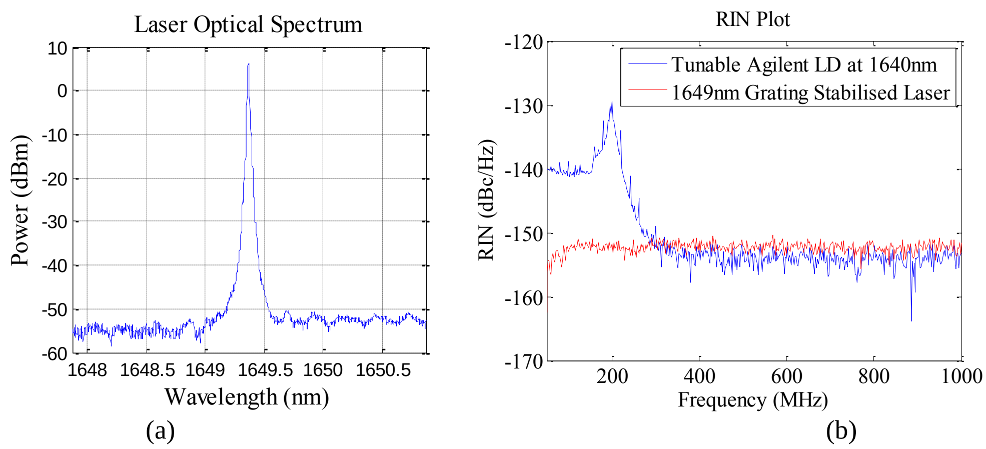


Figure 5. (a) OSA spectrum of laser, limited to 10pm resolution. (b) RIN from radio-frequency spectrum analyser comparing commercial tunable laser (blue) with grating stabilized laser (red).

The current power curve of the laser can be seen in Figure 6 with a slope efficiency of 0.008 W/A and a threshold of ~130mA. Using the larger Bragg grating heater a tuning range of 690 pm has been achieved. The silicon substrate of the chip thermalizes the device enabling up to ~1kHz phase heater modulation and reducing thermally associated instabilities.

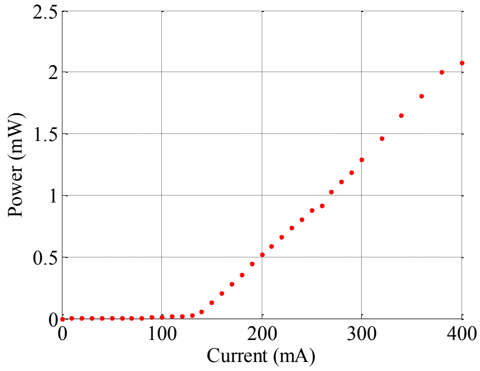


Figure 6. Current power curve, threshold at 130 mA and slope efficiency of 0.008 W/A.

CONCLUSION

We have demonstrated two alternative configurations for building grating stabilized lasers, a purely fiber and an integrated approach. The fiber system has the advantage of employing standard components and coupling techniques. In addition fiber Bragg grating manufacture is much more mature, allowing precise control of the uniformity of the grating structure. Tuning of the Bragg wavelength can be achieved via various routes, strain being convenient as sinusoidal wavelength dither have been achieved at kHz frequencies and also can be used to fine tuning grating center wavelength during manufacture.

The integrated planar grating configuration is far less standard, with very few routes to achieve high quality, i.e. narrow band, Bragg gratings. However the fabrication approach demonstrated here is suitable for mass manufacture and has the ability to simply select the wavelength of operation. The bulk nature of the Bragg grating should also provide greater stability over the fiber counterparts. A current disadvantage in this format is that significant wavelength tuning in these devices is restricted to thermal heating and the associated temporal response.

The advantage of the planar is clear from the ability to fabricate short cavities placing fewer demands on grating length and also the reduction of the final device size.

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