Tunable single-frequency diode laser at wavelength $\lambda = 1.65 \, \mu m$ for methane concentration measurements

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Abstract

This paper deals with the development of a novel single-frequency tunable diode laser with fiber-optic output for gas-analysis applications. The approach we propose is a convenient, simple and cheap solution for spectroscopy of single absorption lines of any gases having absorption bands in the optical fiber transparency window ($0.7 \, \mu m$ to $1.7 \, \mu m$). The presence of fiber-optic output is an additional advantage for remote sensing applications. The laser operation is demonstrated as applied to R7 line of $2\nu_3$ methane absorption band at $\lambda = 1.645 \, \mu m$. The mode-hop-free tuning range of 35 GHz ($1.2 \, \mathrm{cm}^{-1}$) has been achieved.

Keywords: Methane; Tunable diode laser; Fiber grating

1. Introduction

Diode lasers have become a widespread tool for spectroscopic applications. The main advantage of these lasers is inherent simplicity of wavelength tuning by temperature or injection current. However, single-frequency operation is not so easy to achieve with such lasers.

There are several ways of making diode laser generate a single-frequency radiation. In distributed feedback lasers (DFB), a refractive index grating is integrated into the active laser structure. Such lasers demonstrate side mode suppression ratio of more than 30 dB and linewidth of several MHz. The temperature-induced tuning range is about 3–5 nm ($15–25 \, \mathrm{cm}^{-1}$), and the current-induced tuning range is about 1–2 cm$^{-1}$ [1]. Similar results have been achieved for distributed Bragg reflector lasers (DBR), where a grating plays the role of a cavity mirror. The main disadvantage of both DFB and DBR lasers is complexity of the fabrication process, which necessitates intervention into the laser structure with the aim to form a grating. For this reason, such devices are rather expensive.

Another way to obtain single-frequency emission consists in using an external cavity scheme with a bulk grating. In this case, the linewidth can be as narrow as several kHz [2,3]. The wavelength is tuned by rotation of the grating and by changing the external cavity length, which are performed simultaneously. Such an approach enables one to attain mode-hop-free tuning through the entire gain bandwidth of the laser diode (up to 100 nm) [1,3]. However, stable operation requires a high-precision electromechanical system, which also makes such lasers rather expensive. The application of such lasers is justified for scientific purposes, because it becomes possible to investigate a wide variety of gases with just one laser. However, practical applications are usually aimed at detection of a specific gas or a few gases, which involves scanning a single absorption line.

As a simple and cheap solution for spectroscopy of a single absorption line we propose an external cavity scheme (see Fig. 1) with a fiber Bragg grating (FBG). Such a scheme provides single-frequency operation, whereas the wavelength is tuned by controlling the injection current. This approach can be applied to any gases having absorption lines in the optical fiber transparency window.

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2. Laser development

To our knowledge, FBG-based external cavity diode lasers (ECDLs) have not been previously used to obtain current-induced tunable operation. Most of investigations of such lasers are associated with DWDM fiber-optic communication systems, wavelength stabilization, and linewidth narrowing [4–7]. For these applications there is a tendency to minimize the residual reflection $R_2$ (see Fig. 1) down to $10^{-4}$ and to use a narrow-bandwidth ($0.1-0.4$ nm) fiber gratings. Such lasers demonstrate an extremely narrow linewidth ($\sim 1$–$100$ kHz) and stable single-frequency operation with a tuning range as small as several hundreds MHz [8]. At the same time, the spectroscopic applications require a tuning range at least two orders of magnitude larger. To obtain such tunability, the laser design should be modified.

Tunability by injection current control is based on the effect of refractive index variation and consequent variation of the optical path length of the laser cavity. According to the equation $d\nu = \nu \Delta L / L$, the shorter is the cavity, the wider tuning range can be achieved. In the case of an FBG-based ECDL, the shortest cavity is the cavity of the laser diode itself. Therefore, to enlarge the tuning range, one should not completely eliminate reflectivity $R_2$. This reflectivity should be large enough for Fabri-Perot ripples to exist, but small enough for external cavity to dominate over the laser diode cavity. In our experiments, $R_2 = 2\%$ was chosen.

Another key parameter is the bandwidth of the fiber grating. It is the fiber grating bandwidth that ensures single-frequency operation and determines the frequency tuning range. Since the tuning range cannot exceed the FBG bandwidth, one should use sufficiently wide gratings not to restrict tunability. On the other hand, the bandwidth should be sufficiently narrow to provide single-frequency operation. In our investigations, we used fiber gratings with a full width at half magnitude $\Delta \lambda_{FBG} = 0.6$–$1.2$ nm. To prevent mode hops the external cavity length was kept as short as $\Delta d = 3$ mm.

To demonstrate the laser operation, $R7$ line (see Fig. 2) of $2\nu_1$ methane absorption band was chosen. This line has the central wavelength at $\lambda = 1.645$ $\mu$m (6077.0 cm$^{-1}$). A typical linewidth of absorption lines in the near IR is $3$ GHz ($0.1$ cm$^{-1}$), but the $R7$ line is a doublet and has a linewidth of about $6$ GHz ($0.2$ cm$^{-1}$). In this case, the scanning range should exceed $30$ GHz ($1$ cm$^{-1}$) to record the full line shape and the reference level, the latter being necessary for quantitative spectroscopic measurements.

3. Setup

In our experiments, we used a Fabri-Perot-type laser diode based on InGaAsP-heterostructure and emitting at a wavelength $\lambda = 1.65$ $\mu$m. To stabilize and adjust the diode temperature, the laser chip was mounted on a Peltier thermoelectric cooler. The diode cavity had a length $L = 200$ $\mu$m and reflectivity of the rear and front facets $R_1 = 40\%$ and $R_2 = 2\%$, respectively. The fiber grating reflectivity at the Bragg wavelength was about $R_1 = 50\%$. The end of the fiber was tapered in the arc discharge, and a microtens of $10\mu$m radius was formed at the very end of the fiber. The coupling efficiency was about 15%.

From a typical spectrum shown in Fig. 3 one can see that such a laser design allows one to obtain single-frequency radiation with a side mode suppression ratio of almost $20$ dB. Without all the setup the laser radiated several Fabri-Perot modes with almost equal intensities. To investigate tunability, a setup schematically shown in Fig. 4 was used. The radiation emitted from the fiber-optic output of the laser was collimated and passed through the Fabri-Perot etalon, which was made of quartz glass and had a base of $2$ cm ($5$ GHz free spectral range). Then the radiation was received by a photodetector, and an electrical signal was observed on an oscilloscope. The laser was tuned by sawtooth current with a time slope of $20$ mA ms$^{-1}$. A characteristic sinusoidal transmission of the etalon was observed on the oscilloscope, when
Fig. 3. A typical spectrum of the lasers used in the experiments.

Fig. 4. The experimental setup used for tuning range characterization and absorption line detection.

the laser operated in a single-frequency mode. To observe the absorption line, the etalon was replaced by a cell containing methane at room temperature. The length of the cell was 4.5 cm.

4. Results and discussion

By trying different fiber gratings ($\Delta \lambda = 0.6-1.2$ nm), we found that the best-suited grating bandwidth was $\Delta \lambda = 0.9$ nm. In this case, the experimentally observed absorption line is shown in Fig. 5. The more intense absorption line in Fig. 5 was obtained when the gas cell contained methane at a pressure of 1 atm. The other line shape was detected at a lower pressure ($P \approx 0.5$ atm.) of methane. It can be seen from Fig. 5 that the absorption line has a typical doublet structure. The fact that the doublet is worse resolved at a higher pressure is explained by collision broadening. From the etalon fringes plotted on the bottom of Fig. 5 one can conclude that the mode-hop-free tuning range equals 35 GHz ($1.2$ cm$^{-1}$). Fig. 6 presents the experimentally observed R7 line in frequency scale. When the bandwidth of a grating was less than 0.9 nm, the tuning range was already narrower, and for $\Delta \lambda_{FBG} = 0.6-0.8$ nm it did not exceed 15-20 GHz. The grating with $\Delta \lambda = 1.2$ nm was found to have too wide spectral width; therefore, single-frequency operation took place only inside a frequency interval of 6 GHz. The linewidth of the laser developed was not yet measured, but we estimate it to be of no more than several tens of MHz.

The tuning rate $d\nu/dI_p$ was gradually increasing from $0.36$ GHz mA$^{-1}$ to $1.25$ GHz mA$^{-1}$ during the scanning period. By changing the temperature of the laser diode, we were able to adjust the laser module, so that the minimal time required for a single line scanning was 2 ms.

The light intensity curve is shown in Fig. 7. Single-frequency operation was observed in the injection current range from 110 to 170 mA. At the present stage of development, an optical power of 200 $\mu$W was obtained at the single-mode fiber output. This value can be enlarged in future by optimizing the laser module design. In our experiments, the coupling efficiency was only 15%, whereas in commercial devices it can reach 50-70%. Improvement of the coupling efficiency will not only result in optical power increase, but will also yield a stronger side mode suppression ratio. The choice of an optimal residual reflectivity $R_2$ also calls for further research.

The minimization of the mismatch between the absorption line central wavelength and the Bragg wavelength of
the fiber grating is of much importance. To investigate the effect of such a mismatch, the absorption line to be detected was observed during the fiber grating writing process. This experiment is illustrated in Fig. 8, where the transmission spectra of gratings with bandwidths of 0.6 and 0.9 nm are plotted together with the absorption line under investigation. Although the grating with $\Delta \lambda = 0.6$ nm allowed us to obtain a tuning range of 20 GHz ($0.67 \text{ cm}^{-1}$), we failed to observe the full line shape, because the Bragg wavelength of the grating was shifted by 0.1 nm ($0.33 \text{ cm}^{-1}$) with respect to the absorption line central wavelength.

It should also be noted, that the principal limitation on the tuning range of the FBG-based ECDL is imposed by the external cavity mode spacing, which was 50 GHz ($nL = 3 \text{ mm}$) in our experiments.

5. Conclusion

The usage of FBG-based external cavity diode lasers has been proposed for spectroscopy of gases having absorption lines in the optical fiber transparency window (0.7–1.7 $\mu \text{m}$). As an example, this approach has been applied to detection of the R7 line of the $2\nu_3$ methane absorption band at the wavelength $\lambda = 1.645$ $\mu \text{m}$ (6067.0 $\text{cm}^{-1}$). Single-frequency operation tunable by the injection current over a frequency range $\Delta \nu = 35$ GHz ($1.2 \text{ cm}^{-1}$) has been achieved. For applications requiring detection of a single or a few absorption lines, such lasers are very good candidates, being a simple and cost-effective alternative to the widely used DFB lasers.

References