1. Introduction

Some applications require lasers whose line emission can be continuously tuned, with very fine steps, free of mode hopping and with single frequency operation [1]. For instance for gas sensing applications it is usually necessary to scan the laser between ro-vibrational absorption lines of the target molecule, which typically have a separation of a few picometers. Therefore, the laser must be finely tuned in order to match a particular absorption line [2, 3]. Hence the laser tuning must be performed in very small tuning steps and without mode hopping over the spectral region where the ro-vibrational absorption line occurs [1]. Some lasers can usually satisfy these characteristics, for example, DFB laser diodes typically have single mode emission and can be tuned continuously, making them attractive for gas sensing applications. However, due to their characteristics DFB lasers can usually only be used to detect a specific gas and are relatively expensive [4]. In contrast, other lasers can be unsuitable for gas sensing applications since their wavelength tuning is carried...
out in discrete jumps due to different factors such as mechanical stability effects [1]. This type of effects can be observed in some Fabry–Perot diode lasers, which also usually provide multimode emission. Other light source options are fiber lasers, since these can provide narrow linewidth emissions and are relatively low cost because they can be implemented with standard communication components [4]. Several of these optical fiber lasers cannot be tuned continuously due to the mode hopping effect [1, 4–7]. However, some lasers based on optical fibers with continuous tuning have previously been achieved [5–7]. For instance, the laser proposed by [5] was tuned continuously free of mode hopping over a 720 pm (92.3 GHz) spectral region. According to authors this tuning range was obtained by uniformly stretching or heating an optical cavity, which was formed by a couple of Bragg reflectors and a segment of fiber between them. Another example of tunable lasers with single frequency is that proposed by [6], which was based on spatial hole burning and an ytterbium-doped fiber laser with a sample standing-wave geometry. Here, by heating a segment of a fiber, the authors could tune the laser by 5 GHz. Another interesting laser configuration is that presented by [7] which was based on an electro-optically tuned external-cavity diode laser that used a volume Bragg grating (VBBG) as the frequency selective feedback element. Moreover in this configuration Lead Lanthanum Zirconate Titanate (PLZT), which is a transparent ceramic material, was used as the frequency tuning element. This material has a high electro-optic coefficient and therefore by applying to it a certain voltage a 2.5 GHz tuning range without mode hopping was achieved. This laser also has the advantage that no mechanical moving parts were used in the configuration.

In this work a very simple continuously tunable fiber laser is presented. This laser is based on optical fiber and a bulk silicon wafer. Here, the silicon wafer acts as an extrinsic Fabry–Perot interferometer (FPI), which is used as the laser wavelength selecting filter and can be tuned taking advantage of silicon's thermo-optic properties. This FPI is very convenient and simple since no mechanical parts are involved and it is just formed by one standard, uncoated and double side polished wafer. Moreover, the laser emits within the region of 1530 nm, in which acetylene absorbs, and can be tuned with very fine steps before mode hopping occurs. In order to tune the laser the wafer temperature was changed using a standard thermal electric cooler (TEC), achieving a resolution of 84.6 pm °C-1. This point is important since with a change of a few degrees Celsius the laser emission position can be matched with a gas ro-vibrational line. Moreover, as proof of principle two wafers with different thickness were used. Hence, the laser can be finely tuned over 0.9 nm (>100 GHz) when a wafer of 355 μm was utilised. Based on these results we consider that this tuning range can be varied by changing the wafer thickness. Here the laser line position was stabilized over time by just adding a simple proportional-integral-derivative (PID) controller, which can be implemented on an electronic stage. Additionally, simulated and experimental measurements are provided to show the Fabry–Perot performance. Finally, it is important to point out that the laser was implemented using standard and simple components and no mechanical movements are required to tune the laser.

2. Fiber laser setup

The proposed ring fiber laser setup is shown in figure 1. Here, the light of a pigtailed diode laser emitting at λ = 980 nm, delivering a maximum output power of 300 mW, was coupled to a wavelength division multiplexer (WDM, Qphotonics QFBG-L980-200) to pump an erbium doped fiber (EDF, Newport F-EDF-T3) of 3.4 m length. Afterwards, the luminescence generated by the EDF travelled throughout the circulator (Thorlabs 6015-3) from port one to port two where the fiber rotator and the silicon wafer (FPI) were placed. Port three of the circulator was spliced to a 90/10 coupler (Thorlabs 10202 A-90) in order to split the reflected interference spectrum of the FPI into two outputs. Of this signal, 90% was launched to a long period grating (LPG), with attenuation band centered at 1559 nm, rejection strength 3.37 dB and FWHM 15.5 nm. This LPG was used to change the spectral gain of the laser to avoid laser emission in the region of 1550 nm, and finally the LPG was spliced to the WDM-1550 nm port in order to close the ring cavity. The other 10% of the reflected interference spectrum of the FPI was monitored using an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm. In this arrangement a 0.9 nm laser tuning range without mode hopping was achieved by varying the wafer temperature with the TEC (figure 2). Moreover the laser line wavelength was stabilized over time by driving the TEC with a proportional-integral-derivative (PID) controller, which was implemented with an electronic stage.

3. FPI principle of operation

The laser tuning mechanism depends basically on a simple FPI, which has the structure shown in figure 2. It is formed by a double side polished silicon wafer placed at the tip of a single mode fiber (SMF) cleaved with 0° face angle. Here the FPI was
glued to a microcapillary, which helped us to hold the optical fiber. The microcapillary was made using a mixture of a liquid crystal resin with a catalyst in a proportion of 100:1. This mixture could be manipulated to form the microcapillary before it was solidified. Finally, in this arrangement the refractive index of the FPI is \( n \approx 3.4 \), while the cavity length is described as \( d \).

### 3.1. FPI fringe shifting

In order to tune the laser line it was necessary to spectrally shift fringes of the FPI reflection spectrum (\( R_{\text{FPI}} \)). Let us recall that the FPI reflection spectrum can be calculated by means of the Airy formula, which can be described as:

\[
R_{\text{FPI}}(n, T, d, \lambda) = 1 - \frac{1}{1 + \frac{4R[n(\lambda, T)]}{(1 - R[n(\lambda, T)])^2} \sin^2 \left( \frac{4\pi n(\lambda, T) d \cos \theta}{2\lambda} \right)}.
\]  

where \( n(\lambda, T) \), \( R[n(\lambda, T)] \) and \( T \) are the refractive index, the reflectivity and the temperature of the silicon wafer respectively; \( \lambda \) is the wavelength and \( \theta \) is the angle of incidence. Hence, as the FPI cavity length is fixed (\( d \)) therefore the fringes can be shifted by taking advantage of the temperature dependency of silicon’s refractive index [8-13]. Thus by varying slightly the refractive index of the wafer a phase shift can be induced, which consequently shifts the overall FPI spectrum. Here, it is important to point out that silicon’s refractive index as a function of temperature can be modelled as [8]:

\[
n(\lambda, T) = 3.41696 + 0.138497 \frac{\lambda}{\lambda^2 - 0.028} + 0.013924 \left( \frac{\lambda}{\lambda^2 - 0.028} \right)^2
- 2.09 \times 10^{-5} \lambda^2 + 1.48 \times 10^{-7} \lambda^4
+ 1.5 \times 10^{-4}(T - T_0),
\]

where \( T_0 \) is the reference temperature (293 K) and the silicon refractive index temperature coefficient is \( 1.5 \times 10^{-4} \text{K}^{-1} \). As an example, computed FPI reflection spectra of a 355 \( \mu \text{m} \) thickness Si wafer at different temperature values are shown in figure 3. In this figure it can be seen that by varying the temperature within a few degrees Celsius (~15 °C), the FPI fringes can be shifted almost one Free Spectral Range (FSR) of this wafer (~947 pm).

### 3.2. Experimental FPI fringe shifting measurements

In figure 4, measured FPI spectra for two different wafers are presented. In this figure the change in FSR due to wafer thickness can be clearly observed.
Moreover, measured reflection spectra when the temperature of a Si wafer, with 355 μm thickness, is varied are shown in figure 5(a). In this spectrum we localized some reflection fringe peaks, labeled peak 1 to peak 5. Afterwards, we recorded the wavelength peak positions as a function of temperature (figure 5(b)). Here, it can be appreciated that FPI fringe shifting has a linear behavior and also a very low hysteresis.

4. Laser emission

In order to generate two FPI spectra with different free spectral ranges (FSR) two wafers with different thickness were considered. Here the main goal consisted of implementing a laser that emits around 1530 nm, where C₂H₂ absorbs (figure 6(a)), and to tune it with very fine steps, in order to be able to match the laser emission with one of the ro-vibrational lines of C₂H₂ (figure 6(b)). It is important to mention that with the fiber rotator and the LPG it was possible to obtain only one emission line in the 1530 nm region. In this way, the output laser emission had a minimum full width medium height (FWMH) of 28 pm, recorded with the OSA which has a resolution of 20 pm.

The laser emissions recorded with the OSA are presented in figure 7(a). Moreover the laser emission tuning, for each wafer, is shown in figure 7(b). In this figure the solid dots show the wavelength shifting as the wafer temperature increases, while circles show the shifting as the temperature cools down. Here the tuning range of the laser before mode hopping occurred were 950 and 550 pm when wafers with 355 and 505 μm were used, respectively. On average a tuning resolution of 84.8 pm °C⁻¹ was obtained for the two lasers. Moreover it can be appreciated that laser tuning as a function of temperature has a very linear tendency and presents a very low hysteresis (figure 7(b)), as expected due to the behavior of the FPI reflection spectrum shifting as a function of temperature. In this laser the minimum tuning step achieved was ~12 pm, which was limited by the capability of the standard voltage

Figure 5. (a) Measured reflection spectrum of FPI formed by a silicon wafer of 355 μm thickness, shifted as temperature decreases; (b) measured positions of FPI fringe peaks as a function of temperature.

Figure 6. (a) Simulated transmission spectrum of acetylene; (b) measured laser emission tuned to match one ro-vibrational absorption line of C₂H₂. Here the laser emission is normalized for clarity purposes.
4.1. Laser stability

The laser exhibits a very high wavelength stability which is required for gas sensing application. For instance in figure 8 is shown the laser emission spectrum recorded within a period of 30 min in steps of 5 min. Here the temperature was kept fixed during this period of time by driving the TEC with a PID controller (figure 2). This controller was implemented with LabVIEW (National Instruments Inc.)

5. Conclusions

In this work a very simple continuously tunable fiber laser with an extrinsic Fabry–Perot interferometer is presented. This laser can be used in gas sensing applications since it can be finely tuned \( \sim 950 \text{ pm} \) before mode hopping occurs. This tuning range can be enough to tune the laser emission until it can match a ro-vibrational line of a target molecule. Moreover, the extrinsic Fabry–Perot interferometer (FPI) was a simple bulk silicon wafer. This allowed us to tune the laser emission by taking advantage of the thermo-optic coefficient of the silicon. Here the laser can be tuned \( 84.6 \text{ pm/}^\circ \text{C}^{-1} \) by just changing the wafer temperature with a standard TEC driven with a proportional-integral-derivative (PID) controller. Additionally by using this controller the laser can be wavelength stabilized, showing very low shifting during a 30 min period.

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