# Piezo-electric tunable fiber Bragg grating diode laser for chemical sensing using wavelength modulation spectroscopy

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**Abstract:** This paper demonstrates, for the first time to our best knowledge, the application of a tunable external-cavity fiber Bragg grating diode laser in spectroscopic chemical sensing. A tunable fiber Bragg grating external-cavity semiconductor laser is demonstrated with over 10 nm of tuning range. A piezo-actuator was implemented to stretch the grating for rapid wavelength tuning of the laser. The application of such low-cost tunable FBG lasers in spectroscopic chemical sensing was demonstrated in acetylene gas with a wavelength modulation spectroscopy technique.

**OCIS codes:** (050.2770) Gratings; (060.2370) Fiber optical sensor; (300.6360) Spectroscopy, laser

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#10419 - $15.00 USD
Received 24 January 2006; revised 6 March 2006; accepted 7 March 2006

## 1. Introduction

Tunable lasers play important roles in optical sensing. Thanks to the rapid advances in optical communication systems, many tunable lasers originally developed for telecommunication applications have been successfully demonstrated in chemical sensing. These include various temperature-tuned distributed feedback (DFB) lasers, external cavity tunable diode lasers [1], Multi-section distributed Bragg reflector lasers [2], and MEMS-based tunable VCSELs [3]. Although the application requirements for telecommunications share some similarity with those for sensing, many chemical sensing tasks present their own requirements for optical components. Because chemical sensing is often performed in a harsh environment; a rugged, low-cost, portable tunable laser with no moving part is highly desirable. Rapid and wide tuning ranges are also needed to address multiple signature lines of species to minimize detection errors.

In this paper, we demonstrate for the first time, to our best knowledge, the application of an external cavity tunable fiber Bragg grating (FBG) diode laser for chemical sensing. Similar to other tunable lasers in operation, FBG lasers were first demonstrated for telecommunication applications [4-8]. However, FBG lasers possess a number of unique advantages for chemical sensing. Compared with DFB lasers or VCSELs, FBG lasers offer much better temperature stability (13pm/K) over DFB lasers (>100 pm/K) due to the low thermal-optical coefficient of silica fiber. A passive FBG filter can be tuned over a wide (>90 nm) wavelength range [9]. FBG lasers can also be made with high output power (> 10 mW). Since diode lasers with output spectra from visible (e.g. GaN) to mid infrared (e.g., Lead salt laser) are readily available, it may be possible to fabricate FBG tunable diode lasers using either silica fibers or fibers made of other materials to cover a wide spectral range. Such an inexpensive laser could be extremely valuable in spectroscopic gas species identification and concentration analysis for numerous industrial applications, consumer products, and homeland security. Numerous gasses of concern to science and industry have well detailed absorption spectra in the near-IR band. These gasses include CO, HF, water vapor, $N_2O$, NO, $NH_3$, $H_2$, Methane, Acetylene, and many others. In this paper, we demonstrate the application of a rapid PZT-tunable FBG laser to acetylene detection using a wavelength modulation spectroscopy technique.

## 2. Experiments and results

The laser diode used for constructing the tunable FBG laser presented herein is an InGaAs ridge-waveguide laser with a length of 300 μm. One facet of the ridge is coated with a high reflectivity coating (>99%). An anti-reflective coating was coated on the other end of the laser facet adjacent a pigtailed fiber. The coupling efficiency to the fiber is approximately 30%. A second fiber was fused to the pigtailed fiber. The second fiber contained a uniform 1-cm FBG designed with a center wavelength of 1529.5 nm with 50% reflectivity. It was photo-imprinted into a single-mode fiber using a cold writing technique that does not necessitate stripping the fiber jacket [10-11]. The cold writing technique was used here to preserve the mechanical integrity of the fiber under strain to ensure the maximum possible range of wavelength tuning. The fiber grating was located 50 cm from the laser diode. The output power versus the laser injection current is shown in Fig. 1. The spectral width of the laser, measured by an optical spectrum analyzer (Ando 6317C), were instrument-limited at less than 50 pm. The threshold current is estimated to be 18mA with output power increasing at 0.25μW/mA.

In order to provide tunability, the FBG was stretched over a piezo-electric actuator (Melles Griot 17PAS013). The maximum actuation distance is 75 μm with an applied actuation voltage of 75V. Each end of the actuator was fitted with a 5cm diameter “rough tuning” wheel. Each rough tuning wheel was mounted on a 25:1 reduction gear attached to either end of the actuator to allow for mechanical stretching of the FBG similar to that of a violin string. The mechanical tuning range of the FBG laser is shown in the inset of the Fig. 1. By mechanical stretching, over 10 nm of output wavelength tuning can be realized using this simple setup.

#10419 - $15.00 USD Received 24 January 2006; revised 6 March 2006; accepted 7 March 2006

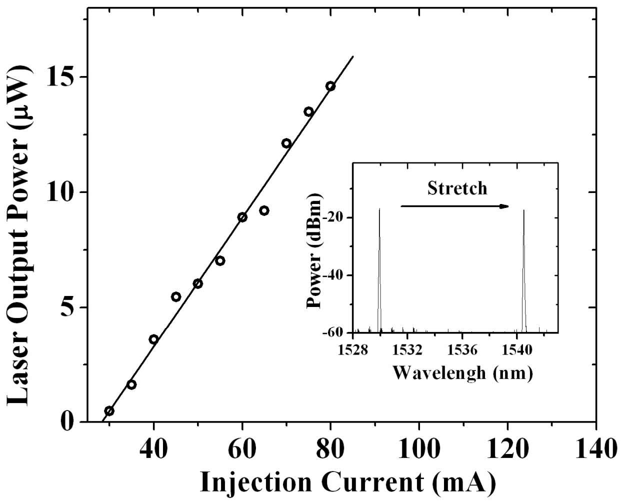

Fig. 1. Tunable laser output power as a function of the injection current Mechanical tuning of the laser with changes in length of the FBG is shown in the inset

The piezo-electric cell was powered via a high voltage amplifier with the capability of producing AC signals with any necessary DC offset. With such control, it was possible to obtain any base-wavelength laser output via manual mechanical stretching. A subsequently introduced DC offset allowed for fine-tuning of the output wavelength via the actuator. Finally, an AC signal generated modulation about the desired output wavelength for chemical detection. Fig. 2 demonstrates the electrical tunability of the FBG laser.

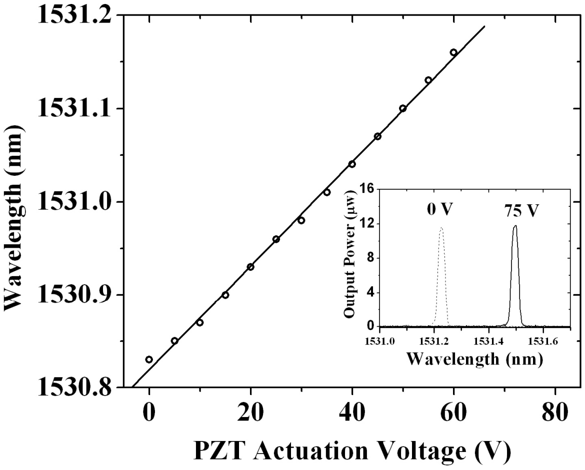

Fig. 2. FBG laser wavelength tuning as a function of piezo-electric input voltage. The optical spectra of the FBG laser with 0 and 75V actuation voltages are shown in the inset of the figure.

It can be seen therein that the full range of movement of the piezo-actuator is capable of tuning the output laser light about 0.35nm. It is noted that the tuning rate is relatively linear. This means that an input actuator voltage translates directly to an output wavelength shift. In actuality, some mechanical hysteresis exists in the return motion of the actuator under bi-directional movement. This hysteresis can, however, be ignored over a very small range of modulation for gas species detection with narrow line widths. Simple feedback circuitry could also be utilized to linearize bi-directional movement. No attempt was made to investigate the longitudinal mode structure of the laser or to prevent mode-hopping. Mode hopping can occur if the number of half wavelengths in the optical cavity changes as the laser is tuned. Although the number of half wavelengths within the stretched fiber (containing the FBG) remains the same as the laser is tuned, the number in the pigtailed (not-stretched) fiber changes. To completely avoid mode hopping, the second PZT actuator can be used to compress a section of fiber within the cavity to compensate the cavity length change.

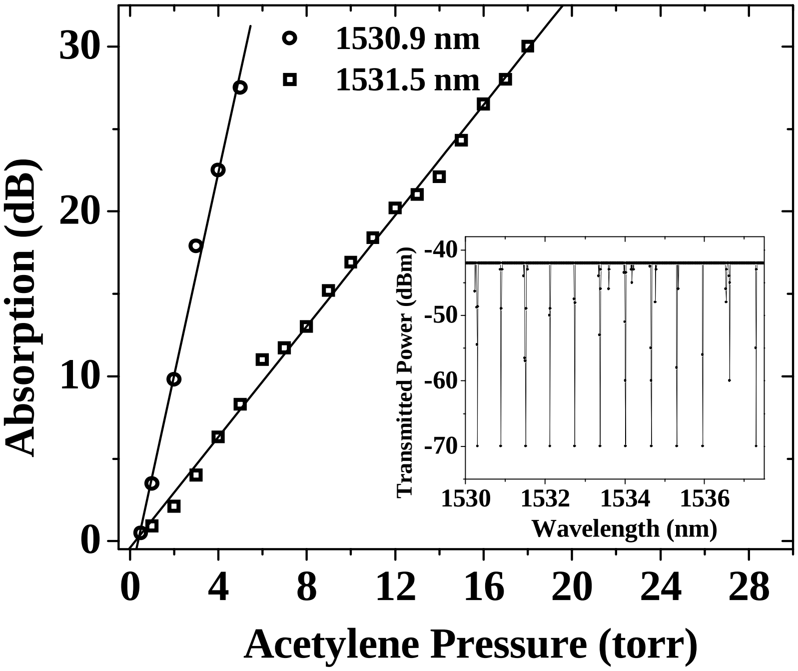

Fig. 3. Acetylene absorption at 1530.9 and 1531.5 nm as a function of the acetylene pressure. Inset: the near IR acetylene absorption spectrum from 1530-1537.5nm. The spectrum was taken at 20 Torr.

To carry out chemical sensing, the output of the FBG laser was terminated in an optical collimator. The collimated laser light was directed into a 1m long vacuum gas cell with fused-silica windows at either end. The vacuum of the gas cell is monitored by a convection gauge. A microscope objective and fiber-coupler were used to re-capture the laser beam. The output was subsequently fed into either a spectrum analyzer (Ando 6317C) for spectral analysis or a fiber-terminated InGaAs photo-detector for real-time observation. Initial chemical sensing experiments with the tunable laser involved mechanically tuning the output wavelength to a known acetylene absorption line and plotting the absorption of the gas as a function of its partial pressure. These results are shown in Fig. 3. The absorption spectrum of acetylene (measured by a commercial tunable laser Santec TSL-210H) at 20 torr from 1530-1537.5 nm is shown in the inset of Fig. 3. In this experiment, absorption near wavelength of about 1530.9nm and 1531.5nm was observed. Fig. 3 demonstrates that the acetylene absorption (dB) for two different near-IR transitions varies linearly with gas pressure. The difference in the slopes of these lines indicates the relative strengths of these transitions.

While static absorption measurements may provide gas concentration information, a potentially much more sensitive chemical sensing method is wavelength modulation spectroscopy. This is demonstrated in Fig. 4. First, the FBG laser is mechanically tuned close

Received 24 January 2006; revised 6 March 2006; accepted 7 March 2006

to the 1530.9-nm acetylene absorption line. The output wavelength of the tunable laser is then rapidly tuned about the absorption peak using the piezo-actuator. Fig. 4 shows the actuation voltage applied to the piezo actuator to provide a sinusoidally varying laser output wavelength around the 1530.9-nm absorption line. An InGaAs photo-detector was utilized to monitor transmitted optical power. Also depicted in the Fig. 4. is the output voltage from the photo-detector. Two distinct dips per cycle of the input actuation voltage can be noted here, again due to the absorption peak of the gas species being coincident with the laser output wavelength at these times. The output of a band pass filter centered at the second-harmonic of the frequency applied to the piezo-electric actuator is also shown in the Fig. 4. It is with this conditioned signal that we measure gas species concentration.

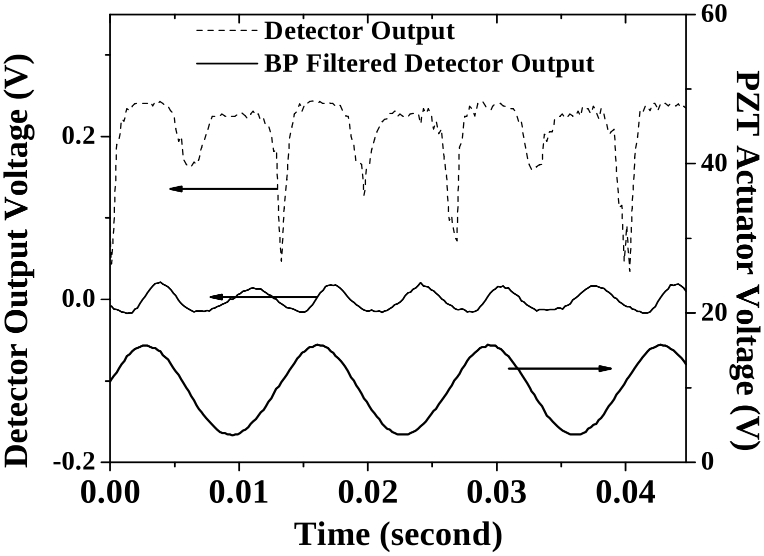

Fig. 4. Acetylene gas sensing using the tunable FBG laser. The piezo-actuation voltage, detected photodetector voltage, and bandpass (BP)-filtered second harmonic output are shown.

Figure 5 shows the correlation between the second harmonic amplitude and the gas concentration for wavelength near 1530.9 nm. A good linearity was observed consistent with the static measurement. The responsivity of the detector was calibrated at 7.7 mV/tor. It is noted that the second harmonic signal in Fig. 5 does not pass through the origin when the acetylene partial pressure reaches zero. This could be due to either inaccuracies in acetylene partial pressure measurements or the existence of an optical etalon in the windowed vacuum test chamber resulting in a small resonance-induced offset. In both static and wavelength modulation absorption measurement, the lowest partial pressure of acetylene measured by the FBG diode laser is 0.5 torr, which is limited by the highest vacuum achievable in our gas cell (150 mtor). When the gas cell approached its highest vacuum, the calibration became less accurate since the partial pressure of air became less controllable in the gas cell. Although it was not the goal of this experiment to produce a tunable with the highest possible sensitivity, the sensitivity of the setup was evaluated. Using the current detection circuit, 0.1 mV change of the photo-diode output can be reliably measured, which leads to a measurement sensitivity of 13 mTor change of acetylene partial pressure or a sensitivity of 17 ppm. Significant improvements could be made to the sensitivity of the system by using a better detection system or performing experiment with a longer optical path.

Received 24 January 2006; revised 6 March 2006; accepted 7 March 2006

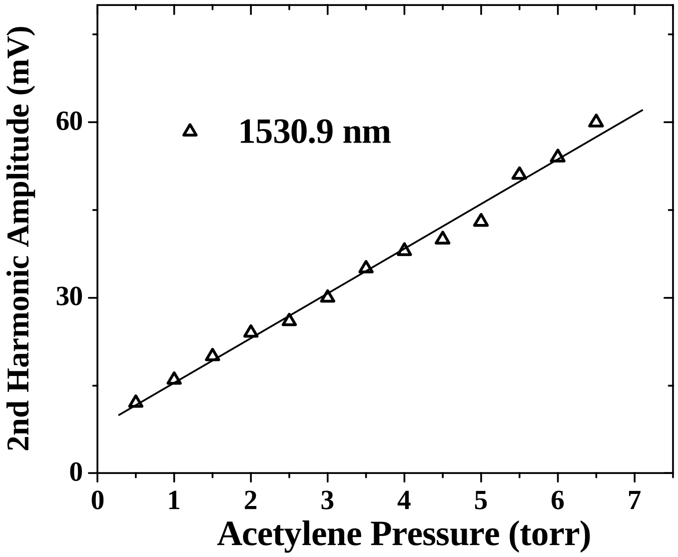

Fig. 5. Acetylene absorption at 1530.9nm varying linearly with pressure is shown. The recovered second harmonic signal amplitude was measured..

## 3. Discussion and conclusion

The tunable FBG laser presented herein provides a low-cost and convenient method for the measurement of gas concentrations for species with absorptive transitions in the near IR band. The tunable FBG laser demonstrated in this letter provides over 10 nm mechanical tuning and 0.35 nm tuning using PZT actuation. Recent developments in tunable FBG devices promise a much wider tuning range. Over 90 nm tuning of FBG center wavelength has been demonstrated by means of mechanical bending [9]. Using a multilayer PZT actuator fused directly to the grating, it is possible to tune the FBG wavelength for over 10 nm with an applied voltage of less than 50 V [13]. The PZT tuning frequency of the laser demonstrated in this paper is about 100 Hz. The maximum tuning frequency is limited by the heavy weight of mechanical stretch apparatus loaded on the PZT actuator. The bandwidth of a PZT actuator can be wider than 100 kHz for a small actuation distance. A lighter fiber mount could therefore be implemented to increase the frequency response.

In conclusion, we have successfully demonstrated a PZT tunable FBG laser that can be rapidly tuned using a PZT actuator. The application of such a low-cost tunable FBG laser in spectroscopic chemical sensing was demonstrated, for the first time to our best knowledge, in acetylene gas sensing using wavelength modulation spectroscopy. The low manufacturing cost, good temperature stability, wide tuning range, and high output power make FBG lasers excellent candidates for the application of chemical sensing in the near IR band.

Received 24 January 2006; revised 6 March 2006; accepted 7 March 2006