Erratum

Investigation of erbium-doped fiber laser intra-cavity absorption sensor for gas detection

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Abstract

Steady state theoretical analysis of an erbium-doped fiber laser intra-cavity absorption sensor shows that high sensitivity can be achieved when the laser is working near threshold but is limited by the spontaneous emission. Experiments are carried out using a linear cavity fiber laser. The general trends of experimental results agree with the theoretical prediction. The use of the intra-cavity sensor for gas detection is demonstrated. A sensitivity of 91 times that of a single-pass absorption sensor is achieved.

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1. Introduction

Detection of pollutant gases such as methane, acetylene, carbon monoxide, and carbon dioxide is important in environmental and pollution monitoring [1]. Optical fiber sensors based on the absorption of light within the low loss window (1–2 μm) of silica fiber allow for remote detection of these gases with additional advantages such as immunity to electromagnetic interference, multiplexing capability, and low cost. The absorption-based sensors that use narrowband lasers or “comb-filter” tuned to the characteristic absorption line or lines of the gas being detected have been proved to offer excellent selectivity [1,2]. Multi-point gas detection has been demonstrated by networking a number of compact micro-optic gas cells, allowing for wide area monitoring at multiple locations and reducing the cost per sensing point [3]. Wavelength modulation spectroscopy and digital filtering techniques have also been applied to improve the performance of the multi-point sensor network, but the etalon effects in the micro-optic cells limit the detection resolution [4].
An alternative technique for high sensitivity absorption measurement is intra-cavity laser spectroscopy [5]. With an absorber directly placed within the laser cavity, the very large number of passes through the absorber can effectively transform a short absorption cell into a highly efficient multi-pass system, and thus improves the detection sensitivity. The implementation of an intra-cavity spectroscopic system in a fiber optic format would allow a detection system with the high sensitivity of the intra-cavity spectroscopy and the advantages of fiber sensors. Furthermore, all fiber intra-cavity systems can use the mature fiber components already developed for communication industry [6], allowing for the realization of cost-effective systems. The broad gain bandwidths of the fiber gain mediums, such as erbium-doped fiber amplifier (EDFA), cover the absorption lines of a number of pollutant gases and thus permit multi-gas detection without needing to use individual lasers with wavelengths designed specifically for the absorption lines of different gases. Some promising results on fiber intra-cavity sensor have already been reported [6,7]. In our previous work, we have made preliminary investigations on the sensitivity of an erbium-doped fiber (EDF) laser intra-cavity absorption sensor [8,9]. The effect of spontaneous emission was however not considered. We here examine the sensitivity enhancement of an intra-cavity fiber laser sensor when the effect of spontaneous emission is considered. The use of the intra-cavity sensor for acetylene gas detection is also presented.

2. Theoretical analysis and simulation

When pumped by 1480 nm laser, a fiber laser using EDF as gain medium can be considered as a two-level system [10]. The temporal behavior of the fiber laser can be described by rate equations as [10,11]

$$\frac{dN_i}{dt} = \eta_i \frac{I_s}{\tau_c} [(1 + N_i)\sigma_{c}N_2 - \sigma_a N_i N_1] - \frac{\delta}{\tau_c} N_i, \quad (3)$$

where $N_1$ and $N_2$ are the population densities of ground level, upper laser level, respectively. $N_0$ is the moderate dopant concentration of the EDF, $T_i$ is the photon number in cavity, $W_p = (\eta_p P_p \sigma_{ap})/S h v_p$, is the pump probability, $P_p$ is the pump power of the pump laser, $h v_p$ is the pump photon energy, $\sigma_{ap}$ is the absorption cross-section at the pump wavelength, $S$ is the fiber core area, $\eta_s$ and $\eta_p$ are the proportions of the signal and pump power within the fiber core, $\sigma_c$ and $\sigma_a$ are the emission and absorption cross-sections of the mode, respectively. $\tau_2$ is the life time of the stable level, $\tau_c$ is the cavity round time, $I_s$ is the length of the EDF, and $\delta$ is total intra-cavity loss including the basic cavity loss and the effect of gas absorption. The term $(\eta_s I_s / \tau_c) \sigma_c N_2$ represents the change of photon number in the cavity due to spontaneous emission. It should be noted that Eqs. (1)–(3) are developed for the case of single longitudinal mode operation. However, for multi-longitudinal mode operation, as long as the bandwidth of laser gain is smaller than that of the gas absorption line, the single mode intra-cavity spectroscopy model is still valid [12]. On the other hand, if the width of the absorption line is smaller than the bandwidth of the laser gain, the spectroscopy is regarded as multimode intra-cavity laser spectroscopy, which has a much higher sensitivity than the single-mode intra-cavity spectroscopy.

If the spontaneous emission is not considered, the steady-state photon number ($\tilde{N}_i$) in cavity can be obtained by setting $dN_i/dt = 0$ ($i = 1, 2$ and $l$) in Eqs. (1)–(3) and expressed the

$$\tilde{N}_i = \frac{A - B \delta}{\delta}; \quad (4a)$$

$$A = \frac{S \tau_c I_s N_0 (W_p \tau_2 \sigma_c - \sigma_a)}{\tau_2 [\sigma_a + \sigma_c]}; \quad (4b)$$

$$B = \frac{S \tau_c (1 + W_p \tau_2)}{\eta_p \tau_2 [\sigma_a + \sigma_c]}. \quad (4c)$$

The output power that is proportional to $\tilde{N}_i$ can be expressed as
It is difficult to obtain an analytical expression for the sensitivity enhancement factor by using Eqs. (9), (6) and (7). We instead evaluated numerically the dependence of sensitivity enhancement factor on the pump power for various intra-cavity losses. Fig. 1 shows the typical results of $K/\Delta \delta$ as a function of pump power. The solid and dash lines are respectively the results with and without the consideration of spontaneous emission. The parameters used in the calculation are given in Table 1. The basic loss of the cavity was taken as $\delta = 7.0$ dB and the loss change is set as $\Delta \delta = 0.2$ dB. The pump power varies with a step of 0.05 mW. At the basic loss of $\delta = 7.0$ dB, the threshold pump power calculated using above parameters is 6.20 mW. As shown in Fig. 1, the sensitivity tends to infinity when the pump power is close to the threshold value if the spontaneous emission is not considered. The pump power where the dash line appears to head for infinity is about 7.08 mW. This value corresponds to the threshold value of fiber laser with basic loss $\delta = 7.0 + 0.2$ dB. If the loss change in cavity is made smaller, the pump power where the dash line appears to head for infinity will be more close to the 6.20 mW. The inclusion of spontaneous emission into the laser equations (solid line) shows that the sensitivity saturates near the threshold. At low pump levels, the sensitivity increases with pump power and reaches a maxi-

![Fig. 1. Theoretical sensitivity as a function of pump power. With (solid line) and without (dash line) the consideration of spontaneous emission.](image)
mum value when the pump power is 6.60 mW, and then decreases with further increase in pump power.

### 3. Experiments and results

Experiments were carried out using a fiber laser shown in Fig. 2. The laser cavity includes an EDFA pumped by a 1480 nm diode laser, a gas cell made from a pair of collimated graded index lenses [2,3], a variable attenuator (#1), a fiber loop mirror, and a tunable optical filter made from a fiber Bragg grating (FBG). The FBG was bought from Bragg Photonics in Canada and has a specified bandwidth of 0.05 nm and reflectivity of 50%. The dopant concentration of 1.5 m long EDF is ~400 ppm. The FBG is used to select working wavelength to be 1528.9 nm, corresponding to one of absorption lines of acetylene (C\(_2\)H\(_2\)) gas. The emission spectral width of the laser is measured to be less than 0.08 nm, limited by the spectral resolution of the optical spectral analyzer (OSA). The actual spectral width should be smaller than this value. This spectral width is comparable to or smaller than the absorption lines of acetylene gas around 1530 nm (under atmospheric pressure). The variable attenuator #1 was used to introduce additional loss to the cavity. The loss introduced by attenuator #1 is relatively broadband, but may be used to simulate the absorption of gas induced loss because the laser spectral width is smaller than that of the gas absorption line. As already mentioned in Section 2, the case studied here is belong to single mode intra-cavity laser spectroscopy category. Although it is less sensitive as compared with the multi-mode intra-cavity spectroscopy [13,14], the single mode intra-cavity spectroscopy does not need a very high resolution spectrometer and is more suited for real time and low-cost gas detection applications. In our present experiment, an OSA was used to measure the output power spectrum of the intra-cavity laser. However, a narrow band filter such as a fibre Bragg grating with its pass band aligned to the gas absorption line can, in principle, be used to measure directly the laser output power. The OSA has a sensitivity of ~90 dBm and was set to a minimum resolution of 0.08 nm to reduce the out-of-band spontaneous emission of the EDFA. Another attenuator (#2) was used to adjust the pump power level.

![Fig. 2. Experiment setup. WDM: 1550/1480 WDM coupler; OSA: optical spectrum analyzer; and EDF: Er-doped fiber.](image-url)
An 1:99 coupler was used to tap a small amount of the pump power for the purpose of pump power monitoring. When the attenuator #1 was set to a minimum loss of 1.61 dB, the threshold pump power for fiber laser system was measured to be 6.24 mW. The dependence of sensitivity enhancement factor on pump power was measured and shown in Fig. 3. The sensitivity enhancement factor was obtained by the following procedure: when variable attenuator #1 was set to 1.61 dB, and the laser output power was measured when the pump power was varied from 5.6 to 7.0 mW at a step of 0.1 mW; the measurement was repeated when the variable attenuator was set to 1.71 dB, corresponding to a round-trip loss variation of $2 \times (1.71 - 1.61) \text{ dB} = 0.2 \text{ dB}$. The difference between the two measurements was then taken and divided by the round-trip loss change $\Delta \delta = 0.2 \text{ dB}$. As expected, the sensitivity increases when the pump power is reduced to close to threshold value, and reaches a maximum value of $\sim 110$ when pump power was $\sim 6.5 \text{ mW}$. It should be pointed out that above sensitivity enhancement factor was calculated by using the nominal reading from the variable attenuator. As specified by the manufacture, the accuracy of the applied single pass attenuation is $\pm 0.03 \text{ dB}$ for the attenuator (EXPO FVA-3100) we used. This would give a round-trip loss change of $\Delta \delta = 0.2 \pm 0.06 \text{ dB}$. The sensitivity enhancement factor could then be in the range from 85 to 157. The measurements were also limited by the stability and the tuning accuracy of the pump power ($\sim 0.1 \text{ mW}$), and the spectral resolution of the OSA.

The intra-cavity system was used to measure the concentration of acetylene gas. The wavelength of the FBG was firstly fine tuned (by applying strain) to an absorption peak of acetylene around 1528.9 nm. The pump power was set to $\sim 6.5 \text{ mW}$, corresponding to the maximum sensitivity point in Fig. 3. Fig. 4(a) shows the spectra of laser output when the gas cell (1 cm long) was filled with 0%, 1%, 2%, 5%, 10% and 20% of acetylene under atmospheric pressure. As plotted in Fig. 4(b), the laser peak output power varies approximately linearly with gas concentration inside the gas cell and drops from $-19.54$ to $-51.50 \text{ dBm}$ when the

![Fig. 3. Measured sensitivity versus pump power.](image)

![Fig. 4. (a) Fiber laser output spectra when the gas cell is filled with different acetylene concentration: 0%, 1%, 2%, 5%, 10% and 20%. (b) Light absorption as a function of acetylene concentration.](image)
acetylene concentration within the gas cell was varied from 0% to 20%. The single pass direct absorption loss of the same cell was also measured by filling the cell with same concentration of acetylene and found to be $\sim 0.35$ dB. This gives a sensitivity enhancement factor of 91 times that of the conventional single pass absorption measurement.

Measurements were also conducted by filling the gas cell periodically with air and 20% acetylene at atmospheric pressure. Fig. 5 shows the results for two air/acetylene filling cycles. The samples (the horizontal axis of Fig. 5) were taken every 2 s. The fluctuation of laser output power was measured to be 0.36 dB (root mean square value), corresponding to a measurement error in terms of minimum detectable acetylene concentration of 2253 ppm. The measurements were found quite reversible with repeatability of 0.37 dB over five measurement cycles. This value of repeatability would cause a measurement error similar to that of the minimum detectable gas concentration and may be due to the instability of the pump laser, polarization effect, thermal effect, and various environmental effects. Further work is needed to minimize these effects and optimize the system performance.

4. Summary

In summary, we have investigated theoretically and experimentally the relationship between the sensitivity and the pump power level of an erbium-doped fiber laser intra-cavity absorption sensor when spontaneous emission is considered. It was found that the sensitivity of the intra-cavity fiber laser sensor could be improved significantly when the laser is working close to the threshold, but limited by the spontaneous emission noise. However, as the sensitivity varies significantly around the threshold even with a slight variation in the pump power, the stability of pump source is therefore crucial to ensure high stability and sensitive absorption measurements. The power level around the threshold is also low, meaning that highly sensitive photo-receiver, preferably with matched wavelength filter to minimize the spontaneous emission noise of the EDFA, is also required. Our experiments have achieved a measurement sensitivity of 91 times higher than that of the single pass absorption measurement and a minimum detectable (acetylene) gas concentration of 2253 ppm.

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References