Chemical Physics Letters 463 (2008) 246–250

Contents lists available at ScienceDirect

Chemical Physics Letters

journal homepage: www.elsevier.com/locate/cplett

CW cavity ring-down spectroscopy (CRDS) with a semiconductor optical amplifier as intensity modulator

Haifeng Huang, Kevin K. Lehmann *

Department of Chemistry, University of Virginia, McCormick Road, Charlottesville, VA 22904-4319, United States

ARTICLE INFO

Article history:
Received 13 June 2008
In final form 8 August 2008
Available online 14 August 2008

ABSTRACT

We summarized both advantages and disadvantages of different light modulators used in cw-CRDS experiments. For the first time, we introduce the use of a semiconductor optical amplifier (SOA) as light modulator in cw-CRDS. A direct comparison of the sensitivity realized on the same instrument using an SOA as modulator with use of an acousto-optic modulator (AOM) has been made. It is found that the SOA has larger extinction ratio (~81 dB) than the AOM. For our instrument, with single-shot initial signal-to-noise ratio of 1400:1, these two modulators are found giving equivalent sensitivity.

1. Introduction

In the past decade, cavity ring-down spectroscopy (CRDS) has become a widely used method for the detection of trace levels of absorption [1,2]. In CRDS, absorption and scattering loss of a sample placed inside of a high finesse optical cavity is measured by an increase in the decay rate of light intensity trapped inside the cavity. Sensitivities to loss as small as 10^{-9}–10^{-11} cm^{-1} are routinely obtained in the visible and near-IR [3], where the highest reflectivity dielectric mirrors are available. The highest sensitivities are usually realized by using a narrow bandwidth continuous wave laser to excite the cavity and then observing the cavity decay by rapidly (compared to the cavity storage time) switching off the input radiation, which is known as cw-CRDS [4,5]. This method gives a more reproducible excitation of a single mode of the cavity, thus minimizing fluctuations caused, by among other reasons, spatial variations in the mirror reflectivity.

In cw-CRDS experiments, the light intensity modulator must have large enough shut-off extinction ratio and fast enough shut-off speed in order to generate clean exponential cavity decay signals. If the extinction ratio of the modulator is not large enough, the remaining optical power couples into the excited mode. Since the optical coherence time of most lasers is less than the life time of photons trapped in the cavity, this extra field adds with random phase and creates an interference noise on the decay [6]. We have completed a systematic study of the signal to noise in cw-CRDS as a function of the effective isolation of the light modulator, and will publish the results in another paper [7]. The shut-off speed of the modulator will determine the shortest decay time constant, hence the maximum absorption that can be measured by cw-CRDS. Unfortunately, most of the commercially available light intensity modulators lack either sufficient transition speed or have an insufficient extinction ratio. In this article, we are going to review both advantages and disadvantages of presently used and potential modulators in cw-CRDS and, for the first time, explore using a semiconductor optical amplifier (SOA) as an intensity switch in cw-CRDS. As we will demonstrate, an SOA meets those two requirements perfectly with some other advantages. Following this section, we will first compare different modulators in cw-CRDS. Then we will explain the details of the experimental setup. Then comparison will be made of the use of an SOA and an acousto-optic modulator (AOM) as light switches are presented. The last part is the discussion and conclusion.

2. Modulators used in cw-CRDS

According to our analysis [7], if the detector noise dominates the system and the ring-down signal is sufficiently sampled, the square of the fraction noise of the extracted cavity intensity decay rate k, caused by the light leakage through the modulator, is proportional to the inverse extinction ratio ϵ_r of the modulators used for cw-CRDS

$$\frac{\sigma^2(k)}{k^2} = \frac{64}{27}\epsilon_r I_0/I_t, \tag{1}$$

where $\sigma^2(k)$ is the variance of the extracted decay rate k, I_0 is the averaged transmission power when the laser is kept on resonance with the cavity, and I_t is the initial power (or trigger threshold) of the ring-down decay signal. This fraction noise of k can be compared to the fluctuations in k that are caused by detector noise. For a least squares fit of the ring-down data at N equally spaced time points separated by Δt in time, in the limits that $k\Delta t \ll 1$ and $N\,k\Delta t \gg 1$, we earlier derived from the analytical covariance matrix of the fit that [8]

---

* Corresponding author.
E-mail address: lehmann@virginia.edu (K.K. Lehmann).

0009-2614/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.cplett.2008.08.030

$$\frac{\sigma^2(k)}{k^2} = 8\,k\Delta t(\sigma_\mathrm{d}/I_t)^2, \tag{2}$$

where σ_d is the root mean square (RMS) detector noise in power units as measured by the A/D converter, assuming it is uncorrelated. (For the correction due to finite detector bandwidth, see [8]). We further assume that the RMS noise of the detector is at least the bit resolution of the A/D so that the finite bit bias is negligible. If we take, for example, $k\Delta t = 0.01$ ($1/\Delta t$ is the sample rate of the A/D) and an initial signal to noise of 1000:1 on the decay (i.e. $\sigma_\mathrm{d}/I_t = 10^{-3}$), we see that without excitation laser leakage through the modulator (i.e. $\epsilon_r = 0$), the fraction noise of k is 0.028% (on a single shot). If we take $I_t = 2.5I_0$ (which is about the maximum that is practical in order not to have too small ring-down rate), the noise in k caused by finite ϵ_r will be $\sim\sqrt{\epsilon_r} = 0.031\%$ for $\epsilon_r = 1 \times 10^{-7}$ (70 dB ON/OFF ratio). Thus for these parameters, an increase of ~50% in the RMS noise of the experiment due to finite extinction ratio is predicted. This example shows we have very stringent requirements on the attenuation of the modulators used for cw-CRDS. In addition to the extinction ratio requirements, the switch must be able to completely attenuate the input laser in a time fast compared to the cavity decay time constant so as not to distort the cavity decay.

Fiber based Mach–Zehnder modulators are very attractive and realize sub-ns intensity modulation [9]. However, commercial units have ON/OFF extinction ratio specifications of only up to 40 dB [10]. We would need to gang at least two of these in series to realize the required extinction ratio, each one of which has a typical insertion loss of 3–4 dB when it is ON. The conventional mechanical switches (including MEMS) that are widely used in fiber optic networks have switching times on the order of a msec and thus are not suitable [11].

Electro-optic (EO) amplitude modulators (i.e. Pockel's cell + polarizers) have also proved problematic for cw-CRDS. Their extinction ratio is limited by the extinction ratio of the polarizers and strain birefringence in the Pockel's cell. More importantly, suitable electro-optic materials are also piezoelectric, which means that rapid switching the electric field generates ultrasonic sound waves that generate strain birefringence [12], which limits the EO effective extinction ratio for well below cw-CRDS requirements [13].

It has been proposed to rapidly switch the laser off resonance with the cavity [14], which can be done with a diode laser by a jump in drive current, instead of attenuating the laser. Our present analysis indicates that, at least for a DFB laser, the excess laser intensity will still enter the cavity. Such lasers have a Lorentzian spectrum with a FWHM, $\Delta\nu$, of a few MHz. As such, even if one were to shift the laser exactly one half of the cavity free spectral range, FSR, the remaining spectral density at the originally pumped cavity resonance would be reduced by a factor of $(1 + (\mathrm{FSR}/\Delta\nu)^2)^{-1}$. Since cavity FSR values between 150 and 300 MHz are typical in CRDS (corresponding to a cavity length of 1–2 m), an effective attenuation of ~ 40 dB is expected. To realize 60 dB reduction of the spectral power at the *initial* frequency, one would have to shift the frequency of the laser by at least 5.5 cavity FSR. Note that light on other cavity modes (including those much closer to the shifted frequency of laser) will cause beating at multiples of the cavity mode spacing, which is typically much higher than the detection bandwidth. Further complicating matter is that at the new frequency, the laser will also be much closer to resonance with some of the higher order transverse modes of the cavity. While any beating between the radiation at these newly resonant modes and the radiation already stored in the cavity will likely be well beyond the bandwidth of the detection system and thus highly damped, the fluctuating intensity injected on this new cavity resonance will contribute noise to the ring-down signal. Also to be considered is that most of the diode laser tuning with current is in fact due to heat; the high frequency current modulation response (~1 MHz) is typically an order of magnitude times smaller than the low frequency response [15]. This means that after a fast step in the current, the laser will continue to change frequency, scanning over higher order modes of the cavity.

In most of our work [3,16] and that of many other groups, an AOM is used to turn off the laser. These can achieve the required extinction ratio, but one must be careful that (1) the traveling acoustic wave has extremely low reflection from the absorbing end of the crystal and (2) that the RF switch used to shut-off the drive to the AOM has very good extinction. We personally have experienced with having to reject an AOM that was the same model as one we have long used because of a weak back reflection led to an incomplete intensity turn off for a time that approximately matched the acoustic round trip time in the AOM crystal. Also, we had to modify one of our commercial AOM drivers by inserting a second RF switch between the RF oscillator and amplifier. We recommend that when one is setting up a cw-CRDS experiment, the value of the effective modulation extinction ratio be carefully measured to ensure a minimum value of 50 dB. One advantage of using an AOM is that light reflected from the cavity back to the laser is double shifted by the RF frequency of the AOM, which reduces the effect of feedback on the laser and thus reduces the degree of optical isolation that is required. While AOMs are practical, they do have some draw backs, including (1) they require substantially more electrical power than the diode lasers and often cost more, especially fiber coupled ones. (2) One must use the first order diffraction of the AOM (the zero order cannot be attenuated with the required extinction ratio) and this must satisfy Bragg's condition. The deflection angle is wavelength dependent and this can limit the laser wavelength tuning range that can be achieved without realignment unless the RF frequency into the AOM is adjusted to maintain Bragg's condition hence efficient coupling to the TEM_{00} modes of the ring-down cavity. (3) The speed that an AOM can be turned off while maintaining the required extinction ratio, which is limited to hundreds of nsec for our AOM, can limit the shortest cavity decay time that one can practically detect, which in turn limits the highest sample concentration that can be determined.

Another approach to intensity modulation, at least with diode lasers, is to quickly shunt the drive current of the laser. This approach is fast, very effective, and does not require additional optical components. However, it does have the draw back that for diode lasers, once the laser current is turned back on, because the temperature control of the laser is strongly related to the laser current, a substantial fraction of a second is often required for the laser frequency to stabilize to something on the order of its linewidth, i.e. a few MHz. This limits the rate that ring-down events can be observed. If one is stabilizing the laser frequency to an absorption line in a reference cell, this intensity modulation and turn-on transient drift complicate the locking.

In this Letter, we will explore using a semiconducting optical amplifier (SOA) [17,18] as an intensity modulator, which is to our knowledge the first time it has been used as such in a cw-CRDS instrument. These are basically diode lasers with AR coatings on both ends; they can also be rapidly switched on and off by modulation of their drive current. However, since the output wavelength is determined by the master oscillator, they do not require a significant time delay once turned back. The unit we have tested has a power gain specification of 20 dB. This is substantially less than our required extinction coefficient. However, it turns out that when they are not pumped by current, the SOAs are strongly absorbent and thus, as we will demonstrate below, we can realize more than the needed extinction ratio. We find that the SOA provides the highest effective extinction ratio of any modulators with sufficient speed that we know of. The use of SOAs is attractive for practical applications of CRDS. They come fiber connected and have broadband gain media (~70 nm at 3 dB below the peak), thus do not have to be aligned when the incident laser is tuned, unlike the free space AOMs we usually use. They amplify the input signal and produce modestly more output power than is available from a DFB laser. This gain should allows one to split the output power of a single laser over many cavities and thus do detection at a large number of points with a single laser without loss of signal to noise or response time of each cell. In this work, we have made a direct comparison of the sensitivity of a cw-CRDS instrument using an AOM with using an SOA. The CRDS decay rate stability (which determines instrument sensitivity) we obtained for these two modulators are nearly identical. Given the advantages of an SOA over an AOM, as discussed above, an SOA should be the modulator of choice in CRDS experiments for those wavelengths for which they are commercially available.

3. Experimental setup

In this work, we used a slightly modified version of a working cw-CRDS instrument that we have previously described [3,16]. As such, we will describe it only briefly, focusing on what has been changed (See Fig. 1). Our setup is similar to other cw-CRDS instruments, including those in commercial trace gas analyzers. We use a cavity formed from two high reflector mirrors (ATFilms) that had a design center coating wavelength of 1540 nm, one flat and one with 1 m radius of curvature, separated by 39.5 cm. The decay time constant of empty cavity is about 221 μs near 1512 nm, corresponding to a mirror total loss of 6 ppm per reflection. The flat mirror is mounted on a plate that can be moved by three PZT actuators. Light from a fiber coupled DFB laser is converted to free space propagation, passes through an optical isolator and then an AOM. The first diffraction order of the AOM is mode matched to the optical cavity through the flat reflector. The cavity length is modulated by applying a 15 Hz triangle wave to the PZTs with sufficient amplitude to scan slightly over one FSR of the cavity (379.5 MHz), which insures that the laser and cavity will come into resonance at least once in each modulation half cycle. When the laser power transmitted through the ring-down cavity reaches the preset threshold, a comparator generates a trigger pulse which rapidly turn off the input laser and triggers the data acquisition by a 12 bit A/D card digitizing at 1 MHz to record the single exponential decay signal. Each ring-down decay is fit with a nonlinear weighted least squares fit to a exponential decay plus a baseline [8].

When using the SOA, the output of the 1512 nm DFB laser diode (NTT Electronics Corporation, NLK1556STG) is attenuated by 13 dB (5% transmission) with fiber coupler (Lightel, 500-17528-01-1), which is then fiber coupled into the SOA (Covega Corporation, SOA 1084-3-0-U-S-S-A-A). The 3 dB optical bandwidth of this SOA is from 1463 nm to 1537 nm. In addition to the amplifier, it has 54 dB of additional optical isolation. The output of the SOA passes a fiber output collimation coupler, a free space isolator (Iso-Wave, I-15-UHP-4), and an AOM (IntraAction, ACM-802AA14). The SOA is driven by a current source (ILX Lightwave, LDX-3620)[19] with maximum output current 0.5 A. The SOA can be driven with up to 0.6 A, but we lacked an appropriate current driver at that level. The SOA drive current is modulated by the external modulation input of LDX-3620. The temperature of the SOA is stabilized to about 23 °C by a TEC control module (Wavelength Electronics, HTC-3000). When the DFB laser works at 8 °C and 20 mA current, the output laser power is 1.8 mW. With driving current of 0.5 A, the output power of the SOA is 6.0 mW, suggesting a gain of 18.2 dB when the 13 dB initial attenuation is included. The laser linewidth after the SOA, measured by the scope to be ~ 10 MHz on the time scale of seconds, is unchanged from the DFB laser. When the SOA's current is off, it strongly absorbs the input laser. Even with incident power of 4.2 mW to the SOA, the output power is only 2.2 nW when the drive current is off, giving an attenuation of 62.8 dB. This suggests that if used as a light switch, the SOA has an extinction ratio about 80 dB. The driving current of the SOA from LDX-3620 was turned off in less than 2 μs. Enhanced by the strongly nonlinear output versus current, the output laser power of the SOA can be switched off in less than 1 μs. In order to turn the driving current of the SOA completely off, the low level of the trigger pulse is set to -30 mV, realized by using a Stanford Research System pulse generator (DG535). A negative modulation voltage to the LDX-3620 will not generate a negative but zero current. The measured optical extinction ratio of the SOA in pulsed mode is larger than 65 dB, limited by the sensitivity of our IR detector. The present switching speed is limited by our current driver; the SOA can be turned off much faster (in sub ns) [20] both because the time scale of recombination of electrons and holes in the SOA is about ns [18] and because of the nonlinear effects of SOA [21]. When the SOA is used as a light switch in the experiment, the AOM RF power is always on. The AOM was not removed from the system as that would have required a complete realignment of the optical path.

With zero input, at our drive current the SOA has an ASE output of ~1 mW (i.e. 1/6 of the power when driven), and this is expected to be reduced by 10 dB when the input of the amplifier is about −10 dBm [17,22], as we do. The mean ASE transmission through the cavity will be reduced, compared to the amplified laser, by a factor of the laser linewidth (which we recently measured, by using homodyne method, to be ~1 MHz in a short time scale (~ ms) [7]) divided by the cavity FSR. Thus, including the ASE suppression by the input power, the ASE contribution to the cavity transmission intensity should be <0.005% of the coherent contribution and thus below our detector noise.

When only the AOM is used as light switch, the coupler and SOA are bypassed. Such a change requires no optical realignment and makes the comparison of the SOA results to the most common cw-CRDS setup. Although the light is almost linearly polarized,

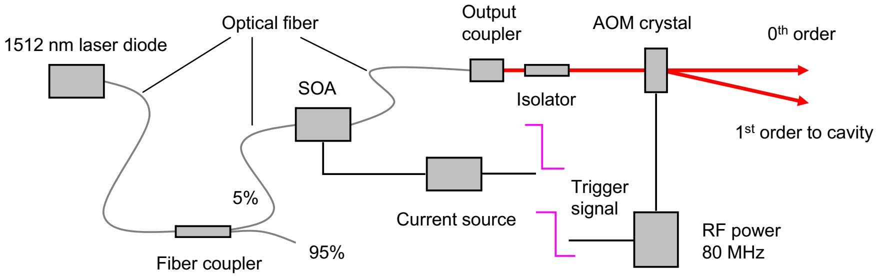

Fig. 1. SOA or AOM as the light switch in cw-CRDS.

normally this bypass will change the polarization state of the light at the position of the fiber output coupler (we do not use polarization maintaining fiber). Consequently, we rotate the isolator to maximize the light power transmitted. Otherwise, we make no changes in the setup to allow the most direct comparison of the two modulation methods. The 80 MHz RF driver used for the AOM is also from IntraAction (ME-801T). By adding two microwave switches (Mini-Circuits, ZYSW-2-50DR) in series between the RF oscillator and amplifier, the ON/OFF extinction ratio of RF power of the driver can reach 73 dB, limited by the noise level of the scope in the measurement. We measured the optical extinction ratio of the AOM with a detector in front of the cavity and with an apperture of 1 mm in front of the detector that matches the size of beam diameter of the TEM_{00} mode at this point (a solid angle of $\sim 10^{-6}$ s.r. from the AOM). This extinction ratio was found to be only 53 dB. This light leakage is due to low angle scattered light by optical elements of the system. Even when the AOM is disconnected from the RF amplifier, the intensity of scattered light does not change and will disappear only when the incident laser is turned off. About 70% of the scattered light intensity is caused by the AOM crystal. The laser frequency of the first order diffraction is shifted by 80 MHz from the input while the scattered light has the unshifted laser frequency when the AOM RF is off. This suggests that any beating frequency due to this scattered in the ring-down signal should be at 80 MHz. However, our detector amplifier includes a low pass RC filter with 3 dB frequency of ~ 300 kHz which removes such high frequency beating.

The total RF power loss caused by both microwave switches is about 2.4 dB, which reduces the maximum output RF power from 1 W down to about 0.6 W. This is less than 0.85 W, the power corresponding the maximum efficiency (~85%) of the first order diffraction. The loss of light power in the first order diffraction can be compensated by increasing the laser current correspondingly. In our experiments, the laser power reaching the cavity is about 2 mW. In the SOA experiment, the AOM RF power was further reduced so that the optical power incident on the cavity was the same in both experiments. We have selected the laser wavelength to avoid the strong absorption lines in this spectral region due to atmospheric water vapor.

4. Results and discussion

When the SOA or AOM is used as the light switch in our cw-CRDS experiment, with the initial signal to noise around 1400:1, the ensemble standard deviation of τ for short term (~min) is 0.06 μs, which corresponds to σ_k/k of 2.7×10^{-4}, or standard deviation in the calculated sample absorption coefficient of 4.1×10^{-11} cm^{-1} per shot. For a longer term comparison, we recorded two ring-down decay data sets for empty cavity for more than one hour when either SOA or AOM was used as light switch. In the experiments, the detector gain setting and the trigger threshold are the same for both modulators. The two ring-down rates (2.8 Hz for SOA and 2.6 Hz for AOM) are similar. Because these two data sets were not recorded simultaneously, the system drift should be different for them. From the recorded data, we found the system drift in the measurement time periods for both data sets was very small (see Fig. 2).

We use Allan variance to analyze the data considering the slow drift of our system. For details of Allan variance, please refer to the listed Refs. [23,24]. The Allan variance gives the observed mean squared fluctuations when samples of different length, N_d data points, are averaged. If the only noise in the system is uncorrelated random noise shot-to-shot, the slope of log–log plot of Allan variance vs. N_d will be negative one, indicative of the expected $1/\sqrt{N_d}$ decrease in noise with averaging. If the system displays a linear drift in time of the cavity loss (and thus decay rate), a log–log plot of Allan variance plot will have a minimum and increase with slope +2 well past this. If the loss changes diffusively (i.e. as a random walk), the slope well past the minimum will be +1. The position of the minimum in the Allan variance plot gives the optimum integration time, and its value gives the minimum variance one can reach by averaging the data. For a finite size time series of data, the uncertainties of the last data points in Allan plot calculated from normal algorithm become larger because the average times of Allan variance decrease with the increase of the average data length [24]. We have proposed a modified algorithm [25] (using continuously moving averaging windows instead of discrete windows) to calculate the Allan variance which gives less statistical uncertainties for the last data points in Allan plots while the result is very close compared with that from the normal algorithm.

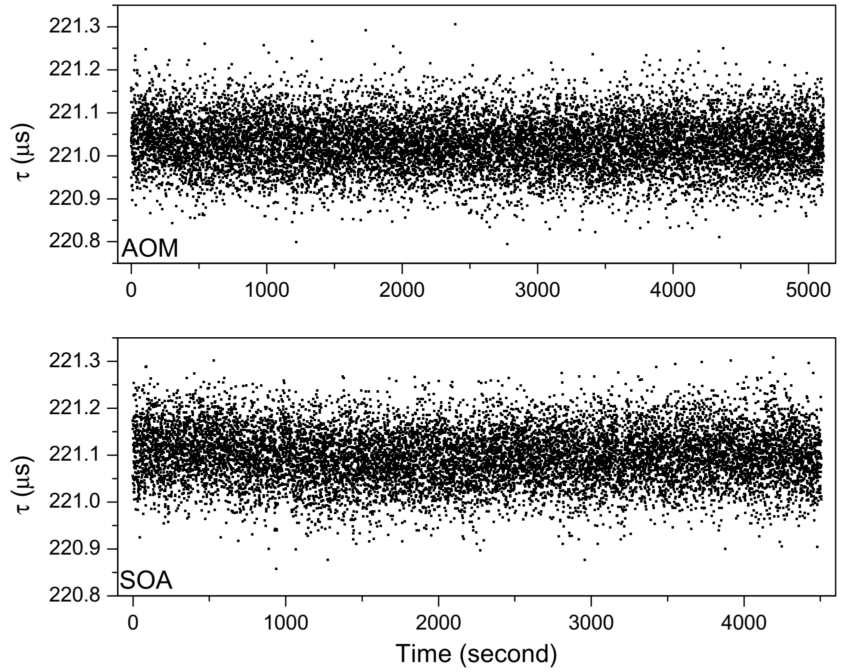

Fig. 2. Extracted decay time constant in time series. The upper part corresponds to AOM as modulator and the lower part to SOA as modulator.

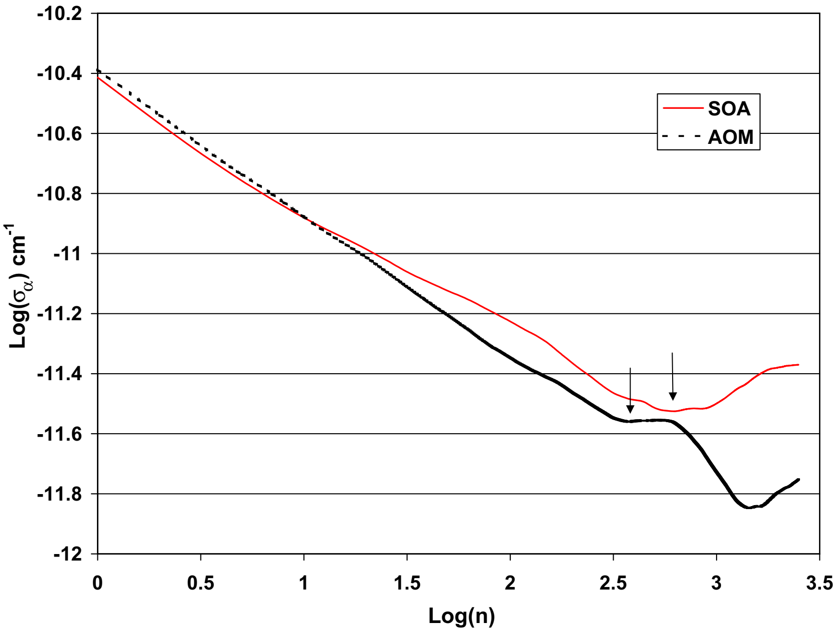

Fig. 3. Allan plots comparison with SOA or AOM as the light switch in cw-CRDS, with two arrows pointing the optimum averaging times. The second minimum in the Allan plot of AOM is caused by unknown noise.

Fig. 3 shows two Allan plots of SOA and AOM switches. To simplify the interpretation, we plot on the vertical axis the square-root of the variance in k and scale it by the speed of light to give RMS noise in absorbance units. From Fig. 3, the optimum averaging for SOA is 624 decays, corresponding to integration time of 3.7 min and minimum dispersion of k/c of 3.0×10^{-12} cm^{-1}. For the AOM switch, the optimum averaging is 373 decays, corresponding to integration time of 2.4 min and minimum dispersion of k/c of 2.8×10^{-12} cm^{-1}. These differences are not significant and likely reflect small changes in our cavity loss drift. These result shows that equivalent cw-CRDS sensitivity can be realized using an SOA or an AOM as an intensity modulator. Here we want to point out that our system is not just limited by simple linear drift in time. The second minimum in the Allan plot of AOM is caused by unknown noise in our system and it is not reproducible. Our experience is that only the first minimum in the Allen variance plot is robust.

5. Conclusion

In this Letter, we have demonstrated the efficacy of using a semiconductor optical amplifier as the light switch in a cw-CRDS instrument with excellent performance. Our experimental results demonstrate equivalent excellent sensitivity when an SOA or AOM is used. The SOA has some advantages over the AOM, including less electric power consumption, optical gain which increases signal to noise ratio for lower power laser sources, faster extinction times allowing faster cavity decays to be measured, and fiber coupling which means the alignment is independent of laser frequency, unlike a free space AOM.

Acknowledgements

This work was supported by the University of Virginia. We wish to thank Dr. Yu Chen and Tiger Optics for lending us the mirrors used in this work.

References

[1] A. O'Keefe, D.A.G. Deacon, Rev. Sci. Instrum. 59 (12) (1988) 2544.
[2] D. Romanini, K.K. Lehmann, J. Chem. Phys. 99 (9) (1993) 6287.
[3] J.B. Dudek, P.B. Tarsa, A. Velasquez, M. Wladyslawski, P. Rabinowitz, K.K. Lehmann, Anal. Chem. 75 (17) (2003) 4599.
[4] K.K. Lehmann, Patent number 5 (528) (1996) 040.
[5] D. Romanini, A.A. Kachanov, N. Sadeghi, F. Stoeckel, Chem. Phys. Lett. 264 (3–4) (1997) 316.
[6] J. Morville, D. Romanini, M. Chenevier, A.A. Kachanov, Appl. Opt. 41 (33) (2002) 6980.
[7] H. Huang, K.K. Lehmann, Appl. Phys. B, submitted for publication.
[8] K.K. Lehmann, H. Huang, Optimal signal processing in cavity ring-down spectroscopy, in: J. Laane (Ed.), Frontiers of Molecular Spectroscopy, Elsevier, Amsterdam, 2008. Chapter 18.
[9] K. Tsuzuki et al., Electron. Lett. 39 (20) (2003) 1464.
[10] Personal communication from EOSpace, Inc., <http://www.eospace.com/>.
[11] C. Marxer et al., J. Microelectromechanical Syst. 6 (3) (1997) 277.
[12] X.D. Wang, P. Basseras, R.J.D. Miller, J. Sweetser, I.A. Walmsley, Opt. Lett. 15 (15) (1990) 839.
[13] J.G. Cormier, Development of an Infrared Cavity Ring-Down Spectroscopy Experiment and Measurements of Water Vapor Continuum Absorption, Ph.D. thesis, University of Toronto, 2002, p. 111 (Chapter 3).
[14] J.W. Hahn, Y.S. Yoo, J.Y. Lee, J.W. Kim, H.W. Lee, Appl. Opt. 38 (9) (1999) 1859.
[15] K. Petermann, Laser Diode Modulation and Noise, Kluwer Academic Publishers, Tokyo, 1988.
[16] H. Huang, K.K. Lehmann, Opt. Express 15 (14) (2007) 8745.
[17] M.J. Connelly, Semiconductor Optical Amplifier, Kluwer Academic Publishers, Boston, 2002.
[18] N.K. Dutta, Q. Wang, Semiconductor Optical Amplifier, World Scientific, New Jersey, 2006.
[19] We believe that neither precision current nor precision temperature controls of the SOA is required. We chose to use the LDX current driver both because we had it available and because the current can be turned off very fast and completely.
[20] K. Stubkjaer, IEEE J. Sel. Top. Quantum Electron. 6 (6) (2000) 1428.
[21] D. Cotter et al., Science 286 (5444) (1999) 1523.
[22] M.J. Connelly, IEEE J. Quantum Electron. 37 (3) (2001) 439.
[23] D.W. Allan, Proc. IEEE 54 (2) (1966) 221.
[24] P. Werle, R. Mucke, F. Slemr, Appl. Phys. B 57 (1993) 131.
[25] H. Huang, K.K. Lehmann, Long Term Stability in cw Cavity Ring-Down Spectroscopy Experiments, manuscript in preparation.