SYSTEM AND METHOD FOR CONTROLLING A LIGHT SOURCE FOR CAVITY RING-DOWN SPECTROSCOPY

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ABSTRACT

An apparatus and method for controlling a light source used in Cavity Ring-Down Spectroscopy. The apparatus comprises a controller that generates a control signal to activate and deactivate the light source based on a comparison of an energy signal from a resonant cavity and a threshold. The light source is activated for a predetermined period based on the stabilization time of the light source and the time necessary to provide sufficient energy to the resonant cavity. Thereafter the controller deactivates the light source for a predetermined time period by interrupting its current source so that the light energy in the cavity ring downs and so that the presence of analyte can be measured. The light energy from the light source is directly coupled to the resonant cavity from the light source.
Fig. 2
Fig. 4
Fig. 5
SYSTEM AND METHOD FOR CONTROLLING A LIGHT SOURCE FOR CAVITY RING-DOWN SPECTROSCOPY

FIELD OF THE INVENTION

[0001] This invention relates generally to absorption spectroscopy and, in particular, is directed to the activation and deactivation of a light source for use with an optical resonator for cavity ring-down spectroscopy.

BACKGROUND OF THE INVENTION

[0002] Referring now to the drawing, wherein like reference numerals refer to like elements throughout, FIG. 1 illustrates the electromagnetic spectrum on a logarithmic scale. The science of spectroscopy studies spectra. In contrast with sciences concerned with other parts of the spectrum, optics particularly involves visible and near-visible light—a very narrow part of the available spectrum which extends in wavelength from about 1 mm to about 1 nm. Near visible light includes colors redder than red (infrared) and colors more violet than violet (ultraviolet). The range extends just far enough to either side of visibility that the light can still be handled by most lenses and mirrors made of the usual materials. The wavelength dependence of optical properties of materials must often be considered.

[0003] Absorption-type spectroscopy offers high sensitivity, response times on the order of microseconds, immunity from poisoning, and limited interference from molecular species other than the species under study. Various molecular species can be detected or identified by absorption spectroscopy. Thus, absorption spectroscopy provides a general method of detecting important trace species. In the gas phase, the sensitivity and selectivity of this method is optimized because the species have their absorption strength concentrated in a set of sharp spectral lines. The narrow lines in the spectrum can be used to discriminate against most interfering species.

[0004] In any industrial processes, the concentration of trace species in flowing gas streams and liquids must be measured and analyzed with a high degree of speed and accuracy. Such measurement and analysis is required because the concentration of contaminants is often critical to the quality of the end product. Gases such as N₂, O₂, H₂, Ar, and He are used to manufacture integrated circuits, for example, and the presence in those gases of impurities—even at parts per billion (ppb) levels—is damaging and reduces the yield of operational circuits. Therefore, the relatively high sensitivity with which water can be spectroscopically monitored is important to manufacturers of high-purity gases used in the semiconductor industry. Various impurities must be detected in other industrial applications. Further, the presence of impurities, either inherent or deliberately placed, in liquids have become of particular concern of late.

[0005] Spectroscopy has obtained parts per million (ppm) level detection for gaseous contaminants in high-purity gases. Detection sensitivities at the ppb level are attainable in some cases. Accordingly, several spectroscopic methods have been applied to such applications as quantitative contamination monitoring in gases, including: absorption measurements in traditional long pathlength cells, photoacoustic spectroscopy, frequency modulation spectroscopy, and interference laser absorption spectroscopy. These methods have several features, discussed in U.S. Pat. No. 5,528,040 issued to Lehmann, which make them difficult to use and impractical for industrial applications. They have been largely confined, therefore, to laboratory investigations.

[0006] In contrast, continuous wave-cavity ring-down spectroscopy (CW-CRDS) has become an important spectroscopic technique with applications to science, industrial process control, and atmospheric trace gas detection. CW-CRDS has been demonstrated as a technique for the measurement of optical absorption that excels in the low-absorbance regime where conventional methods have inadequate sensitivity. CW-CRDS utilizes the mean lifetime of photons in a high-finesse optical resonator as the absorption-sensitive observable.

[0007] Typically, the resonator is formed from a pair of nominally equivalent, narrow band, ultra-high reflectivity dielectric mirrors, configured appropriately to form a stable optical resonator. A laser pulse is injected into the resonator through a mirror to experience a mean lifetime which depends upon the photon round-trip transit time, the length of the resonator, the absorption cross section and number density of the species, and a factor accounting for intrinsic resonator losses (which arise largely from the frequency-dependent mirror reflectivities when diffraction losses are negligible). The determination of optical absorption is transformed, therefore, from the conventional power-ratio measurement to a measurement of decay time. The ultimate sensitivity of CW-CRDS is determined by the magnitude of the intrinsic resonator losses, which can be minimized with techniques such as superpolishing that permit the fabrication of ultra-low-loss optics.

[0008] FIG. 2 illustrates a conventional CW-CRDS apparatus 200. As shown in FIG. 2, light is generated from a narrow band, tunable, continuous wave diode laser 202. Laser 202 is temperature tuned by a temperature controller (not shown) to put its wavelength on the desired spectral line of the analyte. An acousto-optic modulator (AOM) 204 is positioned in front of and in line with the radiation emitted from laser 202. AOM 204 provides a means for providing light 206 from laser 202 along the optical axis 219 of resonant cavity 218. Light 206 exits AOM 204 and is directed by mirrors 208, 210 to cavity mirror 220 as light 206a. Light travels along optical axis 219 and exponentially decays between cavity mirrors 220 and 222. The measurement of this decay is indicative of the presence or lack thereof of a trace species. Detector 212 is coupled between the output of optical cavity 218 and controller 214. Controller 214 is coupled to laser 202, processor 216, and AOM 204. Processor 216 processes signals from optical detector 212 in order to determine the level of trace species in optical resonator 218.

[0009] In AOM 204, a pressure transducer (not shown) creates a sound wave that modulates the index of refraction in an active nonlinear crystal (not shown), through a photothermal effect. The sound wave produces a Bragg diffraction grating that disperses incoming light into multiple orders, such as zero order and first order. Different orders have different light beam energy and follow different beam directions. In CW-CRDS, typically, a first order light beam 206 is aligned along with optical axis 219 of cavity 218 incident on the cavity in-coupling mirror 220, and a zero
order beam 224 is idled with a different optical path (other higher order beams are very weak and thus not addressed). Thus, AOM 204 controls the direction of beams 206, 224.

[0010] When AOM 204 is on, most light power (typically, up to 80%, depending on size of the beam, crystals within AOM 204, alignment, etc.) goes to the first order along optical axis 219 of resonant cavity 218 as light 206. The remaining beam power goes to the zero order (light 224), or other higher orders. The first order beam 206 is used for the input coupling light source; the zero order beam 224 is typically idled or used for diagnostic components. Once light energy is built up within the cavity, AOM 204 is turned off. This results in all the beam power going to the zero order as light 224, and no light 206 is coupled into resonant cavity 218. The stored light energy inside the cavity follows an exponential decay (ring down).

[0011] In order to "turn off" the laser light to optical cavity 218, and thus allow for energy within optical cavity 218 to "ring down," AOM 204, under control of controller 214 and through control line 224, redirects (deflects) light from laser 204 along path 224 and, thus, away from optical path 219 of optical resonator 218. This conventional approach has drawbacks, however, in that there are losses of light energy primarily through the redirecting means contained within the AOM. Other losses may also be present due to mirrors 208, 210 used to direct light from AOM 204 to optical cavity 218. It is estimated that only 50%-80% of light emitted by laser 202 eventually reaches optical resonator 218 as light 206a due to these losses. Furthermore, these conventional systems are costly and the AOM requires additional space and AOM driver (not shown) within the system.

[0012] To overcome the shortcomings of conventional systems, an improved system and method for providing and controlling laser light to a resonant cavity is provided. An object of the present invention is to replace the conventional AOM/control system with a simplified and cost effective control system.

SUMMARY OF THE INVENTION

[0013] To achieve that and other objects, and in view of its purposes, the present invention provides an improved apparatus and method for controlling a light source for use with a resonant cavity. The apparatus includes a controller for receiving a comparison of a detection signal and a predetermined threshold, a comparator generating a control signal to one of activate and deactivate the light source based on the comparison; a first delay circuit coupled to the controller for generating a first delay signal to the controller; and a second delay circuit coupled to the comparator and the controller for generating a second delay signal to the controller based on the comparison of the detection signal and the predetermined threshold.

[0014] According to another aspect of the invention, the light source provides light as an input to the resonant cavity to measure the presence of an analyte in the resonant cavity.

[0015] According to a further aspect of the invention, light from the source is coupled to the resonant cavity by an optical fiber.

[0016] According to yet another aspect of the invention, a collimator couples the light into the resonant cavity.

[0017] According to still another aspect of the invention, a comparator generates an output signal to the controller based on a comparison of the detection signal and a predetermined threshold.

[0018] According to yet a further aspect of the invention, a detector is coupled between the output of the resonant cavity and the comparator, and generates a signal based on the light output from the resonant cavity.

[0019] According to another aspect of the invention, the light source is deactivated based on the first delay signal.

[0020] According to yet another aspect of the invention, the light source is activated after an end of the first delay period.

[0021] According to yet another aspect of the invention, after an end of the first delay period, the light source is activated and energy builds up within the cavity through the current modulation.

[0022] According to still another aspect of the invention, an analyte level present in the resonant cavity is measured during the first delay period.

[0023] According to yet a further aspect of the invention, the controller deactivates the light source by shunting a supply of current for the light source.

[0024] According to yet another aspect of the invention, the light source is a laser.

[0025] The method includes the steps of, detecting a light energy signal output from the resonant cavity; comparing the detected signal with a predetermined threshold; generating a control signal to control the light source based on the comparison; generating a first delay signal to the controller; generating a second delay signal after the end of the first delay signal; providing a current modulation; and measuring a level of the analyte after an end of the second delay signal.

[0026] It is to be understood that both the foregoing general description and the following detailed description are exemplary, but are not restrictive, of the invention.

BRIEF DESCRIPTION OF THE DRAWING

[0027] The invention is best understood from the following detailed description when read in connection with the accompanying drawing. It is emphasized that, according to common practice, the various features of the drawing are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawing are the following figures:

[0028] FIG. 1 illustrates the electromagnetic spectrum on a logarithmic scale;

[0029] FIG. 2 illustrates a prior art CW-CRDS system;

[0030] FIG. 3A illustrates an exemplary embodiment of the present invention;

[0031] FIG. 3B illustrates another exemplary embodiment of the present invention;

[0032] FIG. 4 is an illustration of an exemplary controller of the present invention; and
FIG. 5 is a graph illustrating various delay timing according to an exemplary embodiment of the present invention.

DETAILLED DESCRIPTION OF THE INVENTION

FIG. 3A illustrates an exemplary embodiment of the present invention. As shown in FIG. 3A, light is generated from light source 302, such as a narrow band, tunable, continuous wave diode laser. Light source 302 is temperature tuned by a temperature controller (not shown) to put its wavelength on the desired spectral line of the analytic of interest. Light energy from light source 302 is coupled to fiber collimator 308 through optical fiber 304. Light energy 306 is, in turn, provided by collimator 308 to resonant cavity 318 and substantially parallel to its optical axis 319. Detector 312 is coupled between the output of optical cavity 318 and controller 314. Controller 314 is coupled to light source 302 and data analysis system 316. Data analysis system 316, such as a personal computer or other specialized processor, processes signals from optical detector 312, under control of controller 314, in order to determine the level of trace species (analyte) in optical resonator 318.

Preferably, light source 302 is a temperature and current controlled, tunable, narrow line-width, radiation, semiconductor laser operating in the visible to near- and mid-infrared spectrum. Alternatively, light source 302 may be an external-cavity semiconductor diode laser.

Resonant cavity 318 preferably comprises at least a pair of high reflectivity mirrors 320, 322 and a gas cell 321 on which the mirrors are mounted. Cell 321 can be a flow cell or vacuum cell, for example. Alternatively, and as shown in FIG. 3B, resonant cavity 318 may be comprised of a pair of prisms 324, 326 and a corresponding gas cell 321.

Detector 212 is preferably a photovoltaic detector, such as photodiodes or photo-multiplier tubes (PMT), for example.

Referring now to FIG. 4, a detailed block diagram of controller 314 is shown. As shown in FIG. 4, buffer 402 receives signal 313 (representing the amplitude of the ring down signal) from detector 312 (shown in FIGS. 3A-3B). Comparator 406 receives buffered signal 313 and performs a comparison with a threshold signal 404. In operation, threshold signal 404 is incremented upward until the output of comparator 406 is a zero state. Then, threshold signal 404 decrements until comparator 406 provides an output signal. As a result, threshold signal 404 is based on the level of the ring down signal. In this way, control circuit 408 is able to determine when ring down signal output from detector 312 dissipates.

Control circuit 408 generates control signal 408a based on the dissipation of the ring down signal in order to activate first delay circuit 412. At the end of the first delay period (time t1, as shown in FIG. 5), signal 412a is generated and provided to control circuit 408. In turn, control circuit 408 generates signal 408b to activate second delay circuit 414, and provides signal 408c to switch circuit 410, which in turn activates light source 302 (shown in phantom and described above with respect to FIGS. 3A and 3B). At the end of delay period t2 (shown in FIG. 5), delay circuit 414 generates signal 414a to control circuit 408 to indicate that light source 302 has stabilized and to begin a third time period t3 (shown in FIG. 5). Time period t3 (described in detail below with respect to FIG. 5) is used to ensure that resonant cavity 318 is fully charged through current modulation with light energy prior to measuring analyte concentration. At the end of time period t3, control signal 408c is deactivated, which in turn is used by switch circuit 410 to deactivate light source 302. In one embodiment of the present invention, switch circuit 410 shunts current from light source 302 using conventional power devices to deactivate light source 302.

Coincident with the deactivation of signal 408c, signal 408d is also generated and provided to data analysis system 316 (shown in phantom and described above with respect to FIGS. 3A and 3B). Although signal 408c and 408d are shown as separate signals, it may be preferable to combine them into a single control signal if desired. In such an approach conditioning of signal 408c may be required to provide a convenient control signal logic level (based on digital signals, for example) to provide proper control of data analysis system 316.

Signal 408d (in the two-signal 408c/408d approach) is used by data analysis system 316 to indicate that light source 302 has been deactivated and that the measurement of the analyte should begin. At this point, the process repeats itself to measure successive ring downs by once again initializing first delay circuit 412 through control circuit 408.

Since the above description relates to ongoing measurement of analytes, the circuit needs to be initialized prior to the first measurement. To accomplish this initialization, an initialization signal 420 is provided as an input to first delay circuit 412. Upon activation of initialization signal 420, such as through a button, or control signal from data analysis system 316, for example, delay time to begins. The process then follows the procedure outlined above.

In the exemplary embodiment, switch circuit 410 provides three functions: 1) as a laser current driver providing laser driving current for a desired output of laser power, 2) providing current modulation resulting in energy build-up within cavity 318, and 3) as a current switch/shunt for enabling/disabling current drive to light source 302.

As a result, controller 314 energizes light source 302 to generate energy into resonant cavity 318, employs a first delay to allow light source 302 to stabilize before looking for new data, utilizes a second delay to wait for a build up of sufficient light energy in the cell, then turns off the energy to light source 302. Another delay is employed after energy is removed from light source 302 to allow the light energy to completely ring down. This process is then repeated for a single wavelength ring-down data at a given temperature. Ring-down spectra are processed by the data analysis system 316. These various delays are illustrated in FIG. 5.

As shown in FIG. 5, at time t1, light source 302 is energized by providing operating current I1, which is above the light source's threshold current Ith. Threshold current Ith varies based on the type of light source used. Delay time t1 represents the delay to allow the light source to stabilize. In one exemplary embodiment, delay time t2 is set to about 100 usec. Delay time t3 represents the time to allow the current...
modulation to build up within resonant cavity 318. It should be noted that the time required for the current modulation to build up within resonant cavity 318 is \( << 1 \).

[0046] In an exemplary embodiment, time delay \( t_3 \) is based on the modulation frequency \( f \) of light source 302, and is preferably equal to about 1/ \( f \). Time delay \( t_1 \) is based on the ring down time of resonant cavity 318. In order to allow sufficient time for light energy to "ring down" in resonant cavity 318, time delay \( t_1 \) is preferably set to about ten (10) times the ring down time of the cavity.

[0047] Laser temperature driver 416, under control of convention means (not shown), provides temperature control for light source 302 for the generation of a desired light frequency at a given temperature. The frequency is selected based on the particular analyte of interest.

[0048] Various advantages are realized from the present invention, such as:

[0049] Allowing use of almost 100% of the beam power generated by light source 202 (there may be negligible albeit undetectable losses within optical fiber 304 and collimator 308). Higher intracavity energy build-up provides better signal to noise ratio and reduces shot noise. This is extremely beneficial when a light source is weak. As mentioned above, typically, only about 50-80% of light power goes to the first order when light passes through an AOM.

[0050] Cost savings are realized from eliminating the AOM. A typically commercially available AOM costs approximately $2,000.

[0051] Simplified CW-CRDS setup—This allows more spatial flexibility for the setup arrangements, and eliminates the mechanical and optical sensitivity, introduced by the AOM, to the testing environment.

[0052] Although illustrated and described herein with reference to certain specific embodiments, the present invention is nevertheless not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the spirit of the invention.

What is claimed is:

1. An apparatus for controlling a light source for use with a resonant cavity, the apparatus comprising:
   - a controller for receiving a comparison of a detection signal and a predetermined threshold, the comparator generating a control signal to at least one of activate and deactivate the light source based on the comparison;
   - a first delay circuit coupled to the controller for generating a first delay signal to the controller; and
   - a second delay circuit coupled to the comparator and the controller for generating a second delay signal to the controller based on the comparison of the detection signal and the predetermined threshold.

2. The apparatus according to claim 1, wherein the first delay circuit is initialized by an initialization signal.

3. The apparatus according to claim 1, wherein the light source provides light as an input to the resonant cavity used to measure the presence of an analyte in the resonant cavity.

4. The apparatus according to claim 1, wherein light from the source is coupled to the resonant cavity by an optical fiber.

5. The apparatus according to claim 4, further comprising a fiber collimator coupled between the optical fiber and an input of the resonant cavity.

6. The apparatus according to claim 1, further comprising a comparator to generate an output signal to the controller based on the comparison of the detection signal and the predetermined threshold.

7. The apparatus according to claim 6, further comprising a detector coupled between an output of the resonant cavity and the comparator, the detector generating the detector signal.

8. The apparatus according to claim 1, wherein the light source is deactivated based on a time period of the first delay circuit.

9. The apparatus according to claim 8, wherein the first delay period is based on a ring down time period of the resonant cavity.

10. The apparatus according to claim 9, wherein the first delay period is about 10 times the ring down period.

11. The apparatus according to claim 8, wherein the light source is activated after an end of the first delay period.

12. The apparatus according to claim 8, wherein an analyte level present in the resonant cavity is measured during the first delay period.

13. The apparatus according to claim 1, wherein a period of the second delay circuit is based on a stabilization time of the light source.

14. The apparatus according to claim 13, wherein the second delay period is about 100 msecs.

15. The apparatus according to claim 1, wherein the first delay signal is generated after a third delay period.

16. The apparatus according to claim 15, wherein the third delay period is based on a modulation frequency of the light source.

17. The apparatus according to claim 16, wherein the third delay period is an inverse of the modulation frequency.

18. The apparatus according to claim 15, wherein the third delay period follows the second delay period.

19. The apparatus according to claim 15, wherein light energy builds up within the resonant cavity during the third delay period.

20. The system according to claim 1, wherein the light source is a laser.

21. A system for use with a light source to measure the presence of an analyte in a resonant cavity, the system comprising:
   - a detector coupled to an output of the resonant cavity to generate a detection signal based on a light output from the resonant cavity;
   - a controller coupled to the light source, the controller activating and deactivating the light source based on the detection signal; and
   - a processor coupled to the controller to process the detection signal and determine a level of the analyte present in the resonant cavity.

22. The system according to claim 21, wherein the controller deactivates the light source by shunting a supply of current for the light source.
23. The system according to claim 21, further comprising an optical fiber coupling light energy from the light source to the resonant cavity.

24. The system according to claim 23, further comprising a fiber collimator coupled between an end of the optical fiber and the resonant cavity.

25. The system according to claim 21, wherein the controller activates the light source for a first predetermined time period and deactivates the light source for a second predetermined time period.

26. The system according to claim 25, wherein the first predetermined period is about based on a stabilization time of the light source.

27. The system according to claim 26, wherein the first predetermined period is further based on a modulation frequency of the light source.

28. The system according to claim 21, wherein the light source is a laser.

29. The system according to claim 21, wherein the energy is light energy.

30. A method for measuring the presence of an analyte in a resonant cavity, the method comprising the steps of:

   detecting a light energy signal output from the resonant cavity;

   comparing the detected signal with a predetermined threshold;

   generating a control signal to control the light source based on the comparison;

   generating a first delay signal to the controller;

   generating a second delay signal after an end of a first delay period; and

   measuring a level of the analyte after an end of a second delay period.

31. The method according to claim 30, further comprising the steps of:

   activating the light source following generation of the second delay signal; and

   deactivating the light source during at least said first delay period.

32. The method according to claim 30, further comprising the step of providing an initialization signal to initialize the first delay signal.

33. A system for measuring the presence of an analyte in a resonant cavity, the system comprising:

   detecting means for detecting a light energy signal output from the resonant cavity;

   comparison means for comparing the detected signal with a predetermined threshold;

   control means for generating a control signal to control the light source based on the comparison;

   first delay means for generating a first delay signal to the controller and initiating a first delay period;

   second delay means for generating a second delay signal and initiating a second delay period after an end of the first delay period; and

   processing means for measuring a level of the analyte after an end of the second delay period.

34. The system according to claim 33, wherein said processing means measures a level of analyte during said first delay period.

35. An apparatus for controlling a light source for use in cavity ring-down spectroscopy, the apparatus comprising:

   a controller for receiving a comparison of a detection signal and a predetermined threshold, the comparator generating a control signal to at least one of activate and deactivate the light source based on the comparison;

   a first delay circuit coupled to the controller for generating a first delay signal to the controller; and

   a second delay circuit coupled to the comparator and the controller for generating a second delay signal to the controller based on the comparison of the detection signal and the predetermined threshold.

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