



(22) Date de dépôt/Filing Date: 2014/11/03

(41) Mise à la disp. pub./Open to Public Insp.: 2016/05/03

(51) Cl.Int./Int.Cl. *G01J 3/433* (2006.01),
G01J 3/10 (2006.01)

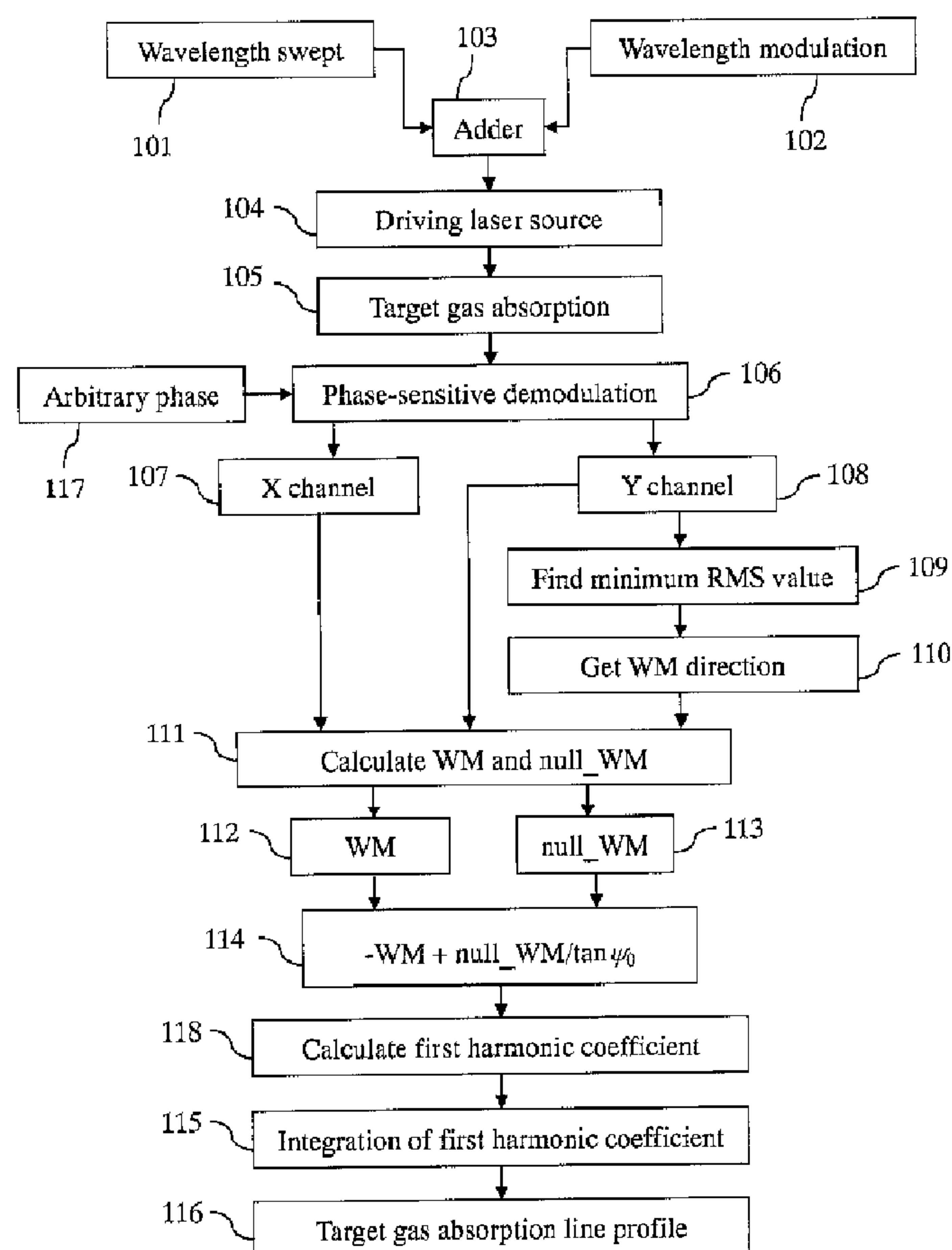
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(54) Titre : SPECTROMETRE INFRAROUGE HAUTE RESOLUTION SANS ETALONNAGE

(54) Title: HIGH RESOLUTION CALIBRATION-FREE INFRARED SPECTROMETER



(57) Abrégé/Abstract:

This invention provides a novel high resolution infrared spectrometer to recover the infrared gas absorption line profile which is determined by gas concentration, pressure and temperature. Above three parameters of target gas, therefore, can be derived from

(57) **Abrégé(suite)/Abstract(continued):**

the recovered line profile, this method is called as a calibration-free gas detection technique. This invention improves the current technique of tunable diode laser spectroscopy (TDLS) and wavelength modulation spectroscopy (WMS) by integrating the first harmonic component of the non-linear wavelength modulated absorption. This invention has been experimentally proved as a high resolution gas detection technique. The data processing in this invention is implemented by a field programmable gates array (FPGA) and relative electronic circuits.

1 ABSTRACT

2
3 This invention provides a novel high resolution infrared spectrometer to recover the infrared gas
4 absorption line profile which is determined by gas concentration, pressure and temperature. Above
5 three parameters of target gas, therefore, can be derived from the recovered line profile, this method
6 is called as a calibration-free gas detection technique. This invention improves the current technique
7 of tunable diode laser spectroscopy (TDLS) and wavelength modulation spectroscopy (WMS) by
8 integrating the first harmonic component of the non-linear wavelength modulated absorption. This
9 invention has been experimentally proved as a high resolution gas detection technique. The data
10 processing in this invention is implemented by a field programmable gates array (FPGA) and
11 relative electronic circuits.

HIGH RESOLUTION CALIBRATION-FREE INFRARED SPECTROMETER

FIELD

[001] The innovation relates generally to infrared spectroscopy and particularly to a tunable diode laser spectroscopy and wavelength modulation spectroscopy, and the method and apparatus to gas detection.

BACKGROUND

[002] The gas monitoring is significant for industrial, environmental and medical applications, such as processing control, air pollution detection, in-situ and non-intrusive clinical diagnosis, greenhouse gas measurement, exhaust gas monitoring of petroleum refineries and vehicles, natural gas pipeline leaking inspections, and so on. For the gas detection in some harsh and remote environments, including high temperature and high pressure engine turbine, very low temperature arctic area, under water or under ice natural gas exploration, the current chemical gas sensors are unavailable due to the temperature sensitivity, short life time and require of frequent calibration. On the other hand, for above applications, additional temperature sensors and pressure gauges are necessary to provide extra information to support an complete measurement. The inherent measurement error due to the sensing principle of different types of temperature and pressure sensors, however, limits the detection accuracy. Moreover, the system cost is higher because of the additional sensors.

[003] A novel calibration-free technique, therefore, is required to obtain gas concentration, temperature and pressure simultaneously via a uniform sensing principle.

[004] Infrared spectroscopy can analyze the sort and concentration of target gas based on infrared absorption. The specific spectrum of the target gas can be distinguished from other types of gas,

1 which is called as “fingerprint” spectrum. The spectral line in gas infrared absorption spectrum is
2 dependent on gas concentration, gas pressure and temperature in line width and line strength,
3 respectively. The simultaneous measurement of gas concentration, pressure and temperature,
4 therefore, can be derived from the detected infrared absorption line profile of target gas.

5
6 [005] Wavelength tunable laser diode is a light source with a narrow line width which is higher
7 than three order of magnitude narrower than the line width of gas infrared absorption line profile.
8 The narrow line width laser beam can be considered as a point when the laser wavelength is tuning
9 to scan through the gas absorption line profile. The high resolution spectral measurement, therefore,
10 can be achieved by the wavelength scales made from such fine wavelength tuning laser source. This
11 technique is called as tunable diode laser spectroscopy (TDLS).

12
13 [006] The laser wavelength tuning typically implements at low frequency, mostly is less than 50
14 Hz. The low frequency noise and other external noise sources such as vibration, power supply
15 ripples can introduce error to the pure tunable diode laser spectroscopy. Similarly to the
16 telecommunication, high frequency modulation can solve the problem caused by low frequency
17 noise. For a laser source, four parameters can be modulated: intensity, frequency/wavelength, phase,
18 and polarization. The pure intensity modulation can be achieved by an external modulator such as a
19 micro-electro-mechanical system (MEMS) rotary mirror. The wavelength modulation can be
20 obtained by modulate the laser diode driving current. A residual intensity modulation, however,
21 appears with the wavelength modulation because the carrier concentration of laser diode is also
22 changed with the driving current. Considering the system cost, the wavelength modulation with the
23 residual intensity modulation is more economical than the pure intensity modulation which needs an
24 external modulator.

25
26 [007] When the laser wavelength is modulated at a high frequency and is also tuned at a low
27 frequency to scan through an absorption line profile of the target gas, the non-linear line profile and
28 the periodic modulated wavelength can generate a periodic and non-linear signal which can be

1 decomposed as a Fourier series. Every term of the decomposed Fourier series corresponds to a
2 harmonic component of the absorption line profile. A phase sensitive demodulation technique can be
3 used to obtain an individual harmonic component. Such method is the wavelength modulation
4 spectroscopy.

5
6 [008] The original absorption line profile can be recovered from the demodulated harmonic
7 component through further data process. Some published research articles have introduced the
8 absorption line profile recovery based on the residual amplitude modulation (RAM). However, the
9 detection sensitivity is poor due to the weak RAM signal. The main part of the demodulated
10 harmonic component is caused by the wavelength modulation. Therefore, a high sensitive line
11 profile recovery should be derived by the wavelength modulation term, not the weak RAM term.
12 This invention is developed based on above background and analysis to recover the target gas
13 absorption line profile from wavelength modulation.

14 15 16 SUMMARY

17
18 [009] This invention is an infrared spectrometer that is capable to measure the target gas
19 concentration, pressure and temperature simultaneously based on the recovery of gas absorption line
20 profile. Two spectral techniques are used in this invention: tunable diode laser spectroscopy and
21 wavelength modulation spectroscopy. A wavelength tunable laser diode based on distributed
22 feedback (DFB) configuration or with the discrete mode (DM) is used as the light source. The
23 wavelength tuning range of the light source should reach the target gas absorption spectrum. Near
24 infrared DFB or DM laser diodes or mid-infrared DFB quantum cascade lasers (QCL) can cover the
25 overtone/combine or fundamental absorption spectrum, respectively, of most sorts of gas.

26
27 [010] For an infrared active gas, which means the gas has the infrared absorption, the
28 fundamental absorption spectrum at mid-infrared region from 3 to 12 microns is 2 to 3 orders of

1 magnitude stronger than the overtone or combine absorption spectrum at near infrared region from
2 0.8 to 3 microns. However, the price of near infrared laser diode is lower than the mid-infrared QCL.
3 The gas absorption line profile recovery in this invention is independent on the near or mid-infrared
4 tunable light source. In this invention, near infrared tunable laser diode is selected as the light source
5 by considering the economical cost. Nevertheless, the light source can be replaced as a mid-infrared
6 QCL for the application of very high sensitive detection.

7
8 [011] The technique of gas absorption line profile recovery in this invention is based on the first
9 harmonic component of the wavelength modulated absorption signal. For a low modulation index,
10 such first harmonic is proportional to the first derivative of the absorption line-shape. Therefore, the
11 target absorption line profile can be recovered by integrating the first harmonic component of the
12 wavelength modulated absorption signal and compensating the amplitude difference between the
13 first harmonic and the first derivative. This technique is called as first harmonic integration
14 spectroscopy (FHIS).

15
16 [012] The wavelength modulated absorption signal can be demodulated by the phase sensitive
17 detection. A lock-in amplifier instrumentation or a digital signal processor (DSP) or field
18 programmable gate array (FPGA) based lock-in circuit can demodulate the gas absorption signal at
19 the modulation frequency to obtain the first harmonic component. This is different from the
20 common harmonic detection of TDLS which demodulates the signal at double modulation frequency
21 to get the second harmonic component. In this invention, the FPGA based lock-in circuit is
22 implemented by considering the system integration and cost. The modulation and tuning for the
23 laser diode are also accomplished by the FPGA and relative circuits in this invention.

24
25 [013] Two common methods can be used to measure the absorption by the target gas:
26 photoacoustic technique, and photodiode direct detection. The photoacoustic signal is generated by
27 the periodic gas absorption and the consequent periodic local thermal variation and pressure change.
28 The photoacoustic amplitude is proportional to the gas absorbance and laser power. The photodiode

1 direct detection measures the transmitted laser after the gas absorption, which is independent to the
2 laser power. So a division calculation is necessary to obtain the transmittance of the target gas. The
3 sum of gas absorbance and transmittance is equal to 1. The division calculation is not easy to
4 implement for the analog or digital circuit. The photoacoustic method, hence, is more suitable to
5 achieve an actual spectrometer. Moreover, the acoustic sensing can be accomplished by a low price
6 microphone that is insensitive to the laser wavelength. On the other hand, the photodiode has its
7 own work wavelength range and the price of the photodiode is higher than a commercial
8 microphone. When the light source of the spectrometer is selected as a mid-infrared QCL, the
9 photoacoustic technique is much better than the photodiode detection because of the very high price
10 and the cooling requirement of the mid-infrared photodiode. So the photoacoustic technique is used
11 in this invention to measure the gas absorption.

12
13 [014] The spectrometer in this invention is designed to detect one sort or more than one sorts of
14 gas by choosing the available wavelength of the laser diode to be close to the target gas absorption
15 region. In near infrared range, the absorption spectra of different sorts of gas are overlapped, which
16 lets the multiple gas detection be possible by an individual laser diode, such as measuring the
17 concentrations of acetylene and water vapor simultaneously at the wavelength of 1.53 microns.

18
19 [015] The spectrometer in this invention works at near infrared region. It can be applied in the
20 area of natural gas exploration, pipeline or compressed natural gas (CNG) leakage detection and
21 under well natural gas and pressure monitoring by recovering the absorption line profile of methane
22 at the wavelength close to 1.66 microns. The simultaneous measurement of multiple parameters,
23 including gas sort, gas concentration, pressure and temperature, is especially significant for the
24 applications of natural gas processing and transmission under water and is also important to the
25 process control and exhaust monitoring of petroleum refineries. Meanwhile, the greenhouse gas
26 such as carbon dioxide, nitrous oxide and methane, the explosive gas such as acetylene, poisonous
27 and natural gas accompanied sulphide gas, e.g. H_2S , ammonia in food factories can all be detected
28 by such spectrometer in this invention. Another application area is the remote sensing because the

1 optical fiber can transmit the laser over a long distance with a low loss. The sensing head of the
2 spectrometer can reach the human unsuitable spot to implement the detection. Moreover, a
3 distributed sensing network can be accomplished by the multiple address technique of optical fiber
4 to measure the gas parameters at different locations by an individual light source to save the system
5 cost.

6
7
8 BREF DESCRIPTION OF THE DRAWINGS

9
10 [016] FIG. 1 is the flow chart of theoretical principle and data processing for this invention.

11
12 [017] FIG. 2 is the drawing of photoacoustic gas cell and the V-groove mount.

13
14 [018] FIG. 3 is the system setup of this invention.

15
16 [019] FIG. 4 is the measurement result of two channel signals by the phase sensitive
17 demodulation at an arbitrary detection phase, this is one example of this invention.

18
19 [020] FIG. 5 is the recovered first harmonic coefficient for the following integration, compared
20 with the simulated result.

21
22 [021] FIG. 6 is the recovered target gas absorption line profile, compared with the theoretical line
23 profile.

24
25 [022] FIG. 7 is the detail of finite trapezoid elements integration for the first harmonic coefficient
26 integration to recover the target gas absorption line profile.

DETAILED DISCRIPTION

[023] The detailed principle of this invention and the data processing is shown in FIG. 1. The wavelength modulation **102** for a tunable laser diode can be accomplished by a sinusoidal current adds by an adder **103** on a injection ramp current which drives the laser diode **104**. The ramp driving current **101** can sweep the wavelength of the laser diode through a wavelength range to reach the target gas absorption line and then generate the gas absorption, this is the key point of the TDLS. The additional sinusoidal current modulation causes a wavelength dither, can be written as (in wavenumber which is equal to the inverse of wavelength): $\nu_m = \nu + \delta\nu \times \cos(\omega t - \psi_0)$, where ν_m is the laser frequency (wavenumber) combines the frequency dither; ν is the laser frequency sweeps over the absorption line by a ramp injection current; $\delta\nu$ is the amplitude of frequency dither under the current modulation; ω is the angular frequency of the sinusoidal modulated current; ψ_0 is the phase lag between the residual intensity and the wavelength modulation of the laser diode. The incident laser intensity I_{in} to the target gas is varied by two mechanisms: one is the continuously changing by the ramp current I_0 , the other one is the sinusoidal amplitude variation ΔI by the current modulation, can be written as: $I_{in}(\nu) = I_0(\nu) + \Delta I(\nu) \times \cos(\omega t)$.

[024] Photoacoustic signal is proportional to the absorbed laser intensity by the target gas **105** based on Beer-Lambert law in the case of $\alpha(\nu)Cl \ll 1$: $I_{abs} = I_{in} \alpha(\nu)Cl$, where I_{abs} is the absorbed laser intensity, $\alpha(\nu)$ is the function of the target gas absorption line at wavenumber ν , C is concentration of measured gas, and l is absorption length. The absorption profile $\alpha(\nu)$ is the product of absorption coefficient α_0 at line centre ν_0 and the Lorentzian profile assuming for the lineshape $f(\nu)$: $\alpha(\nu) = \alpha_0 f(\nu)$, $f(\nu) = \{1 + [(\nu - \nu_0)/\gamma]^2\}^{-1}$, where γ is the half-width of the line profile. The line width of the absorption line is dependent on gas concentration (C), pressure (P , in unit of atm) and temperature (T , in unit of K):

$$\gamma(P, T) = \left(\frac{T_0}{T}\right)^n \left[\gamma_{air}(P_0, T_0) \cdot P \cdot C_{air} + \gamma_{gas}(P_0, T_0) \cdot P \cdot C_{gas} \right] \quad (1)$$

where γ_{air} and γ_{gas} are air broadening coefficient ($\text{cm}^{-1}/\text{atm}$) and self-broadening coefficient ($\text{cm}^{-1}/\text{atm}$) of target gas, respectively, and n is the temperature coefficient of the absorption line, above three parameters can be looked up in HITRAN Database under the reference conditions of $P_0=1$ atm and $T_0=296$ K. The line strength of the absorption line is defined as its integration area which is also relative to the temperature. Therefore, when one or more absorption line profiles are recovered, the gas concentration, pressure and temperature can be derived.

[025] Substituting $\omega t - \psi_0$ as $\theta(t)$ for convenience, and rewriting the absorption signal in the case of laser wavelength tuning and modulation, as:

$$I_{\text{abs}}(\theta) = \frac{I_{\text{in}} \alpha_0 C l}{1 + \left(\frac{\nu_L - \nu_0 + \delta \nu \cos \theta}{\gamma} \right)^2} = \frac{I_{\text{in}} \alpha_0 C l}{1 + (\Delta + m \cos \theta)^2} \quad (2)$$

Where $\Delta = (\nu_L - \nu_0)/\gamma$ expresses the laser frequency sweeps through the lineshape, $m = \delta \nu/\gamma$ is defined as the modulation index. The periodic even function $I_{\text{abs}}(\theta)$ can be analyzed by a Fourier series. Harmonic components of such Fourier series can be extracted by a phase sensitive detection. The first harmonic component has the same pattern with the first derivative of gas absorption line but needs to multiply a amplitude correction coefficient, when m is less than 0.2. Consequently, the absorption line profile can be obtained by integrating the first harmonic component. However, the actual first harmonic component is disturbed by a DC component and a second harmonic component caused by the residual laser intensity modulation. The integration of the measured first harmonic signal, therefore, includes unwanted parts which distort the line profile recovery. For signals demodulated by two-channel **107**, **108** phase sensitive detection **106**, a pair of orthogonal components can be obtained along a setting axis and its perpendicular axis. It has been proved that a phase lag exists between the wavelength modulation and residual amplitude modulation for a diode laser. Two pairs of different demodulation signals of the first harmonic component, hence, can be obtained along the setting axis of amplitude modulation (AM) or the axis of wavelength modulation (WM) **112**. The orthogonal axes of AM and WM are defined as null_AM and null_WM **113**, respectively.

[026] The phase sensitive demodulated first harmonic orthogonal pairs along AM/null_AM and WM/null_WM **112, 113** axes can be written as following, respectively:

(a) when the X-axis is aligned along “AM”:

$$\begin{aligned} X_axis\ output &= A \left\{ a_0(\nu) \cdot \Delta I(\nu) - a_1(\nu) \cdot I_0(\nu) \cos(\psi_0) + \frac{1}{2} a_2(\nu) \cdot \Delta I(\nu) \cos(2\psi_0) \right\} \\ Y_axis\ output &= A \left\{ a_1(\nu) \cdot I_0(\nu) \sin(\psi_0) - \frac{1}{2} a_2(\nu) \cdot \Delta I(\nu) \sin(2\psi_0) \right\} \end{aligned} \quad (3)$$

(b) when the X-axis is aligned along “WM” **110**:

$$\begin{aligned} X_axis\ output &= A \left\{ -a_1(\nu) \cdot I_0(\nu) + \left(a_0(\nu) + \frac{1}{2} a_2(\nu) \right) \cdot \Delta I(\nu) \cos(\psi_0) \right\} \\ Y_axis\ output &= A \left\{ \left(a_0(\nu) - \frac{1}{2} a_2(\nu) \right) \cdot \Delta I(\nu) \sin(\psi_0) \right\} \end{aligned} \quad (4)$$

where A is the absorbance at line centre ν_0 which is equal to the product of absorption coefficient α_0 at line centre, gas concentration C and optical path length l : $A = \alpha_0 Cl$; a_0 , a_1 and a_2 are DC, first and second coefficients of Fourier series, those terms with the coefficient a_n means the n^{th} harmonic component, ψ_0 is equal to the phase lag between AM and WM subtracts π or 180 degrees.

[027] The second harmonic term ($2f$) in the first harmonic ($1f$) demodulated signal can be considered as negligible because of its tiny value for low m . The DC component in $1f$ is the distortion term and should be eliminated in order to pursue the following first harmonic integration. A calculation among two-channel data and the tangent value of the phase lag between AM and WM can accomplish it. Above processing and assumption are based on the demodulated $1f$ signals along the axes of AM/null_AM or WM/null_WM accurately. For an individual absorption line with $m < 0.2$, the symmetrical property of the line profile and consequent DC, 1st and 2nd Fourier coefficients can get the AM axis easily: two equal peaks and almost zero value at line center in Y-axis signal. For the WM axis **110** selection, a symmetry pattern and the maximum value at the line center corresponds to

the signal along the axis of null_WM. However, when the target gas concentration is low, such as 100 parts-per-million (ppm), the noise level should be considered because it can distort the symmetric waveform and can disturb the values at above special positions. So the previous description of the AM and WM axes selection is difficult. On the other hand, if the absorption line is overlapped with other lines which will be common when the gas temperature is high up to several hundred degrees Celsius and then the “hot band” lines become strong, the symmetries of the absorption line and the Fourier coefficients are not valid any more. In this case, the two peaks in Y-axis signal of the demodulation along AM axis are not equal probably, and the value at line center may not be equal to zero.

[028] Because of no background signal, the photoacoustic spectroscopy is easier to get the demodulation signals along WM axis than AM axis. But it has been mentioned above that the noise influences the selection of WM axis for the case of low concentration. In order to get the distinct output signals with a good signal-to-noise ratio (SNR) from the phase sensitive detection, an arbitrary detection phase for the phase sensitive detection is chosen to ensure the demodulated signals in two channels have obvious magnitudes and clear waveforms. On the other hand, two channel signals with any phase shift φ from the measured axis can be calculated by the following equation:

$$\begin{aligned} X_axis\ output &= X_axis\ input \times \cos(\varphi) + Y_axis\ input \times \sin(\varphi) \\ Y_axis\ output &= -X_axis\ input \times \sin(\varphi) + Y_axis\ input \times \cos(\varphi) \end{aligned} \quad (5)$$

where the X- and Y-axis outputs are calculated by the measured two-channel signals (X- and Y-axis inputs) and the phase shift. In the Y-axis signal of WM, there is no I_0 term only is ΔI term, so a conclusion can be deduced that the Y-axis signal of WM has the minimum root mean square (RMS) value **109**. This means the X- and Y- signals of WM can be derived by above equations and a simple calculation by searching the minimum value, this is the data process of step **111** in FIG. 1. When the WM (X) **112** and null_WM (Y) **113** signals are confirmed according to above description, the first harmonic coefficient a_1 can be derived by further calculation because a_2 has been assumed as negligible for $m < 0.2$, this is the step **114** in FIG. 1:

$$a_1(\nu) \cdot I_0(\nu) = -X_axis\ output + Y_axis\ output / \tan(\psi_0) \quad (6)$$

The first harmonic $a_1(\nu)$ calculated by above equation is proportional to the first derivative of the absorption line, this is the step **118** in FIG. 1, so it can be integrated to recover the target gas line profile **116**, this is the step **115** in FIG. 1.

[029] FIG. 2 presents the drawing of the photoacoustic gas cell based on the low price glass tube **202**. The dimensional size of **202** is 30 mm long, 1.8 mm inner diameter and 2.8 mm outer diameter. The inner diameter of the gas cell **202** is much less than the length, so the longitudinal resonant mode can be generated by such gas cell. The gas cell **202** is hold by a V-groove base **201**, and the V-groove base **201** is put in a closed gas chamber. This means the photoacoustic gas cell is a open gas cell. The acoustic wave can be reflected at the two ends of the gas cell to generate the standing wave at the resonant frequency of the gas cell **202**. A high sensitive microphone **203** is the acoustic sensor to measure the resonant signal generated by the gas absorption. The microphone **203** is mounted at the center of gas cell where the anti-node of photoacoustic wave occurred for the first longitudinal resonant mode. The fiber **314** pigtailed gradient refraction index (GRIN) lens **204** delivers and collimates the laser beam to the gas cell. The diameter of the GRIN lens is 10 mm long, 2.8 mm diameter. The GRIN lens **204** is also mounted on the V-groove **201**. At the opposite end of the V-groove **201**, a ceramic solid cylinder **205** with the diameter of 2.8 mm is mounted that acts as a laser beam dump for safety.

[030] The system setup is illustrated in FIG. 3. The single-mode tunable DFB or DM laser diode **303** works at near infrared region is acted as the light source mounted on a laser PCB module to connect the external current driving **302** and temperature controller **301**. The temperature controller **301** and the laser diode driver a **302** re commercial modals. An alternative rare earth ion doped or Raman fiber amplifier **313** can enhance the laser power to increase the detection sensitivity. The type of the fiber amplifier **313** depends on the sort of the target gas and the wavelength range of the laser source **303**. Single-mode low loss optical fiber **311** is used as the transmission medium of laser.

[031] The swept ramp current **307** and the sinusoidal modulation signal **308** are added by a field programmable gate array (FPGA) integrated circuit chip **305**. The digital waveform data of 1Hz ramp signal **307** and the sinusoidal modulation **308** with the first longitudinal resonant frequency of the photoacoustic gas cell **202** are calculated advanced and saved in a Electrically Erasable Programmable Read-Only Memory (EEPROM) **306**. The program developed by inventor of this invention for FPGA **305** can read the data of ramp and sine wave from EEPROM **306** and adds them as a combination signal and then output from FPGA **305** to a digital to analog converter (DAC) **304** to convert the digital combination signal to an analog signal which is connected to the laser current driving module **302**. The analog acoustic signal is detected by the microphone **203** and is converted to a digital signal by an analog to digital converter (ADC) **309**. The digital detected signal is an input signal of FPGA **305** and is demodulated by a phase-sensitive lock-in module which is one part of the program developed by inventor for FPGA **305**. The X and Y components or amplitude and phase components of the first harmonic component of the detected absorption signal can be obtained simultaneously by the phase-sensitive lock-in module.

[032] A single mode optical fiber coupler **321** with the coupling ratio of 10:90 is used to split the output power of the laser diode **303**. The 90 percent laser power **319** is amplified by the alternative optical amplifier **313** and then the amplified laser beam **314** passes through the target gas in gas cell **202**, and the rest 10 percent laser power **320** is split again by a single mode optical fiber coupler **322** with the coupling ratio of 50:50. Therefore, 5 percent laser beam **315** is monitored by a low noise photodiode **310** to play as a power reference and the other 5 percent laser beam **316** is connected to a fiber optic etalon **312** to be a wavelength reference for the swept wavelength/wavenumber of the laser diode **303**. On the other hand, the dither frequency of the sinusoidal wavelength modulation can also be measured by the fiber optical etalon **312** to calculate the value of m .

[033] The two channel X **107** and Y **108** signals can be demodulated by the lock-in module in FPGA **305** easily in an arbitrary detection phase with the reference sync signal same frequency as

the sinusoidal modulation. The amplitude of X^2+Y^2 alone wavelength and the current detection phase $\tan^{-1}(Y/X)$ can be calculated. This can help the program of FPGA 305 to estimate the available amplitudes of X and Y channels to achieve a good signal-to-noise ratio (SNR) for both channels. If the SNR for one channel is not good, the program of FPGA 305 can automatically glancing adjust the detection phase to get big signals for both channels. This means the exact WM direction 110 is not necessary to find out by fine tuning the detection phase which wastes more processing time. Consequently, the actual WM (X) 112 and null_WM (Y) 113 signals can be calculated by program of FPGA 305 based on above theoretical analysis to find the minimum RMS of Y channel signal by iteration algorithm. Here, one example with the target gas of 100 parts-per-million (ppm) acetylene and 1.53 microns laser wavelength is implemented in order to verify the invention. FIG. 4 presents the obtained X and Y signals by the two channel phase sensitive demodulation at an arbitrary detection phase, “Z” in FIG. 4 is the index of measured data, and “S” in FIG. 4 is the measured signal amplitude in unit of volt.

[034] The first coefficient of the Fourier series a_1 can be derived by the calculation of $-\text{WM} + \text{null_WM} / \tan(\psi_0)$ and also by the normalizing of the power reference. The calculated signal is the integrated term for the following integration, presented in FIG. 5 comparing with the simulated integration term of a_1 (after the amplitude compensation). The “W” in FIG. 5 is the wavelength, in unit of nanometer (nm) , and the “N” in FIG. 5 is the amplitude with an arbitrary unit. It can be seen from FIG. 5 that the noise has distorted the waveform of the integration term, especially at two ends corresponding two wings of the target absorption line. The final integrated result processed base on the above description is illustrated in FIG. 6, which is the recovered target absorption line profile 116. The “W” in FIG. 6 is the wavelength, in unit of nanometer (nm) , and the “A” in FIG. 6 is the absorbance of the target gas with the concentration of 100 ppm. The algorithm of curve integration is based on the sum area of finite trapezoid elements, shown in FIG. 7, $B_i=(Y_{i+1}+Y_i)(X_{i+1}-X_i)/2$, $A_i=\sum_{n=-\infty}^i B_n$. All above calculations are accomplished by the program of FPGA 305 developed by the inventor.

1 [035] A good agreement is achieved between the experimental result shown in FIG. 6 and the
2 theoretical data of the Voigt profile, but errors exist at two wings because of the noise at those
3 regions shown in FIG. 5. The most part of the absorption line profile, however, has been recovered
4 perfectly. The important information of the target absorption line profile like the half width and line
5 strength can be achieved from the recovered line profile, in order to obtain the gas pressure based on
6 the pressure broadening effect on half width of the line profile, or to get the gas temperature
7 according to the line strength which is dependent on the temperature.

8
9 [036] The whole measurement time is equal to the total sampling time plus the data processing
10 time. The total time for the absorption line profile recovery of low concentration gas is less than 30
11 seconds for the primary prototype of the invention. It is much suitable for the quick in-suit
12 measurement.

13
14 [037] It would be readily apparent to a person of skill in the art that the above procedures may
15 be configured with minor adjustments to either the sort of the target gas, the type and wavelength of
16 the laser source, the use of a plurality of detection methods, or the use of an alternative integration
17 circuit chip to process the data including the phase sensitive lock-in module, ramp and sine wave
18 generation and combination, and trapezoid area calculation based integration.

19
20 [038] The foregoing embodiments and advantages are merely exemplary and are not to be
21 construed as limiting the present invention. The present teaching can be readily applied to other
22 types of apparatuses. Also, the description of the embodiments of the present invention is intended
23 to be illustrative, and not to limit the scope of the claims, and many alternatives, modifications, and
24 variations will be apparent to those skilled in the art.

1 CLAIMS

- 2
- 3 1. An infrared spectrometer for gas detection comprises gas absorption line profile recovery
4 technique based on the integration of the first harmonic component of the wavelength modulated
5 absorption.
6
- 7 2. The infrared spectrometer recited in claim 1 wherein said the integration is based on the sum
8 calculation of the area of finite trapezoid elements.
9
- 10 3. The infrared spectrometer recited in claim 2 wherein said an arbitrary detection phase is used in
11 the phase sensitive demodulation to get a good signal-to-noise ratio.
12
- 13 4. The infrared spectrometer recited in claim 3 wherein said the root mean square (RMS) value of
14 Y channel signal is calculated to find the minimum RMS value by an iteration algorithm to
15 obtain the WM (X) and null_WM (Y) signals.
16
- 17 5. The infrared spectrometer recited in claim 4 wherein said the $-WM + \text{null_WM} / \tan(\psi_0)$ is
18 calculated and the laser power ramp is normalized to achieve the first coefficient a_1 of the Fourier
19 series. The first coefficient a_1 is the first harmonic component to be integrated to recover the
20 infrared absorption line profile of the target gas.
21
- 22 6. The infrared spectrometer recited in claim 1 wherein said a photoacoustic gas cell with the
23 length of 30 mm, inner diameter of 18 mm and outer diameter of 28 mm is used to measure the
24 gas absorption and convert the absorption to an acoustic signal.
25
- 26 7. The infrared spectrometer recited in claim 6 wherein said the gas cell has two open ends and
27 works at the first longitudinal resonant mode.
28
29

- 1 8. The infrared spectrometer recited in claim 6 wherein said a microphone is used to measure the
2 acoustic signal.
3
- 4 9. The infrared spectrometer recited in claim 6 wherein said a V-groove base is used as the mount
5 of the gas cell.
6
- 7 10. The infrared spectrometer recited in claim 6 wherein said a GRIN lens to collimate the laser
8 beam into the gas cell.
9
- 10 11. The infrared spectrometer recited in claim 6 wherein said a beam dump is used to stop the laser
11 beam after the transmission from the gas cell.
12
- 13 12. The infrared spectrometer recited in claim 6 wherein said common mode operation of laser on
14 the optical fiber and gas cell permit measurement of gas concentration, pressure and temperature
15 which are derived by the recovered absorption line profile of the target gas in gas cell.
16
- 17 13. The infrared spectrometer recited in claim 12 wherein said a wavelength tunable single mode
18 laser is used as the light source, the laser source can work at near or mid-infrared region.
19
- 20 14. The infrared spectrometer recited in claim 13 wherein said a current driver module and a
21 temperature controller module are used to control the laser source.
22
- 23 15. The infrared spectrometer recited in claim 13 wherein said the laser source can sweep its laser
24 wavelength through a defined range by a low frequency ramp current.
25
- 26 16. The infrared spectrometer recited in claim 13 wherein said the laser source can be modulated by
27 a sinusoidal modulation current with the frequency same as the first longitudinal resonant
28 frequency of the photoacoustic gas cell.
29
- 30 17. The infrared spectrometer recited in claim 13 wherein said a FPGA IC chip, ADC, DAC,

1 EEPROM and other IC chips and external circuit are used to implement low frequency ramp
2 sweeping combines high frequency wavelength modulation, phase sensitive lock-in
3 demodulation, iteration calculation of minimum RMS of Y signal, curve integration based on
4 finite trapezoid elements sum area calculation, gas concentration, pressure and temperature
5 calculation, other add, subtract, product and division calculation.
6

7 18. The infrared spectrometer recited in claim 13 wherein said a single mode optical fiber coupler to
8 split 10 percent laser beam to do the laser power reference and laser swept wavelength scaling.
9

10 19. The infrared spectrometer recited in claim 18 wherein said another single mode optical fiber
11 coupler is used to split above 10 percent laser beam to both 5 percent for the laser power
12 reference and laser swept wavelength scaling.
13

14 20. The infrared spectrometer recited in claim 14 wherein said a printed circuit board (PCB) is used
15 to be the mount of the laser source and to connect the current driver and temperature controller
16 to the laser source.
17

DRAWINGS

FIG. 1

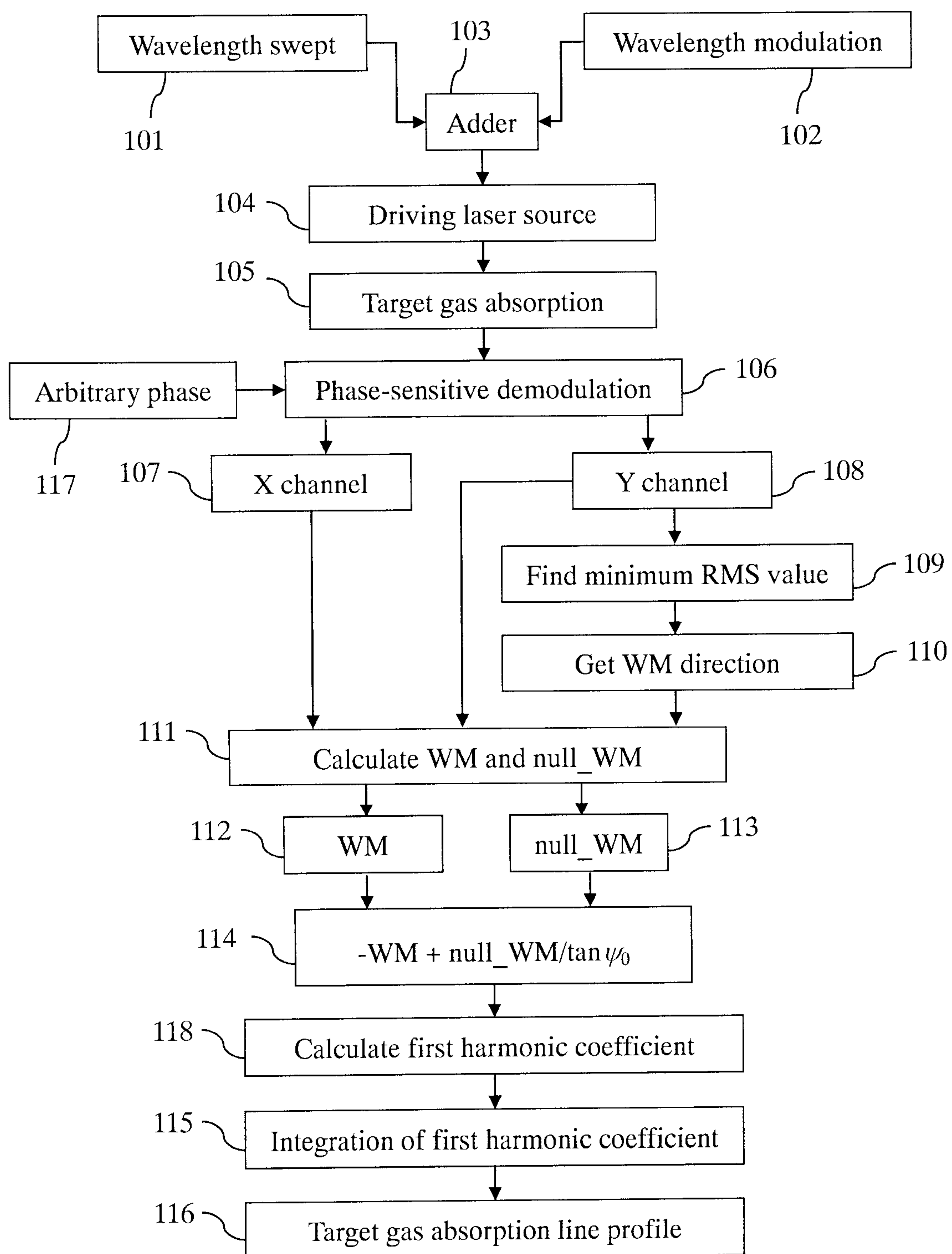


FIG. 2

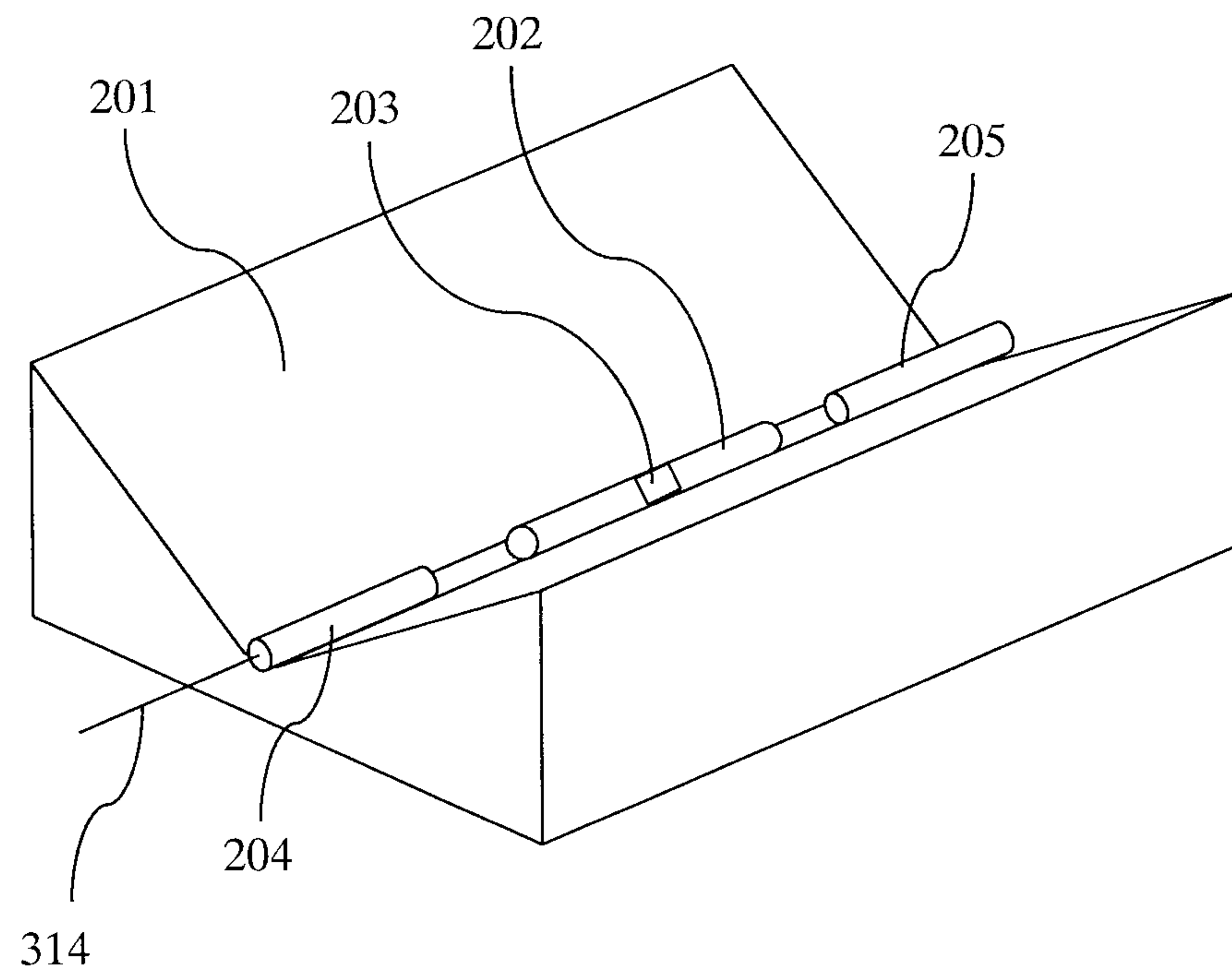


FIG. 3

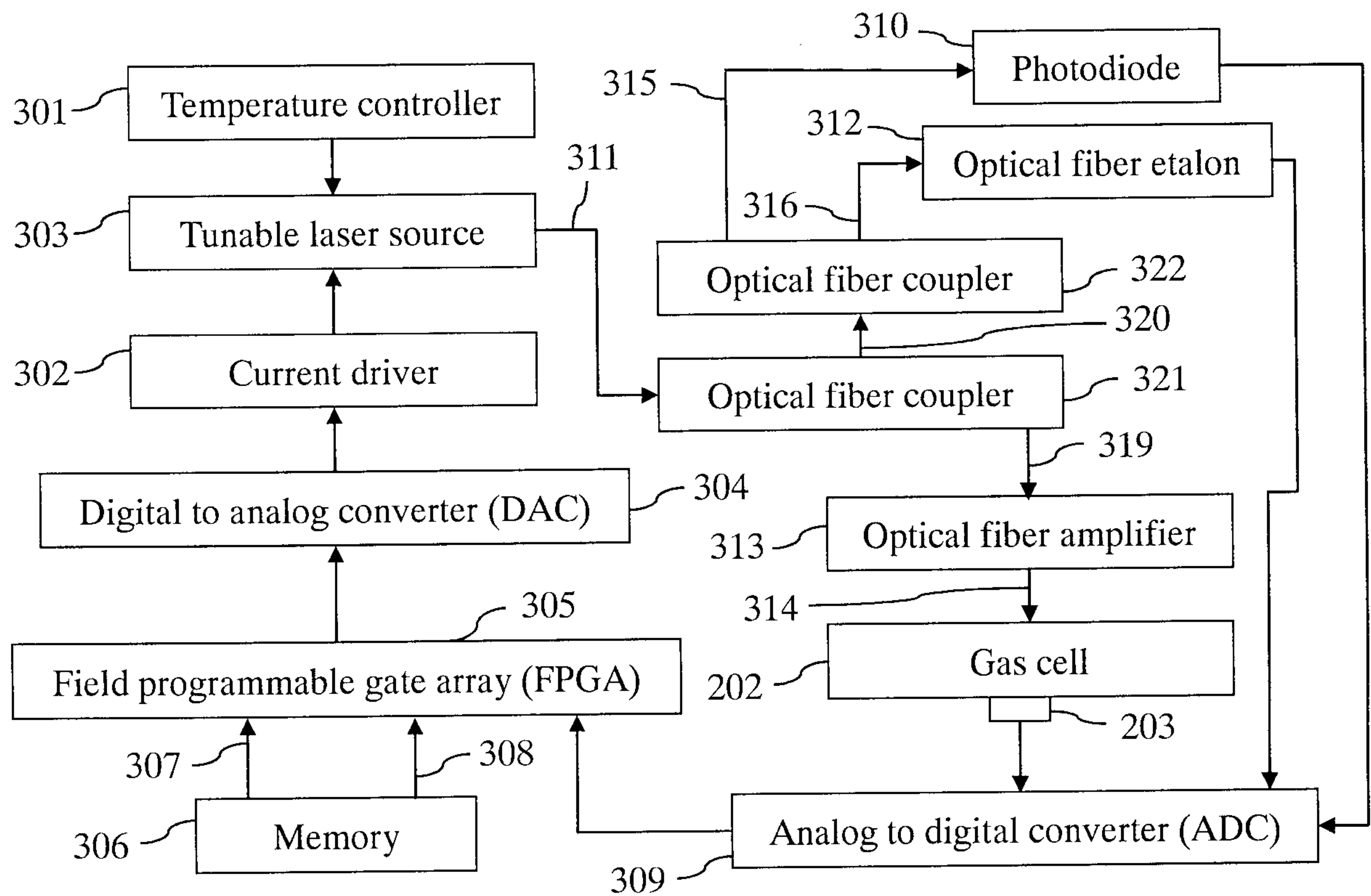


FIG. 4

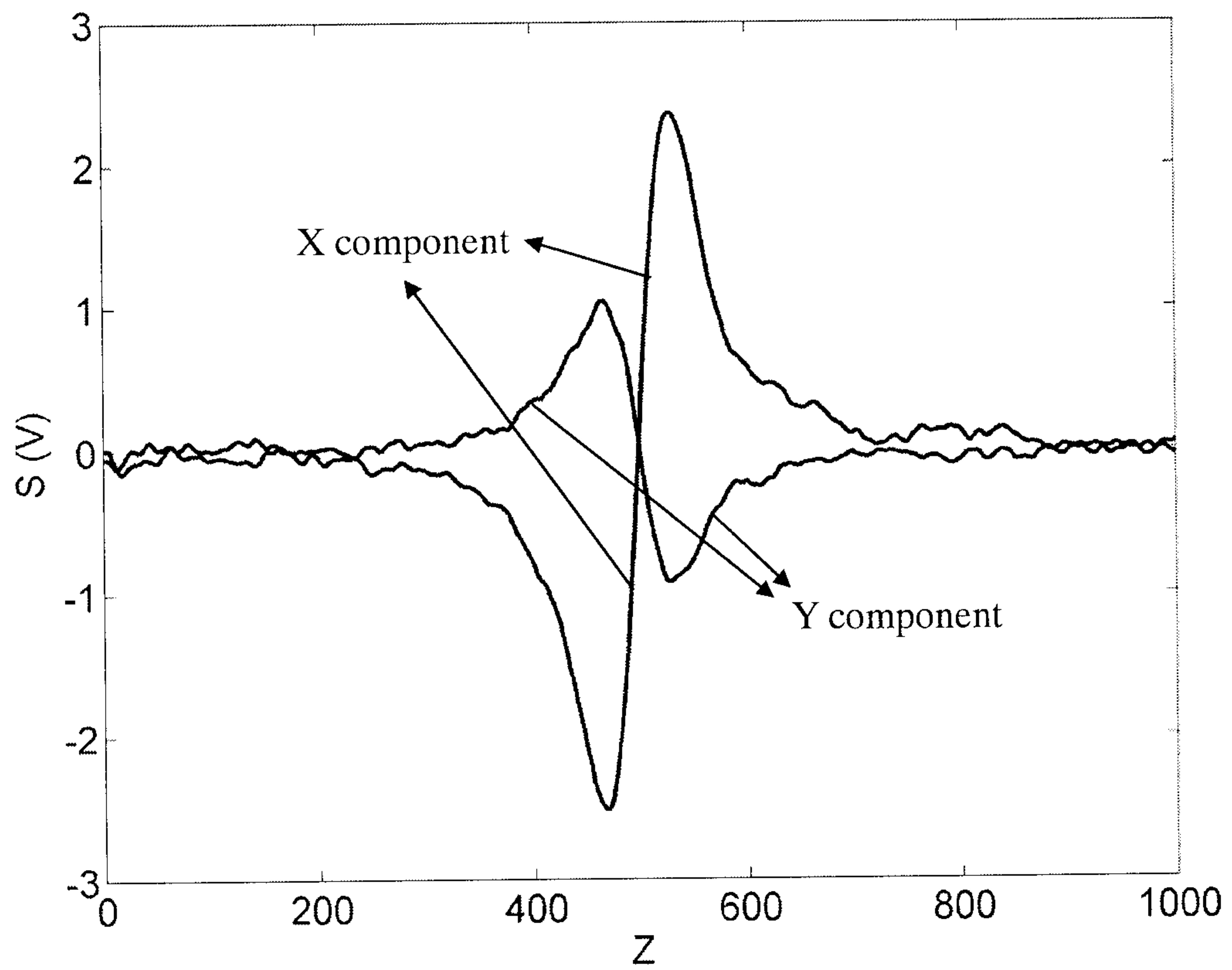


FIG. 5

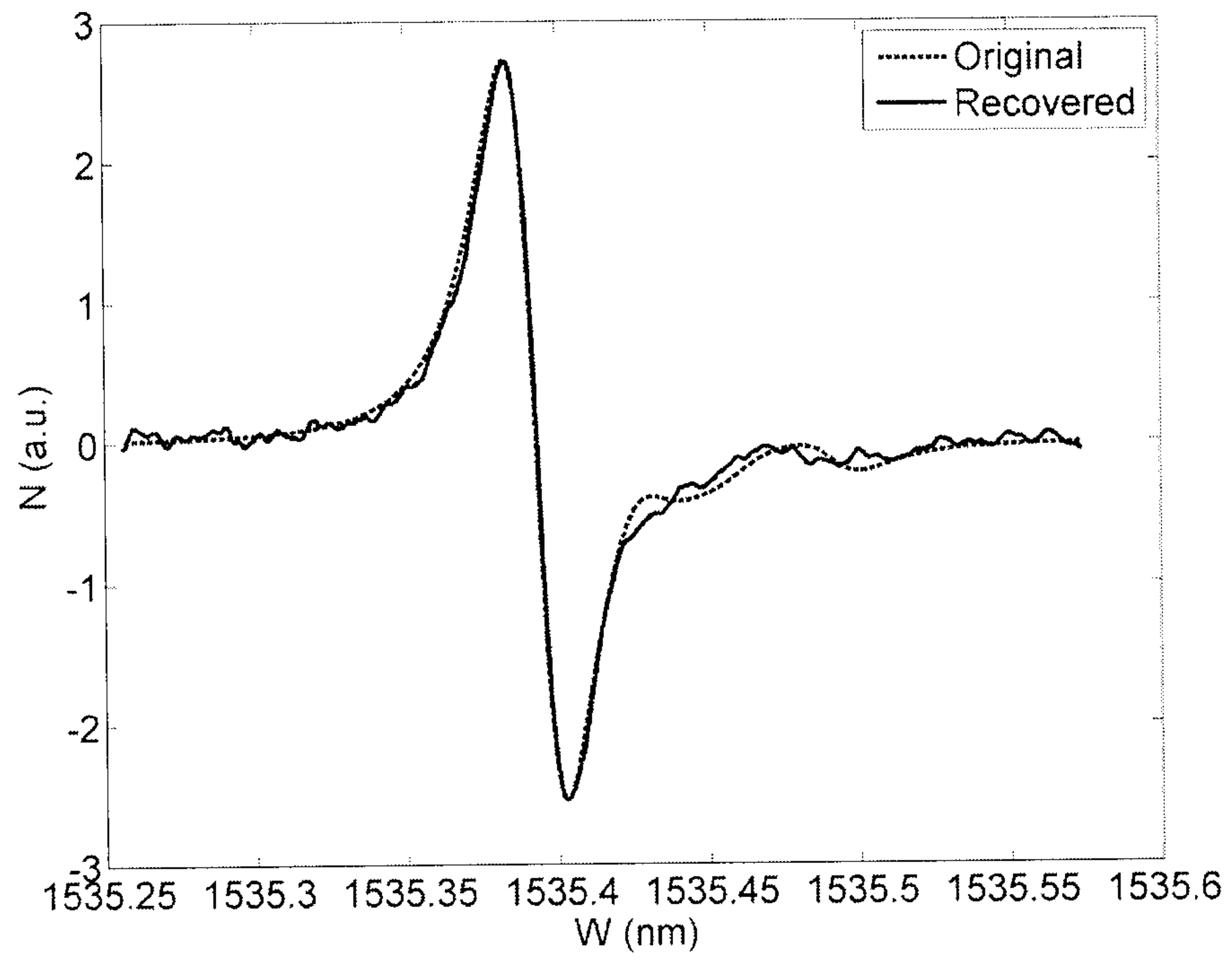


FIG. 6

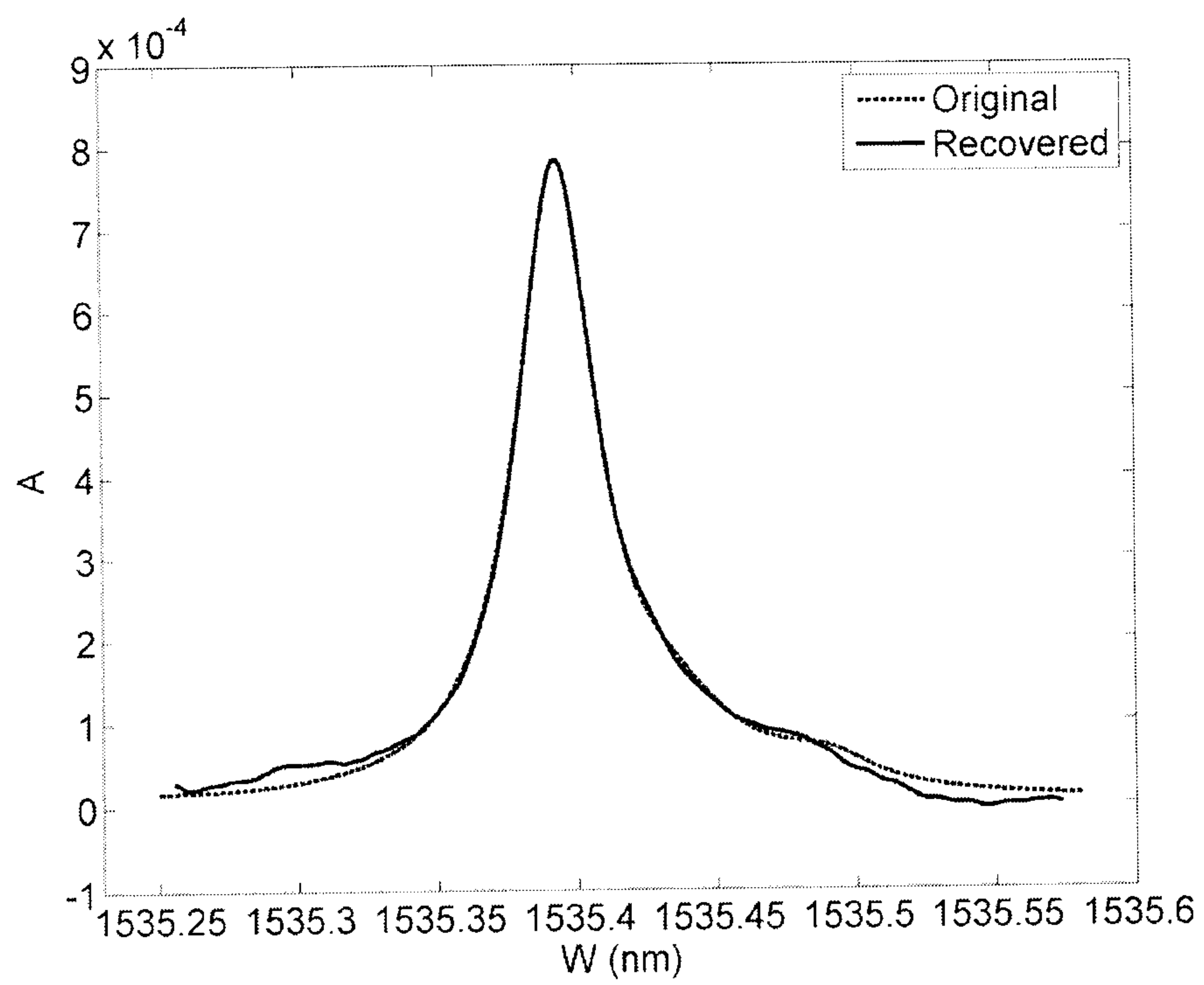


FIG. 7

