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Quantitative Detection of C_2H_2 Gas Based on an Infrared Laser Gas Sensor

Jiagui Tao[1, a],Jinglei Shi[1, b] and XiaoXing Zhang[2,c]

[1] State grid jiangsu electric power research institute nanjing 210003 china

[2] State Key Laboratory of Power Transmission Equipment & System Security and New Technology(Chongqing University)，Chongqing 400044，China;

[a]taojiagui@163.com, [b]13770982780@163.com, [c]zhxx@cqu.edu.cn

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Abstract. Detection of C_2H_2 gas in transformer oil is significant for diagnosing the operating state assessment of power equipment. The paper develops an infrared laser gas sensor to detect the C_2H_2 gas in transformer oil, and also introduces the system structure in detail. A gas-absorbed laser cell that contains a series of laser reflectors is designed and used in our detection system, which adds the optical path without changing the volume of the cell. 1529.16nm is chosen as the characteristic spectrum line of C_2H_2 gas, and concentration of C_2H_2 gas is quantitatively analyzed based on least square method. The experiment result shows that in certain volume fraction range of acetylene, the absorbance has a good linear relationship with the acetylene concentration, and the minimum detection limit for acetylene is 10μL/L. In general, the developed infrared laser gas sensor can detect C_2H_2 gas in transformer oil effectively.

Introduction

Dissolved gases in transformer oil are important characteristic quantities to characterize early latent fault of power transformer. Real-time analysis of the composition and proportion of the dissolved gases in oil, determining the type, extent and trends of transformer latent failures, those all have great significance to ensure the stable, reliable, and safe operation of transformer[1]. C_2H_2 gas is the main sign to distinguish two type faults, overheating and discharge[2]. C_2H_2 is also a major feature gas produced by two kinds of high-energy discharge, arc discharge and spark discharge[3-4]. Therefore, C_2H_2 is selected as a main feature gas to characterize the discharge fault of transformer. the presence of C_2H_2 gas can help to judge whether partial discharge, spark discharge or arc discharge are occurred, and also the severity of the failure in oil-paper insulation. Nowadays, there are four main methods being used on detecting dissolved gas in transformer oil. Those methods include gas chromatography[5-6], infrared spectrum[7], photoacoustic spectrum[8-9], sensor array[10-11] and on-line monitoring device. Gas chromatography method is the most effective and extensive one, but it has some shortcomings such as suffering pollution easily, need of cleaning in time and difference of separation effect based on temperature. Therefore, it is not suitable for on-line detection[12]. Photoacoustic signal detected by photoacoustic spectrum is weak and usually amplified by lock-in amplifier. However, lock-in amplifier and pressure variation form absorption process of photoacoustic cell result in noise. Those noise have influence on photoacoustic signal, so we can not get accuracy result based on detection deviation of the signal. There are some problems about stability of the sensor array response and its choice, and cross sensitivity on gas detection brings difficult in identifying different gas.

Every gas molecular structure has their characteristic absorption lines respectively. Infrared laser gas sensor based on the theory can identify different gases and detect their content accurately. This method is wide used on environment monitoring[13], environmental protection[14-15] and so on. The paper used distributed feed-back laser diode as light source and designed a infrared laser gas sensor. At last, the paper made a quantitative analysis on C_2H_2 gas volume fraction based on least square method.

Design of infrared laser gas sensor

2.1 System components

Detection device of infrared laser gas sensing system as shown in Fig. 1, is mainly composed of a light source (laser light source), a semiconductor laser driver, temperature controller, gas-absorption chamber (optical transmission means), a photodetector, an oscilloscope and other components. The semiconductor laser driver controls current size by adjusting the laser power output. The temperature controller controls the output wavelength of laser by adjusting the temperature. The laser light source emits laser having a specific and tunable frequency. The absorption chamber is a place for absorption of gas molecules and the laser. At last, the photodetector converts the light intensity signals to voltage signals which can be detected by oscilloscope. Experimental procedures are as follows: The laser light source controlled by a semiconductor laser driver and a temperature controller emits laser light having a certain frequency. Then the laser light enters the optical transmission unit through the optical fiber collimator and causes absorption reaction with C_2H_2 in the absorption chamber. Later, the laser enters a photodetector. The photodetector can detect light intensity signals before and after the absorption and converted the light intensity signals into voltage signals. Voltage signals will be detected by a oscilloscope. The each component content of the gas to be detected can be obtained by the absorbance proportion according to the Beer-Lambert Law.

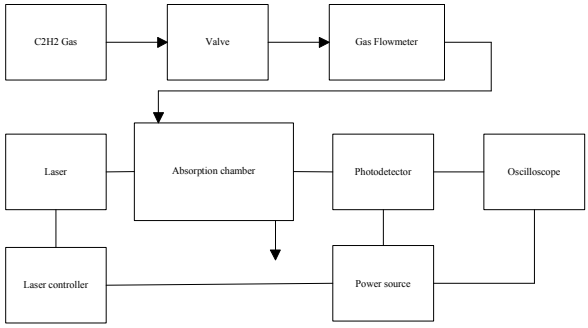

Fig.1 Structure chart of detection device

2.2 Selection of the light source and the photodetector

Based on the C_2H_2 infrared absorption spectrum provided by HITRAN database (Fig. 2), and taking into account the cross-interference with other gases dissolved in transformer oil in the spectral region, the paper choose 1529.16 nm absorption lines as C_2H_2 characteristic absorption spectra.

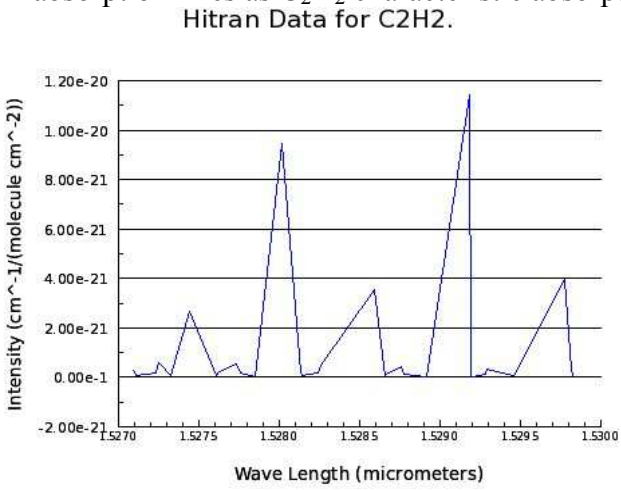

Fig.2 Elaborate absorption spectrum of C_2H_2

DFBLD have advantages of a narrow linewidth, a high stability power output and its center wavelength can be adjusted. Furthermore, the laser wavelength is tunable by controlling current and temperature, so the design meets the requirements. Photodetector is a core element to achieve a photoelectric signal conversion. The photodetector in the system uses photodiode manufactured by 5 mm Ge material. When laser light irradiate on the effective surface of the photodetector, a potential

difference can form on the device. Light intensity will be perceived according to the size of potential difference. The photodetector have advantages of low noise, fast response and a wide detection range of wavelengths.

2.3 Design of the gas absorption chamber

Gas absorption chamber is a core component of the sensor. The design of the gas chamber and optical transmission unit has a direct impact on the detection performance of the sensor. The main principles for the gas chamber design are as follows. Effective distance for light absorption in gas chamber should be as long as possible. Namely, the absorption optical path should be long. A coupling loss of every portions of the optical path transmission unit should be as small as possible, so that the coupling state can be stable, the noise generated will be small. Therefore, the paper designs a series lens group transmission gas chamber, as shown in Fig. 3. The laser reflects along a single direction by the mirror in the optical path transmission unit. The reflected light will not return to the original optical path, so the influence of interference effects generated by the encounter of the incident and reflected light can be avoided. The infrared light reflects by a single direction, thereby effectively increases the light absorption process and improves the detection sensitivity of sensor. The connection of series lens group transmission gas chamber is relatively simple, which decreases the coupling loss, effectively improves the stability of the coupling and improves coupling efficiency.

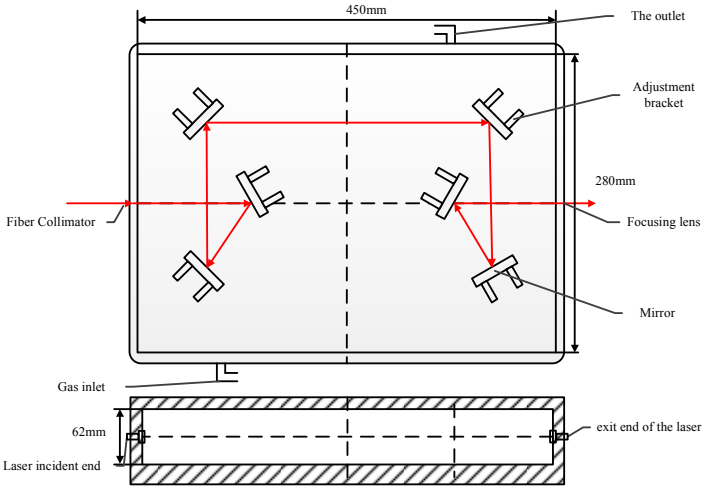

Fig.3 Structure of series lens group transmission gas chamber

Analysis of the sensor performance

3.1 Test of DFBLD light source radiation characteristics

The DFBLD tunable function can be achieved by controlling the operating temperature and injection current of the laser. Therefore, determining relationship between the output wavelength, the operating temperature and injection current of the laser has an important role for accurate positioning of the gas characteristic absorption spectrum. In experimental tests, the paper use 5235 type laser controller and 4205 type temperature controller produced by Arroyo Instruments Company to adjust injection current and operating temperature of DFBLD, and use Japan NF company AQ6317B type spectrum analyzer to record output wavelength of the laser. When the injection current is 50 mA, working temperature is 21, 22, 23 and 24 ˚C, the relations between the laser output wavelength and the operating temperature is as shown in Fig. 4. When the working temperature is 21 ˚C, injection current is 30, 40, and 50 mA, the relations between the laser output wavelength and the injection current is as shown in Fig. 5.

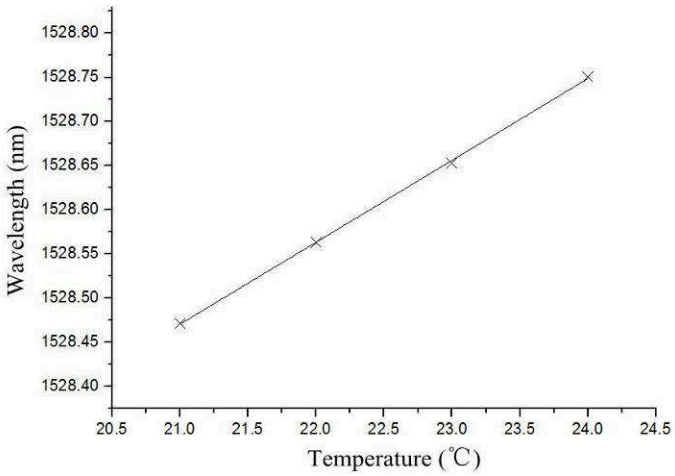

Fig.4 Fitted curve of DFBLD's output wavelength changing with the working temperature

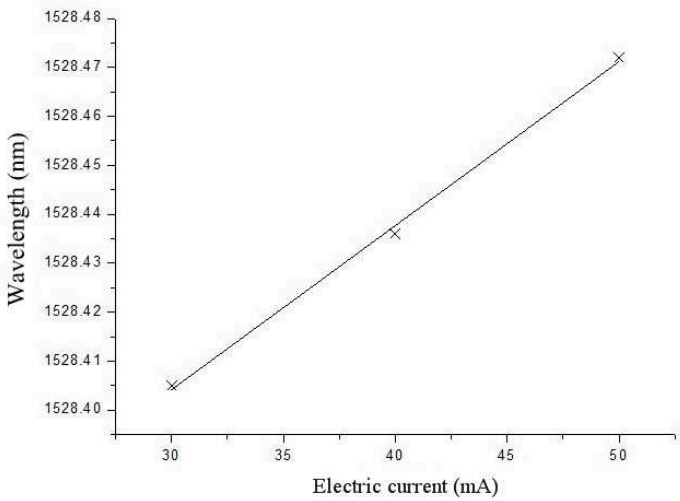

Fig. 5 Fitted curve of DFBLD's output wavelength changing with the input current

As shown in Fig. 4 and 5, when the injection current is 50 mA, working temperature is 22, 23 and 24 ˚C, the output wavelength of 1528.563, 1 528.653, and 1528.751 nm respectively. The wavelength spacing is 0.090 and 0.098nm. DFBLD die temperature varies by 1 ˚C, when the wavelength varies about 0.10 nm. Namely, the wavelengths - temperature modulation change rate of DFBLD within the test temperature range is about 0.10 nm / ˚C. When the working temperature is 21 ˚C, injection current is 30, 40, and 50 mA, the output wavelength of 1 528.405, 1 528.436, and 1528.472 nm respectively. The DFBLD injected current varies 10 mA, when the output wavelength of varies about 0.034 nm. Namely, the current - wavelength modulation change rate within the injection current range is about 0.0034 nm / mA.

Choose characteristic absorption lines of C_2H_2 gas at 1529.16 nm wavelength as its peak characteristic absorption lines. In order to ensure the detection process of C_2H_2 gas has good absorption and accuracy, the paper conducted several tests to detect the spectral radiative properties of DFBLD through spectrum analyzer. When the injection current is 100 mA and temperature is 26 ˚C, the output wavelength of the laser is 1529.14 nm.

3.2 Optical path transmission loss test of the absorption chamber

The purpose of optical path transmission loss test is to test the light intensity transmittance under transmission loss when there is no C_2H_2 gas in the gas chamber. Optical transmission loss Include coupling loss caused between the light source and the optical fiber, the optical fiber and the optical fiber, the optical fiber and the components. Ambient gas absorption, optical fiber materials intrinsic absorption, impurity absorption, scattering losses and the lens transmittance limit can also cause transmission loss. Because of light loss in the transmission of various reasons, the optical path transmission loss test is necessary for the presence of a variety of losses in light transmission. The test result is shown in Table 1. In case of the power loss of every link of the gas chamber remains

unchanged, apart from the initial power of laser is relatively small, which results in large deviations of transmittance. The data obtained shows that the light transmission rate remains stable around 88% in other phases. The light transmission intensity meets the requirements of the signal processing system. The transmission performance and the collimating effect of the infrared laser sensing system are good. Therefore, a reasonable optics connection can meet the detection accuracy requirements.

Table 1 Experiment of optical fiber loss

Injection current /mA	Incident light intensity voltage signals /V	Emitted light intensity Voltage signals /V	Transmittance /%
20	0.58	0.55	94.8
30	1.72	1.55	90.1
40	2.86	2.54	88.8
50	4.00	3.52	88.0
60	5.15	4.52	87.8
70	6.29	5.55	88.2
80	7.43	6.63	89.2
90	8.57	7.74	90.3
100	9.72	8.84	91.0

3.3 Test results and quantitative analysis

3.3.1 Detection experiment of C_2H_2 gas in transformer oil

The paper used semiconductor laser controller and temperature controller to confine working wavelength of laser into 1528.405, 1528.563, and 1529.14 nm. Under the 3 different detectable wavelength ,10, 20, 40, 60, 80, 100 μ L/L C_2H_2 gas allocated by computer RCS2000-A are respectively piped into absorption chamber(at normal atmospheric pressure) to be tested and repeated 3 times. The voltage signals reflecting light intensity before and after test should be noted. According to the data of experiment, average value is gotten by the 3 experimental values, which reflects the relationship between the absorbance under different wavelengths and the volume fraction of C_2H_2 gas, as shown in Fig. 6.

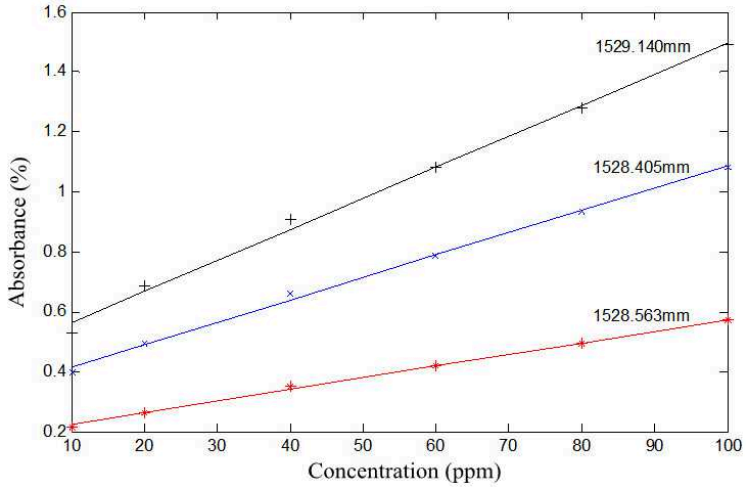

Fig. 6 Relation curve between the absorption and the C_2H_2 concentration under different wavelengths

According to the Beer - Lambert law: under the condition of certain distance between laser and gas molecule, when temperature, pressure and line strength of absorption lines is invariant that is to say absorption coefficient is invariant, volume fraction becomes direct ratio with absorbance in the detection scope of the volume fraction of C_2H_2 gas. Specific performance: when the gas volume fraction is higher, the density of gas molecules , the number of crashing C_2H_2 gas molecule in per optical path length, the probability of being stimulated, the number of photons absorbed, and the absorbance is larger while light intensity decreases. Experimental results and theoretical results are the same.

The absorbance is obviously different when the detection wavelength changes. The detection wavelength is related to the line intensity of the absorption lines. When the temperature, pressure and gas concentration are certain, absorption coefficient is only related to the line intensity of the absorption lines. Namely, the large line intensity, the greater the absorption coefficient and the absorbance. As shown in figure 2, 1529.14 nm spectral corresponds to the maximum line intensity, 1528.405 nm follows, 1528.563 nm is minimum. The results are unanimous with the research of HITRAN database, which demonstrates the correctness to choose 1529.16 nm as the characteristic absorption spectrum line wavelength of C_2H_2 gas from the side. The standard relational curves between absorbance and gas concentration at a given wavelength indicate that: When C_2H_2 gas volume fraction range 10~100 μL/L, absorbance and C_2H_2 gas volume fraction approximately follows a linear relationship. The C_2H_2 gas sensor can be used for the qualitative detection of the volume fraction within the interval. When C_2H_2 gas volume fraction is less than 10μL/L, the measured voltage signal is almost unchanged. Therefore, further research should be conducted for lower volume fraction detection of C_2H_2 gas.

3.3.2 Detection and quantitative analysis of C_2H_2 gas

The ultimate goal of the infrared laser gas sensor is to make a quantitative analysis for the gas volume fraction to be detected according to the absorbance under a given temperature, pressure, and detection wavelength. The paper used least squares method to make a linear regression analysis between absorbance and different volume fraction of C_2H_2 gas under a given temperature, pressure and detection wavelength. Based on the relationship, the C_2H_2 gas volume fraction to be measured can be inverse obtained by absorbance in the actual detection.

Making linear fit to figure 6 using the method of least squares, the data are shown in Table 2. A_λ' (unit, %) is absorbance corresponding to detection wavelength. c_0 (unit, μL/L) is concentration of C_2H_2 gas. Therefore, C_2H_2 gas concentrations to be measured can be inverse obtained according to relationship between C_2H_2 gas concentrations and absorbance under certain detection wavelength.

Table 2 Fitting relationship between absorption and C_2H_2 concentration based on the least-square method

Detection wavelength /nm	Relationship between absorbance and concentration	Goodness of fit	Sample variance
1 528.563	$A_\lambda=0.18771+0.00387C_{C_2H_2}$	0.99145	0.00975
1 528.405	$A_\lambda=0.34497+0.00739C_{C_2H_2}$	0.99261	0.01730
1 529.140	$A_\lambda=0.46726+0.01025C_{C_2H_2}$	0.99216	0.02470

Conclusions

(1) Based on the gas molecules IR theory and Beer-Lambert law, the paper successfully designed a kind of infrared laser gas sensor. Designed a series lens group and applied it to the design of transmission chamber. The structure increases the absorption of the optical path in case of the constant volume. As a result, the sensor obtains a higher detection sensitivity.

(2) Making an experimental analysis of the sensor performance, the wavelengths - temperature change modulation rate of DFBLD is 0.10 nm / ˚C and the current - wavelength modulation change rate is 0.0034 nm / mA. When the injection current is 100 mA, temperature is 26 ˚C, the output wavelength of the laser is 1 529.14 nm, and light intensity transmission rate remains stable at 88%, which meets the requirements of the signal processing system.

(3) Within a certain range of C_2H_2 gas volume fraction, there is a good linear relationship between the absorbance and the C_2H_2 gas volume fraction. The relationship between the absorbance and the C_2H_2 gas volume fraction can be calculated through least squares method. The sensor can meet the requirements of C_2H_2 gas detection in transformer oil.

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