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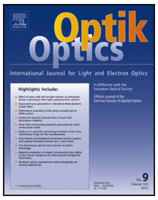

Research on high sensitivity of resonant enhancement laser intracavity photoacoustic spectroscopy technology

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ABSTRACT

Laser intracavity photoacoustic spectroscopy (ICPAS), in combination laser intracavity absorption (ICAS) with photoacoustic spectroscopy(PAS) technology is presented. It can effectively enhance the photoacoustic signal intensity by means of increasing the laser power and overlapping in phase when the laser beam passed through the acoustic wave detector every time. Two sets of experimental results were obtained when probing the water vapor with the effective absorption coefficient, k_{eff}, $1.06 \times 10^{-6}\mathrm{cm}^{-1} \times \mathrm{ppm}^{-1}$ in the air using a tunable distributed feedback laser diode (DFB-LD) and validate the relevance of the reported mathematical model. It can be found that for a quartz-enhanced photoacoustic spectroscopy(QEPAS) sensor system, the relationship between the second harmonic current amplitude I_{2f} and the laser power W_L is linear, and the slope of the fitting results is 285.0809 pA/mW compared to that of theoretical calculation 278.7025 pA/mW, with the fitting constant of 17.1318 pA, which was corresponding to the laser power less than 0.0601 mW and for a resonant photoacoustic(PA) cell sensor system, the relationship between the second harmonic voltage amplitude U_{2f} and the laser power W_L is also linear, and the slope of the fitting results is 108.8463 mV/mW compared to that of theoretical calculation 111.26 mV/mW, with the fitting constant of 0.4875 mV, which was corresponding to the laser power less than 0.0045 mW.

1. Introduction

Laser intracavity absorption spectroscopy(ICAS)gas sensors based on absorption spectroscopy [1–3] have played important roles in gas detection due to their desirable features: improved sensitivity, multigas detection [4] and compact configuration. Since traditional transmission sensors [1] such as laser external cavity absorption spectroscopy (ECAS) gas sensors detect the optical energy transmitted through the analytical sample gas and the gas absorption is always very weak, so it has big background transmitted signal. While considering the gain effect of gain medium [5] in laser intracavity, the transmitted light intensity decreases because of the gas absorption, yet it is amplified by the gain medium, so the variation of the transmitted light intensity due to the increased optical absorption path length is limited. Therefore, the sensitivity of laser ICAS gas sensors for trace gas detection is not definitely higher than that of laser ECAS gas sensors, especially when

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the pump laser is saturated. And photo-detector(PD) will have bad resolution when the laser power is beyond its detection region for laser ICAS gas sensors, whose laser power often dozens of times that of laser ECAS gas sensors.However, photoacoustic spectroscopy(PAS) [1,6–11] has zero-background nature and detects the gas absorption laser energy directly. And the photoacoustic(PA) signal intensity can be enhanced by optical enhancement technology such as a quartz-enhanced photoacoustic spectroscopy(QEPAS) [1,7,12–15] sensor using a quartz tuning fork(QTF) with an optical resonator and a resonant PA cell [1,6,8–9] by placing it inside a Fabry-Perot build up cavity. Suppose the value of the laser modulation frequency, f, is 10 kHz, then the corresponding circle time can be $T = \frac{1}{f} = 10^{-4}$s, if the laser cavity length $L = 3$ cm, considering the light velocity is $c = 3 \times 10^8$m/s, the time that the photons pass through the laser cavity every time is estimated to be $t = \frac{L}{c} = \frac{3\text{cm}}{3\times10^8\text{m/s}} = 10^{-10}\text{s} << T$, therefore, the PA signal can overlap in phase and enhance the signal intensity greatly when the laser beam passed through the acoustic wave detector every time. Enhancement of detective sensitivity can be obtained by putting the gas cell and the acoustic detector inside the laser cavity. In sight of this, the concept of laser intracavity photoacoustic spectroscopy(ICPAS), in combination ICAS with PAS is proposed. The PA signal intensity can be obviously enhanced by increasing the intracavity laser power and overlapping in phase when the laser beam passed through the acoustic wave detector every time by means of optical resonant enhancement technology. So it can enhance the sensitivity for trace gas detection and improve the signal to noise ratio greatly by laser ICPAS technology.

2. Theoretical analyses

Here are the description of the two theoretical models [12,8] including QEPAS for trace gas detection and traditional PA cell photoacoustic spectroscopy below in the literature.

2.1. Mathematical model of a QEPAS sensor

When the radial distance r, from the axis of the beam, is larger than the width of the laser beam, σ, the optically generated acoustic pressure wave [12] is well approximated by

$$P(r,t) \approx \frac{(\gamma\text{-}1)\omega k_{eff} W_L}{8v^2}\left[J_0\left(\frac{\omega r}{v}\right)\cos(\omega t) + Y_0\left(\frac{\omega r}{v}\right)\sin(\omega t)\right] \qquad (r >> \sigma) \tag{1}$$

Where t is time and γ is the adiabatic coefficient of the gas. The resonant frequency of the tuning fork, f, the frequency of the second harmonic PA signal can be expressed by the angular frequency $\omega = 2\pi f$. And the effective absorption coefficient, k_{eff}, denotes the amplitude of the second Fourier component of the gas absorption coefficient k, the maximum value of k_{eff} is 70% of $k(\lambda_0)$, where λ_0 is the gas absorption central wavelength, W_L is the laser power and v is the speed of sound. Here J_0 and Y_0 are the zeroth-order Bessel functions of the first and second kinds, respectively. Using the coordinate transformation $(x, y) = (r\cos\theta, y_0 + r\sin\theta)$ and the decomposition $P(r, t) = p(r)\exp(i\omega t)$, then the force density [12] on the tines of the tuning fork can be expressed in terms of the laser beam position, y0, as

$$f(y;y_0) = T_{TF} \times [p(r_i) - p(r_o)] \tag{2}$$

Where

$r_i = \left[\left(\frac{g}{2}\right)^2 + (y - y_0)^2\right]^{\frac{1}{2}}$, $r_o = \left[\left(W + \frac{g}{2}\right)^2 + (y - y_0)^2\right]^{\frac{1}{2}}$, T_{TF}, W, g are the thickness, the width and the gap between the tines of the tuning fork, respectively. The displacement [12] of the end point of its each tine of the tuning fork due to the acoustic pressure wave is given by

$$u_L = \frac{\left|M_1(y_0)\right|}{2\beta\omega}\Phi_1(l) \tag{3}$$

And the maximum piezoelectric current [12] when the laser is centered at $y = y_0$ on the y axis is

$$I(y_0) = \frac{\alpha\Phi_1(l)}{\beta}\left|\mathrm{M}_1(y_0)\right| \tag{4}$$

Where $M_1(y_0) = \frac{1}{\rho A}\frac{\int_0^l f(y;y_0)\Phi_1(y)dy}{\int_0^l \Phi_1^2(y)dy}$,

Here $\Phi_1(y) = \mathrm{ch}\lambda_1 y\text{-}\cos\lambda_1 y + \gamma_1(sh\,\lambda_1 y\text{-}\sin\lambda_1 y)$ is the1th eigenfunction of the uniform Euler-Bernoulli beams [16] with eigenfrequency ω_1, where we approximately equals ω_1 t ω, the resonant angular frequency. The coefficient, γ_1, in the equation of $\Phi_1(y)$, is $\gamma_1 = -\frac{sh\lambda_1 l\text{-}\sin\lambda_1 l}{ch\lambda_1 l + \cos\lambda_1 l}$, where $\lambda_1 l = 1.875$ is the root of the cantilever frequency equation [16]. And α, β, l, ρ, A are the effective piezoelectric coupling constant, the damping coefficient, the length, density, and the cross-sectional area of the tuning fork, respectively.