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Angular Piezo Actuator Controlled Laser Resonator for Precise Sensing of Respiratory Diseases †

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Abstract: Breath analysis is a powerful technique for detection of respiratory diseases, including asthma and chronic obstructive pulmonary disease (COPD). Nitric oxide (NO), nitrous oxide (N_2O), carbon dioxide (CO_2) and carbon monoxide (CO) present in breath sample acts a marker for respiratory disease. A system is proposed to design a Breath Analyser instrument. Its subsystems consist of a compact fast response laser system for analysis of multiple gases by infrared absorption. For quantitative analysis of trace gases in human breath, patient's breath sample is collected inside a gas chamber. Two ends of gas chamber are mounted with concave mirrors with special type of mirror holders which have two angle adjustment piezo actuators. Angle adjustment piezo actuators are used to compensate for any angular misalignment in order of micro radians. Third piezo actuator is used for expansion of laser resonator. Special mirror holder consists of three plates which are supported with guide pins. Mirror is mounted on tilt plate which can be rotated in vertical and horizontal direction with the help of two piezo actuators. This mirror holder structure is made of stainless steel and can be used in any type of air and vacuum environment. It is found that for linear misalignment given to any mirror of optical cavity, the angular misalignment exists and vice versa. Thus artifact elimination of laser cavity is sensitive process. With three piezo actuator based special mirror holders, a precise measurement of laser absorption can be done.

Keywords: COPD, Angular Artifact Adjustment Peizo Actuator (AAAPA)

1. Introduction

Breathing is a complex process of gas exchange by diffusion of gasses over the lung capillaries. Exhaled breath contains thousands of molecules, which are at the level of parts per billion (ppb) or even parts per trillion (ppt) [1,2]. These molecules can provide important information about functioning of respiratory system. When IR laser interacts with these molecules, each molecule exhibits a strong absorption peak. A patient's breath sample is collected inside a gas cell and wavelength of laser is tuned with respect to absorption peak for particular gas. According to Lambert-Beer's law [2], The transmitted light intensity depends of path of laser within gas sample and absorption strength of gas molecules. An optical resonator system can be used for detection of particular gases within breath sample. The laser resonator works on the multiple reflections across two boundaries of the mirrors. The optical system consists of high finesse Fabry-Perot resonator inside a gas chamber. When gas molecules interact with IR laser, the photo diode records the change in intensity of laser which corresponds to absorption from particular gas molecules as shown in Figure 1.

By detecting the absorption of gases, we can detect and monitor a disease with gas molecules [3]. The following Table 1. shows list of disease associated with particular gas molecules.

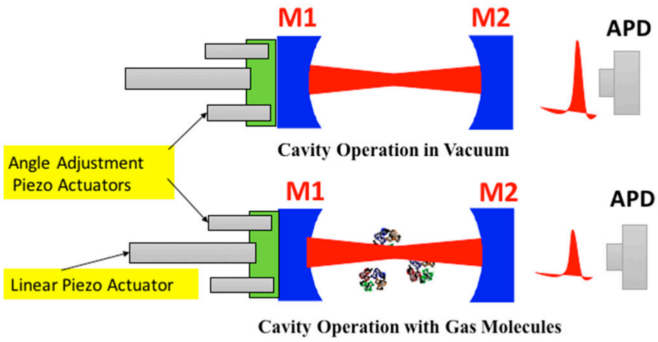

Figure 1. Laser absorption inside cavity with and without gas molecules.

Table 1. Gas associated with disease in breath sample

Breath Gas	Disease
Nitric Oxide (NO)	Asthma
Carbon Mono Oxide (CO)	Oxidative Stress, Anemia
Acetone ($(CH_3)_2CO$)	Diabetes
Ammonia (NH_3)	Liver disease
Ethane (C_2H_6)	Alzheimer's disease
Pentane (C_5H_{12})	Lung Cancer, Breast Cancer

2. Design of Mirror Holder with Angular Artifact Adjutment Piezo Actuator

The optical cavity assembly consists of two concave mirrors. In order to have precision control over cavity length, one of concave mirror was supported by a special mirror holder. This mirror holder consists of base plate, middle plate and tilt plate. Concave mirror is mounted on tilt plate with a semicircular thin ring as shown in Figure 2. For the precise control of length of cavity, piezo actuator is attached to base plate. The piezo actuator which is used for cavity length scanning pass through the base plate and connected to middle plate. Motion of middle plate drives the tilt plate. Special mirror holder is constructed to overcome any angular misalignment in vertical and horizontal plane. For this purpose two angle adjustment piezo slots are provided on base plate. Angle adjustment piezo are fixed at base plate as shown in Figure 3.

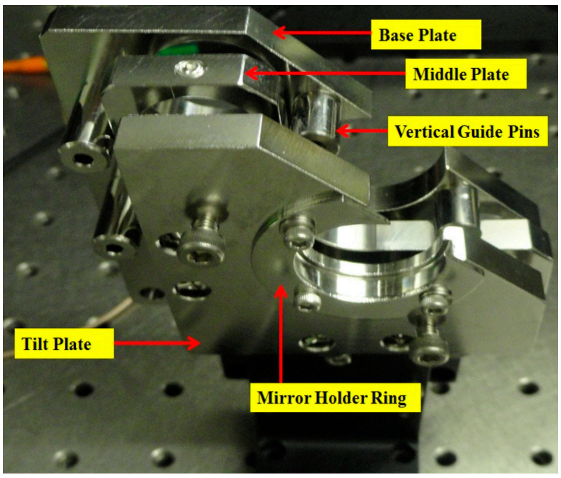

Figure 2. Structure of three plates of mirror holder.

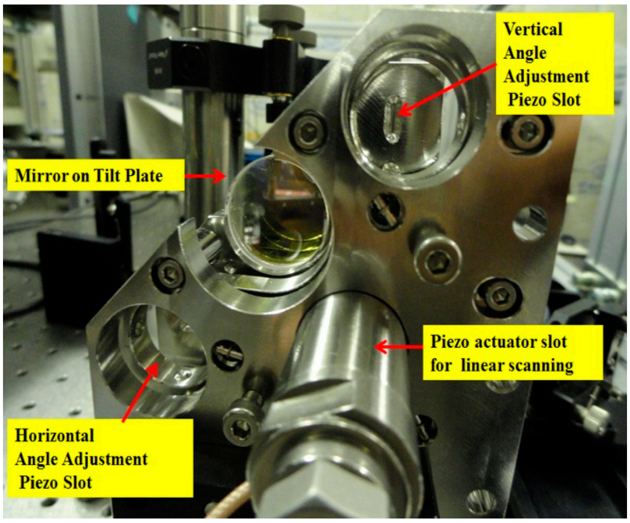

Figure 3. Piezo actuator slots on base plate.

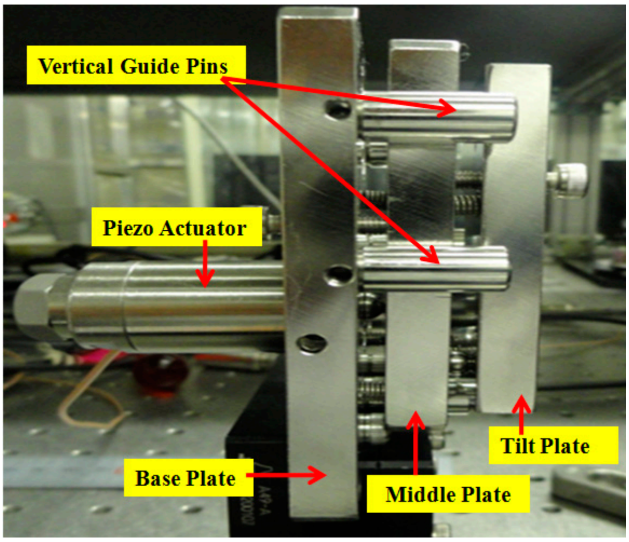

Figure 4. Middle plate in between vertical guiding pins.

They pass through middle plate and are connected to the tilt plate. Angle adjustent piezo provides angular displacement to tilt plate in vertical and horizontal direction. A long cyilindrical piezo actuator is used for cavity length expansion, while two short cyilindrical piezo actuator are used for angular displacement as shown in Figure 3. There are two vertical guiding pins and two base guiding pins on base plate as shown in Figures 4 and 5. The middle plate is tightly fixed between four guiding pins. Both concave mirrors of optical cavity are designed for 1064 nm wavlength. The radius of curvature of both concave mirrors is 420.3 mm. Distance between concave-concave mirror is kept at 840 mm. All mirrors used in cavity design are of 1 inch diameter.

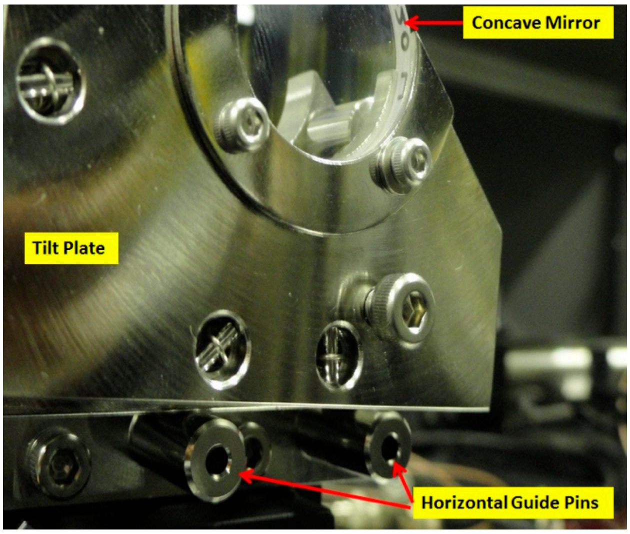

Figure 5. Horizontal guide pins position.

3. Experiment with Two Mirror Resonator

3.1 System Setup

We utilized a mode locked solid state laser with wavelength of λ = 1064 nm. This laser has repetition rate of 178.5 MHz. Its output power is 500 mW. Lens system is used to make the laser beam match to the TEM_{00} mode of the cavity. Spherical lens system consists of two spherical lenses and is used to make laser beam divergence free and well collimated. Once the beam enters inside two mirror resonator it gets reflected from another concave mirror and continues to do so. If length of resonator corresponds to repetition rate of laser, resonance condition can be achieved. At resonance laser cavity, will have its own build up power and acts as an enhancement cavity [4,5]. To observe the excitation of various modes of the cavity, the cavity length was swept repeatedly by the piezo actuator. The piezo actuator is driven by a sinusoidal wave through a high voltage amplifier. When gas sample is injected inside high enhancement cavity, intra-cavity absorption of transmitted light takes place. Photo-diodes are used to monitor light intensity.

3.2 Finesse of Two Mirror Resonator

Sharpness of the resonance width is represented by the optical cavity finesse (F), it is defined from the reflectance of the two mirrors of optical cavity as [6]

$$\mathrm{F} = \pi\sqrt{R_{eff}}/(1 - R_{eff}) \quad (1)$$

where R_{eff} is effective reflectivity of resonator defined by

$$R_{eff} = \sqrt{R_1 R_2} \quad (2)$$

Design reflectivity (R_1 and R_2) of both concave mirrors are 99%. Theoretical finesse of resonator is 312. Finesse is measured experimentally by finding with the ratio of Free Spectral Range (FSR) to width of resonance at half maximum ($\delta\theta$) of Airy function. FSR is distance between peaks of two consecutive 0th order modes [7].

$$\text{Experimental Finesse} = \mathrm{FSR}/\delta\theta \quad (3)$$

Experimental Finesse is obtained as 300.2 ± 10.

In Figure 6, the blue waveform shows the voltage of piezo actuator, which means cavity length expansion. The green waveform shows the signal from photo diode detecting the cavity transmitted laser power.

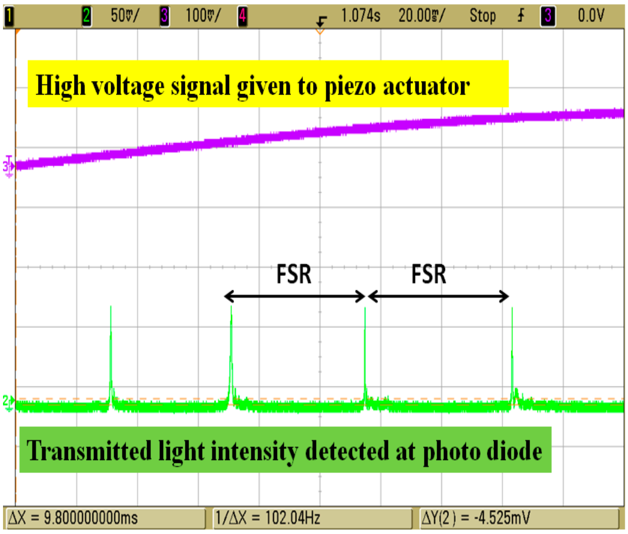

Figure 6. Transmitted laser and piezo volatge signal.

4. Results

4.1. Experiment with Two Angular Artifact Adjustment Piezo Actuator

Figure 7 shows the feedback setup of laser absorption based breath analysis. The reflected light from optical cavity contains the information of resonance. This reflected light can be used to generate an error signal by tilt locking method. The error signal indicates how far cavity is from resonance. The error signal is processed with PID controller and given to linear piezo actuator of two mirror cavity. According to generated error signal, the piezo either expands or shrinks. Thus cavity length can be increased or decreased with piezo actuator. Thus total resonance condition can be maintained throughout breath analysis operation. The dynamic range of piezo actuator is 20 μm.

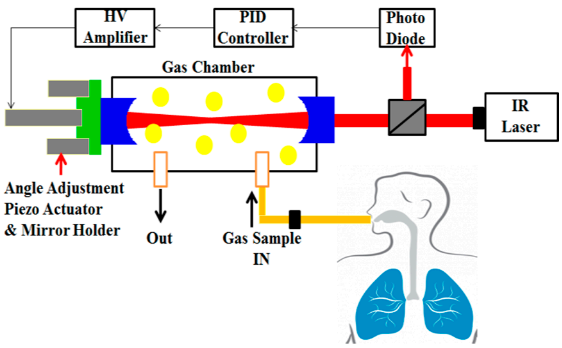

Figure 7. Feedback control system for laser resonator.

To overcome misalignment during resonance process, we used angle adjustment piezo actuators as shown in Figure 8. By giving DC voltage to angle adjustment piezo we can check their performance. Figure 9 shows two different cases of piezo operation. In first case no voltage is given to angle adjustment piezo actuator. There is no change in transmitted light intensity is observed. In second case, we provide 800 mV DC voltage to horizontal angular adjustment piezo and 50% loss of transmitted intensity is observed at photo diode. By further increasing applied voltage to 800 mV DC, transmitted light intensity is recovered. Thus by this operation, we conclude that angle adjustment piezo can be used to compensate for any angular misalignment given to resonator and experiment can be performed without any loss of laser beam intensity inside gas chamber. As gas chamber is closed during experiment so it is very difficult to fine tune mirrors externally for any misalignment.

With special mirror holder, we can control motion of mirror externally and operate cavity at resonance.

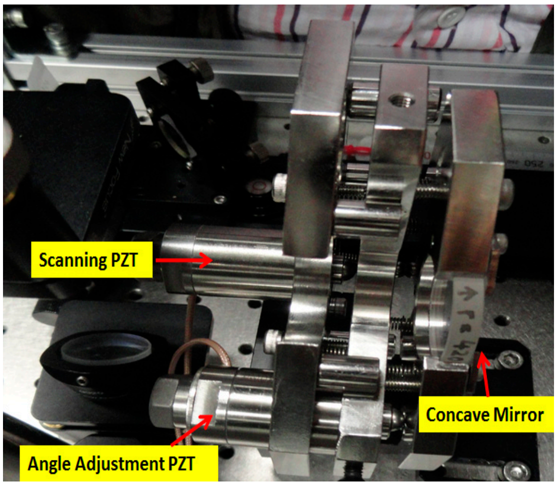

Figure 8. Two Piezo actuator setup.

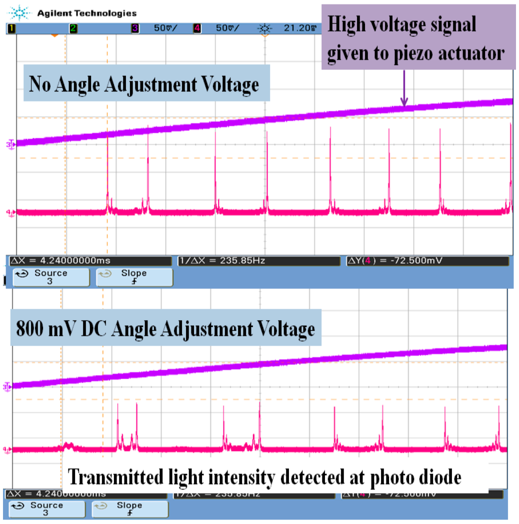

Figure 9. Experiment results of two piezo operation.

4.2. Sensitivity of Two Mirror Resonator

Figure 10 shows study of laser beam misalignment inside cavity, when any one mirror of cavity is subjected to position or angular shift. Two concave mirror M1 & M2 of resonators are highly sensitive to misalignment [8]. If one of the concave mirrors is subjected to both position and angular misalignment, then it is very important to know the total angular and position misalignment for the laser beam. The Δ indicates position misalignment while θ indicates angular misalignment. For any misalignment to mirrors of resonator, there will be drastic change in position of laser beam. In this experiment, each concave mirror is subjected to position misalignment of 1 μm and angular misalignment of 1 μ-rad. The change in position and angle of laser beam is observed. The following table shows experimental result of observed laser misalignment inside resonator. M1 stands for first concave mirror and M2 stands for second concave mirror. The following Table 2 shows the effect of misalignment of mirror towards laser beam position inside cavity.

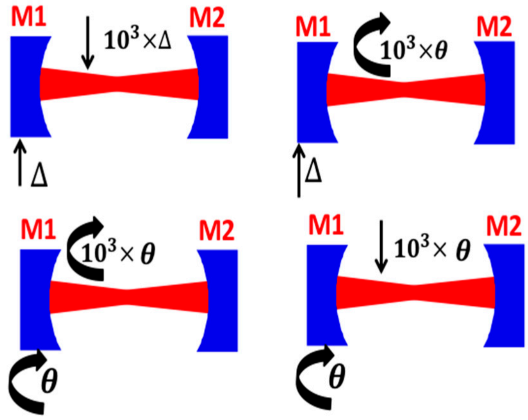

Figure 10. Position and Angular artifacts given to two mirrors and corresponding position and angular shift occurred to laser beam inside cavity.

Table 2: Parameters for four mirror resonator

Mirror	Position Shift (m)	Angle Shift (rad)
M1 (1μm)	-1.61488×10^{-3}	3.84615×10^{-3}
M1 (1μ-rad)	-6.78461×10^{-4}	1.61588×10^{-3}
M2 (1μm)	1.61588×10^{-3}	-3.84615×10^{-3}
M2 (1μ-rad)	6.78882×10^{-4}	-1.61588×10^{-3}

5. Analysis

From Table 2, it is clear that for 1 μm position misalignment to any mirror results in position shift of laser beam in order of mm. The same can be observed for angular misalignment of 1 μ-rad as it leads to laser beam position and direction in order of mm. Most Important thing to note is for any position misalignment of mirror results in both position and angular misalignment of laser beam. Also any angular misalignment of mirror results in both angular and position misalignment of laser beam. The misalignment of the order of μm results in angular and position shift of laser beam which is 1000 times higher the value of mirror misalignment value. With Angular Artifact Adjustment Piezo Actuator (AAAPA), the position and angular artifacts can be removed simultaneously. In principle, when there is position change in laser beam inside cavity then linear scanning piezo actuator corrects the position misalignment. At the same instant the angular piezo actuator corrects the angular misalignment caused by position misalignment of the mirror. Similarly, when there is angular shift of laser beam inside the cavity, the angular piezo actuator corrects the angular misalignment and the linear scanning piezo actuator can correct the position misalignment caused due to angular tilt of mirror. Thus, there is significance of AAAPA mirror holder to keep the resonance. The two angle adjustment piezo actuators of special mirror holder can nullify angular misalignment to cavity mirror. The longer piezo actuator which is used for cavity length expansion can be used for position misalignment of laser beam. The laser absorption based breath analysis is as sensitive process for detection of respiratory disease. The angular and position misalignment are generally neglected in clinical trials. In that case, laser absorption of gases is not perfect specially in case of low volume of gases. Thus the three piezo based laser cavity can be an effective tool for precise and accurate measurement of gases in breath sample. We demonstrated that for laser absorption based breath analysis, the AAAPA mirror holder is very important to operate laser cavity at resonance for longer duration of period.

Author Contributions: Arpit Rawankar and Jyoti Gondane conceived and designed the laser experiment. Ankit Ravankar designed the mechanical special mirror holder with three piezo actuators and performed analysis of angular artifacts.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

COPD: Chronic Obstructive Pulmonary Disease
AAAPA: Angular Artifact Adjustment Peizo Actuator
FSR: Free Spectral Range

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