A NEW KIND OF LASER MICROPHONE FOR PHOTOACOUSTIC APPLICATIONS

Chen-Chia Wang, Sudhir Trivedi, and Feng Jin
Brimrose Corp. of America, 7720 Belair Road, Baltimore, MD 21236

V. Swaminathan*
US Army, RDECOM-ARDEC, Picatinny, NJ 07806-5000

Narasimha S. Prasad
NASA Langley Research Center, Mail Stop 468, Hampton, VA 23681

ABSTRACT

We present in this paper a new kind of laser-based microphone device capable of detecting minute displacements of the microphone diaphragm, leading to drastically improved sensitivity in detecting the impinging pressure waves like acoustic waves and water waves over existing state-of-the-art laser and fiber-optic microphones. The drastically improved sensitivity in detecting diaphragm surface displacements of the novel laser microphone leads to niche applications including the photoacoustic detection of molecules and compounds with long standoff detection distances as well as highly sensitive technology for monitoring submarine activities. Preliminary experimental demonstration of the novel laser microphone technology is presented, validating the theoretical modeling that is also presented.

1. INTRODUCTION

The nation has been facing in recent years various security challenges posed by the ever technology-savvy adversaries who constantly evolve their approaches in inflicting psychological, economical, and physical damages to the nation and the people. Case in point is the deployment of car bombs which are relatively low cost, easy to deploy rapidly and difficult to detect and/or deter with a desirably long and safe standoff distance. The presence of chemicals like explosives exhibits itself in at least two independent physical parameters: the added weight of the explosives and its containers to the overall gross weight of the carrier vehicle and, secondly, spectroscopic fingerprints left by traces of the explosive molecules and compounds. Because sufficient amount of explosives are needed to inflict damages to the targets, their presence can modify the gross weight of the carrier vehicle significantly. On the other hand, the presence of explosive molecules and compounds can be unambiguously identified by detecting their spectroscopic fingerprints because each molecule has its own specific spectroscopic features. A reasonable course of counter-measure is then to first identify the vehicles with excessive mechanical weight and subsequently deploy spectroscopic technologies to interrogate the suspect vehicles and further identify the species and concentrations of targeted molecules and compounds that might be present. The gross weight of a vehicle can be estimated by monitoring its natural resonant frequency as the vehicle is subject to external force excitations like running over a speed bump. On the other hand, the spectroscopic fingerprints of molecules can be detected using photoacoustic spectroscopy (Wojcik et al., 2006), provided that long standoff detection distances can be achieved which would then offer field applicable operations without confining the test objects to laboratory based environments.

We have recently demonstrated a novel laser-based vibrometer whose optical speckle-tolerant nature makes it ideal for assessing the gross weight of passing vehicles. The laser vibrometer technology is based on the combination of pulsed illumination light sources and a kind of photoconductors termed photo-electromotive-force (photo-EMF) sensors (Rodriguez et al., 2003). The pulsed light sources can be Q-switched lasers or mode-locked lasers while the photo-EMF sensors are semiconductor devices that are highly photosensitive and exhibit orders of magnitude in resistivity changes upon the illumination of light. The unique combination of pulsed light sources and photo-EMF sensors leads to the photo-EMF pulsed laser vibrometer (PPLV) which possess the unique features of optical speckle-tolerance and exceptional sensitivity in monitoring the vibration of surfaces like that of the diaphragm of a microphone device. Indeed, we have recently applied PPLV to monitor the gross weight of passing vehicles. The PPLV technology has also been further evolved and adapted to a highly sensitive laser microphone for detecting the presence of pressure waves, including acoustic waves propagating in the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
DEC 2008	**N/A**	**-**

4. TITLE AND SUBTITLE	
A New Kind Of Laser Microphone For Photoacoustic Applications	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Brimrose Corp. of America, 7720 Belair Road, Baltimore, MD 21236**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002187. Proceedings of the Army Science Conference (26th) Held in Orlando, Florida on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**7**	

air or underwater. The novel PPLV laser microphone features drastically improved detection sensitivity in monitoring the surface displacement of pressure-wave sensing diaphragms. This enables photoacoustic spectroscopic technologies to be incorporated with the PPLV laser microphone with correspondingly improved detection sensitivity for explosive molecules detection as well as the extension of standoff detection distances estimated to be in excess of tens of meters.

We present in the following the working principles of the laser microphone, whose validity is demonstrated by preliminary experimental demonstrations. Some pathways for further improvement in detection sensitivity are then discussed briefly.

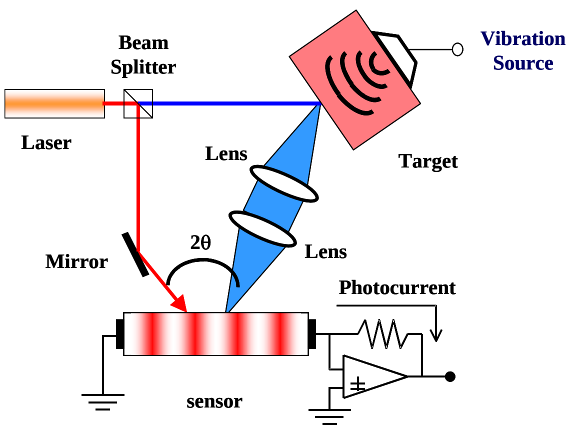

Fig. 1. Schematic of the PPLV when used to monitor remotely the surface vibration of a target.

2. PRINCIPLES OF PPLV LASER MICROPHONE

The operation principles of the PPLV laser microphone can be understood by first considering the way the PPLV operates. Figure 1 depicts a schematic of the PPLV setup when it is used to monitor remotely the surface vibration of a target, for example, the casing of a rotary motor or turbine engine. A pulsed light source like Q-switched or mode-locked laser emits a light pulse train which is split into two branches: the reference light beam travels via a mirror onto the photo-EMF sensor without being subjected to any intentional external perturbations. The probe light beam, on the other hand, is directed onto the target under surveillance. Due to the optically diffusive nature of essentially all the objects we face in our natural environment, the back-scattered probe light beam typically requires the use of collection optics, as shown in Figure 1, to collect and project it onto the photo-EMF sensor. The photo-EMF sensor is an optical motion sensor that generates photocurrents whenever the optical fringe pattern falling onto its active area exhibits motion. Note in Figure 1 that the reference and probe light beams impinge onto the photo-EMF sensor with a non-zero angle. In fact, θ is ~ 1^{o} in most of our experiments. Such non-zero intersection angle guarantees that the fringe intensity pattern formed by the reference and probe light beams will be set in motion as long as there is any temporal phase difference between the two light beams. Note that such temporal phase differences are readily generated by the target whose vibrating surface imposes phase modulations onto the back-scattered probe light beam. The photocurrents generated by the photo-EMF sensor are closely correlated in characteristics with the temporal phase variations it senses between the reference and probe light beams and hence the surface vibration characteristics of the target under surveillance.

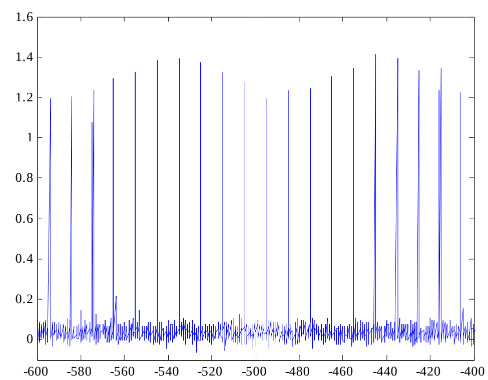

Fig. 2. Temporal photocurrent pulse train generated by the photo-EMF sensor embodied in a PPLV when the target was vibrating sinusoidally at 10 kHz and with the surface displacement value of 1 nm.

It is appropriate here to introduce some experimental data illustrating the behaviors of the PPLV just described. In Figure 2 we show the photocurrent pulse train generated by the photo-EMF sensor as the probe light beam was subject to phase modulations with the frequency of 10 kHz and the surface displacement of 1 nm. We note the discrete, pulsed nature of the photocurrents generated by the photo-EMF sensor which is not surprising considering the pulsed nature of the light source deployed in the PPLV. More interesting is the fact that the envelope of the photocurrent pulse train exhibits a sinusoidal variation with the characteristic frequency of 10 kHz, identical to that of the surface vibration applied to the test target. The amplitude of the sinusoidal envelope function of the photocurrent pulse train determines the sensitivity of the PPLV in monitoring the surface motion of targets. We thus conclude that the PPLV described in Figure 2 can readily resolve surface vibrations with the displacement value of 1 nm, a value that can also be resolved by typical optical interferometric techniques.

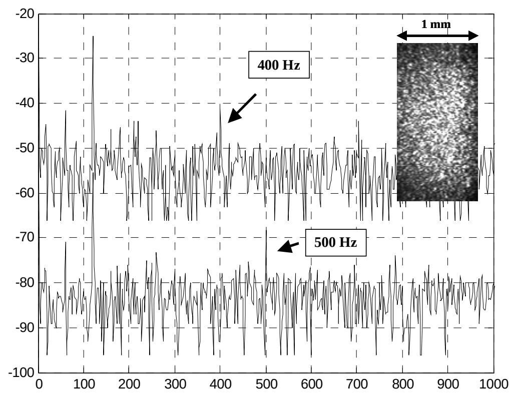

Fig. 3. Vibration spectra of one piece of 60-grit sandpaper that was vibrated sequentially with the frequencies of 400 Hz (upper trace) and 500 Hz. (lower trace), both with the surface displacement of 120 pm. The inset shows the optical speckle pattern of the back-scattered probe light beam. Note that the spectra have been vertically shifted for visual clarity purposes.

To demonstrate the superior detection sensitivity of the PPLV, we depict in Figure 3 the surface vibration spectra detected by the PPLV from one piece of 60-grit sandpaper. The sandpaper was vibrating at the frequencies of 400 Hz and 500 Hz, sequentially, but both with the same surface displacement value of 120 pm. Note that the PPLV was able to decipher the small displacement surface vibrations even in the presence of abundant background noise. In fact, the signals are both higher than their adjacent noise level by approximately 10 dB, indicating the possibility of achieving even better surface displacement resolution, all without data averaging. Furthermore, the optical speckle-tolerance of the PPLV is evidenced by the probe light beam intensity pattern shown in the inset of Figure 3.

Significant improvements in surface vibration displacement resolution are needed if the PPLV were to be applied for photoacoustic analysis of targets with standoff distances in the tens of meters. This is due simply to the fact that the amplitude of the incoming pressure wave drops off as a function of the standoff distance and hence more sensitive technology is needed to decipher such weak amplitude signals. This technological challenge can be resolved by embedding the PPLV in the configuration of a laser microphone. Figure 4 is a schematic drawing of the PPLV laser microphone which is very similar to that of the PPLV shown in Figure 1 with the exception that the remote target under test is now replaced in the PPLV laser microphone by the pressure-wave sensing interface and/or diaphragm. Also modified in Figure 4 is the addition of a reflective mirror that assists the probe light beam in achieving multiple-bounces from the pressure-wave sensing diaphragm.

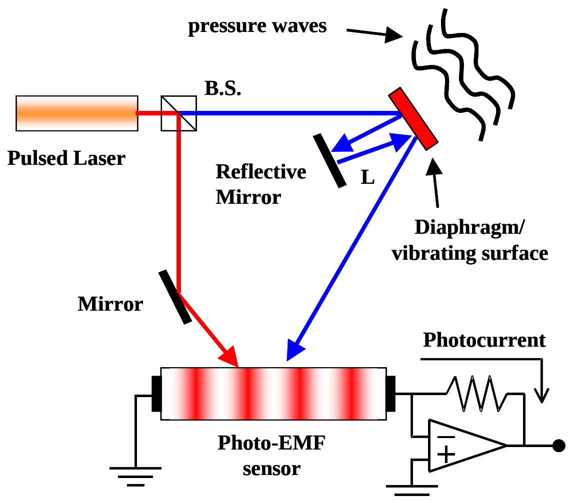

Fig. 4. One typical embodiment of the PPLV laser microphone for pressure wave sensing, including photoacoustic spectroscopic analysis of explosives.

The operation principles of the PPLV laser microphone can be understood by considering the following: the pressure waves, including those emitted by explosive molecules upon excitation with an IR laser of a suitable wavelength (Van Nesse et al., 2008), travels from the explosive molecules located at the standoff distance away from the PPLV laser microphone. The pressure wave impinges onto the diaphragm which conforms its surface to the temporal variation of the pressure waves by modulating its surface displacements. The probe beam of the PPLV laser microphone, assisted by the reflective mirror, repeatedly interrogates the diaphragm. With every single bounce from the vibrating diaphragm, the probe light beam acquires a single unit of phase modulation corresponding to the displacement value of the diaphragm. By increasing the total number of bounces to N, the effective total phase modulation imposed onto the probe light beam by the diaphragm is increased by the same factor of N. Thus the PPLV laser microphone effectively amplifies the impinging pressure wave amplitude by the factor of N or, equivalently, increasing the sensitivity of the diaphragm by N. Because the PPLV output signal strength is proportional to the surface displacement value of the diaphragm, the design of the PPLV laser microphone tricks the sensor into generating photocurrent signals whose strength is also amplified by the same factor of N. There are two unique and attractive attributes of the PPLV laser microphone: (1). The amplification of signal strength is nearly instantaneous (on the order of ns time scale) and no time-averaging, which is commonly used in spectroscopic analysis of low concentration molecules, is ever required, (2) the noise level of the PPLV detection system is not increased with the signal strength, leading to drastically improved detection signal-to-noise ratios (SNRs) which in turn improves the detection sensitivity and increases the standoff detection distances of photoacoustic sensing technology incorporated with PPLV laser microphone.

Simple mathematical modeling on the PPLV laser microphone has also been developed. We assume for simplicity that the incident pressure wave is sinusoidal in nature which causes the pressure-wave sensing diaphragm to undergo surface deformations that can be described as

$$d\, sin(\omega\, t) \tag{1}$$

where d is the surface displacement value of the diaphragm and ω is the angular frequency of the incident pressure wave. Every single time the probe light beam interrogates the diaphragm, such surface deformation imposes onto it an amount of phase modulation, ϕ_0, given by

$$\phi_0\,(t) = 4\,\pi\, d\, sin(\omega\, t) / \lambda \tag{2}$$

where λ is the wavelength of the light beam used by the PPLV laser microphone. If the PPLV laser microphone is configured as a N-pass microphone, i.e., the probe light beam interrogates the diaphragm repeatedly for N times, then the total amount of phase modulation suffered by the probe light beam upon its final exit from the diaphragm-reflective mirror assembly is given by

$$\phi\,(t) = \Sigma_n\; d\, sin[\omega\, t + (n - 1)\, \phi_0] \times 4\pi / \lambda \tag{3}$$

where n = 1, 2, 3….N, and the static phase $\phi_0 = \omega \times 2$ L/c, where L is the separation between the vibrating diaphragm and the mirror (Fig. 4) and c is the speed of light, is the additional phase delay experienced by the probe light beam upon its round-trip passage between the diaphragm and the reflective mirror. It can be seen from Eq.(3) that, if the phase shift $N \times \phi_0 << 1$, the total phase modulation can be approximated by

$$\phi\,(t) \approx N \times d\, \sin(\omega\, t) \times 4\,\pi / \lambda = N \times \phi_0\,(t) \tag{4}$$

It can be seen from Eqs.(2, 4) that by adopting the multiple-pass geometry, the PPLV laser microphone does indeed effectively amplify the magnitude of the pressure waves under detection. How such amplification translates into signal strength gains can be further understood by noting that, for a given amount of temporal phase difference between the reference and probe light beams, the photo-EMF sensors output photocurrent density can be approximated by

$$j^{\Omega}\,(t) = \kappa\, \phi\,(t) \times P_{\text{probe}}(t) \tag{5}$$

where $P_{\text{probe}}(t)$ is the probe light beam power density impinging onto the photo-EMF sensor and κ is a constant whose value is determined by the sensor material characteristic parameter values, the reference light beam intensity, laser wavelength, and the intersection angle between the reference and probe light beams at the sensor surface. Noting that the temporal phase difference between the reference and probe light beams is actually the same as the amount of phase modulation imposed onto the probe light beam of the PPLV laser microphone, it thus becomes clear from Eqs.(4,5) that the PPLV laser microphone effectively magnifies its output photocurrent strength by using the multiple-bounce configuration. More importantly from a detection point of view is the fact that the multiple-pass approach, while increasing the useful signal output strength, does not increase the noise level since both the thermal noise and the laser shot noise remain un-changed as the number of bounce/passes is increased in the PPLV laser microphone. Thus it is expected that the adoption of the multiple-pass PPLV laser microphone shall lead to significantly improved sensitivity in resolving surface vibrations with minute displacement values and, equivalently, a much improved detection SNR.

3. EXPERIMENTAL DEMONSTRATION

We now present some preliminary experimental data demonstrating the validity of the PPLV laser microphone as well as the theoretical modeling presented in the previous section. Note that in the experiments reported below, a mirror agitated controllably by a piezo-electric transducer was used to mimic the function of the diaphragm. Also, a passively Q-switched Nd:YAG laser built in our laboratory was used as the light source. The homemade pulsed light source was quite unstable and produced laser pulse trains with the repetition rate of approximately 1.2 kHz – 4 kHz. The laser pulse width varied between 20 – 40 ns while the laser pulse amplitude exhibited fluctuations approaching roughly 10% of its norm. Such instability in laser pulse amplitude posed limitations on the resolution of the PPLV laser microphone in sensing pressure waves. Fortunately such challenge can also be resolved by adopting commercially available light sources with greatly improved laser pulse amplitude stability (~ 0.1%).

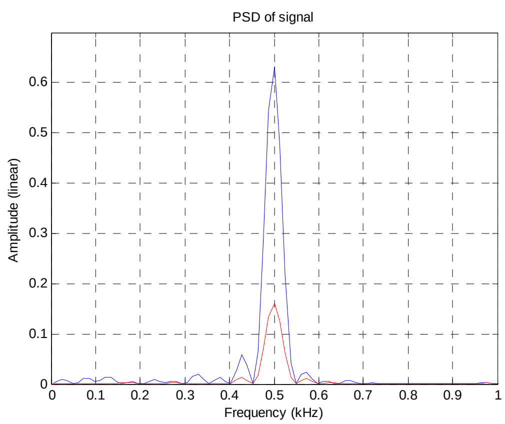

Fig. 5. Power spectra of the target surface vibration detected by the 1-pass (red trace) and 2-pass (blue trace) PPLV laser microphone.

We illustrate in Figure 5 the target's surface vibration spectra (plotted in terms of power spectral density) detected by the 1-pass (red trace) and 2-pass (blue trace) PPLV laser microphone when the target was agitated sinusoidally at the frequency of 500 Hz and the surface displacement of 3.2 nm. It is clear from Figure 5 that the 2-pass PPLV laser microphone significantly improved the detected signal strength which turned out to be better than that sensed by the 1-pass PPLV laser microphone by a factor of $2^2 = 4$, as expected. Note that the signal power spectral density will be amplified by the factor of N^2 when the signal is amplified by N.

Theoretical analysis presented in the previous section stipulates that the PPLV laser microphone output signal strength should continue to grow if the total number of passes it supports is increased. Indeed, we show in Figure 6 the power spectra detected by the 3- (blue curve), 4- (red curve), 5- (black curve), and 6-pass (magenta curve) PPLV laser microphones when the target was vibrating sinusoidally with the frequency of 500 Hz and the displacement of 400 pm. As expected, the PPLV laser microphone output signal strength (in terms of power spectral density) grows in proportion to N^2, with N being the number of passes supported.

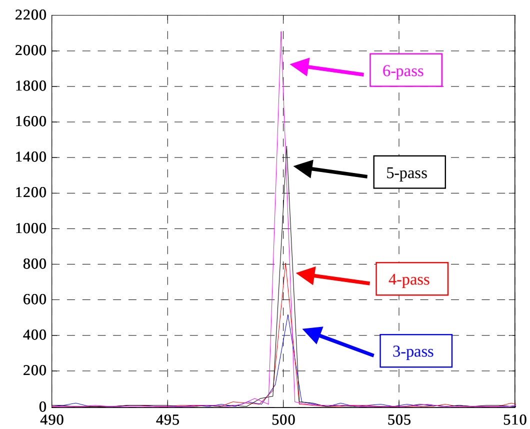

Fig. 6. Surface vibration spectra (expressed in terms of power spectral density) of the target detected by the 3- (blue), 4- (red), 5- (black), and 6-pass (magenta) PPLV laser microphones. The target was vibrated sinusoidally at 500 Hz with the surface displacement of 400 pm. The x-axis represents frequency in hertz while the y-axis represents the power spectral density (arbitrary unit).

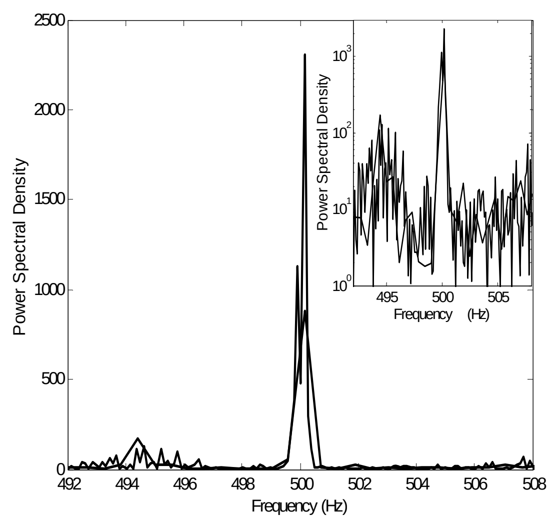

Fig. 7. Surface vibration spectra detected by the 23-pass PPLV laser microphone. The target was vibrating at 500 Hz with the surface displacement of 40 pm. The inset shows the same traces plotted in logarithm scale.

In order to improve the sensitivity for the detection of traces of explosive molecules and elongate significantly the standoff detection distance in the context of photoacoustic spectroscopic analysis, it is highly desirable to further improve the detection sensitivity of the PPLV laser microphone in sensing the surface displacement of the diaphragm. As Eqs.(4,5) predict that stronger signal currents can be generated with higher number of passes, we thus increase further the value of N to around 23 by adjusting the configurations of the diaphragm and the reflective mirror. Figure 7 shows the power spectra detected by the 23-pass PPLV laser microphone when the target was agitated sinusoidally at 500 Hz and the surface displacement value of 40 pm. The dotted trace was taken over a time window width of roughly 1.8 sec while the solid curve was taken over that of ~ 8.7 sec. Even though the target's surface exhibited the displacement of merely 40 pm, the PPLV laser microphone was able to detect vividly the underlying vibration signals with corresponding spectral peaks elevating from their adjacent noise floor by nearly a factor of 1000. Such excellent SNR indicates that the PPLV laser microphone, in the conditions described by Figure 7, was capable of deciphering even smaller surface displacement values. If we define the minimally detectable surface displacement as that when SNR = 1, it is then concluded from Figure 7 that the PPLV can sense surface displacement as small as 1.3 pm. Note again that better resolution in sensing diaphragm displacement enhances the sensitivity for trace molecule detection. Similarly, the standoff detection distance is also increased correspondingly.

4. DISCUSSIONS

To further lengthen the standoff detection distance as well as improve the detection sensitivity for explosive molecule detection, further improvements in diaphragm surface displacement detection is needed. This can be achieved by increasing the signal strength, reducing the noise floor, or both. It is clear from discussions above that the PPLV laser microphone can greatly improve its output signal strength by ramping up the total number of passes it supports for the probe light beam to interrogate the diaphragm. Fortunate also for the PPLV laser microphone is the fact that the noise floor is not affected as the number of bounces is increased since both the thermal noise and shot noise are independent of the number of bounces the probe beam makes. Thus one simple solution for improving the detection sensitivity of PPLV laser microphone is to ramp up the total number of passes it supports. Note that the maximal number of passes is limited by the laser pulse width, the optical losses of the system, as well as the arrangement between the diaphragm and the reflective mirror (Siegman, 1986). Any more passes higher than the maximal value would simply contribute to signal distortion and the generation of harmonics and reduce the detection SNR.

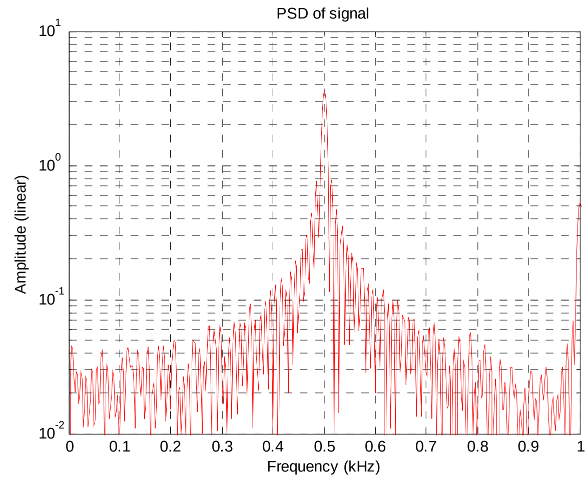

Fig. 8. Vibration spectrum detected by the PPLV laser microphone with 0.1% laser pulse amplitude fluctuations.

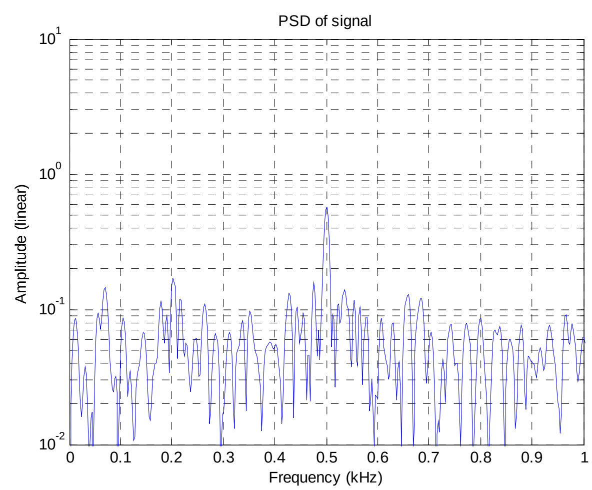

Fig. 9. The same spectrum (as shown in Fig. 8) sensed by a PPLV laser microphone with the noisy light source which had the laser pulse amplitude fluctuation of 10%.

Another method of improving the performance of the PPLV laser microphone is to reduce the noise floor by, for example, reducing the laser shot noise by employing light sources with improved laser pulse amplitude fluctuations. Indeed, in the following experiment we compare the performance of two identical PPLV laser microphones with the only exception that the lasers used exhibited varying degrees of laser pulse amplitude fluctuations. In Figure 8 we show the vibration spectrum sensed by the PPLV laser microphone with a stable light source specified to have the laser pulse amplitude fluctuation of 0.1% while in Figure 9 the same spectrum sensed by the PPLV laser microphone built around a relatively noisy light source with 10% laser pulse amplitude fluctuations is shown. It is obvious that the quiet PPLV laser microphone produced significantly cleaner results than the noisy one. In fact, it can be argued from Figures 8 and 9 that the quiet PPLV laser microphone with 0.1% laser pulsed amplitude fluctuation produced the signal peak whose strength is roughly a factor of 6 greater than that from the noisy PPLV laser microphone. Further, the quiet PPLV laser microphone's noise floor is reduced by a factor of 2.5 (roughly). Overall, the deployment of a more stable light source easily improved the performance/resolution of the PPLV laser microphone by more than a factor of 10. Combined with increasing the number of passes supported by the PPLV laser microphone, we expect to improve the detection sensitivity of the PPLV laser microphone in sensing diaphragm movements by a factor of 50, corresponding to the minimally detectable surface displacement value of approximately 30 fm. The corresponding standoff detection distance is expected to be in the tens of meters.

5. CONCLUSIONS

In conclusion, we have demonstrated preliminarily a new type of laser microphone capable of detecting with drastically improved sensitivity and resolution the surface movement of pressure wave sensing diaphragms. Such improved detection sensitivity allows more accuracy in detecting the presence of targeted molecules like explosives as well as the extension of standoff detection distances. While we have demonstrated accurate reading of surface displacements as small as a few picometers, directions for further improvement in the PPLV laser microphone's performance are also developed with preliminary experimental validation.

ACKONWLEDGMENTS

The authors from Brimrose Corporation acknowledge the partial financial support by US Army ARDEC under contract # W15QKN-07-P-0546.

REFERENCES

Rodriguez, P., Trivedi, S., Jin, F., Wang, C.-C., Stepanov, S., Elliott, G., Meyers, J., and Khurgin, J., *Appl. Phys. Lett.*, **83**, 1893-1895.

Siegman, A. *Lasers*, University Science Books, Sausalito, CA (1986).

Wojcik, M., Phillips, M., Cannon, B., Taubman, M., 2006: Gas-phase Photoacoustic Sensor at 8.41 mm using Quartz Tuning Forks and Amplitude-Modulated Quantum Cascade Lasers, *Appl. Phys. B*, **85**, 307-313.

Van Nesse, C.W., Senesac, L.R., and Thundat, T., 2008: Standoff Photoacoustic Spectroscopy, *Appl. Phys. Lett.*, **92**, 234102.