Human Life Signs Detection Using High-Sensitivity Pulsed Laser Vibrometer

Chen-Chia Wang, Sudhir B. Trivedi, Feng Jin, Serguei Stepanov, Zhongyang Chen, Jacob Khurgin,
Ponciano Rodriguez, and Narasimha S. Prasad

***Abstract*—We demonstrate experimentally the detection, in a remote and noncontact manner, of human life signs using a high-sensitivity pulsed laser vibrometer. The high surface displacement detection sensitivity of the photo-electromotive-force (photo-EMF) pulsed laser vibrometer, combined with its tolerance to the presence and moderate temporal variations of optical speckles in the light beams, allows the detection of human heartbeats, breathing, and gross physical movement from essentially any part of a human subject's surface, even in the presence of clothing, all the while without limiting the interrogation points to specific locations like the chest and carotid areas. In contrast to conventional Michelson interferometer-based laser vibrometers, the photo-EMF pulsed laser vibrometer (PPLV) does not require the use of retroreflective tapes or special electronic filtering to retrieve vividly the biological subject's life signs. Experimental results demonstrating the detection of life signs from various parts of biological subjects' bodies, with or without the coverage of clothing are presented. We also demonstrate the monitoring of a human subject's heart movements by interrogating the back of his/her hand. Results from using PPLV to determine extremity blood circulation at various levels of proximal occluding pressures are also presented.**

***Index Terms*—Biomedical acoustics, biomedical measurements, medical diagnosis, optical velocity measurement, photodetectors, vibration measurement.**

I. INTRODUCTION

MEDICAL techniques abound that are capable of monitoring patients' life signs including heartbeat rate [1], [2], respiratory rate, and blood pressure. However, these techniques generally require the physical attachment of sensor heads through wires and cables onto specific parts of the patient's body. This creates challenges in that good physical contact with the patient's body must be maintained. In some instances, the presence of wires and cables for signal conduction may impose inconveniences to patients and medical personnel alike. Furthermore, situations do exist in which good, wired physical contact with the human subjects are impossible or clearly undesirable. For example, it is unwise to have direct physical contact with potential victims in a chemical, biological, or radioactive attack scenario. Recently, laser-based remote sensing techniques have emerged and appear to be ideal for select medical applications [3]. These conventional laser vibrometers based on Michelson interferometers measure the movement of the patient's skin caused by, for example, heartbeats and breathing. They have been applied to monitor the heartbeat of patients directly from the chest and carotid areas where impacts on the skin surface displacement by the pulsation of the heart is the most profound. Such limited accessibility might hinder the ability of conventional Michelson interferometer-based laser vibrometers to monitor human life signs in situations in which these areas could not be readily exposed due to associated injuries and dressings or in chemical, nuclear, or biological attack victims who might be dangerous to come in physical contact with. Furthermore, conventional Michelson interferometer-based laser vibrometers suffer from two major hurdles, i.e., limited sensitivity to surface displacement detection and their intolerance to the presence of optical speckles in the light beams. The presence of optical speckles can cause sudden signal dropoffs in conventional Michelson interferometer-based laser vibrometers [3]. That is, a sudden phase change in the speckles can lead to a correspondingly sudden drop in optical power reaching the photodetector of conventional laser vibrometers leading, in some cases, to false interpretation of the diminished output. This is evidenced by the necessity of deploying retroreflective tapes and electronic signal filtering in previous studies using conventional laser vibrometers to monitor human subjects' heartbeats from their chest areas [3]. Furthermore, the limited sensitivity to surface displacement detection of conventional laser vibrometers implies that they must interrogate specific locations on the human subject's body where the skin displacement caused by heartbeats is the most significant. Deviations from those specific areas or coverage by clothing can rapidly diminish the detected signal strength [3], rendering conventional Michelson interferometer-based laser vibrometers less attractive in retrieving human vital signs outside of a well-controlled hospital or laboratory-based environment.

Recently, we developed a highly sensitive pulsed laser vibrometer based on the combination of a pulsed light source and the photo-electromotive-force (photo-EMF) sensor. We have demonstrated experimentally the real-time detection of surface

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C.-C. Wang, S. B. Trivedi, and F. Jin are with the Brimrose Corporation, Baltimore, MD 21236 USA (e-mail: ccwang@brimrose.com; strivedi@brimrose.com; fjin@brimrose.com).

S. Stepanov is with the CICESE, Ensenada 22860, Mexico (e-mail: steps@cicese.mx).

Z. Chen and J. Khurgin are with the Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, MD 21218 USA (e-mail: zychen@brimrose.com; jakek@jhu.edu).

P. Rodriguez is with the Instituto Nacional de Astrofísica, Óptica y ElectrónicaI, Puebla 7200, Pue. Mexico (e-mail: ponciano@inaoep.mx).

N. S. Prasad is with the NASA Langley Research Center, Hampton, VA 23681 USA (e-mail: n.s.prasad@larc.nasa.gov).

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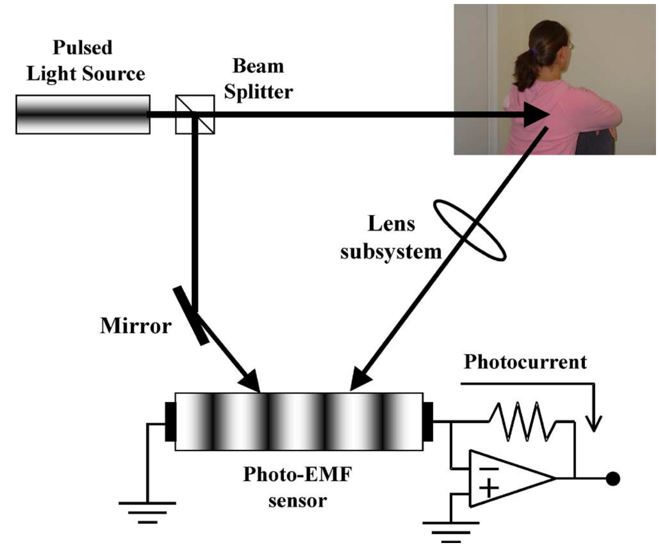

Fig. 1. Schematic of the experimental setup for the PPLV for human life signs detection. Note that the laser interrogation point is on the surface of the subject's clothing and no exposed skin is required.

vibrations with the displacement of 75 pm in the frequency range of several hundreds of Hertz and in the presence of abundant speckles in the light beams reaching the detection area of the photo-EMF sensor [4]. Such high sensitivity in surface displacement measurement and the tolerance to optical speckles allow the photo-EMF pulsed laser vibrometer (PPLV) to be deployed to monitor the life signs of humans and other biological subjects from essentially any part of their bodies, with or without clothing covering and without requiring any surface pretreatments like the attachment of retroreflective tapes or the deployment of special electronic filtering in order to eliminate the sudden dropoffs in the vibrometer output. We present, in this paper, experimental demonstrations using PPLV to detect the heartbeats, respirations, and gross physical movement of human subjects. Contrasting results obtained from a lifeless house mouse are also presented to demonstrate the feasibility of using the PPLV to differentiate deceased victims from survivors. Furthermore, results of a preliminary study using PPLV to monitor the blood flow in the extremities of human subjects are also presented.

II. OPERATING MECHANISM OF THE PHOTO-EMF PULSED LASER VIBROMETER

To illustrate the operating mechanism of the PPLV, Fig. 1 depicts a typical experimental arrangement used to monitor the life signs of human and other biological subjects. A pulsed light source, either a passively Q-switched Nd:YAG laser $(\mathrm{wavelength} = 1064\ \mathrm{nm})$ or an amplitude-modulated diode laser $(\mathrm{wavelength} = 850\ \mathrm{nm})$, was used as the light source. It emitted a train of light pulses which was further split into the reference and probe light beams. The reference light beam impinged upon the photo-EMF sensor directly, while the probe light beam was directed towards the test subjects' clothed surfaces, onto the hands and fingernails of other human test subjects, and onto the back of a lifeless white albino house mouse. The probe light beam back scattered from the subject's surface was collected by the lens subsystem and projected onto the active area of the photo-EMF sensor. Comparison with the reference light beam occurs within the photo-EMF sensor which generates photocurrent pulses that can be used to extract useful information, including the subject's heartbeat rates, strength, and temporal signatures. The photo-EMF sensors are generally semiconductor-based photodetectors that, unlike photodiodes which are direct detection devices that respond only to the optical intensity impinging on them, reacts to the spatial and temporal motion of the optical intensity patterns incident on their active areas [5]. Such movement in the impinging optical intensity pattern can occur due, for example, to the temporal phase modulations suffered by the probe light beam upon its backscattering from the subject's surface that is vibrating caused by the subject's heartbeat, breathing, or gross physical movement. Also contributing is the fact that the reference and backscattered probe light beams intersect at the photo-EMF sensor with a nonzero angle, with 1° being a quite typical value. Such nonparallelism between the two interfering light beams causes the resultant optical intensity pattern to physically move across the active area of the photo-EMF sensor whenever the two light beams have different instantaneous frequencies. Note that such nonparallel light beams will diminish the output signal strength from a photodiode due to averaging, rendering it less effective in motion sensing when embodied in the form of a conventional laser vibrometer.

As the impinging photons are absorbed by the photo-EMF sensor, photocarriers like electrons and/or holes are generated with a spatial distribution pattern within the sensor resembling that of the incident optical intensity pattern. In an overly simplified modeling, these free charge carriers would try to follow the moving optical intensity pattern as it travels across the active area of the photo-EMF sensor. Since electric charge carriers' motion constitutes currents, such photocurrents generated by the photo-EMF sensor can, thus, be used to decipher the motion of the impinging optical intensity pattern and, in turn, reveals information on the phase modulations imposed onto the backscattered probe light beam by the vibrating surface of the test subject. As a result, characteristics of the surface vibrations caused by, for example, the subject's heartbeats, can be determined by detecting the photocurrents generated by the photo-EMF sensor embodied in the configuration of a pulsed laser vibrometer [6]. Note that no photocurrents are generated by the photo-EMF sensor when the intensity pattern is stationary. The photo-EMF sensors used in the experiments reported in this paper were based on cadmium telluride doped with vanadium (CdTe:V) crystals grown in house at Brimrose Corporation. The active area of the sensor had the width of 1 mm and the height of approximately 3 mm.

Fig. 2 shows one typical temporal trace generated by the PPLV when the target surface under investigation was vibrating sinusoidally with the frequency of 10 kHz and the surface displacement of 1 nm. The light source used was an amplitude-modulated diode laser with the wavelength of 850 nm. The photo-EMF sensor generated photocurrent pulses under the stimuli of incident laser pulses and, hence, the discrete nature of the photocurrents. The photocurrent generated by the sensor can be approximated as $j_0(\mathrm{t}) = j_{\mathrm{pv}}(P_{\mathrm{probe}}(\mathrm{t}) + P_{\mathrm{ref}}(\mathrm{t})) + j_{\Sigma}(\mathrm{t})$,

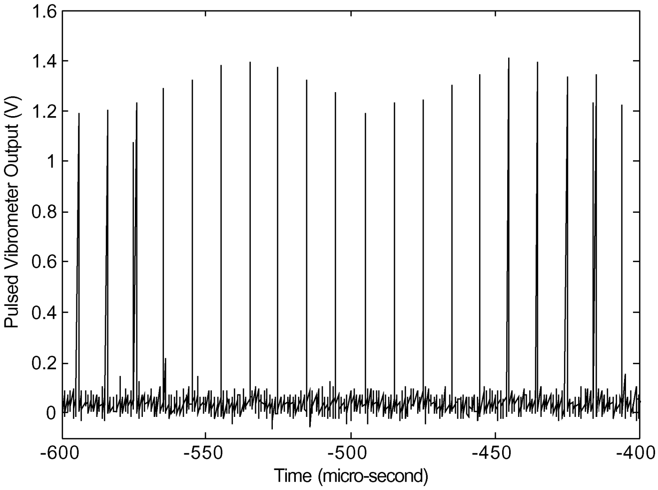

Fig. 2. A typical temporal waveform generated by the PPLV. The target surface was being agitated sinusoidally with the frequency of 10 kHz and the surface displacement of 1 nm. The light source was an amplitude-modulated diode laser operating at the wavelength of 850 nm.

where j_{pv} is the photovoltaic current whose magnitude is determined by the incident optical power densities of the probe light beam, $P_{\mathrm{probe}}(\mathrm{t})$, and the reference light beam, $P_{\mathrm{ref}}(\mathrm{t})$, as well as the sensor's material characteristics. The information-carrying photo-EMF current can be expressed as $j_{\Sigma}(\mathrm{t}) = \kappa \times D_{\mathrm{S}}(\mathrm{t}) \times P_{\mathrm{probe}}(\mathrm{t})$, where $D_{\mathrm{S}}(\mathrm{t})$ is the surface displacement of the vibrating surface and κ is a constant determined by the geometrical factors of the sensor, photon energy, as well as the reference laser power density [6]. The temporal dependence of the various parameters accounts for the pulsed nature of the incident light beams, as well as the surface vibration being monitored. Note that the photovoltaic current functions to add a quasi-dc offset to the overall photocurrent output from the photo-EMF sensor. The useful photo-EMF current, on the other hand, depends both on the incident light intensity levels, as well as the displacement of the surface vibration being sensed by the backscattered probe light beam. For given light intensities, the photo-EMF current amplitude varies in proportion to the surface displacement being detected. As a result, the envelope of the photocurrent pulse train thus mimics the surface displacement being detected by the PPLV, a claim that is evidenced by the temporal trace shown in Fig. 2 whose envelope demonstrates a sinusoidal variation identical to the agitation applied to the test surface.

The sensitivity of photo-EMF sensors embodied in prior-art techniques for surface vibration monitoring, for example, laser ultrasonic detection and diagnostics, has been studied previously [7], [8]. However, these prior-art techniques all involve the use of continuous-wave light sources with relatively high average power levels in order to compensate for the lower detection sensitivity of photo-EMF sensors [7]. One distinguishing advantage of PPLV, on the other hand, is the improved surface vibration detection sensitivity due to its use of pulsed light sources. This argument can be validated by comparing the surface vibration detection signal-to-noise ratio (SNR) of the PPLV to those of the conventional photo-EMF continuous-wave laser vibrometers. With the maximal detection angular frequency of $\omega_{\max}$, the electrical detection bandwidth of the photo-EMF continuous-wave laser vibrometer is required to be approximately $B_{\mathrm{cw}} = \omega_{\max}/2\pi$, leading to the assumed signal-to-noise ratio of SNR_{cw} in the presence of the average optical power density of P_0. By maintaining the same average optical power levels while adopting a pulsed laser with the duty cycle of $\chi \equiv \tau_{\mathrm{p}}/T_p \ll 1$, where τ_{p} is the laser pulse width and T_p is the period of the pulse train, the PPLV generates photocurrents whose magnitudes are increased by a factor of χ^{-1} due to the concentration of laser energy within the short-time duration of the laser pulse. In order to decipher the resultant photocurrent pulses, the detection bandwidth of the PPLV must be increased to approximately $B_{\mathrm{pulsed}} = 1/\tau_{\mathrm{p}}$. Assuming that the amplifier noise current dominates the detection process, the SNR can be defined as the ratio of photo-EMF current to the rms value of amplifier noise current and the increase of detection bandwidth invariably increases the magnitude of the noise current. The SNR of the PPLV can then be written as

$$\begin{aligned}\mathrm{SNR}_{\mathrm{pulsed}} &= \mathrm{SNR}_{\mathrm{cw}} \times \chi^{-1}/(B_{\mathrm{pulsed}}/B_{\mathrm{cw}})^{1/2} \\ &= \mathrm{SNR}_{\mathrm{cw}} \times (\omega_{\max} T_p/2\pi\chi)^{1/2}. \qquad (1)\end{aligned}$$

Nyquist theorem [9] dictates that faithful reconstruction of the analog signal can be achieved from a series of discrete samples whose sampling rate is at least a factor of 2 greater than the highest frequency component of the analog signal, i.e., $\omega_{\max} T_p \leq \pi$. As a result, the maximal SNR of the PPLV for monitoring surface vibrations is given by

$$\mathrm{SNR}_{\mathrm{pulsed}}^{\max} = \mathrm{SNR}_{\mathrm{cw}}/(2\chi)^{1/2}. \qquad (2)$$

Because the duty cycle of the pulsed laser can be quite small, i.e., $\chi \ll 1$, the PPLV can enhance the measurement SNR by a large factor. For example, the SNR can be increased by a maximal amount of 70.7 with the duty cycle of $\chi = 10^{-4}$, a value that is commensurate with the light source used in the experiments reported in this paper.

III. EXPERIMENTS

A. The Big Picture: Detection of Heartbeat, Breathing, and Gross Physical Movement

The feasibility of using the PPLV to monitor human subject's heartbeat, breathing, and gross physical movement is demonstrated in Fig. 3, which depicts the temporal traces detected from two male human subjects with no known major health conditions over a relatively broad time window of 40 s. In this experiment, the human subjects were asked to sit on a chair at the end of the optical table on which the PPLV was housed. The probe laser beam interrogated the right side of the subjects' backs, towards their right arms and displaced away from the hearts. The subjects wore daily clothing of typical materials, color, and knitting patterns. The passively Q-switched Nd:YAG laser was used as the light source, offering the average probing power of approximately 140 μW. It was quite unstable and emitted light pulses with the width of approximately 40 ns at the repetition rate of roughly 2.5 kHz. The collection lens had the diameter of 1 inch and the focal length of 4 inches. The probe light was backscattered from the subjects' clothing and sent to the photo-EMF sensor for deciphering. During the procedure, the

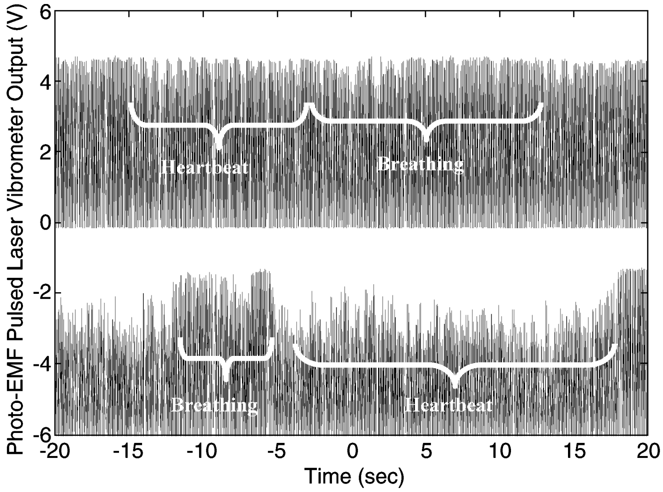

Fig. 3. Life signs of two male human subjects detected by the PPLV from the right hand side of their backs. Heartbeats of the subjects are indicated by the higher frequency pulses in the output from the pulsed laser vibrometer, while breathing is represented by the lower frequency bulky plateaus in the output.

subjects were requested to exhale initially and, after inhaling, hold their breath for as long as possible so as to minimize any smearing of the heartbeat signals by their respirations. As indicated by Fig. 3, various structures are present in the temporal traces output by the PPLV. The bulky, low-frequency plateaus were caused by the respiratory motion of the subjects causing the interrogation point on the clothing surface of the subject to shift in and out of the focal point of the collection lens and, hence, fluctuations in the collected backscattered probe light beam power. Once the human subject stopped breathing, vivid periodic photocurrent pulses resembling heartbeats appeared. Note that even though the laser interrogation points were displaced away from the subjects' chests and the carotid areas and the laser beam did not reach the subjects' skins, vibrations caused by their heartbeats coupled through to their clothing and, once again, the high-sensitivity and optical speckle tolerance of the PPLV allowed the successful detection of their life signs.

In contrast to the active signs of life detected from the human subjects shown in Fig. 3, an interesting comparison was performed using the PPLV to interrogate for life signs in a deceased common white albino house mouse (*mus musculus*) with no commonly accepted observable signs of life such as movement, respirations, or heart beat. As can be seen from Fig. 4, absence of photocurrent spikes corresponding to heartbeats or respirations, as shown in Fig. 3, is notable as the lifeless mouse generated flat-line responses from the PPLV.

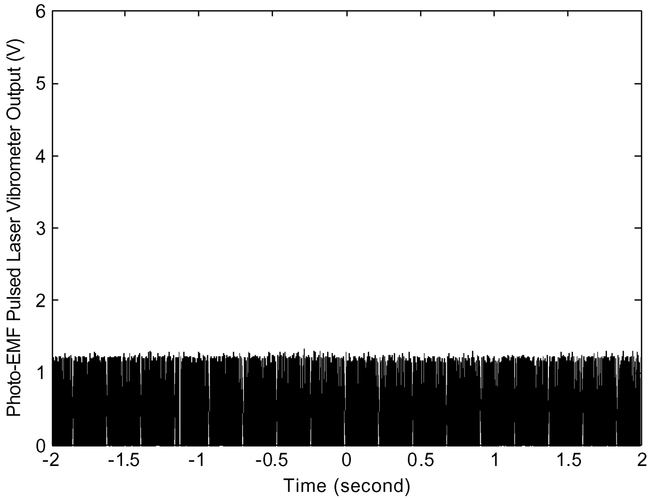

Fig. 4. Life signs of a deceased white albino house mouse detected by the PPLV. Its flat-line response does not show any spikes indicative of heartbeats nor slow frequency fluctuations suggestive of breathing action of the mouse, two features that are clearly shown in Fig. 3 taken from two healthy male human subjects.

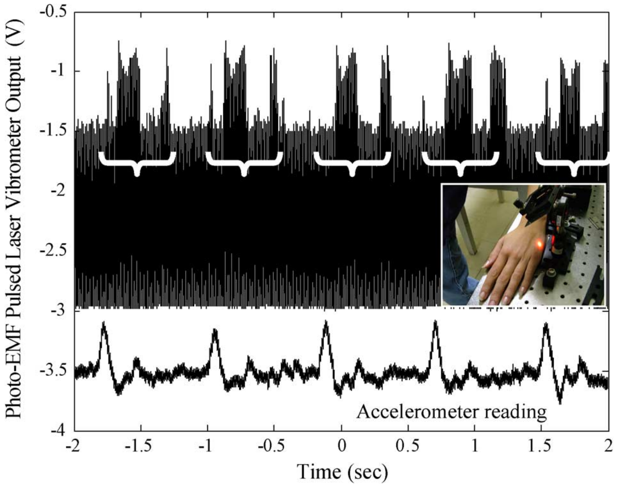

Fig. 5. Human heartbeat waveforms detected by the PPLV (upper trace) from the back of the subject's hand and that from a contact accelerometer firmly pressed onto the carotid area of the subject (lower trace). Even though the subject was allowed to breath normally, the noncontact PPLV detected a clear picture of the heart movement of the subject, including secondary waves. The laser interrogation point is indicated by the inset.

B. The Small Picture: Detection of Human Heart Movement

As opposed to the global view of the detected human subjects' heartbeats, respirations, and gross physical movements depicted in Fig. 3, we applied the PPLV to monitor the individual heartbeat pulses of a human subject over a much shorter time window of 4 s with the goal of deciphering in more detail the movement of the subject's heartbeat. In this experiment, the PPLV was used to detect individual pulsations from the back of the human subject's hand. The subject, while standing, placed his/her hand on the table with the probe light beam impinging in an approximately perpendicular manner, as shown in the inset of Fig. 5. The average incident probe beam power was smaller than 200 μW onto the subject's hand. Note that unlike the tests described in Fig. 3, the subject breathed normally in this experiment, and Fig. 5 depicts one temporal trace detected by the PPLV from such an experiment. For comparison reasons, one trace detected from the same subject using a contact accelerometer pressed firmly onto his/her carotid area was also displayed. Fig. 5 shows that the PPLV was able to detect clearly the individual heartbeats of the subject, as indicated by the signal peaks enclosed by the inverted curly brackets in Fig. 5. Similar to more conventional techniques like electrocardiograms (ECGs), we note that the heartbeats detected by the PPLV consists of multiple secondary waves. However, affirmative interpretations of the nature of these secondary waves must

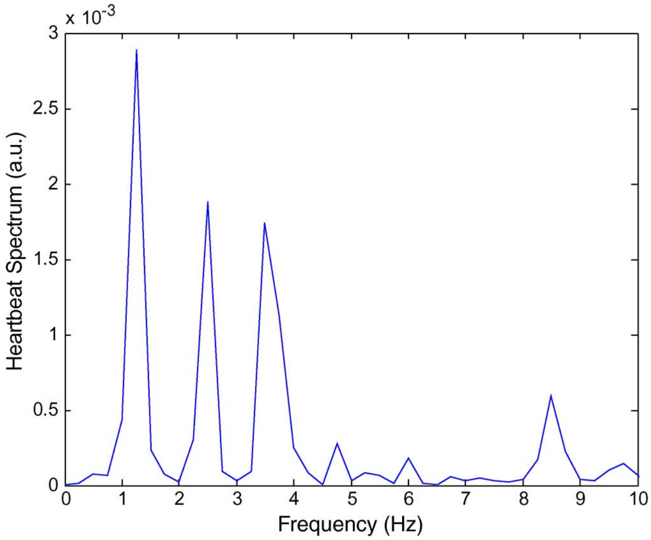

Fig. 6. Spectrum of the subject's heartbeat detected by PPLV and shown in Fig. 5. The spectrum exhibits the presence of strong signal peaks at approximately 1.25 Hz and its harmonics, leading to the estimated heartbeat rate of 75 beats per minute.

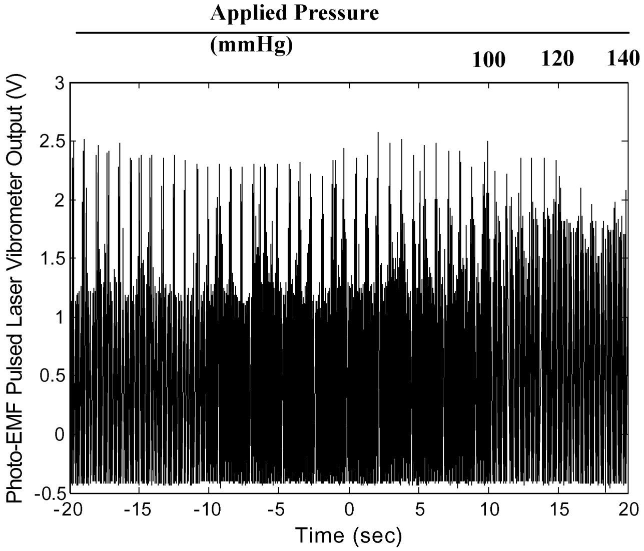

Fig. 7. Human subject's life signs detected from his/her fingernail by the PPLV as the blood pressure cuff applied various amounts of pressure onto his/her forearm to manipulate the amount of blood flow onto the subject's fingers. Note the marked decrease of heartbeat signal strength detected by the PPLV as the blood pressure cuff applied pressure levels close and beyond the systolic pressure of the subject.

be obtained in future investigations by correlating PPLV readings with those offered by conventional techniques like ECGs. Fig. 5 also shows that the output of the PPLV offers a real-time reproducible tracing of the human subject's heart movement as does the contact accelerometer. Of course, the PPLV has a potentially significant advantage over the contact accelerometer and ECG in that it provides a noncontact, noninvasive technique that does not require physical contact with subjects and does not require direct exposure of their skin to the laser beam.

Quantitative information like the subject's heartbeat rate can be readily determined from Fig. 5 by calculating its corresponding spectrum. Fig. 6 shows the resultant spectrum, indicating the presence of strong signal peaks occurring at the frequencies of approximately 1.25 Hz and its various harmonics, leading to the estimated heartbeat rate of 75 beats per minute for the subject under test.

C. Detection of Blood Circulation to Extremities

Many medical situations exist that require determination of blood flow conditions in the patient's extremities either for diagnosis or for development of an effective treatment plan. Examples include arteriosclerotic disease predominantly in the lower extremity arteries of both diabetic and nondiabetic patients, suspected vasospastic diseases, nonocclusive vascular disorders in which the arteries may be normal but blood flow is reduced because of arterial entrapment, and in the perioperative period after arterial operations on injured or otherwise diseased arteries. In injured extremities being monitored for compartment syndrome, it might be useful to be able to demonstrate and quantify blood flow through intact dressings or casts. It might also be useful to be able to assess blood flow in the bed of lower extremity ulcers repetitively without removing the dressing.

We tried to determine in a very crude experiment the extent of blood flow to the extremities of a human test subject by interrogating the subject's heartbeats from his/her fingernail using the PPLV. In this experiment, a proximally applied blood pressure cuff was used to variably and briefly obstruct blood flow to the extremity of a human volunteer in apparent good health. Fig. 7 depicts a temporal trace generated by the PPLV from interrogating the subject's fingernail while the blood pressure cuff applied different amounts of pressure to the subject's forearm. As Fig. 7 shows, when the applied pressure from the blood pressure cuff was lower than the pretest systolic pressure of the subject, which was approximately 120 mmHg, the pulsations detected by the PPLV kept an approximately constant amplitude. As the applied pressure was increased to values closer to the subject's systolic pressure, the amplitudes of the pulsations detected by the PPLV began to decrease correspondingly. When the applied pressure was 20 mmHg (at 140 mmHg) above that of the subject's systolic pressure level, periodic pulsations detected by the PPLV at lower levels of applied pressure disappeared completely. In their place, however, were signals consistent with random movement of the surface of the subject's fingernail. The cause of these random movements is not clear at present, but they could have been caused by involuntary muscle twitches related to restriction of blood flow or simply as a reflex phenomenon related to the minor discomfort of the blood pressure cuff. Visibly, there was no gross movement of the digit during this phase of the experiment. We are assuming that all blood flow was cut off, but we do not have verification of that with another modality of testing. These phenomena can be further elucidated in future experiments.

Note that in this experiment the human subject's finger was placed on the table top with a normal incidence of the probing laser beam. The average incident probe beam power was approximately 250 μW. The subject's nails were clear and without any nail polishes. Similar to the experiment reported in Section III-B, the human subject was in standing position and breathed normally within the 40 s of data acquisition period.

The results shown in Fig. 7 demonstrated the feasibility of using the PPLV to monitor the blood circulation conditions to the extremities of human subjects. Note once again that the highly sensitive and speckle-tolerant nature of the PPLV enabled the real-time determination of human signs of life from the subject's fingernail without using any retroreflective tapes and special electronic filtering to eliminate dropoffs encountered by conventional Michelson interferometer-based laser vibrometers. Even though the laser interrogation location was on the fingernail, a place far displaced from the conventional interrogation points of the chest and carotid areas of the human subjects, the high sensitivity of the PPLV readily allowed remote, noncontact determination of the human subject's signs of life.

IV. CONCLUSION

In conclusion, we have demonstrated that a highly sensitive pulsed laser vibrometer that is tolerant to the presence of speckles in the light beams can be used to detect the life signs of biological subjects, including humans, from essentially any part of the subject's body. We presented experimental data showing that the PPLV was able to monitor the human subject's heartbeat, respirations, and gross physical movement in a noncontact and remote fashion. We also demonstrated that signs of life (heart beat and respirations) could be detected through intact clothing without requiring any exposed skin. Furthermore, we also showed phasic changes in pulsed laser vibrometer signals from circulatory changes in the back of the subject's hand that correlated well with those taken by an accelerometer over the carotid artery. We also showed that the pulsed laser vibrometer signal has primary and secondary peaks which with further experimentation may be correlated to specific cardiac events such as the onset of systole and diastole. We further probed and validated the feasibility of using the PPLV to determine in real-time blood flow conditions to the extremities of human subjects by identifying the correlation between the heartbeat signature strength from the subject's fingernail with the extent of restriction on blood flow. These experiments suggest a possible use of the PPLV in monitoring life signs in settings extending beyond well-controlled laboratories.

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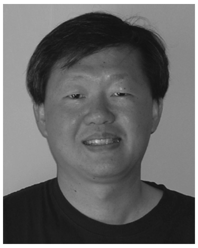
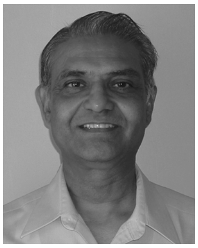


Chen-Chia Wang was born in Kaohsiung, Taiwan, in 1966. He received the B. S. degree from the National Taiwan University, Taipei, and the M.S. and Ph.D. degrees in electrical engineering from The Johns Hopkins University, Baltimore, MD.

After a brief stint at the NEC Research Institute in Princeton, NJ, he joined the Optics Group at the Brimrose Corporation of America, Baltimore, in 1998. His research activities involve the fields of laser metrology, optoelectronic devices, semiconductor sensors, optical communication components, as well as carpentry.



Sudhir B. Trivedi received the M.Sc. and Ph.D. degrees in solid-state physics from the Maharaja Sayajirao University of Baroda, Baroda, India, in 1973 and 1978, respectively. He did his Postdoctoral work at the Rensseler Polytechnic Institute during 1983–1986 in the area of growth and defects in II-VI semiconductor.

He joined Brimrose Corporation, Baltimore, MD, in 1986, where he is currently a Director of Research and Development. His research activities include synthesis and characterization of photonic materials and their applications.

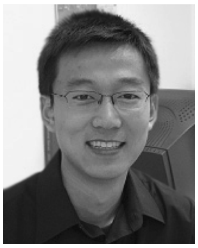
Feng Jin received the B.S. and M.S. degrees from the Electronic Department, Tsinghua University, Beijing, China, in 1993 and 1996, respectively, and the Ph.D. degree from the Department of Electrical and Computer Engineering, The Johns Hopkins University, Baltimore, MD, in 2001.

He had been working on high-speed quantum well electroabsorption light modulators, numerical analysis on novel quantum dot structures, applications of photoelectromotive force effect, low jitter passive Q-switched solid-state laser, etc. He recently joined Brimrose Corporation in developing optical fiber communication components.

Serguei Stepanov was born in Leningrad, USSR, in 1950. He received the M.Sc. degree in physics and the Ph.D. degree from the Leningrad Polytechnic Institute, Leningrad, in 1973 and 1979, respectively, and the Dr. Sc. degree from the Department of Quantum Electronics, A.F. Ioffe Institute, Leningrad, in 1988.

In 1973, he was with the Department of Quantum Electronics of A.F. Ioffe Institute. In 1992, he worked in Mexico, first at INAOE, Puebla, and since 2003, at CICESE, Ensenada. He is the coauthor of three books and about 200 scientific publications. His most important results were obtained in the fields of photorefractive materials, anisotropic diffraction, nonstationary recording of photorefractive gratings, and non-steady-state electromotive force. Now, he is continuing research work in different areas of physics and applications of dynamic gratings and, in particular, of those recorded in rare-earth doped optical fibers.

Dr. Stepanov is a Fellow of the Optical Society of America (OSA). He received the International Commission on Optics Prize (ICO'85) and the Best Application of Photorefractive Materials Prize (1999).



Zhongyang Chen was born in China in 1979. He received the B.S. degrees in physics and economics from Beijing University, Beijing, China, in 2001, and the M.S.E. and Ph.D. degrees in electrical and computer engineering from The Johns Hopkins University, Baltimore, MD, in 2003 and 2007, respectively.

He has been working in lasers, semiconductor sensors, and optoelectronic devices areas.

Jacob Khurgin, photograph and biography not available at the time of publication.

Ponciano Rodriguez, photograph and biography not available at the time of publication.

Narasimha S. Prasad was born in Bangalore, India. He received the M.S. degrees in physics, electrical engineering, and electrical communication engineering disciplines, and the Ph.D. degree in nonlinear optics from New Mexico State University, Las Cruces, NM, in 1994.

He is an Aerospace Technologist in the Laser Remote Sensing Branch under Systems Engineering Competency at NASA Langley Research Center, Hampton, VA. His expertise includes solid-state lasers, nonlinear optics, remote sensing systems, hard target imaging, free-space optical communications, novel IR materials, nanotechnology-based thermoelectrics, and hollow waveguides. He has 18 years of R&D experience. Previously, he worked at Coherent Technologies, Inc., Louisville, CO, where he developed optical transceivers spanning near-IR to long-wave IR for lidars and ladars under various defense programs. He has more than 65 publications and five patents.

Dr. Prasad is a member of the Optical Society of America (OSA) and the International Society for Optical Engineers (SPIE).