Experimental techniques for imaging and measuring transient vapor nanobubbles

E. Y. Lukianova-Hleb¹ and D. O. Lapotko^{1,2,a)}

¹Department of Biochemistry and Cell Biology, Rice University, Houston, Texas 77005, USA

²Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA

(Received 5 November 2012; accepted 6 December 2012; published online 26 December 2012)

Imaging and measuring transient vapor bubbles at nanoscale pose certain experimental challenges due to their reduced dimensions and lifetimes, especially in a single event experiment. Here, we analyze three techniques that employ optical scattering and acoustic detection in identifying and quantifying individual photothermally induced vapor nanobubbles (NBs) at a wide range of excitation energies. In optically transparent media, the best quantitative detection can be achieved by measuring the duration of the optical scattering time-response, while in an opaque media, the amplitude of the acoustic time-response well describes NBs in the absence of stress waves. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4772958>]

Transient thermal evaporation and the generation of vapor bubbles are one of the basic processes accompanying non-stationary high-temperature heat- and mass-transfer in liquids. The science and the methods for the detection of inertial vapor bubbles of various origins were well developed for macro- and micro-sized bubbles and mainly employ their ability to emit pressure and to scatter the incident light.^{1–26} Recent developments in nanoscience reduced the spatial and temporal scale of vapor bubbles to nanometers and nanoseconds.^{7–10,23,27–33} Unlike their larger analogs, vapor nanobubbles (NBs) require much higher sensitivity and resolution of the detection methods for their imaging, quantification, and identification among other phenomena, such as transient heating and the generation of stress waves. Here, we analyze several experimental techniques for the imaging and quantitative analysis of transient vapor nanobubbles as single events and we troubleshoot some related errors. Due to the multiple biomedical applications of NBs and related phenomena,^{34–38} it should be noted that we consider the transient events, but not the materials (particles) that are often also called nanobubbles.^{39,40} We also do not consider the cavitation of pre-existing bubbles that is well studied elsewhere.⁴¹

While NBs may have various sources of energy (the heating of liquid above the boiling threshold, local rarefaction, and plasma discharge), we employed an experimental model of a single NB in water. Such a model provides maximal precision, control, and reproducibility in NB generation through the localized transient photothermal heating of liquid above the evaporation point. This was achieved through the optical excitation of individual 60 nm gold nanospheres in water with single short laser pulses (70 ps and 532 nm) at specific fluences above the NB generation threshold. We used the plasmonic conversion of optical energy into heat to control the maximal diameter and lifetime of the NBs through the fluence of a single laser pulse, as described in detail previously.^{8–10,33} This experimental model includes an internal metal nanoparticle (NP) that acts as the source of the

bubble energy during bubble generation and prevents the development of extreme temperatures and sonoluminescence at the collapse stage,^{8,42} unlike “classical” bubbles that are generated in homogeneous media.^{43,44} Another important difference in the model employed is the absence of an external acoustic field that is often used alone or in combination with optical energy to generate a vapor bubble.^{44,45} The above conditions and the nanoscale size resulted in a single cycle of the vapor nanobubble that did not oscillate.

First, we consider imaging methods. Optical scattering phenomena allow both NB imaging and monitoring of its dynamics.^{7–10,14–18} Direct imaging of slower and larger macro- and micro-bubbles employed different cameras and light sources.^{13,46–52} There is a possibility of using a continuous light source and of capturing a short transient NB with high-speed image detectors.^{53–57} However that would require a nanosecond gating speed, sub-micron spatial resolution, and the corresponding high optical sensitivity. Dynamic transmission electron microscopy and time-resolved diffraction of X-rays^{31,57} can even better provide direct imaging of the dynamics of an NB. Unfortunately, the cost and technical complexity of such solutions turn them into unique tools with very limited availability.

Alternatively, the imaging of a transient NB can also be realized with much more affordable equipment using slow cameras and pulsed light sources (Figure 1(a)), providing

- (1) Pulsed illumination with a shorter duration than an NB lifetime within a nano- and pico-second range;
- (2) Sufficient energy of the optical pulse to compensate the very small scattering cross-section of an NB;
- (3) Precise synchronization of the illuminating pulse with the NB source.

These requirements suggest a pulsed laser as the illumination source. The illumination angle and the numerical aperture of the collecting lens further determine the signal-to-noise ratio of this imaging scheme. Forward scattering results in the maximal scattering efficacy but cannot be fully separated from incident light that creates a high background. We achieved the best results with angled side illumination (Figure 1(a)), providing that the numerical aperture of the imaging

^{a)}Rice University, Department of Biochemistry and Cell Biology, 6100 Main Street, MS-140, TX 77005, USA. E-mail: dl5@rice.edu. Telephone: 713-348-3708. Fax: 713-348-5154.

FIG. 1. Methods for detecting vapor nanobubbles in liquid: (a) optical time-resolved scattering imaging is obtained with a short probe laser pulse and a slow image detector, (b) optical scattering (extinction) time-response is obtained with a continuous focused probe laser pulse and a fast photodetector, and (c) acoustical time-response is obtained with an ultrasound detector.

(collecting) lens is lower than the angle of incidence of the illuminating radiation. In this case, the lens collects only the light scattered by the NB. This scheme allows the imaging of a single transient NB with a lifetime down to 10 ns (Figure 2(a-I, inset)). The 100 ps illumination pulse of 1 μ J at 576 nm was directed at 45° to the sample cuvette (μ -Slide VI, ibidi LLC, Verona, WI) with an optically variable delay relative to the excitation pulse, and the NB was imaged with 10 $\times$ -63 $\times$ microscope objectives. Most of the current CCD- and CMOS-based cameras can do such imaging. We used Andor Luka EMCCD (charged coupled device with electronic multiplication) and Cannon 50D (equipped with a CMOS sensor) stock cameras, both with long exposure times in the dark, to avoid precise synchronization with the NB excitation laser pulse. In

this method, the pixel image amplitude is used as an NB metric, but it is not very practical: (i) any deviation in the alignment of the probe beam would require the re-calibration of the system and (ii) this metric will not characterize the maximal diameter of an NB when one fixed time delay is applied. The advantage of this method is in the relatively precise identification of an NB and its location. It also shows the number of NBs if multiple events occur (Figure 2(b-I, inset)).

The maximal diameter of an NB is the most important parameter that also characterizes the amount of energy received by the bubble.^{1-6,8} It can be measured with another optical scattering technique that employs the monitoring of the intensity of a continuous probe beam with a broadband high-speed photodetector. The beam is focused at the NB and its scattering by the NB changes its axial intensity, which is measured as a time-response with the photodetector. In one method, the beam is pointed at the low noise detector through the aperture and produces a high base level (Figure 1(b)). An NB scatters the light and thus increasingly reduces the axial intensity of the probe beam during its expansion stage and brings it back to the base level during its collapse stage. This results in the bubble-specific shape of the time-response (Figure 2(a-I)). Technically, the detector measures the optical extinction of the probe beam but since an NB does not absorb any optical energy, the extinction becomes equal to its scattering component. Due to the scattering nature of such a signal, we define it as a “scattering.” This definition assumes the absence of any transient optical absorbance developed simultaneously with an NB. If such absorbance emerges (due to plasma formation or any non-linear modification of the optical properties of the

FIG. 2. (a) Three methods of detecting a single NB. I: Optical scattering (extinction) time-response obtained with continuous probe laser shows the expansion and collapse of an NB (metrics—amplitude and duration) and time-resolved optical scattering imaging (inset) with a pulsed probe laser (metric—a pixel image amplitude). II: Acoustical time-response obtained with an ultrasound sensor (metric - an amplitude). (b) The same signals obtained for several simultaneously generated NBs of different maximal diameter. (c) Influence of the experimental settings: I: The diameter of the continuous probe beam is increased by 10%-15% and the angle of incidence of the pulsed probe beam increased from 45° to 135°; II: The resonance frequency of the acoustic sensor is decreased from 10 to 5 MHz. Corresponding signals as shown in (a) are shown with dashed lines. Scale bar is 15 μ m.

media), the method may characterize an NB incorrectly.^{58,59} In another method, the beam is pointed off the detector aperture and produces a low base level at the detector. In this case, only the light scattered by an NB will reach the detector and will increase its output signal, also producing a time-response with a bubble-specific shape.

The most precise way to measure the maximal diameter of a single NB is to measure the duration of the NB-specific signal (Figure 2(a-I)), which was shown to correlate to its maximal diameter.^{1-6,8} The amplitude of the NB response also depends upon the maximal diameter of the NB, but is very sensitive to experimental factors that are difficult to control. The first is the diameter and divergence of the probe beam at the NB's plane. The smaller the beam waste, the higher the sensitivity of NB detection. An increase in the beam's diameter by 10%-15% and/or a slight deviation of the beam axis may cause a several-fold decrease in the signal amplitude of a dip-shaped NB signal (Figure 2(c-I)). Such conditions occur during changing the sample chamber or while scanning a heterogeneous sample across the beam. The simultaneous generation of multiple NBs around different sources of thermal energy (for example, in suspension around optically absorbing molecules or nanoparticles) instead of a single one, increases the signal amplitude, but such an increase is just an ensemble effect (Figure 2(b-I)). The simultaneous generation of several NBs of different maximal sizes influences not only the amplitude but also the shape of the NB time-response (Figure 2(b-I)). Smaller NBs form a sharp front and fewer large NBs form a long tail of lower amplitude. While the generation of NBs under some settings may typically involve such a multi-NB pattern, it is still possible to estimate the lifetime of the largest NBs that represent the maximal deposition of the thermal energy by measuring the duration of the time-response at the reduced level instead of at half of maximum. However, the best rule is to avoid such distorted signals because they may lead to misinterpretation of the bubble parameters.⁵⁸ In all three considered cases (single NB, single NB with misaligned probe beam, and multiple NBs), the durations of the bubble-specific signals could be linked to the maximal diameter of the NB (or the largest NB as in Figure 2(b-I)), while their amplitudes differed significantly and, therefore, their use as NB metrics may lead to artifacts.⁵⁹

The third method of NB detection employs the pressure waves generated during the bubble expansion and collapse^{23,26} (Figure 1(c)). In the case of a single inertial bubble, the pressure and rarefaction waves produce a typical signal (Figure 2(a-II)). This is definitely the simplest and the least expensive method of the three, because it does not require expensive optical sources, optics, and sensors. In addition, it detects NBs in optically opaque media, so is probably the most universal of the methods. The most obvious metric of the acoustic signal is its maximal (peak-to-peak) amplitude. However, the correct identification and measurement of an NB with a standard acoustic detector can be challenging in a single pulse mode. Most detectors have a resonant frequency of 10 MHz and lower where their sensitivity is the maximal. For small NBs with lifetimes from 5 to 100 ns, the corresponding pressure rise times and associated frequencies seem to be higher than the resonant frequencies of most acoustic sensors. Therefore, the sensor signal does

not show the real pressure, but rather represents a response function of the sensor. In this case, the amplitude of the output signal of the acoustic sensor significantly depends upon its resonant frequency and may cause a significant error (Figure 2(c-II)). For a specific acoustic sensor, the amplitude of its output also depends upon the number of simultaneously generated NBs (Figure 2(b-II)). Therefore, a reliable measurement of the NB diameter through the amplitude of acoustic response assumes that a single NB is generated.

The next important task is the identification of an NB and its discrimination from other phenomena, such as transient heating or stress waves (Figure 3). The optical scattering response identifies heating through a thermal lens effect that allows the detection and measurement of rapid heating and gradual cooling due to thermal diffusion (Figure 3(a-I)). This purely refractive effect does not produce any optical scattering like an NB does. Next, under high transient temperatures at short time scales, the generation of stress waves (and shock waves) also influences the refractive index of the media and creates a distinct short (relative to the bubble and heating time scale) signal of nanosecond duration that is determined by the speed of sound and the aperture of the probe beam (Figure 3(c-I)). Both phenomena can be clearly distinguished from the bubble (Figure 3(b-I)). However, all these three different phenomena do not much influence the shape of the acoustic response, but rather its amplitude (Figure 3(II)), which is minimal for heating, increases for a bubble and becomes the maximal for stress waves. Therefore, an acoustic time-response is much less bubble-specific than an optical scattering time-response.

The above analysis compares three methods for the detection of NBs under fixed excitation conditions. However, in reality, the generation of NBs may occur in a wide range of excitation fluences from pulse to pulse and even within the aperture of a single pulse. These factors cause a wide variation in the maximal diameter of an NB. Therefore, it is important to understand the range of the linear correlation between the NB metric and its excitation conditions that determines the NB maximal diameter. We compared the four discussed above metrics, the pixel amplitude of the scattering image, the amplitude and duration of the optical scattering time-response, and the amplitude of the acoustic response, as functions of the fluence of the excitation laser pulse, the parameter in this model determines the maximal diameter of the NB when the fluence exceeds the NB generation threshold. All bubbles were generated in water around individual identical gold nanospheres. This model provided a very precise deposition and conversion of optical energy into a bubble. Three types of signals, optical response, image, and acoustical response were obtained simultaneously for each individual event.

For the scattering image, we observed the relatively early saturation and non-linear behavior of the pixel image amplitude compared to the duration of the time-response (Figure 4(b)). Time-resolved scattering images were obtained under a fixed delay between the excitation and probe laser pulses. With an increase in the maximal NB diameter and lifetime, the moment of illumination moved further from the moment when the NB reaches its maximal diameter. This explains the observed non-linear effect of the pixel image amplitude. Another technical limitation of the imaging

FIG. 3. Simultaneously obtained optical scattering (or extinction) (left) and acoustic (right) time-responses of three different phenomena. (a): Transient heating of the gold nanoparticle and the media with a single laser pulse at a fluence below the NB generation threshold; (b): single transient vapor nanobubble generated around gold nanoparticle; (c): NB accompanied by a stress wave that produces a sharp and short optical signal in the very beginning of the time-response.

method is the dynamic range of the image sensor. If it is less than 60 dB, a wide range of NB diameters would cause either saturation of the images of large bubbles or low sensitivity in the detection of small bubbles.

Next, we analyzed the amplitude of optical scattering time-response (Figure 4(a)). The dependence of their amplitude and lifetime upon the fluence showed a non-linear saturation of the amplitude compared to the lifetime. The non-linear behavior of the response can be explained by the effect of the limited numerical aperture of the collecting lens and the blocking effect of the large bubble on the probe

beam. In addition, at high excitation energies, the amplitude of the response can be influenced by the concurrent optical signal associated with the stress wave (Figure 3(c-I)). Therefore, the use of the optical response amplitude as a metric of the bubble or even of the energy conversion efficacy is not appropriate, and may lead to an artifact data for the photo-thermal responses of ensembles of gold NPs.⁵⁹ In contrast, the dynamics of the optical response can be much better quantified through the lifetime that correctly describes both the maximal diameter of an NB and the efficacy of the energy conversion.

FIG. 4. Dependence of the NB metrics upon the optical excitation fluence that determines the maximal size of NB. (a): Lifetime (dots) and amplitude of the optical scattering time-response (cross). (b): Lifetime (dots) of the optical scattering time-response and the pixel image amplitude of the time-resolved optical scattering image (cross) at the fixed delay of 10 ns. (c): Amplitude of acoustic time response. (d): Amplitude of acoustic time-response versus the lifetime of optical time-response.

The amplitude of the acoustic response demonstrated two quasi-linear zones (Figure 4(c)). To explain their origin, we detected the acoustical and optical responses simultaneously for single NBs under a wide range of excitation fluences, and plotted the acoustic amplitude as a function of the NB lifetime (Figure 4(d)). Two zones for acoustic signals became even more pronounced with an apparent threshold associated with the NB lifetime around 350 ns that also corresponded to the fluence of 150 mJ/cm². A detailed analysis of the optical time-responses revealed one difference: the optical responses of NBs larger than 350 ns included an additional component that can be attributed to a stress wave generated due to the high laser-induced temperature in a gold NP (Figure 3(c-I)). Its additional impact added to the NB-generated pressure at the acoustic sensor. However, this effect occurs when the NB lifetime exceeds 300 ns, which corresponds to the maximal diameter above a micrometer, so this is no longer a “nano”-bubble. For smaller bubbles of nano-size, both the acoustic amplitude and the duration of the optical scattering time-responses provided almost linear signal-energy dependences and showed a good correlation.

We analyzed three detection techniques for imaging and measuring transient vapor nanobubbles generated as single events at nanoscale around laser pulse-heated metal nanoparticles. In optically transparent media, the location of nanobubbles can be best determined with time-resolved optical scattering imaging by using a delayed short optical pulse with regular CCD or CMOS cameras. The best quantitative analysis of vapor nanobubbles in the widest range of excitation energies and bubble diameters can be achieved by measuring the duration (lifetime) of the optical scattering time-response by using a low-power continuous laser and matching photodetector. In the case of opaque media, the amplitude of the acoustical time-response provides good sensitivity and linearity in a range of excitation conditions that are limited by the onset of stress waves that additionally increase the amplitude of the nanobubble signal. The simultaneous use of two or three of these methods provides the best results in the identification, imaging, and measuring of transient nanobubbles in a single event experiment.

This work was supported in part by National Institute of Health Grant R01GM094816.

¹L. Rayleigh, *Philos. Mag.* **34**, 94 (1917).

²M. S. Plesset, *Trans. ASME: J. Appl. Mech.* **16**, 277 (1949).

³G. A. Askaryan, A. M. Prokhorov, G. F. Chanturiya, and G. P. Shapiro, *Sov. Phys. JEPT* **17**, 1463 (1963).

⁴P. A. Barnes and K. E. Rieckhoff, *Appl. Phys. Lett.* **13**, 282 (1968).

⁵J. Neumann and R. Brinkmann, *J. Appl. Phys.* **101**, 114701 (2007).

⁶J. Roider, E. S. El Hifnawi, and R. Birngruber, *Lasers Surg. Med.* **22**, 240 (1998).

⁷D. Lapotko, E. Lukianova, S. Shnip, G. Zheltov, M. Potapnev, V. Savitsky, O. Klimovich, and A. Oraevsky, *Proc. SPIE* **5697**, 82 (2005).

⁸E. Y. Lukianova-Hleb, Y. Hu, L. Latterini, L. Tarpani, S. Lee, R. Drezek, J. H. Hafner, and D. O. Lapotko, *ACS Nano* **4**, 2109 (2010).

⁹E. Y. Hleb and D. O. Lapotko, *Nano Lett.* **9**, 2160 (2009).

¹⁰D. O. Lapotko, *Opt. Express* **17**, 2538 (2009).

¹¹C. L. Kling and F. G. Hammit, *Trans. ASME D: J. Basic Eng.* **94**, 825 (1972).

¹²W. Lauterborn, *Appl. Phys. Lett.* **21**, 27 (1972).

¹³C. D. Ohl, A. Philipp, and W. Lauterborn, *Ann. Phys.* **507**, 26 (1995).

¹⁴O. Yavas, P. Leiderer, H. K. Park, C. P. Grigoropoulos, C. C. Poon, W. P. Leung, N. Do, and A. C. Tam, *Phys. Rev. Lett.* **70**, 1830 (1993).

¹⁵A. Vogel and W. Lauterborn, *J. Acoust. Soc. Am.* **84**, 719 (1988).

¹⁶P. L. Marston, *J. Opt. Soc. Am.* **69**, 1205 (1979).

¹⁷J. S. Stroud and P. L. Marston, *J. Acoust. Soc. Am.* **94**, 2788 (1993).

¹⁸T. J. Asaki, D. B. Thiessen, and P. L. Marston, *Phys. Rev. Lett.* **75**, 2686 (1995); *Erratum*: **75**, 4336 (1995).

¹⁹J. G. Fujimoto, W. Z. Lin, E. P. Ippen, C. A. Puliafito, and R. F. Steinert, *Invest. Ophthalmol. Vis. Sci.* **26**, 1771 (1985).

²⁰D. F. Gaitan, L. A. Crum, C. C. Church, and R. A. Roy, *J. Acoust. Soc. Am.* **91**, 3166 (1992).

²¹B. P. Barber and S. J. Putterman, *Phys. Rev. Lett.* **69**, 3839 (1992).

²²A. Plech, V. Kotaidis, M. Lorenc, and J. Boneberg, *Nat. Phys.* **2**, 44 (2006).

²³C. P. Lin and M. W. Kelly, *Appl. Phys. Lett.* **72**, 2800 (1998).

²⁴J. Neumann and R. Brinkmann, *Appl. Phys. Lett.* **93**, 033901 (2008).

²⁵R. Brinkmann, G. Hüttmann, J. Rögner, J. Roider, R. Birngruber, and C. P. Lin, *Lasers Surg. Med.* **27**, 451 (2000).

²⁶H. Chen and G. Diebold, *Science* **270**, 963 (1995).

²⁷D. Lapotko and G. Kuchinsky, *Proc. SPIE* **2390**, 89 (1995).

²⁸A. Vogel, N. Linz, S. Freidank, and G. Paltauf, *Phys. Rev. Lett.* **100**, 038102 (2008).

²⁹A. Vogel, J. Noack, G. Hüttmann, and G. Paltauf, *Appl. Phys. B* **81**, 1015 (2005).

³⁰C. M. Pitsillides, E. K. Joe, X. Wei, R. R. Anderson, and C. P. Lin, *Biophys. J.* **84**, 4023 (2003).

³¹V. Kotaidis, C. Dahmen, G. von Plessen, F. Springer, and A. Plech, *J. Chem. Phys.* **124**, 184702 (2006).

³²V. Kotaidis and A. Plech, *Appl. Phys. Lett.* **87**, 213102 (2005).

³³E. Y. Lukianova-Hleb, X. Ren, J. A. Zasadzinski, X. Wu, and D. O. Lapotko, *Adv. Mater.* **24**, 3831 (2012).

³⁴D. S. Wagner, N. A. Delk, E. Y. Lukianova-Hleb, J. H. Hafner, M. C. Farach-Carson, and D. O. Lapotko, *Biomaterials* **31**, 7567 (2010).

³⁵E. Y. Lukianova-Hleb, X. Ren, D. Townley, X. Wu, M. Kupferman, and D. Lapotko, *Theranostics* **2**, 976 (2012).

³⁶E. Lukianova-Hleb, D. Wagner, M. Brenner, and D. Lapotko, *Biomaterials* **33**, 5441 (2012).

³⁷D. Lapotko, E. Lukianova, and A. Oraevsky, *Lasers Surg. Med.* **38**, 631 (2006).

³⁸D. Lapotko, A. Shnip, and E. Lukianova, *Lasers Surg. Med.* **33**, 320 (2003).

³⁹K. K. Jain, *BMC Med.* **8**, 83 (2010).

⁴⁰B. E. O'Neill and N. Rapoport, *Ther. Delivery* **2**, 1165 (2011).

⁴¹M. Ashokkumar, *Ultrason. Sonochem.* **18**, 864 (2011).

⁴²D. Lapotko and K. Lukianova, *Int. J. Heat Mass Transfer* **48**, 227 (2005).

⁴³W. Lauterborn, T. Kurz, R. Geisler, D. Schanz, and O. Lindau, *Ultrason. Sonochem.* **14**, 484 (2007).

⁴⁴T. Kurz, D. Kröninger, R. Geisler, and W. Lauterborn, *Phys. Rev. E* **74**, 066307 (2006).

⁴⁵B. Krasovitski, H. Kislev, and E. Kimmel, *Ultrasonics* **47**, 90 (2007).

⁴⁶Z. Z. Wong, O. D. Kripfgans, A. Qamar, J. B. Fowlkes, and J. L. Bull, *Soft Matter* **7**, 4009 (2011).

⁴⁷P. Marmottant, M. Versluis, N. Jong de, S. Hilgenfeldt, and D. Lohse, *Exp. Fluids* **41**, 147 (2006).

⁴⁸S. T. Thoroddsen, T. G. Etoh, and K. Takehara, *Annu. Rev. Fluid Mech.* **40**, 257 (2008).

⁴⁹R. L. Stover, C. W. Tobias, and M. M. Denn, *AIChE J.* **43**, 2385 (1997).

⁵⁰N. C. Keim, P. Möller, W. W. Zhang, and S. R. Nagel, *Phys. Rev. Lett.* **97**, 144503 (2006).

⁵¹O. Lindau and W. Lauterborn, *J. Fluid Mech.* **479**, 327 (2003).

⁵²W. Lauterborn and W. Hentschel, *Ultrasonics* **23**, 260 (1985).

⁵³H. Ohtake, T. Hayashida, K. Kitamura, T. Arai, J. Yonai, K. Tanioka, H. Maruyama, and T. Eto, *Broadcast Technol.* **28**, 2 (2006).

⁵⁴W. F. Kosonocky, G. Yang, C. Ye, R. K. Kabra, L. Xie, J. L. Lawrence, V. Mastrocolla, F. V. Shallcross, and V. Patel, *Dig. Tech. Pap.-IEEE Int. Solid-State Circuits Conf.* **39**, 182 (1996).

⁵⁵W. Lauterborn, A. Judt, and E. Schmitz, *Opt. Lett.* **18**, 4 (1993).

⁵⁶H. Shiraga, S. Fujioka, P. A. Jaanimagi, C. Stoeckl, R. B. Stephens, H. Nagatomo, K. A. Tanaks, R. Kodama, and H. Azechi, *Rev. Sci. Instrum.* **75**, 3921 (2004).

⁵⁷W. E. King, G. H. Campbell, A. Frank, B. Reed, J. F. Schmerge, B. J. Siwick, B. C. Stuart, and P. M. Weber, *J. Appl. Phys.* **97**, 111101 (2005).

⁵⁸E. Boulais, R. Lachaine, and M. Meunier, *Nano Lett.* **12**, 4763 (2012).

⁵⁹V. Zharov, *Nat. Photonics* **5**, 110 (2011).