Time-gated backscattered ballistic light imaging of objects in turbid water


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Time-gated optical imaging of objects in turbid water was carried out in a backscattering geometry using light pulses of different pulse widths and a time-gated detection scheme with variable gate widths. Experimental results demonstrate that ultrashort pulsed illumination with ultrashort gated detection significantly improve image contrast as compared to any other combinations. These results are important for imaging objects embedded in turbid media, such as cloud, fog, smoke, murky water, and biological tissues for military, civilian, and medical applications. © 2005 American Institute of Physics. [DOI: 10.1063/1.1846145]

Direct optical imaging of targets embedded in a turbid medium, such as coastal waters, fog, cloud, or biological tissue is a challenging problem because scattering and absorption of light by the medium attenuates available signal. What is even more important, multiple scattering of light blurs images and imparts a noise background that detrmines image contrast, and in severe cases, buries the image in clutter.1–3 The imaging problem due to multiple scattering is further exacerbated in a backscattering geometry as light starts to get backscattered as soon as it enters the scattering medium generating a strong noise background that can be much higher than the signal returned from the target. Improvement of optical image quality and contrast in the backscattering geometry is urgently imperative for a variety of remote sensing applications including shallow water surveying,4 and underwater mine detection.5 Time-gated imaging is a versatile technique for enhancing the quality of images of objects in turbid media by selecting the ballistic and snake light,6,7 and reducing noise due to the multiple-scattered light. The current laser range gating (LRG) approaches used in underwater imaging employ light pulses of several nanosecond duration [commonly 532 nm second-harmonic output of a Q-switched Nd:yttrium aluminum garnet (YAG) laser] and gating time comparable to pulse duration.8 The effect of pulse width and gate width on the performance of underwater LRG systems, in particular on the picosecond and femtosecond time scales, is not yet adequately explored.

In this letter, we report on the effect of the pulse duration of the imaging light, and time gate width of the detection scheme on the image contrast in a backscattering imaging arrangement using short (130 fs) and long (3.5 ns) light pulses, and short (80 ps) and long (500 ps) time gates. We find that the combination of short pulse illumination with range-resolved short time gating leads to dramatic improvement in image contrast, which is a highly significant result for remote sensing and underwater imaging applications.

The experimental arrangement for imaging using backscattered light is schematically shown in Fig. 1. The turbid water sample used in the experiment was a suspension of titanium dioxide (TiO2) particles (DuPont Ti-Pure R-960) of median size 0.5 μm in distilled water contained in a 100 mm × 100 mm × 150 mm transparent plastic cell. A 50 mm × 50 mm US Air Force Positive Target (chrome patterns vacuum deposited on 1.5-mm-thick soda-lime glass) was used as the target to be imaged. The target was placed in the middle of the cell such that the test patterns on its surface were 50 mm away from the front surface of the cell. The bars in Group 0 Element 4 of the target with 1.41 lp/mm were imaged in this experiment.

Short and long laser pulses of duration of 130 fs and 3.5 ns, respectively, were used to illuminate the target in turbid water. Both pulses had a center wavelength of 800 nm and were derived from a Kerr-lens mode-locked Ti:sapphire oscillator and amplifier system7 operating at a repetition rate of 1 kHz. The amplifier system consisted of a regenerative amplifier, and a multipass power amplifier (MPPA). The 3.5 ns pulses were generated when the MPPA was not seeded enabling it to operate as a free-running Ti:sapphire laser pumped from two opposite ends by two Q-switched Nd:yttrium lithium fluoride (YLF) lasers.8 The average power was maintained at 60 mW with a beam diameter of 4 mm for both 130 fs and 3.5 ns pulses.

A fraction of the backscattered light was collected by a camera lens and directed to an ultrafast gated intensified camera system (UGICS), consisting of a time-gated image intensifier fiber optically coupled to a charge couple device (CCD) camera. The orientation of the target was adjusted such that when the cell was filled with clear water, specular reflection from the target was directed toward the camera lens. The UGICS provided a time gate whose full width at half maximum (FWHM) duration could be varied from 80 ps to 6 ns. The gate position could be varied over 0–20 ns.

FIG. 1. A schematic diagram of the experimental arrangement.
range. The short and long FWHM gate widths used in this study were 80 and 500 ps, respectively. The UGICS recorded time-resolved two-dimensional (2D) images, each of which is a 2D intensity distribution, $I(x, y, t)$, integrated over the gate duration at the gate position $t_i$. Resulting images were stored on a personal computer and could be analyzed using image analysis software.

We first measured the temporal profiles of the 130 fs pulse in the transmission and backscattering geometries with the target in place, as shown in Figs. 2(a) and 2(b), respectively, using a streak camera. Multiple scattering of light in the turbid water broadened the temporal profiles of the pulses. The temporal profile of the transmitted pulse was fitted to a light propagation model based on the diffusion approximation of the radiative transfer equation to estimate the transport length, $l_t$, of the turbid water. The $l_t$ was estimated to be 8.1 mm, and the round-trip distance from the cell surface to the target was $\sim 12.3 l_t$. The temporal profiles of the 3.5 ns pulse were measured using a high-gain fast photodiode and a fast oscilloscope. The temporal profiles provided signatures of temporal location of ballistic light both in the forward scattering and backscattering configurations. The ballistic light signature was found to be more vivid in the profile of the 130 fs pulse, and temporal position of returning ballistic signal was used as a guide to assess the optimal gate position. The zero time was taken to be the moment the pulse entered the turbid water.
The temporal profile of Fig. 2(a) shows that, in the transmission geometry, the ballistic light arrives the earliest (at the ballistic time, $t_b \sim 470$ ps) and is separated in time from the diffusive light. In contrast, Fig. 2(b) shows that, in the backscattering geometry, the ballistic light is engulfed in the strong noise resulting from backscattering of light from suspended particles in turbid water. The diffuse backscattered light starts emerging right after the input pulse enters the front edge of the sample at the zero time. The temporal position of the ballistic photons backscattered from the target, 470 ps in Fig. 2(b), matches the round-trip time from the input surface to the target. It is this temporal overlap of ballistic signal with dominant noise of diffuse light that makes direct imaging in backscattering geometry more difficult than that in transmission.

In order to examine the effects of pulse width and gate width on the image quality, 2D images were recorded using the following four combinations: (a) short pulse–short gate (SP-SG), (b) short pulse–long gate (SP-LG), (c) long pulse–short gate (LP-SG), and (d) long pulse–long gate (LP-LG). Four sets of time-resolved and time-sequenced 2D images recorded in the backscattering geometry using the above-mentioned pulse-width gate-width combinations are presented in Figs. 3(a) and 3(b), respectively. Also presented are the profiles of the backscattered 130 fs (SP) and 3.5 ns (LP) pulses. Figure 3(a) presents the images recorded using 130 fs pulse (SP) at gate positions of 0, 100, 375, 475, 575, and 1250 ps and gate widths 80 ps (SG) and 500 ps (LG). Only the SP-SG combination with the SG centered on the ballistic time (475 ps) provided a well-resolved image showing the bars in the target. The result is understandable, since the range-resolved time-gated image is a convolution of the backscattered light pulse with the gate pulse centered at the gate position. With SP illumination, the backreflected ballistic pulse was short and the SG centered on the ballistic time could capture it completely along with whatever backscatter noise entered within the 80 ps (width of SG) time window. The LG centered on the ballistic time captured the backreflected ballistic pulse, but collected backscattered noise for a longer time of 500 ps (width of LG), which seems to have masked the image. For other gate positions, the time gate was not well positioned to detect the ballistic, image-bearing light and a direct image of the target was not obtained.

Figure 3(b) displays the images recorded using 3.5 ns pulses (LP) at gate positions of 0, 475, 7000, and 10 000 ps and gate widths 80 ps (SG) and 500 ps (LG). None of the eight images resolved the bars in the target. As discussed in connection with the images in Fig. 3(a), if the gate position does not overlap with the ballistic time a direct image may not be expected. However, the SG and LG centered on the ballistic time could not resolve the bars either. Since the pulse energy for both SP and LP were the same, the same number of photons was spread out over a much longer time interval in the LP and corresponding intensity level was much lower compared to that for SP. The backscattered LP temporal profile did not exhibit a well-defined ballistic component as was observed for the SP in Fig. 3(a). Even though different temporal windows were searched, the intensity of the ballistic component seems to have been inadequate to form a direct well-resolved image above the ubiquitous scattered light noise and electronic noise background.

The results presented here demonstrate that time-resolved imaging using ultrashort pulsed illumination and matched time-gated detection provides better images than any other pulse-width gate-width combinations. These results also seem to indicate that the use of long pulses with either short or long gates does not provide well-defined images. However, laser range gating with nanosecond pulses and continuous wave imaging had some success, although the image quality and contrast were often poor. Much higher pulse energy and/or average power and a longer geometrical path are used in those experiments resulting in: (a) enough ballistic photons for forming observable image; and (b) some reduction in detected multiple-scattered photon because the solid angle subtended by the detector is smaller for a longer geometric path than that used in the experiments reported here. What the results of the present study do demonstrate is that even in the extreme cases when long pulse–long gate or continuous-wave approaches fail to provide a useful direct image, a combination of a short pulse and short gate can succeed.

Ultrashort pulsed illumination with ultrashort gated detection scheme enhances the signal-to-noise ratio not only by reducing the backscatter noise from the light being used in the measurement, but also by reducing the ambient background light from natural and man-made sources. The result presented here is expected to have significant impact on remote sensing and underwater surveillance using lidar (light detection and ranging), and will be useful for biomedical imaging applications as well.

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