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Time-gating scheme based on a photodiode for single-photon counting

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Abstract

A fast, simple, and low-cost optical time-gating scheme for counting single photons is presented. Its construction consists of a silicon photodiode connected in series with a 50 Ω resistor and that operates in the photoconductive mode. The temporal resolution at the FWHM of the photon counting system was measured to be 62 ps. The profile of a single-photon pulse measured with the counting system agreed well with analytical results. The system was also used to successfully resolve a pair of targets with 4 mm separation inside a highly scattering medium by the use of time-gated early-arriving photons.

Time-gated or time-correlated single-photon counting systems offer a way to detect extremely faint light pulses resulting from light propagation through a highly scattering and/or absorbing medium. In biological tissue imaging using near-IR light for example, the light is scattered and absorbed as it propagates through the tissue. Consequently, time-domain single-photon counting techniques are often employed to improve the spatial and depth resolution [1,2]. Photons that undergo minimal scattering events travel shorter distances and thus are the first to reach the detector. Therefore, by time gating the detected photons, one is capable of selecting only the early-arriving ones, which carry precise location information about the target being imaged inside the tissue.

Several time-domain instruments for counting single photons exist. These include time-correlated single-photon counting systems [3,4], time-gated systems such as gated image intensifiers [5,6] and streak cameras [7,8], measurement setups based on nonlinear techniques [9–11], and gain modulation of avalanche photodiode detectors (APDs) [12]. Time-correlated and gated image intensifier counters are relatively large and expensive and so may not be suitable in situations where portability, cost, and accessibility are important. Nonlinear methods require rather high optical power budgets and so are only limited to laser systems that are capable of delivering such high power levels. Photon counting systems based on the gain modulation of APDs offer a trade-off between cost and complexity and optical power levels. Unfortunately, this method cannot be applied to single-photon detectors such as photomultiplier tubes that cannot be gain modulated.

In this Letter, we present to the best of our knowledge a relatively simple, inexpensive, low-power, and fast time-gating scheme using a photodiode for counting single photons. A similar scheme has been used by Villa *et al.* [13] for sampling radio frequency signals in analog-to-digital converters. We present here for the first time to our knowledge a time-gated photon counting technique that employs this scheme.

The circuit diagram of the optical time-gating scheme is shown in Fig. 1. The components of the gate are a silicon photodiode (PD) (Thorlabs FDS02), whose cathode is connected to a $50\ \Omega$ resistor (R) and then ground (GND). The anode of the PD serves as the electrical input into which the output of a photomultiplier tube (PMT) (Hamamatsu R7400U-20) is connected. The negative PMT signal, together with a $-5\ \text{V}$ DC bias, allows the PD to operate in the reverse-biased or photoconductive mode. In this way the depletion layer of the photodiode gets fully depleted so that its response time is dominated by the carrier-drift time, thereby improving its response time. The gate operation may be described as follows: the presence of a negative electrical signal (PMT signal) at the input of the PD increases the width of its depletion region. Therefore, photons (from the reference laser beam) incident on the optical input of PD are converted to electron-hole pairs that generate current and result in a voltage drop across the R. In contrast, in the absence of any electrical input signal, the incident photons generate a relatively reduced current and hence potential drop across the R. This is also the case when an electrical signal is present but no optical signal. In the case when neither photons nor PMT electrical signal is present, no measurable voltage is detected across the R. For this experiment, a $2\ \text{mW}$ average power light pulses incident on the PD generated a $-7\ \text{mV}$ peak-to-peak signal in the absence of any PMT signal. However, after injection of a $-0.8\ \text{V}$ peak-to-peak signal from the PMT [and constant fraction discriminator (CFD)], the gate output increased to $-11\ \text{mV}$. Again, the presence of the $-0.8\ \text{V}$ signal with no optical input yielded a $-5\ \text{mV}$ peak-to-peak signal at the gate output. Therefore, by setting up a threshold voltage slightly above $-7\ \text{mV}$ (in this Letter provided by the photon counter) at the gate output, the photodiode-resistor arrangement acted as a fast electro-optic shutter or gate. This gate is open only when there is the simultaneous presence of both the reference laser beam and PMT signal. In the closed state, no output voltage is detected.

The experimental setup for measuring temporal point spread functions (TPSFs) using this scheme is shown in Fig. 2. A stream of $100\ \text{fs}$ pulses having a repetition rate of $80\ \text{MHz}$ is emitted from a Ti:sapphire laser with $400\ \text{mW}$ peak power output. This pulse stream is split into two by the beam splitter (BS) into a reference beam and sample beam. The light from the sample beam, with a beam diameter of $2\ \text{mm}$, is directed at the sample, and the exiting attenuated beam is coupled into a $1\ \text{mm}$ diameter multimode fiber. The output of the fiber connects to the PMT for detection of the extremely weak light intensity at the single-photon level. The output of the PMT goes to the amplifier stage (Amp), CFD, gate, and finally photon counter. The reference beam goes to an optical delay line consisting of a pair of orthogonally arranged mirrors mounted on a motor-driven translation stage. By moving this stage, the reference beam can be delayed or advanced relative to the sample beam. The beam from the delay line is coupled into the optical input of the gate via another multimode fiber. The temporal profile of a pulse is measured by counting the number of photons registered by the photon counter as the delay line is scanned across the entire pulse. For each position of the delay line, representing a particular point in time on the single-photon pulse, the number of photons over a time period is counted and recorded. A histogram, made up of the photon counts versus time, then gives the pulse profile. Using this setup, the impulse response of the system was first measured. For this measurement, the sample in Fig. 2 was replaced with an attenuator that reduced the incident light to the single-photon level. Next, the system was calibrated as follows. With the optical input of the gate kept at $2\ \text{mW}$, the temporal profile of the laser beam was determined. The photon counter's input discriminator threshold level was then increased slightly, after which the pulse profile was determined again. As the threshold is increased, the photon counts also decrease; however, the pulse width becomes shorter and shorter until it tapers off at a certain optimal discriminator threshold level of the photon counter. At this level, any more increase in the threshold further decreases the photon counts but does not noticeably change the pulse width. This calibration procedure is only done once during the TSPF measurements. Figure 3 shows the impulse response of the

system obtained in this way. It can be seen that the temporal resolution at the FWHM is 62 ps.

The TPSF measurement obtained using the system was also compared to the analytical result. For this, an intralipid solution having an absorption coefficient, μ_a , of 0.02 cm^{-1} and reduced scattering coefficient, μ'_s , of 6 cm^{-1} was used as the sample in Fig. 2 and the TPSF measured. The solution was in a transparent container 3.2 cm thick. The analytical equation for the TPSF was obtained from [14] for a semi-infinite boundary with $\mu_a \ll \mu'_s$. Figure 4 shows the TPSF derived from both the experiment and the analytical equation, and it is seen that the two temporal profiles closely match each other.

In another experiment, the time-gated photon counting system was evaluated to determine its ability in resolving two $4 \text{ mm} \times 4 \text{ mm}$ targets that were separated by 4 mm and immersed in a highly scattering medium. The targets used were two plastisols having the optical properties $\mu_a = 0.14 \text{ cm}^{-1}$ and $\mu'_s = 6.5 \text{ cm}^{-1}$. The scattering medium used was an intralipid solution with optical properties of $\mu_a = 0.02 \text{ cm}^{-1}$ and $\mu'_s = 8.0 \text{ cm}^{-1}$. A transparent plastic square container, measuring 3.5 cm on the side, was filled with the intralipid solution. The two plastisol targets, separated by 4 mm, were placed in the middle of the container as shown in Fig. 5 so that they were spaced about 1.5 cm from the front and back ends of container. Additionally, the container was mounted on a translation stage to enable its entire length to be scanned across the laser beam path. With the laser source and detector positions fixed, the translation stage was moved in 2 mm increments, and for each position, the TPSF was measured. A total of 11 TPSFs, from 11 different positions along the container, were obtained in this manner.

For the detection of the targets, the photon counts from the TPSFs were integrated over a shorter 0–200 ps time window and contrasted with a longer 0–1380 ps time window. The integrated counts were simply taken to be equivalent to the area under the TPSF curve for the respective time windows. Figure 6 shows the normalized counts for each position of the translation stage as it was scanned across the laser beam path. The two targets are also indicated in Fig. 6 to show their positions relative to the measured counts. As expected, since the smaller 0–200 ps time window has less diffuse photons, it clearly resolves the two targets. The two minima observed for this time window, which are located at the –4 mm and 4 mm positions, correspond to the centers of the two targets. On the other hand, the longer 0–1380 ps time window contains much more diffused photons and hence is unable to provide adequate spatial resolution to resolve the two targets. This result is complemented by other works on time-resolved imaging [5,7], demonstrating that the use of early-arriving photons improves spatial resolution.

In conclusion, a fast time-gating scheme based on a photodiode has been presented. Its light weight and compactness makes it attractive for implementing portable time-gated single-photon counters. Additionally, the simplicity and low-cost construction potentially allows it to have widespread usage. The temporal resolution at the FWHM was measured to be 62 ps. This resolution can further be improved by the use of faster photodiodes and PMTs with shorter transit time spread (TTS). The photodiode that was used in this experiment has 47 ps rise time and 246 ps fall time, whereas the PMT has a TTS of 230 ps.

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Fig. 1.
Circuit diagram of the optical gating scheme.

Fig. 2.
(Color online) Experimental setup of the time-gated single-photon counting system. BS, beam splitter; M, mirror; PMT, photomultiplier tube; Amp, amplifier stage; CFD, constant fraction discriminator.

Fig. 3.
(Color online) Impulse response of the time-gated single-photon counting system.

Fig. 4. (Color online) TPSF of a 6 cm^{-1} reduced scattering coefficient intralipid solution compared with the analytical result. The solution is in a transparent container of 3.2 cm thickness.

Fig. 5.
(Color online) Setup for detecting and resolving two targets separated by 4 mm embedded in a highly scattering medium.

Fig. 6.
(Color online) Normalized photon counts obtained for the target-pair positions across the laser beam path. The target locations with respect to the counts are also indicated.