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Photon Counting Chirped Amplitude Modulation Ladar

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14. ABSTRACT
This work developed a method using Geiger-mode avalanche photodiode (GM-APD) photon counting detectors in the U.S. Army Research Laboratory's chirped amplitude modulation (AM) ladar receiver to yield sensitivities approaching the shot noise limit. Such sensitivities represent about four orders-of-magnitude improvement over the sensitivities of the currently used unity-gain, opto-electronic mixing metal-semiconductor-metal detectors. These sensitivity improvements may enable very compact, low power, eye-safe, and/or long-range ladars with low cost, low bandwidth readout integrated circuits for foliage and camouflage penetration, target ID, manned and unmanned ground and air vehicle navigation, three-dimensional face recognition, battle damage assessment, and change detection. Variants of the chirped AM ladar using a GM-APD that is experimentally assembled and tested and the benefits of new single photon counting detector products to the chirped AM ladar architecture are discussed.

15. SUBJECT TERMS
laser radar, ladar, avalanche photo-detectors, Geiger mode detectors, chirped amplitude modulation

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1. Objective

This work is a follow-on to the prior year's effort to develop a method using Geiger-mode avalanche photodiode (GM-APD) photon counting detectors in the U.S. Army Research Laboratory's chirped amplitude modulation (AM) ladar receiver to yield sensitivities approaching the shot noise limit. Such sensitivities represent about four orders-of-magnitude improvement over the sensitivities of the currently used unity-gain, opto-electronic mixing (OEM) metal-semiconductor-metal (MSM) detectors. These sensitivity improvements may enable very compact, low power, eye-safe, and/or long-range ladars with low cost, low bandwidth readout integrated circuits for foliage and camouflage penetration, target ID, manned and unmanned ground and air vehicle navigation, three-dimensional face recognition, battle damage assessment, and change detection. This year, another variant of the chirped AM ladar is experimentally assembled and tested, and new single photon counting detector products are evaluated in terms of their benefits to the chirped AM ladar.

2. Approach

2.1 Photon Arrival Pattern

Although for a single photon detection the output voltage of a GM-APD single photon counting module (SPCM) is a count pulse of constant amplitude that is not proportional to the light power, the AM waveform can be recovered since the mean arrival rate of photons at the detector is proportional to the light power, even though individual photon arrivals are randomly distributed.[1] Thus, the mean photon arrival rate and, therefore, the photon count rate output by a GM-APD SPCM will be modulated by an amplitude modulation of the light power, as shown in figure 1. This process is akin to the use of pulse position modulation to convert analog amplitude signals to digital data streams in digital telecommunications systems.

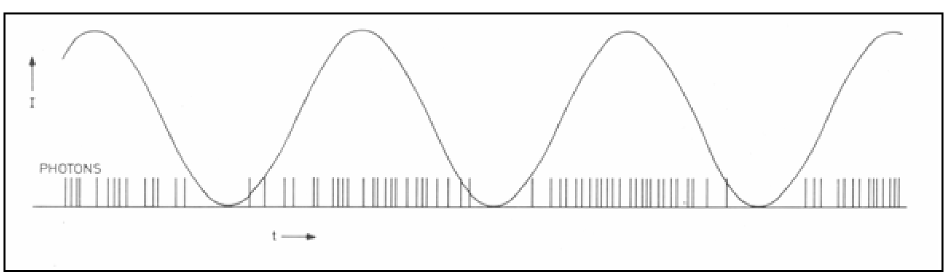

Figure 1. Random photon arrival pattern for a fully modulated sinusoidal intensity.

[1] Drain, L. E. *The Laser Doppler Technique;* John Wiley & Sons: New York, 1980; pp 145–147.

The constant amplitude pulse from a GM-APD photon counting module has a duration equal to the quenching time of the quenching circuit following the GM-APD; this usually dominates the GM-APD dead time. Typically, the dead time can be from tens of nanoseconds to several microseconds, although shorter dead times are attainable with specially designed quenching circuits. The rise time of the count pulse, however, is typically sub-nanosecond. This sets the upper limit of the photon counting receiver bandwidth and, therefore, the minimum achievable timing/range resolution. The inverse of the dead time sets the upper limit on the photon arrival rate since subsequent photons incident on the receiver in times less than the dead time from the arrival of the previous photon will not produce a count pulse. This results in errors in the measurement of the arrival rate modulation.

2.2 Chirped AM Ladar With GM Detector

A block diagram of one embodiment of the chirped AM ladar with a GM detector is shown in figure 2. Chirped modulated laser light is transmitted toward the target where some of the light is reflected back to the ladar.[2] On the return path, the chirped AM waveform is preserved, with a round-trip time shift, so that the mean photon arrival rates at the receiver are modulated with the time shifted chirp waveform. As shown in the block diagram of the photon counting chirped AM ladar architecture in figure 2, the GM-APD's output count pulse edge triggers a short pulse generator to output a short pulse of a duration that is less than or equal to $1/(4 \cdot f_{chirp\_max})$, where f_{chirp_max} equals the maximum frequency in the chirp waveform. The resulting arrival rate modulated short pulses are mixed with a radio-frequency local oscillator (LO) having the same chirp waveform as the transmitter to produce a series of random pulses with mean arrival rates modulated by the product of the LO and received light modulation waveforms, i.e., the

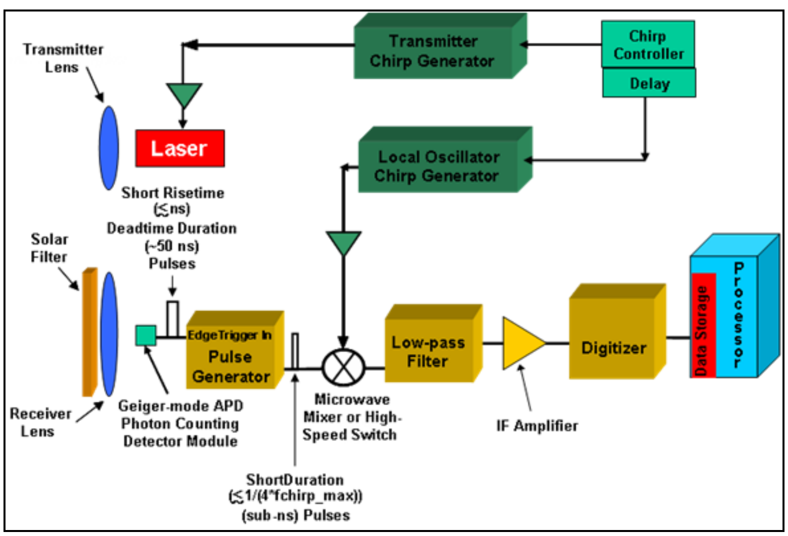

Figure 2. Photon counting chirped AM ladar architecture.

[2] Stann, B. L.; Ruff, W. C.; Sztankay, Z. G. *Optical Engineering* **1996**, *35* (11), 3270–3278.

intermediate frequency (IF) waveform. Low pass (or band pass) filtering the mixer output yields a sinusoid with a frequency proportional to the round-trip time between the ladar transceiver and the target. Digitizing the IF waveform and taking the magnitude of the fast Fourier transform (FFT) of the data produces the IF magnitude spectrum for which there is a peak at a frequency proportional to the round-trip time with an amplitude proportional to the mean return signal.

3. Results

3.1 Prior Director's Research Initiative (DRI) Work

In the prior year, we developed a computer simulation of the photon counting chirped AM ladar technique in MathCAD* and presented results from the computer simulation using a two-sided, sinusoidal chirp LO and a signal consisting of one-sided, Poisson distributed pulses with square wave chirp-modulated mean arrival rates. This configuration corresponds to the postdetection mixing configuration discussed in figure 1. We computed the theoretical current/voltage signal-to-noise (S/N) for the simulation parameters and showed that it was within 4% of the computer simulation.

A proof-of-principle (POP) laboratory optical experiment with a Perkin-Elmer, fiber pigtailed silicon GM-APD SPCM (60 % photon detection efficiency at 785-nm wavelength) and a ~785-nm wavelength, fiber pigtailed diode laser was also set up in the prior year. The optical experiment used here is very similar to that of the photon counting chirped AM ladar in figure 2 except that the generic laser was replaced with a fiber pigtailed diode laser and used only one chirp generator. The free-space round-trip path between the ladar transceiver and the target is replaced with an all optical fiber path from the transmitter to the receiver through variable optical attenuators. The attenuators varied the number of received photo-counts from a few hundred to a few thousand to verify the predicted scaling of the S/N for the IF signal's magnitude spectrum.

In this experiment, the effective chirp bandwidth was 10.24 MHz. We measured 245 background counts (dark counts + ambient light counts) and 800 total counts for the measurement. Figure 3 shows the resulting magnitude spectrum.

The measured electrical current/voltage S/N for these results is 7.9, which is 19.4% lower than the calculated S/N of 9.8 for the given signal and background counts. The discrepancy in S/N between the theoretical value and the experimentally measured value may be caused by excess counts due to noise in subsequent electronics such as the IF filter amplifier, less than unity mixing efficiency, chirp nonlinearity, and/or incomplete modulation of the laser. For a background count of 245 counts and an excess noise count of 434 counts, as for the experimental

* MathCAD is a trademark of Mathsoft Inc.

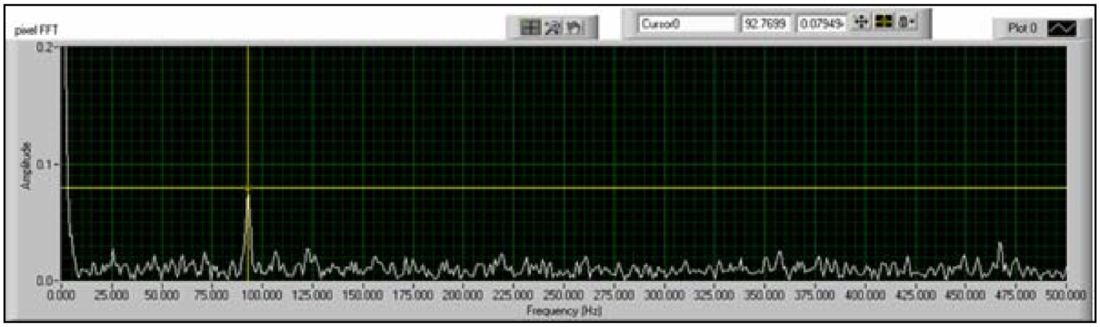

Figure 3. Magnitude spectrum of the IF waveform from the first chirped AM ladar.

results presented here, the noise equivalent photocounts (NEPh) are calculated to be 54.1536. Thus, with a photon detection efficiency of 60%, a background count of 245 counts, and an excess noise count of 434 counts, the NEPh sensitivity for the experimental setup is 54.1536/0.6 = 90 photons. Since estimates of the NEPh sensitivity of the existing unity gain solid state detector-based chirped AM ladar breadboard is about a million photons, these experimental results indicate an improvement in sensitivity by about four orders-of-magnitude.

3.2 Follow-on DRI Work

In the follow-on DRI, an alternate configuration for the POP ladar, shown in figure 4, was assembled. Here, the LO modulates the excess bias voltage above and below the GM-APD's breakdown bias voltage to cause OEM with the LO. In this OEM configuration, the detector's minimum gate duration must be less than one-half of the reciprocal of the highest frequency in the chirp waveform, and the maximum gate repetition rate must be at least equal to the highest frequency in the chirp waveform. In the OEM configuration, the output of the SPCM will have an envelope that is modulated with the IF waveform recovered by low-pass or bandpass filtering. As usual, digitizing the IF waveform and taking the magnitude of the FFT of the data produces the IF magnitude spectrum for which there is a peak at a frequency proportional to the round-trip time with an amplitude proportional to the mean return signal.

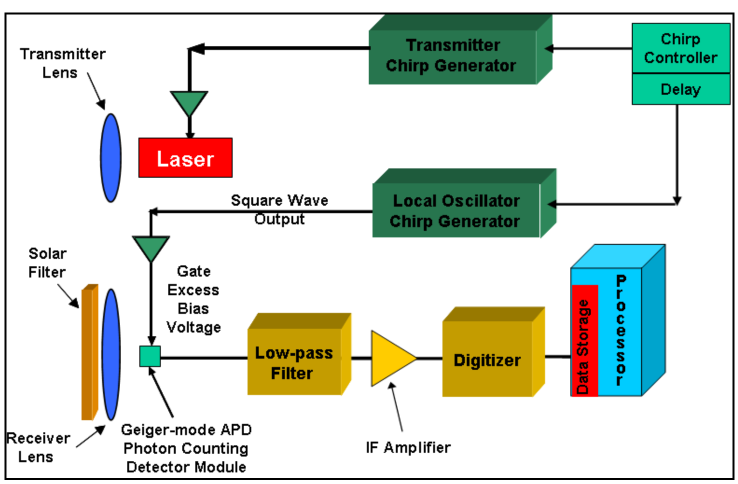

Figure 4. Photon counting chirped AM ladar with OEM.

To test the OEM configuration shown in figure 4, the laboratory setup shown in figure 2 was modified by removing the sub-nanosecond pulse generator and microwave mixer. The sinusoidal LO signal was then put into the trigger input of a pulse/signal generator to produce a chirped square wave between 0 and 5 V amplitude. This square wave LO was applied to the gate input of the Perkin-Elmer SPCM. Since the minimum gate duration for the Perkin-Elmer SPCM is 50 ns, the maximum chirp frequency that can be used in this setup is about 10 MHz. Most of the microwave components in the setup have a frequency response that starts to roll off below 10 MHz. Thus, the useful chirp bandwidth is very limited for this setup in the OEM configuration. For the experiment, we chirped from 9 to 10.49 MHz for a chirp bandwidth of 1.49 MHz, over a 1.024-s duration. In order to get sufficient delay time, a chirp generator with two direct digital synthesizers (one for the signal and one for the LO) was used so that a desired delay between the signal and LO chirps could be programmed. For this experiment, the delay was set at 100 μs. The power spectrum of the IF waveform for this experiment, accumulated over 5 s at a 1 kS/s sampling rate, is shown in figure 5.

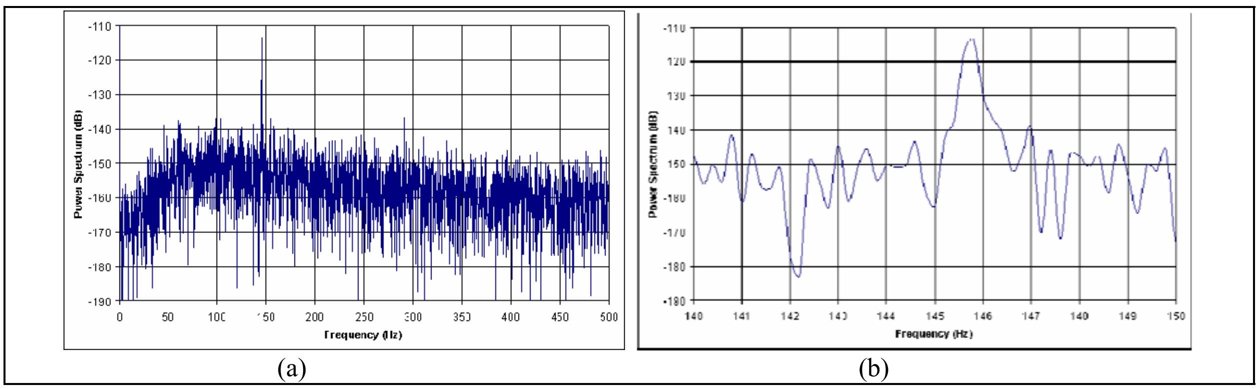

Figure 5. Power spectrum of the IF waveform for the experiment in the OEM configuration (a) over a 500-Hz IF bandwidth and (b) "zoomed" in from 140 to 150 Hz.

Based on the chirp bandwidth, chirp duration, and delay time, the predicted frequency of the peak in the IF spectrum is 145.5 Hz. For this experiment, the number of signal counts is 265,000 and the number of background counts is 700. The predicted electrical power SNR for these parameters is 42.18 dB, and the measured electrical power S/N for the results shown in figure 5 is 36.42 dB, which differs from the theoretical prediction by –5.76 dB. This corresponds to a factor of about 4× lower electrical power S/N and about 2× lower electrical current/voltage S/N than theoretically predicted. The source of S/N loss in this experiment is currently unknown but may be due to incomplete modulation of the laser, excess noise caused by gating the SPCM at high frequencies, excess noise from the IF amplifier, excess noise during the "flyback" time between chirps, and/or peak spreading due to anomalies in the chirp.

The two prior ladar embodiments demonstrated the sensitivity advantage of using the GM-APD over the unity gain MSM detectors. A problem with using the GM-APD is that the dead time limits the bandwidth of the chirp modulation which, in turn, limits the ladar range resolution. As an example, the Perkin-Elmer SPCM has a dead time of 50 ns, which limits the maximum chirp frequency to 10 MHz; this corresponds to a maximum range resolution of 15 m. For most of the applications considered for ladar, such as imaging objects the size of a military vehicle, a range resolution of 0.25 m is desirable. This resolution requires a chirp bandwidth of 600 MHz. To obtain these higher chirp bandwidths, placing an electro-optical modulator (EOM) driven by the LO signal in the light path before the GM-APD is suggested (see figure 6).

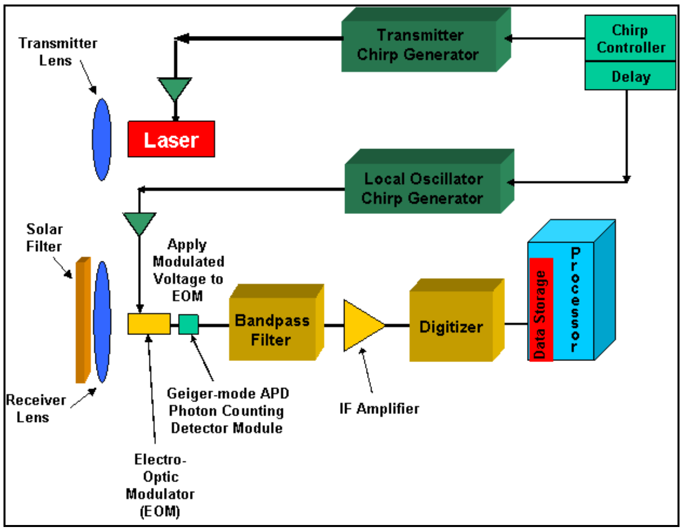

Figure 6. Photon counting chirped AM ladar with separate OEM.

This will convert the incoming microwave modulated light into a light signal containing an IF component that can be "sampled" by the GM-APD. Because the IF in most chirped AM ladar applications will be below 1 MHz, the dead time of the GM-APD is not usually an issue. Quantum-well EOMs are built at the near and short wave IR bands with several gigahertz of bandwidth, and Mach-Zender EOMs are built at 1.55 μm with up to 40 GHz of bandwidth. Use of these devices can lead to range resolutions in the low millimeter regime.

Continued study of the photo counting chirped AM ladar also includes an effort to replace the Perkin-Elmer SPCM now used. This module, which costs around $6000, is responsive from 650 to 850 nm, with a 50-ns dead time and 100 dark counts per second. It is preferable to build the next generation of ladars at 1.55 μm wavelength for eye safety and, further, take advantage of the many commercial off-the-shelf components built at this wavelength by the telecom industry. A new infrared photon counting module that operates at eye-safe wavelengths is being developed by Lepton Technologies. Its sensitivity is 4e+4 A/W and dark count is 80/ s; it operates linearly. This module, mated with a commercially available Mach-Zender EOM in the ladar of figure 6, moves the operation to an eye-safe wavelength, and by virtue of its linearity, eliminates the problem of saturation that is commonplace with GM detectors. The saturation issue requires that the laser power be adaptively set according to range and target reflectivity so that the detector does not continuously output pulses, thereby losing target range information.

4. Conclusions

The prior DRI simulation and experimental results reviewed here demonstrate the viability of the photon counting chirped AM ladar technique and verify the theory of operation and theoretical SNR calculations. The most important gain with photon counting is an improvement in sensitivity by a factor of more than 10^4 over the current MSM detector scheme. In the follow-on DRI, shortcomings in the resolution capability of the ladar demonstrations in the original DRI caused by the long dead time associated with photon counting detectors are shown. Modifying the ladar architecture is suggested by placing an EOM in the receive light path to down-convert the microwave modulated light signal returning from the target into a low-frequency IF signal, thus eliminating the problem caused by dead time. Also noted is a new photon counting module that will become available which will move the operating wavelength into the eye-safe band, simplify the design, and most likely improve the performance by allowing the ladar to operate over a high dynamic range not possible with the existing SPCMs.

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