Flash Camera Options for Coherent Imaging

By

Dr. Paul McManamon
Exciting Technology LLC & University of Dayton

Introduction:
We are coming into a time when flash imaging is available for coherent lidar applications. Over the last 20 years we have developed various flash camera options.[1] Each flash imaging camera option has benefits and drawbacks. Most of these detectors however were not developed for coherent imaging. Historically for coherent imaging scientists wanted a strong local oscillator. More recently the ability to measure Doppler shift, and the ability to measure the field, including phase, have been important aspects of coherent imaging.[2] These recent applications will be significantly enabled by flash imaging. Measuring Doppler shift point by point on a bridge, or on an engine, or on the ground, could have some value, but if you measure it in a flash image then you can instantaneously see the vibration spatial modes across the object being imaged. Flash imaging will enable many important applications associated with area vibration measurements. Another important application will be multiple input, multiple output, MIMO, lidar imaging. An array of 32 x32 format, or more, cameras behind multiple apertures could capture the field in high resolution.[3] If for example we have a hex 19 set of receive apertures we would have 5 apertures across the largest dimension, and if we use multiple transmitters separated across approximately the width of the receive array, and use 32 x 32 format cameras, we can capture coherent images as large as about 300 x 300.

Cameras we might consider include Geiger Mode APDs, GMAPDs, Linear Mode APDs, LMAPDs, pin diodes, and framing cameras. Spatial heterodyne coherent imaging can use low bandwidth framing cameras. GMAPDs, LMAPDs, and pin diodes can be used for temporal heterodyne. They have fast enough time response to measure range based upon the time it takes light to get to an object and return. Pin diodes may require a strong LO. GMAPDs will require a weak LO, and LMAPDs could require anywhere from a strong to a weak LO, depending on camera sensitivity.

Geiger Mode APDs for Coherent Imaging

Existing Geiger Mode APDs, GMAPDs, are framing cameras at up to 186 Khz for the 32 x 32, and up to 105 Khz for the 32 x 128 camera, but a GMAPD camera available by the end of the year will provide asynchronous read out. Each detector will fire and be independently reset as soon as possible. The dead time will be 400 nsec to 1 μsec. Ideally it will be 400 nsec, but to be safe we will count on no more than 1 μsec. That means each detector can continuously respond at a 1-2.5 Mhz rate. This FPA will have 32 x 32 detectors. As we group detectors together it will be possible to respond at a higher rates, but with fewer effective detectors. For example a 4 x 4 super pixel array of detectors could respond at a 16-40 Mhz rate. The full detector array could respond at .9 Ghz, limited by the read out electronics, not the dead time per detector. If it was limited by detector dead time then its response would be 1-2.5 Mhz. Then it would however be acting as a single super pixel.

Gieger mode APDs are ideal both because of sensitivity, resulting in only needing a low power local oscillator, LO, and because they inherently capture a “full waveform”. They have a simple digital read out circuit. The main drawbacks with GMAPDs for temporal heterodyne coherent imaging are background noise/backscatter and narrow dynamic range. Usually background noise/ backscatter is not an issue with coherent imaging, but it will be for GMAPDs. A narrow filter will be required, and applications with high background or backscatter, and applications with a highly variable scene, will be problematic. A 1 nm filter, which is very narrow, is 126 Ghz at a carrier wavelength of 1550 nm. With a 100 Mhz to maybe 2 or 3 Ghz detector we normally would not bother with a filter, but for GMAPDs we have to worry about photon blocking

With these cameras we have to use a low power local oscillator to do temporal heterodyne,[4] with the LO and the return signal about the same amplitude. The beat between them modulates the probability of an avalanche. A disadvantage of the weak LO approach is the signal amplitude, and that the LO need to be approximately matched. GMAPD coherent lidar will have a narrow dynamic range. A method will need to be set up to make sure the LO matches the return signal in amplitude. This could be an issue for scenes with significant differences in reflectivity. Often foliage has a higher reflectivity then manmade objects. A weak LO does not increase the sensitivity of the detector, but in the case of the GMAPD the cameras are already very sensitive.

We can obtain a Princeton Lightwave 32 x 32 framing camera with some defective pixels for $75 K. The new ITAR restricted 32 x 32 asynchronous read out camera will cost $225K when it is available. In terms of my desired FPA for coherent flash imaging once we have the asynchronous read out 32 x 32 the next step would be to increase that to 128 x128. In addition to working to reduce dead time that would be a near ideal GMAPD for flash imaging. While it is possible with a limited read out capability windowing a 128x128 down to 32 x 32 will be useful, we would then run into dead time

Pin Diode, or Linear Mode APDs, LMAPDs, for Coherent Imaging

As an alternative to a GMAPD camera we can use a pin diode with no amplification or a linear mode APD, LMAPD. There are 2 basic types of LMAPDs. There are HgCdTe LMAPDs, which have k=0. k is the ratio of holes to electrons generated during the avalanche. With k=0 the excess noise generated by an FPA is much less then with a value of k above zero, and avalanche breakdown does occur. HgCdTe cameras have low excess noise, about F=1.3, as a result of k=0. This is actually lower than the McIntyre theory, which would place the excess noise factor about 2. Excess noise is noise added due to the amplification process. When you only amplify the # of electrons, not the holes, you can keep excess noise low. The disadvantages of k=0 APDs are they need a physically larger cooler than a TE cooler because they operate near 100 deg K, and they are not commercial available, so cost more. On the positive side they can have a gain of 1000 or more, so are sensitive and use a lower power LO.

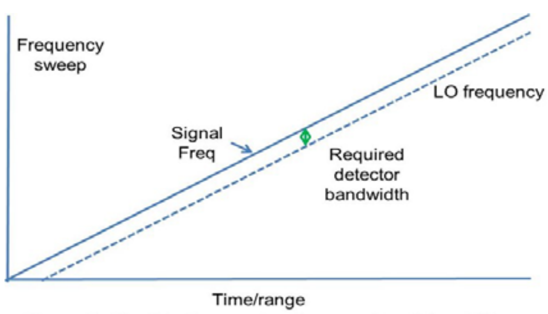

Figure 1: Stretch Processing Sweeps the LO and the transmitter in sync

One of the issues with LMAPDs is you need to develop a fast ROIC to read out the signal and record it behind each detector. While you can do better than that it is likely you might have on the order of 100 Mhz bandwidth. In that case you might want to do stretch processing, as shown in Figure 1 in order to have high range resolution.

InGaAs LMAPDs for Coherent Imaging: I plan on liking these FPAs once they are available with a high enough frame rate to sample phase well enough for multiple applications, but they are not there yet. They should be relatively low cost, and have good enough sensitivity to reduce the required LO power, maybe not to the level of a GMAPD, but quite a bit, and they should not have the dynamic range issue associated with GMAPDs

Voxtel and ASC have InGaAs LMAPDs as commercial products. Voxtel has cameras with k~.2, and is developing multi-stage cameras with k~.02. The k~.2 cameras can have gain of 5-20, whereas the k~.02 cameras can have gain of about 75, or even more, before the excess noise becomes unmanageable. For a temporal heterodyne lidar the extra sensitivity is not a significant issue, so we will only consider the lower gain Voxtel cameras, not the multi-stage cameras. Higher gain, and more sensitivity may mean the ability to use a lower power LO. Voxtel does have some cameras that are effectively AC coupled. If we need a high LO power, due to limited sensitivity, then we will want AC coupling.

One benefit of LMAPDs is you can capture a full scene on a single pulse. Also the full 3D image can be read out simply, but the disadvantage is we need a complex read out circuit. This can limit the read out rates. Each pixel needs significant electronics under it. Ideally we can have a full waveform sample in each detector element, but often a LMAPD camera only has the ability to capture one, or a limited #, of samples in each angle/angle pixel. The VX 806 only captures 3 samples in each detector. It costs $54K per camera. The VX 819 provides 24 samples in range that can be separated by 2 nsec to 16 nsec per sample. It has a 128 x 128 format, a 100 Mhz bandwidth, a 94 hertz frame rate, a jitter of < 100 psec, and a 50 µm pitch. If we window it down to a 32 x 32 format it has a frame rate of 990 hertz, and for a 16 x 16 format a frame rate of 2075 hertz. We can see from figure 2 that is all we want to do is sample a single sine wave 24 samples is not bad, so long as they are separated appropriately. Figure 3 shows sampling a single beat frequency, but also sampling a more complex waveform, the sum of 4 frequencies. We see as the waveform gets complex 24 samples is not providing good insight into the underlying waveform. Figure 4 then shows an attempt to detect pseudo random codes using only 24 sample. In this case we take a chip length of 10 nsec, and 3 nsec sampling. With 24 samples and 3 nsec sampling we only have a 72 nsec period over which to take samples.

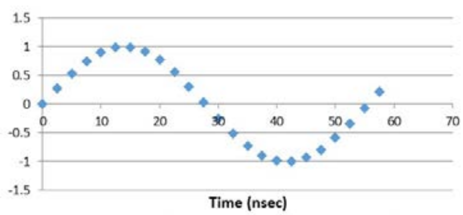

Figure 2: 24 samples @ 2.5 nsec with 18 Mhz beat freq

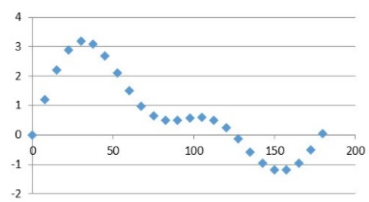
Figure 3a: Sum of 4 sine waves, 11, 7, 5, and 3 Mhz,

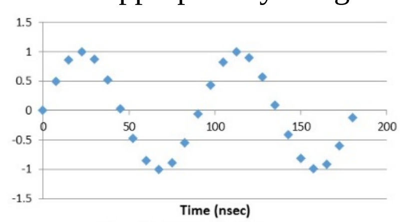

Figure 3b: 11 Mhz single sine wave

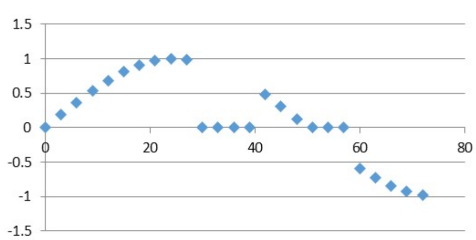
Fig 4: 10 nsec chip length, 3 nsec samples, and 10 Mhz beat frequency

We can see 24 samples is not sufficient. My ideal for a LMAPD would be at least 50 samples, and high frame rate, at least 10 Khz. We could have a continuous sample rate as high as we can, possibly 1- 10 Mhz. If we had either of these in a 128 x128 format with a single stage of InGaAs APD this would be a nearly idea coherent FPA. It would eliminate the dynamic range issue of GMAPDs. While it would require more LO power it should not be prohibitive.

HgCdTe LMAPDs for Coherent Imaging:

Raytheon and DRS have HgCdTe LMAPD cameras, but neither have commercial FPA cameras, so each FPA camera purchased would be a program with the provider. DRS was awarded a DARPA LRT contract for a camera suitable for both direct detection and coherent detection. The LRT program is basically complete, but the results have not been publically released. Many of the considerations would be similar to the InGaAs APDs for flash heterodyne imaging, but the array would be more sensitive, more expensive, and would need a 100 degree cooler. Otherwise many of the parameters would be similar. A lower power LO than the LMAPD InGaAs cameras could be used, due to increased sensitivity.

Low bandwidth Framing Cameras for Spatial Heterodyne Coherent Imaging

Spatial heterodyne does not require high bandwidth detectors capable of responding on a time period that allows speed of light based range measurement. Instead the camera merely needs to capture a spatial image. Multiple cameras are available, from Sensors unlimited, FLIR systems, and others. Voxtel has had a recent effort with AFRL to develop some cameras specifically for this application.

Summary:

GMAPDs are available now for use in flash coherent temporal imaging, and they are moderately priced. For situations where we do not have significant background, or backscatter, and where the target is not highly variable in reflectivity they are a good choice, and will get better when the asynchronous camera becomes available. They also have Ghz bandwidth, so can easily provide high range resolution. LMAPDs will be better for cases with high background or backscatter levels, or for cases with highly variable reflectivity, but will require LFM stretch processing to obtain high range resolution. HgCdTe cameras are not available commercially, but you should be able to buy them with high enough sample rates to do flash coherent imaging right. We should be able to use low power LOs with HgCdTe LMAPDs if desired. No one has yet paid to develop the ROICs to sample often enough with InGaAs LMADS detectors, but these will be attractive options once available. At this time limited flash coherent imaging situations could be implemented with InGaAs flash coherent imaging. They are cheaper than the HgCdTe LMAPD cameras now, and are likely to be less expensive when they have appropriate ROICs. I plan on liking the InGaAs LMAPD cameras when they become available with enough sampling.

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[1] PF McManamon, P Banks, J Beck, AS Huntington, EA Watson, "A comparison flash lidar detector options", Proc. SPIE 9832, Laser Radar Technology and Applications XXI, 983202 (May 13, 2016); doi:10.1117/12.2229068; http://dx.doi.org/10.1117/12.2229068

[2] PF McManamon, "Perspectives on the Future of Coherent Ladar", 17th Coherent Laser radar Conference, CLRC, 2013, Barcelona.

[3] JR. Kraczek, PF. McManamon, and EA. Watson, "High resolution non-iterative aperture synthesis," Opt. Express 24, 6229-6239 (2016)

[4] L. A. Jiang and J. X. Luu, "Heterodyne detection with a weak local oscillator," Appl. Opt. 47(10), 1486–1503 (2008)