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Flash Lidar Detector Options for Coherent Imaging

By

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Why Use Coherent ladar?
(Instead of direct detection)

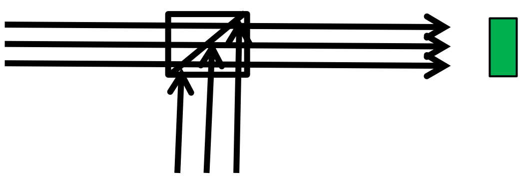
- Can use poor detectors
  - Because a strong LO hides noise
  - I think this was the main first main reason for coherent lidar
    - Most of the lidars in the 70's and 80's were CO2 coherent lidars for this reason
- Direct, highly accurate, measurement of velocity
  - Can do a precise measurement of velocity
  - I think this was the second main reason for using coherent lidars
- **Can directly measure the return field**
  - **I think this is the main future reason for using coherent lidar**
- Easy to use a high duty cycle waveform
  - Can use FM chirp, or pseudo random codes, instead of pulses
  - Efficient cw lasers are easier to build

What Can I do if I Can Measure the field?

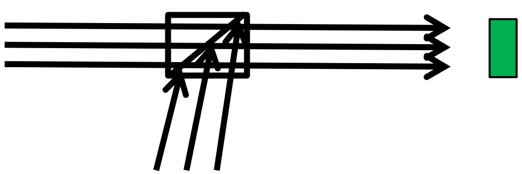
- Lensless imaging
  - Can capture field in pupil plane, or image plane, or anywhere in between
    - Once you have the field you can flip between pupil and image plane using a Fourier transform
- Can digitally focus after the fact
- Can process (zoom in) on any part of the illuminated area
- Can compensate for the atmosphere after field capture
  - Using a sharpness metric, or another approach
  - Can even compensate for extended turbulence
- Can Synthesize larger virtual apertures
  - Can coherently combine sub-apertures to form a larger pupil plane array aperture
  - Can using a moving aperture to synthesize a large aperture

Flash Imaging Detector Options

- **Temporal Heterodyne Imaging**
  - Gieger Mode APDs, GMAPDs, InGaAs
  - Linear Mod APDs, LMAPDs
    - LMAPDs, HgCdTe
    - LMAPDs, InGaAs
  - Pin Diode Camera
- **Spatial Heterodyne Imaging**
  - Can use low bandwidth framing cameras



Temporal Heterodyne
-LO is offset in frequency so you can measure plus and minus frequencies
- Detector can respond to the beat frequency between the return and the LO – can measure phase



Spatial heterodyne
-LO is same frequency, but offset in angle
-Fringes across the detector array allow measurements of spatial phase variations
-- Uses framing camera with low bandwidth

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What do We Want in a Flash Camera for Coherent Imaging?

- Common Camera Desires
  - High sensitivity so LO power does not need to be high
  - Relatively large formats
    - From 32 x 32 up to 256 x 256, or more
  - Rugged, cheap, small, low power consumption
- For Temporal heterodyne
  - Enough samples in a row to sample the temporal beat frequency between the LO and return signal
  - High enough sample rate to sample any motion of interest
  - Full waveform sampling would be nice, but not required
    - Burst sampling is okay
  - AC coupling if a strong LO is used
    - Or will lose dynamic range
- For spatial heterodyne (Digital Holography)
  - High enough spatial sampling to sample the beat frequency between the return signal and the LO (depends on angle between the two)
  - Large Formats
  - Cheap

Why do we care about the power of the LO, and Gain?

- Gain can reduce noise

$$SNR = \frac{G^2 R_\lambda{}^2 P_s^2}{2eBG^2 F R_\lambda \left[P_s + P_{LO} + P_{bk} + P_{dks} \right] + 2eBi_{dks} + 4(ktB / R_L)}$$

  - With a strong LO we can eliminate noise
- Excess Noise Factor, F, Limits Gain in LMAPDs
  - HgCdTe has low F (about 1.3) due holes not ionizing during gain
  - GMAPDs are digital, so F is not important
- Prefer a weak LO to save power and cooling
  - LO can be weak if we do not need it for sensitivity
  - LO has to be weak for GMAPDs, or lidar will be blind

GMAPD Comments

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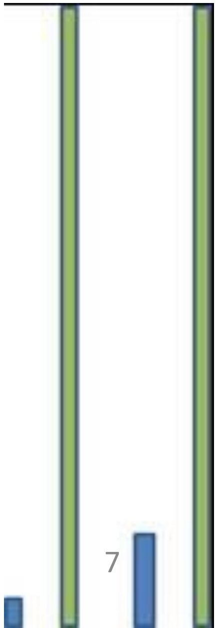
- Pulse output is the same avalanche no matter how many photons hit the detector
  - Noise on the amplified signal does not matter. Each detection counts as 1
- Dead time after avalanche
  - 400 nsec – 1 µsec
  - Causes issues with high brightness background
- TE cooling
- Simple read out circuits, but more complex processing
- Low noise, so easy to predict performance
- Cost is moderate
- Commercial FPAs are available



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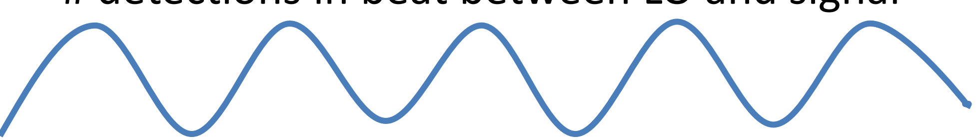
Geiger Mode APD Heterodyne

- MIT/LL has done heterodyne using Geiger mode APDs*
- Made LO about the same intensity as the return signal
- Beat between LO and signal varies with time, resulting in a variation of # of detections
- Grouped pixels into 4 x 4 arrays to get more statistics

detections in beat between LO and signal



*L.A.Jiang, J.X.Luu, “Heterodyne detection with a weak local oscillator”, APPLIED OPTICS/Vol 47, No. 10, 1 April 2008, p1486-1503

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GMAPDs for Coherent Flash Imaging

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- **Current commercially available arrays**
  - 32 x 32 array that will frame at 186 Khz
  - 32 x 128 array that will frame at 105 Khz
- Projected array
  - Asynchronous read out 32 x 32 array that will “frame” at about 1 Mhz
    - Limited by detector dead time
    - Can group detectors into super pixels to increase frame rate, but with fewer pixels
- Digital read out
- Simple ROIC
- Continuous read out (full waveform)
- Detect beat frequency by changing probability of detection
- Ghz class bandwidth
- **Dynamic range issue** (my opinion)
  - LO and signal must be about the same intensity
  - I worry about highly variable reflectivity in a scene
- **Bright sun can still be an issue**
  - Normally don’t worry about background for heterodyne system
  - Want a narrow filter, say 1-1.5 nm
- **Low power LO** nice, from a power and cooling perspective

Filter Widths vs traditional Heterodyne linewidths

- In frequency lasers are broad band
  - For 1.55 μm

Δ λ (nm)	Δf (Ghz)
0.1	13
1	126
10	1265
100	12650

$$B = -\frac{c}{\lambda^2}\Delta\lambda$$

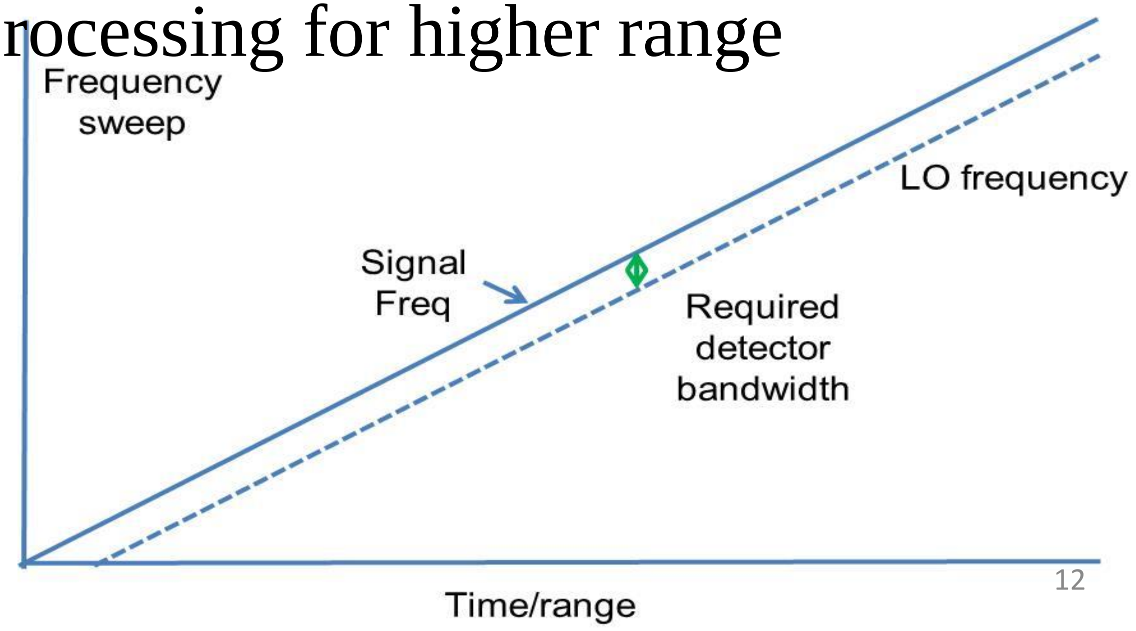
  - Normally why bother with a 1 nm (126 Ghz) filter when doing heterodyne?
    - Your detector might have a 100 Mhz- 3 Ghz bandwidth

What I would like in a GMAPD Coherent Flash Imaging Camera

- The soon to be available 32 x 32 asynchronous camera is really nice.
  - But if I use 4 x 4 super pixels it would only be an effective 8 x 8 array
- Make is 128 x 128 and I'd be fairly happy
  - Even larger would be nice from a super pixel point of view
  - Even at 128 x128 if I use 4 x 4 super pixels it would only be an effective 32 x 32 array
- Of course it goes without saying that cheaper and smaller are nice

Bandwidth Limitations

- LMAPDs often have bandwidth limitations around 100 Mhz
  - This has to do with developing the read outs
- A restriction, but not a big deal for coherent imaging
  - Can do stretch processing for higher range resolution



InGaAs Pin Diodes and LMAPDs for Coherent Flash Imaging

- **I plan on liking these when they are available with the right read out rates**
  - Currently available cameras are marginal for coherent imaging
  - Price of cameras is nice
    - Not the right read out rate, but I am paying $54K for a 128 x 128 LMAPD
- Even pin diode cameras are okay if they are AC coupled
  - It will mean a stronger LO
  - AC coupling means we do not lose dynamic range with a strong LO
  - Disadvantage of AC couple is no passive viewing
    - Passive scene does not change enough to see with AC coupling

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InGaAs LMAPD Comments

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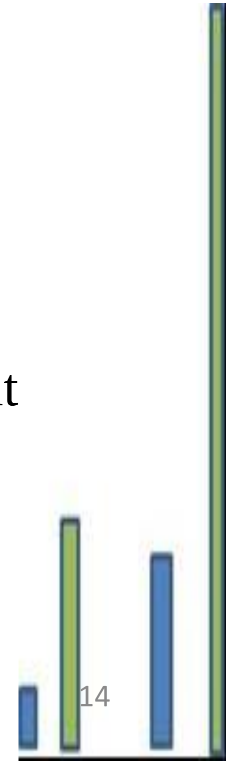
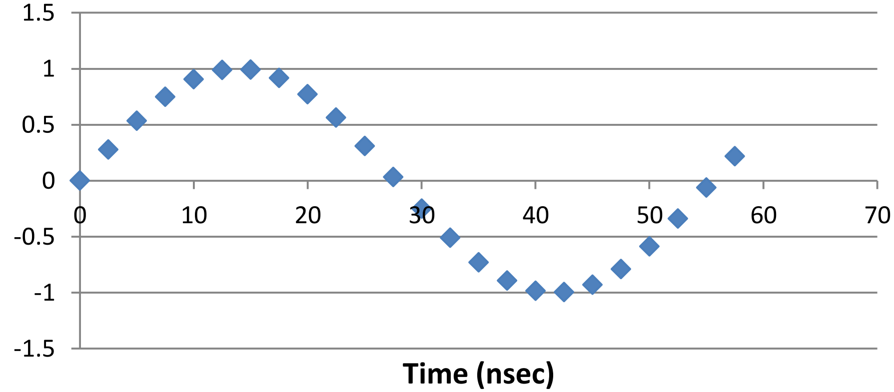
- Low to moderate gain with a single stage (5-20)
- Research in multi-stage InGaAs LMAPDs with higher gain
  - Can have an effective k of .04, could approach HgCdTe performance
- Complex ROICs, especially if multiple ranges are captured per detector
  - For coherent imaging you can either operate in burst mode with multiple range samples to sample the waveform, or have a high frame rate for full waveform sampling
- Can make a direct detection image on a single pulse
- Simple processing to make a direct detection image
- TE cooling, or temp controlled
- Moderate to low cost.
- Commercial pin diode arrays and low gain LMAPDs are available
  - $54K for a moderate gain 128 x 128 array, but not the right read out rate for flash coherent imaging
- Modelling of direct detection is more complex, due to low gain
  - Must keep track of noise sources
- Requires a high energy per pulse laser for direct detection



Available InGaAs LMFPAs

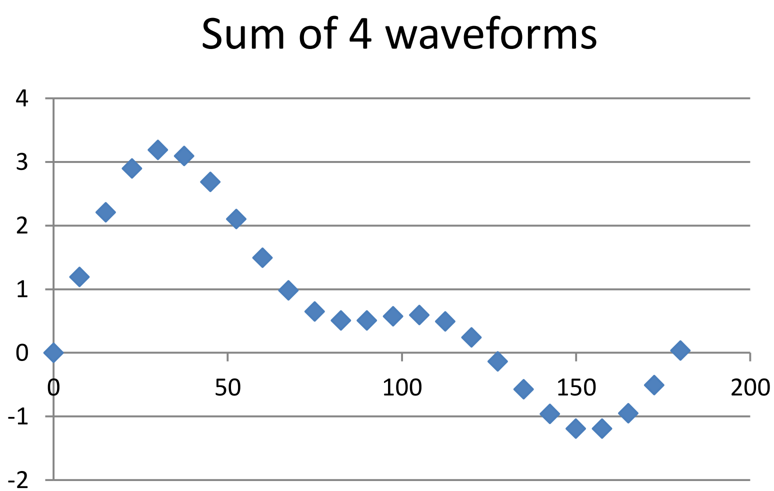
- The Voxtel VX 819 captures 24 samples
  - 2 -16 nsec sample rate
    - Limits the range of LO frequency offsets
  - 94 hertz frame rate
    - This is really low for most applications
  - 990 hertz frame rate for 32 x 32 format
  - 2075 hertz frame rate for 16 x 16 format
  - 128 x128 format
  - 100 Mhz Bandwidth
  - A jitter of < 100 psec, and a 50 μm pitch
- Can be interesting to sample lower frequencies in vibrometry, using an LO that is not offset very far in frequency

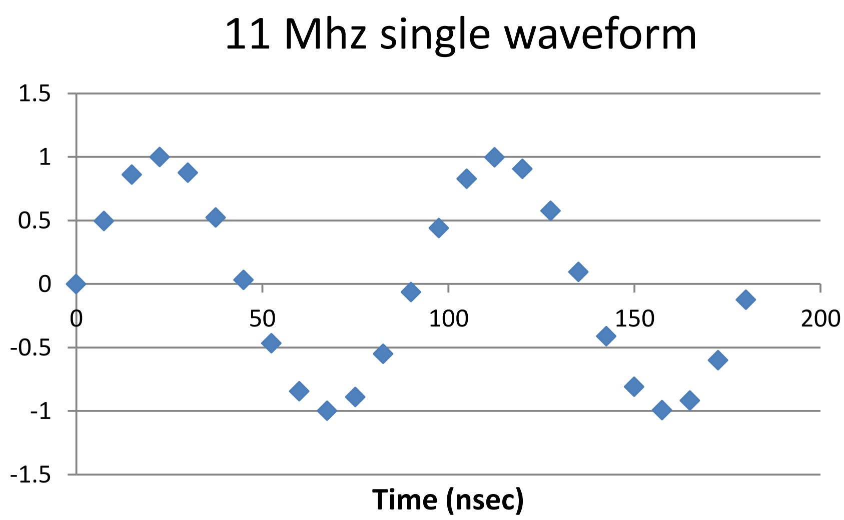
- 24 samples @ 2.5 nsec
- 18 Mhz beat freq



More frequency Sampling using the VX819 Camera

- @ 11 Mhz
- A sum of 11 Mhz, 7 Mhz, 5 Mhz, and 3 Mhz

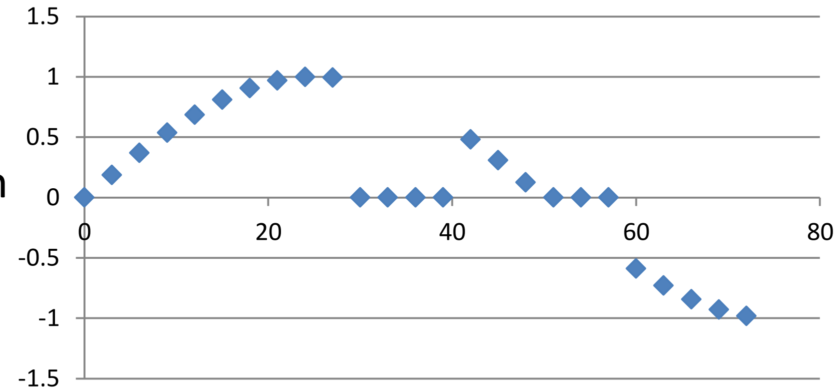




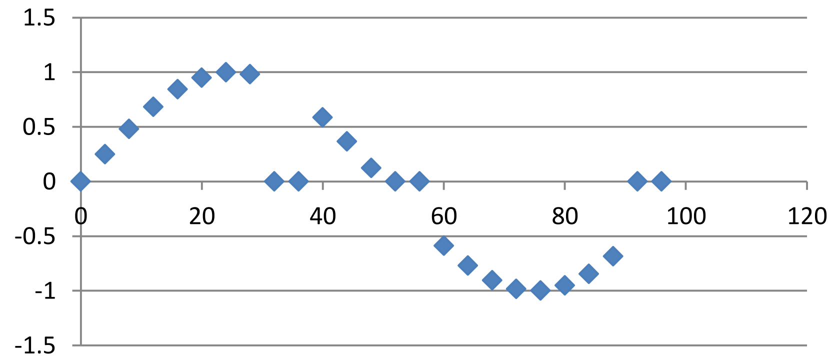
Can use pseudo random codes

- Assume a 10 nsec chip length and 4 chips in a code, with a code of 1's and 0's
- 24 samples is restrictive

-10 Mhz beat freq
-3 nsec samples of waveform



- 10 Mhz beat freq
- 4 sec samples



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What I want in a InGaAs LMAPD camera for Coherent flash imaging

- Challenge will be read outs.
- Burst mode
  - At least 50 samples in range
  - At least 32 x32, but prefer 128 x128
  - At least 10 Khz frame rate
- Continuous
  - As high as possible frame rate
  - Ideally chose 32 x 32 or 128 x128, with lower frame rate for larger camera
- Can go “high” gain multi-stage avalanche with DC coupling
- With single stage coupling I’d like to chose AC or DC coupling
- Prefer costs < $60K, and of course small

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HgCdTe LMAPD Comments

- Pulse output is linearly related to # of input photons
- HgCdTe can have gain as high as 2000 without high excess noise
  - k=0, F~ 1.3
- Can make a 3D image on a single pulse
- Images are formed quickly and with limited processing
- Need to use relatively high energy per pulse lasers
- ROICs are complex, especially for many range captures per pixel
- Have to run colder with a 5 µm cut off FPA, so need a larger cooler (nominal coke can size)
  - Research in shorter wavelength cut off/high temperature HgCdTe
    - Shorter wavelength cut off would require higher voltage drivers
- Can passively image in the MWIR and NIR
- HgCdTe LMAPDs are not commercial products
  - Currently expensive

HgCdTe LMAPD Arrays

- Exact characteristics of arrays have not yet been publically released
- ROIC limitations will be similar to InGaAs arrays
  - Complex ROICs
- Sensitive arrays, so can use a low power LO

What I want in a HgCdTe LMAPD camera for Coherent flash imaging

- Challenge will be read outs.
- Burst mode
  - At least 50 samples in range
  - At least 32 x32, but prefer 128 x128
  - At least 10 Khz frame rate
- Continuous
  - As high as possible frame rate
  - Ideally chose 32 x 32 or 128 x128, with lower frame rate for larger camera
- Low LO power because of great sensitivity
- Prefer a commercial product to get costs down
- Of course keep minimizing cooler size, unless can go to lower λ cut off, and higher operating temperature

Spatial Heterodyne

- We are in good shape for Flash Spatial Heterodyne
- Could combine with OTOF lidar
  - OTOF lidar can do traditional range resolution
    - mm to feet
  - Spatial heterodyne can do precise range resolution using two wavelengths, and synthetic wavelength.
  - The two could be combined for interesting results
    - Both use low bandwidth framing cameras
- Huge format visible cameras are available
  - My phone can take video at 24 frames per second with a format of 3840 x 2160
- Larger formats are becoming available for the near IR
  - 256 x 320 and up

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Voxtel camera for Spatial Heterodyne

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- 64 x 64 format
  - Large enough if used in an array of apertures
- Burst of 18 frames in a snapshot mode
  - Can speckle average
  - 50 nsec – 100 nsec sample time
    - Want laser pulse width narrower than the sample time
    - 10 Mhz sample rate during the burst
- 250 hertz frame rate for the bursts.
- Estimate an input-referred read noise of about 125 electrons RMS, based on the circuit simulation

oTOF Lidar

- Could combine with spatial heterodyne
- Uses commercial 2D cameras
- Makes a 3D image on a single pulse
- Uses Pockels cell to rotate polarization, and ratio of intensity in corresponding detectors to measure range
  - Need to align two cameras well
- Very cheap and capable visible cameras
- NIR cameras cheaper than high bandwidth cameras
- High grey scale
- Provides range average in a mixed pixel

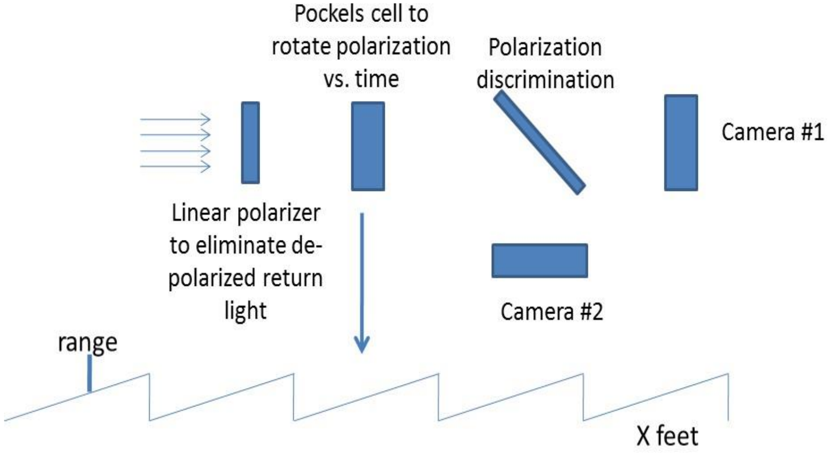

Figure 10 : Diagram of the LIMARS polarization based 3D Flash Ladar concept.

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Summary

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- Multiple GMAPD arrays can be used for flash coherent temporal heterodyne imaging
  - Framing 32 x 32, 32 x 128 GMAPDs are available NOW, and soon an asynchronous 32 x 32.
  - Low dynamic range coherent imaging
  - TE cooled
  - I'd like an asynchronous 128 x 128, or even larger
  - **If I was building a flash coherent imager now, and did not have significant backscatter, background, or variable target reflectivity issues this would be a good choice**
- InGaAs LMAPDs
  - **I think I'll really like these when available**
  - Will not have the dynamic range or background/backscatter issues of GMAPDs
  - I hope someone pays to make a high rep rate camera with some sample depth (at least 36 samples. I prefer 50 samples)
  - They should be relatively inexpensive
  - Can be TE cooled
  - Moderate to good sensitivity, so moderate power LOs
- HgCdTe LMAPDs
  - Sensitive, so can use low power LOs
  - Need to be cooled
  - **Can't comment on what is available right now, but inherently like sensitivity and dynamic range. Many similar limitations to other LMAPDs, but more sensitive**
- Spatial heterodyne FPAs
  - Flash imaging cameras available NOW.
  - Same cameras as for NIR passive imaging, or could use 2D imaging cameras
  - Specifically designed APD from Voxtel for AFRL