Geiger-Mode Avalanche Photodiodes for Imaging and Lidar

To:

Quantum-Limited Imaging Detectors Symposium

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Advanced Imaging Technology
Outline

• Motivation
  – Why pursue 3D imaging technology?
  – Why use Geiger-mode avalanche photodiodes (APDs)?
• Hybridized 32x32 focal planes
• Ladar systems and images
• Conclusions
Shortcomings of Conventional Imaging

• When the 3D world is projected into a flat intensity image, there is a huge information loss.

• Image processing algorithms attempt to use intensity edges to infer properties of 3D objects.

• Consequences of lost information for automated image segmentation and target detection/recognition:
  – Depth ambiguity
  – Sensitivity to lighting, reflectivity patterns, and point of observation
  – Obscuration and camouflage
Ladar Imaging System

- Imaging system photon starved
  - Each detector must precisely time a weak optical pulse
  - Sub-ns timing, single photons

Color-coded range image
Geiger-Mode Imager: Photon-to-Digital Conversion

Quantum-limited sensitivity
Noiseless readout
Photon counting or timing

Pixel circuit

Digital timing circuit

Digitally encoded photon flight time

APD

Lenslet array

APD/CMOS array

Focal-plane concept
Gain of an APD

- Ordinary photodiode
- Linear-mode APD
- Geiger-mode APD

Response to a photon:

$I(t)$

Breakdown
Geiger-Mode Operation

![Geiger-Mode Circuit Diagram]

- APD
  - $V_B = 26\, \text{V}$
- Voltages:
  - $+5\, \text{V}$
  - $-25\, \text{V}$
  - $+1\, \text{V}$

Graphs:
- ARM
- OUT
- Time

Breakdown
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APD Structure and Characteristics

- Detection probability as high as >60%
- Dark-count rate as low as hundreds of counts/s
- Timing jitter < 150 ps
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Pixel Timing Circuit

13-bit timing value

11-bit counter

\(\phi_1\)

Transparent latch

\(\phi_1\)

\(\phi_2\)

Transparent latch

\(\phi_2\)

“Freeze” signal from APD

Clock

90-degree delay

Photon detection
32x32 Timing Circuit Array

0.35-µm CMOS process fabricated through MOSIS
1.2 GHz on-chip clock
Two vernier bits
0.2-ns timing quantization
100-µm spacing to match the 32x32 APD array

Timing image/histogram measuring propagation of electronic trigger signal
Bump Bonding vs. Bridge Bonding

Detector array

CMOS readout circuit

Epoxy backfill
Bridge-Bonded APD/CMOS

- APD active area
- CMOS contact pad
- CMOS circuit
- APD p contact
- APD n contact
32x32 APD/CMOS Array with Integrated GaP Microlenses
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Laser Radar Brassboard System (Gen I)

- 4 × 4 APD array
- External rack-mounted timing circuits
- Doubled Nd:YAG passively Q-switched microchip laser
  (produces 30 µJ, 250 ps pulses at $\lambda = 532$ nm)
- Transmit/receive field of view scanned to generate $128 \times 128$ images

Taken at noontime on a sunny day
Conventional vs Ladar Image

Conventional image

3D image
Lincoln 3D Imaging Laser Radar Evolution

<table>
<thead>
<tr>
<th>Gen I</th>
<th>Gen II</th>
<th>Gen III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-based</td>
<td>Airborne</td>
<td>Compact</td>
</tr>
<tr>
<td>4 x 4 detectors</td>
<td>32 x 32 detectors w/ microlens array</td>
<td>Compact</td>
</tr>
<tr>
<td>0.532 µm</td>
<td>0.780 µm</td>
<td>0.532 µm</td>
</tr>
<tr>
<td>Mass: 50 kg</td>
<td>Mass: 23 kg</td>
<td>Diffractive beam forming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass: 9 kg</td>
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Airborne Laser Imager Research Testbed  Space Laser Radar Design Initiative
Foliage Penetration Experiment

View from 100 m tower

Laser radar on tower elevator

Objects under trees
Conclusions

- Ladar imaging facilitates robust object recognition, image segmentation, camouflage penetration, and multisensor fusion.

- Geiger-mode APD/CMOS arrays an enabling technology for compact high-performance systems:
  - Quantum-limited sensitivity
  - Pixel-level digitization and noiseless readout

- 32x32 APD/CMOS focal planes developed and demonstrated in ladar systems.