Fabrication and characterization of free-standing infrared pixels for high speed IR detector applications

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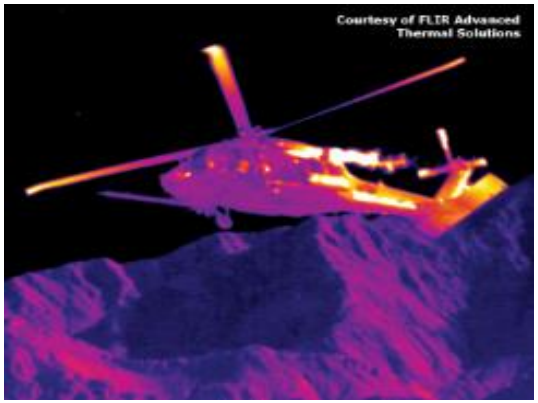
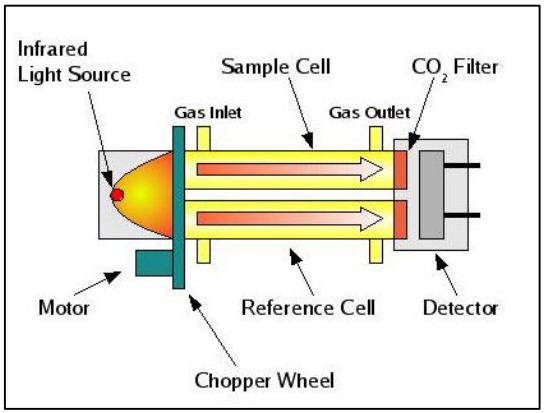
Infrared detectors have many applications

Security and surveillance



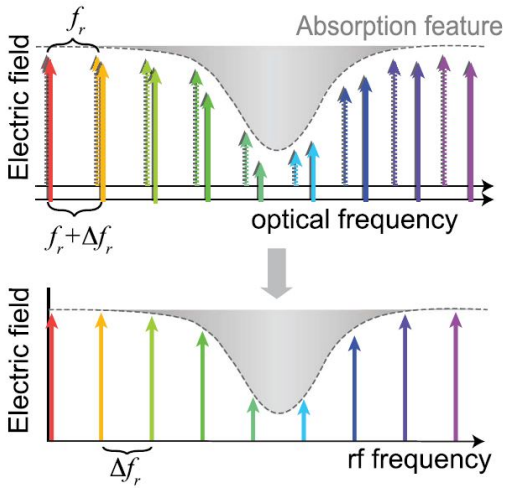
Optics & Photonics News (April 2011).

Gas analyzers



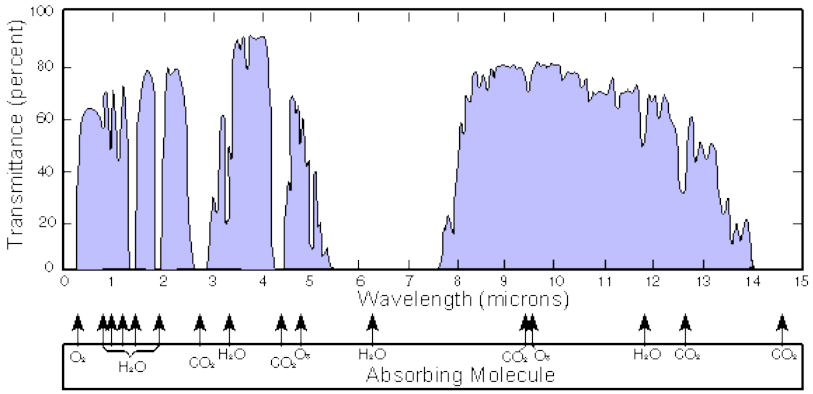
esrl.noaa.gov

Dual Comb Spectroscopy



I. Coddington, *et. al.*, "Dual-comb spectroscopy." *Optica* 3, no. 4, 2016.

Communications

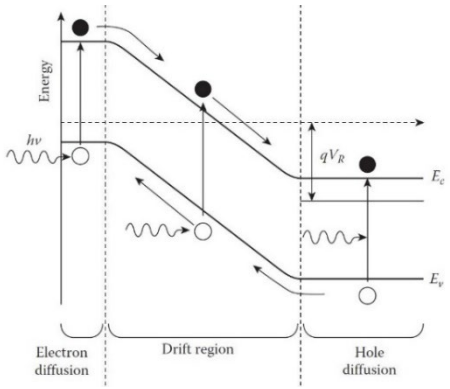


wikipedia.org/wiki/Infrared_window

Existing IR photodetectors are fundamentally limited

PIN Junction Photodiode

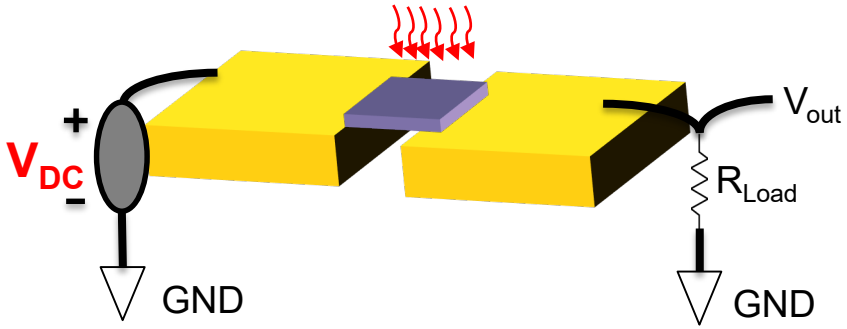
Reverse biased PIN junction band diagram



A. Rogalski, *Infrared Detectors*, CRC Press, Taylor & Francis, 2011, 215

- Excited electron-hole pairs swept out of junction as photocurrent.

Photoconductive Cell



S. Dev, Infrared Detection and Material Char. using Microwave Resonators, 9, 2019

- Conductivity modulated by light, which is read out across a load.

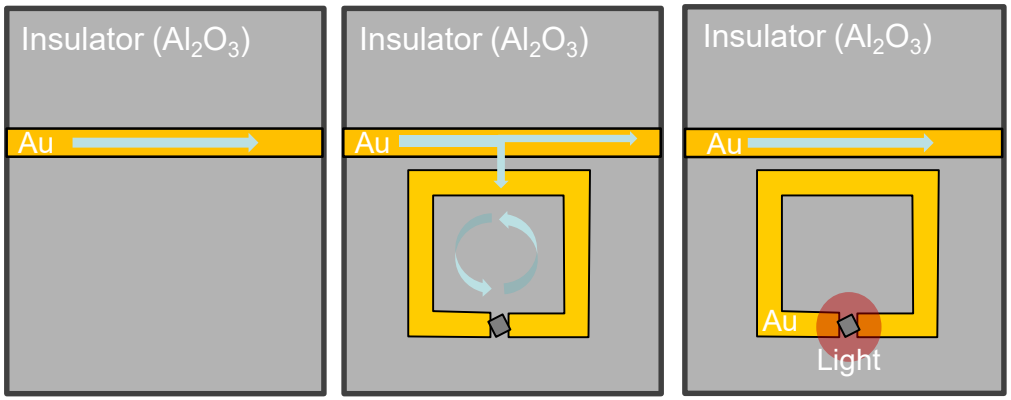
Drawbacks:

- Junction capacitance limits speed (PIN junction).
- Invasive ohmic contacts (PCD)
- Collection of DC current.

We seek to explore novel detector architectures.

Optically modulating pixel-loaded split ring resonators

Detector architecture



Microstrip

SRR loaded with IR pixel coupled to microstrip

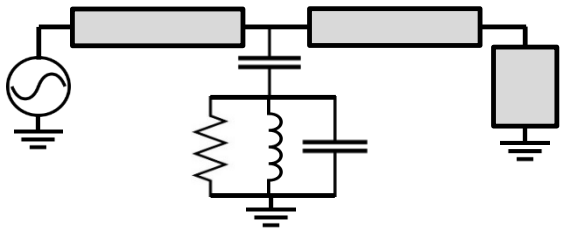
Pixel-loaded SRR responds to light, modulating RF transmission

- Fields capacitively couple from microstrip to SRR.
- Circuit resonance results in frequency dependent transmission.
- Pixel photoconductivity changes microstrip transmission.

$$\sigma(t) = q[n(t)\mu_n + p(t)\mu_p]$$

Is this configuration suitable for high speed detectors?

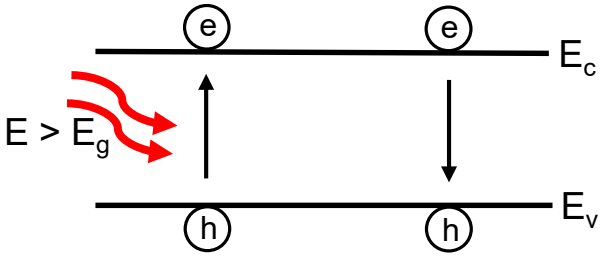
Circuit Limitations:



Generic transmission line model

Circuit returns to equilibrium after $\tau_{rc} \sim Q/\omega_0 < 1$ ns.

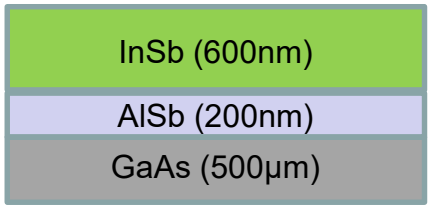
Material Limitations:



Excited electron-hole pairs recombine after time τ_{mc}.

InSb IR pixel fabrication

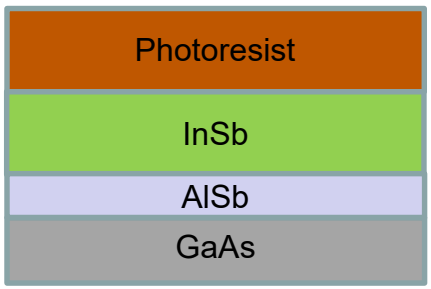
Starting sample



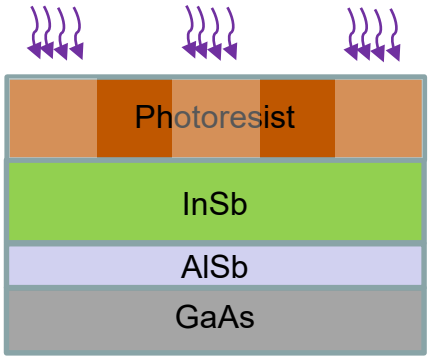
Starting sample (MBE by Bank group) contains lattice mismatch between InSb/AlSb and GaAs to introduce defects and decrease carrier lifetime.

Pixel Fabrication Process

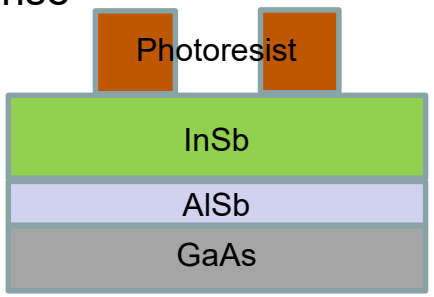
1. Spinning photoresist



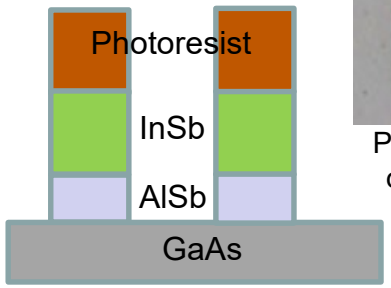
2. Mask alignment and photolithography

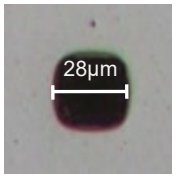


3. Developer bath and H_2O rinse



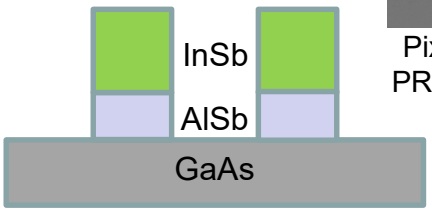
4. ICP Dry etch

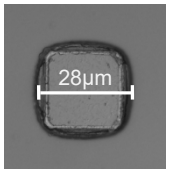




Pixel after dry etch

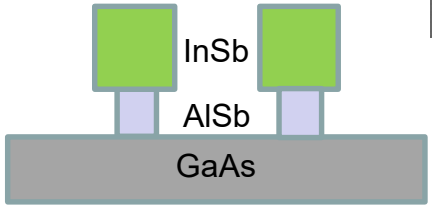
5. Acetone and RIE O_2 clean

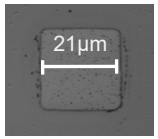




Pixel after PR removal

6. HF undercut etch

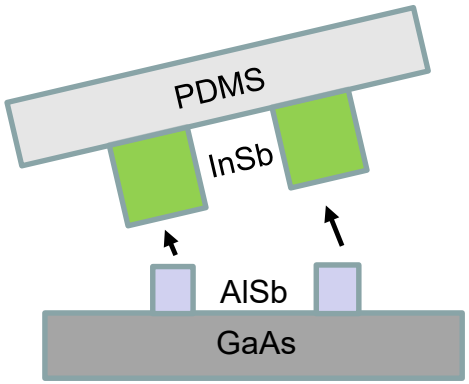


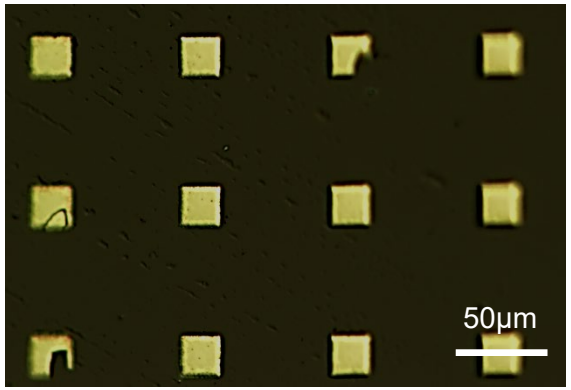


Pixel after wet etch

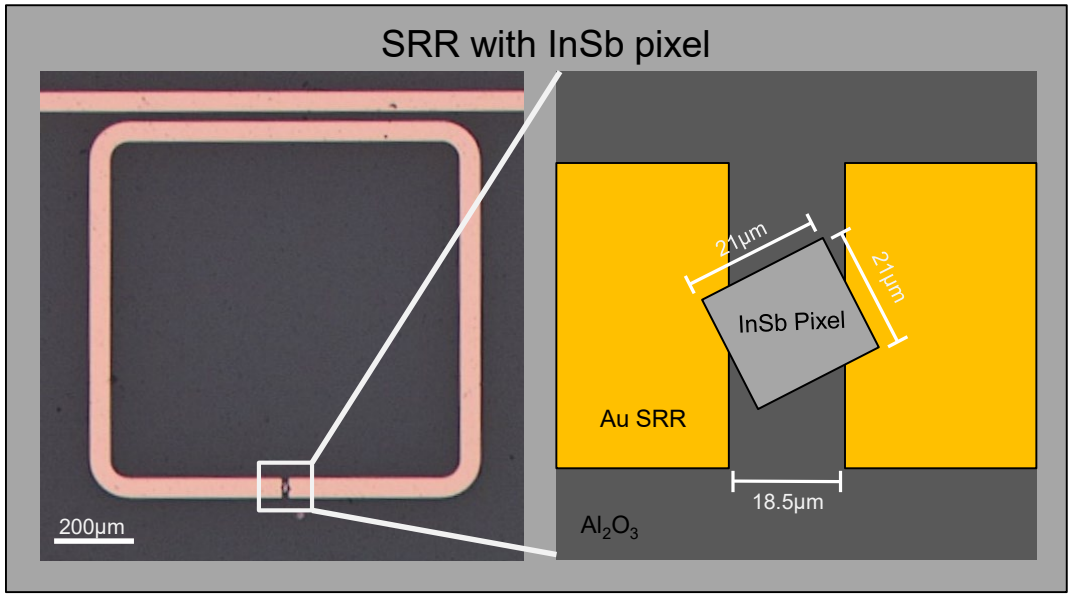
InSb IR pixel and SRR circuit fabrication

7. PDMS pixel peel off





InSb pixel array on PDMS stamp after peel off

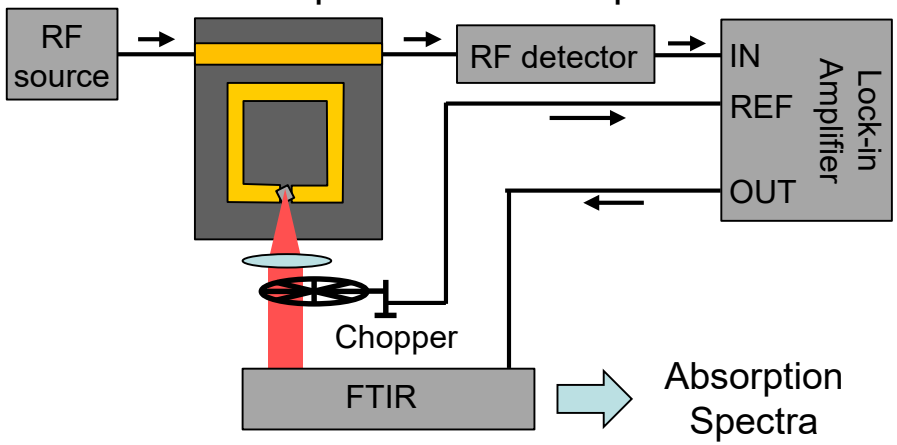


- 1mm x 1mm SRRs fabricated on Al_2O_3 via UV photolithography, metallization, and liftoff.
- SRRs contain 10nm Ti adhesion layer, 280nm Au layer.
- 50μm wide SRR and microstrip lines.
- 30μm coupling gap between SRR and microstrip.
- Pixel transfer by Yimeng Wang (Tutuc Group).

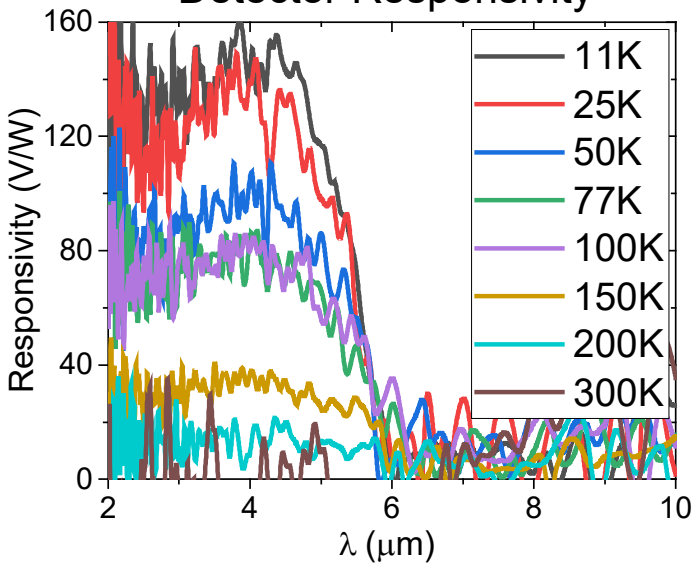
Detector circuit characterization

Spectral Responsivity

Experimental Setup



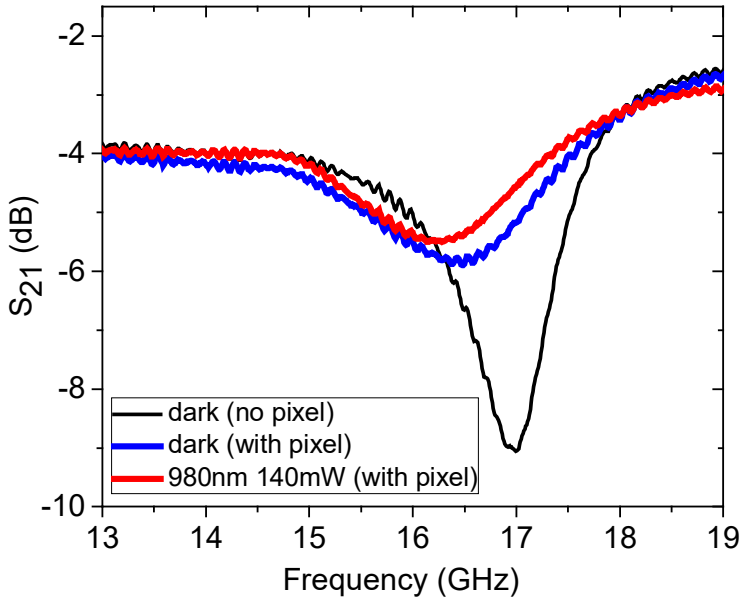
Detector Responsivity



Normalization with spectrally flat thermal detector.

Absorption cutoff corresponds to InSb bandgap at ~0.21eV.

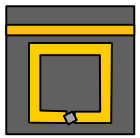
RF Frequency Response



- Light induces photoconductivity in InSb.
- S_{21} dip weakens and red shifts under illumination.

InSb pixel lifetime characterization using μ-TRMRR

SRR loaded with InSb pixel

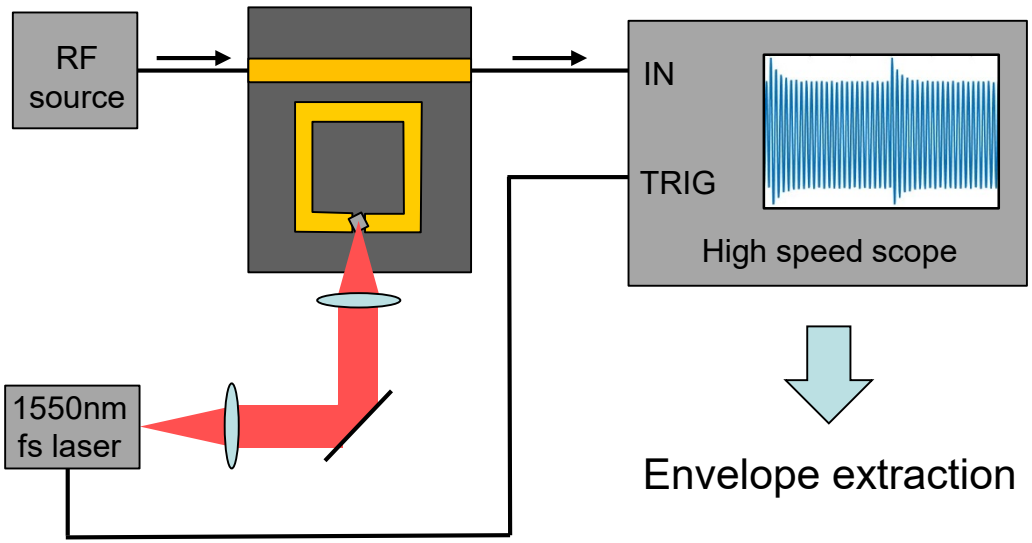


μ-TRMRR
(**M**icron scale-**T**ime **R**esolved **M**icrowave **R**esonator **R**esponse)

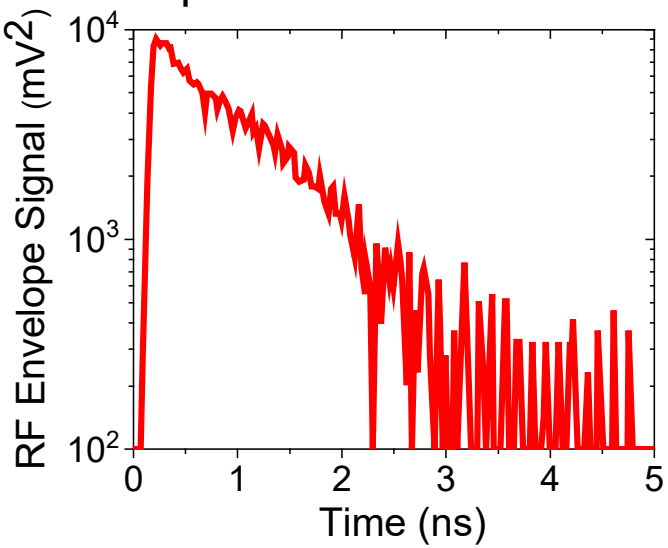
- Carrier lifetime measurement technique with direct electrical readout of carrier dynamics.

S. Dev, Y. Wang, et al., *Nature Comm.*, 10, 1625, 2019

Experimental Setup



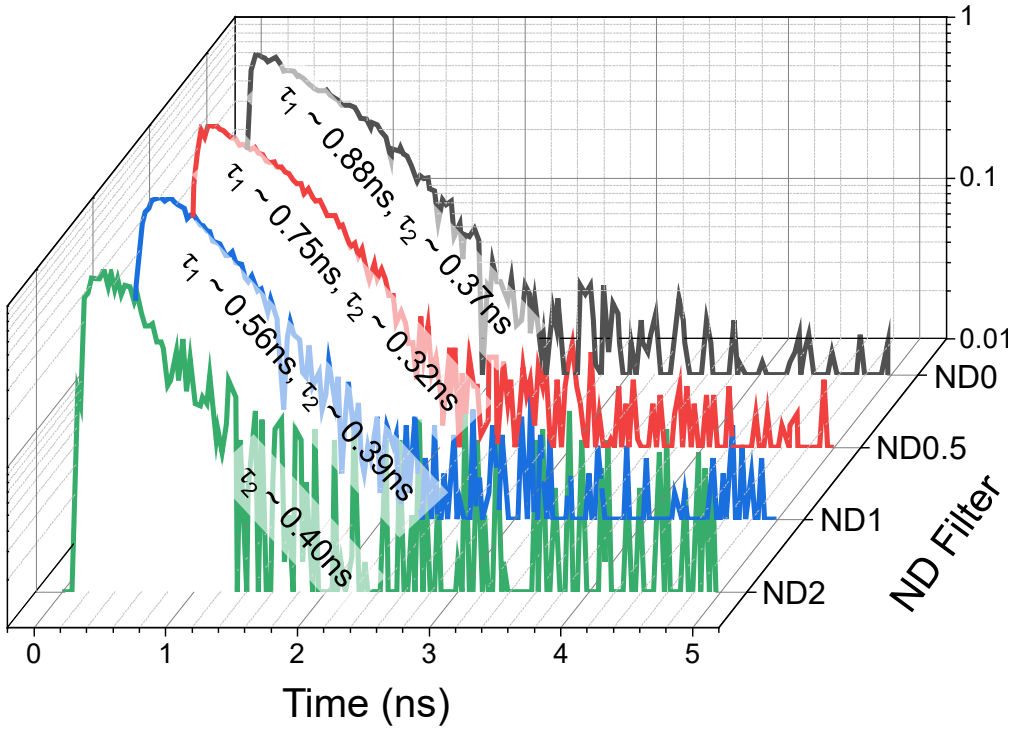
μ-TRMRR Readout



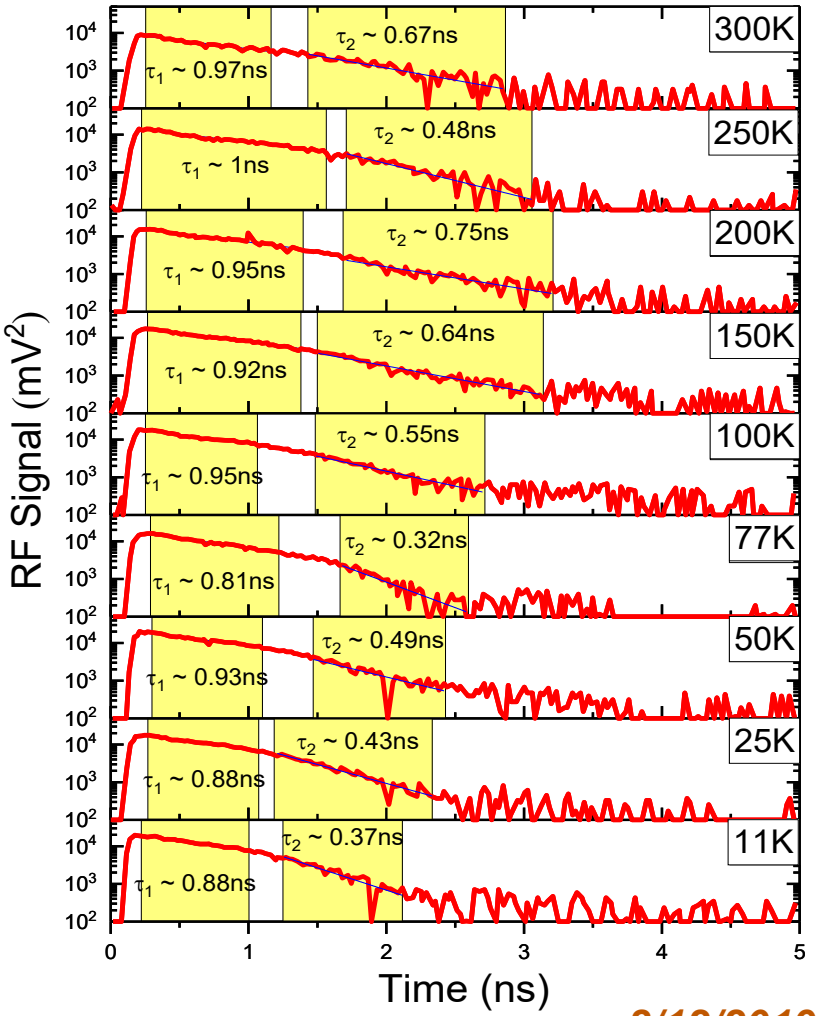
Room temperature measurements reveal **sub-nanosecond recombination lifetimes.**

Carrier lifetime power and temperature dependence

Power Dependence (11K)



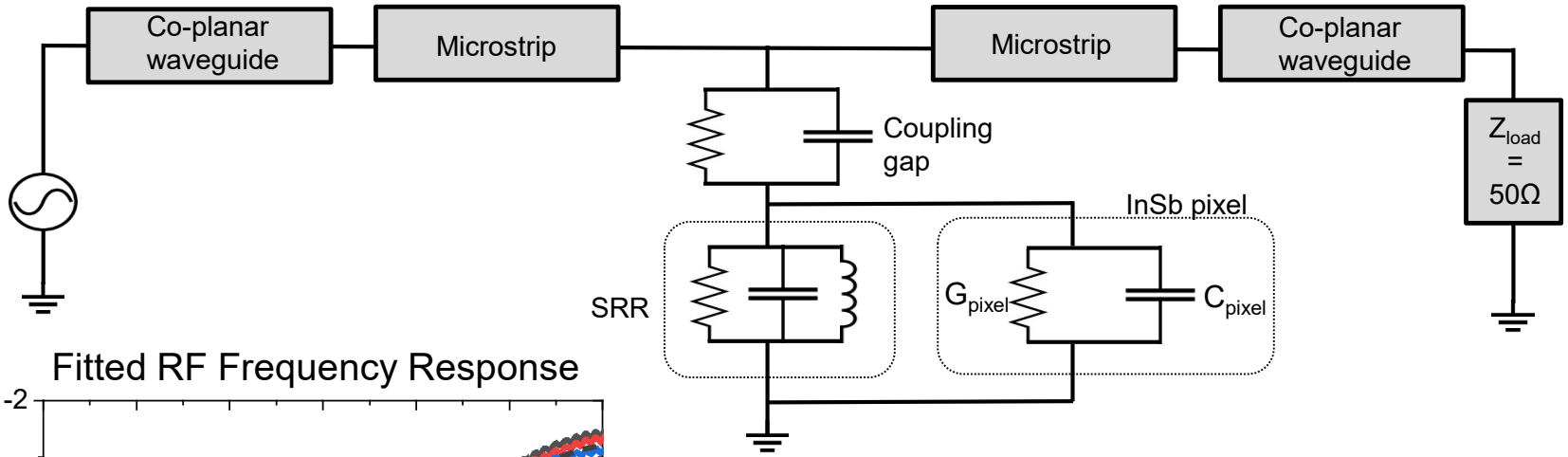
Temperature Dependence

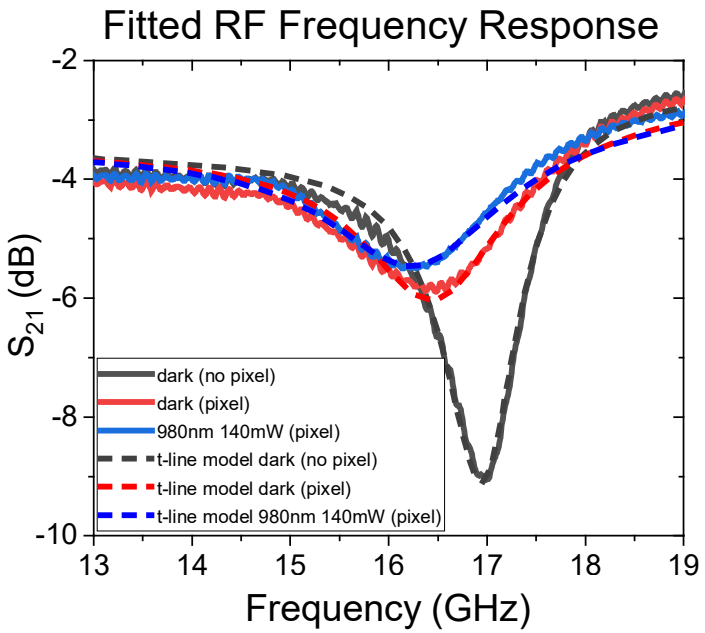


- μ-TRMRR fit with exponential in two regions yield two different lifetimes.
- Lifetime decreases with fall in temperature
- τ_1 decreases with fall in incident power, τ_2 is relatively consistent

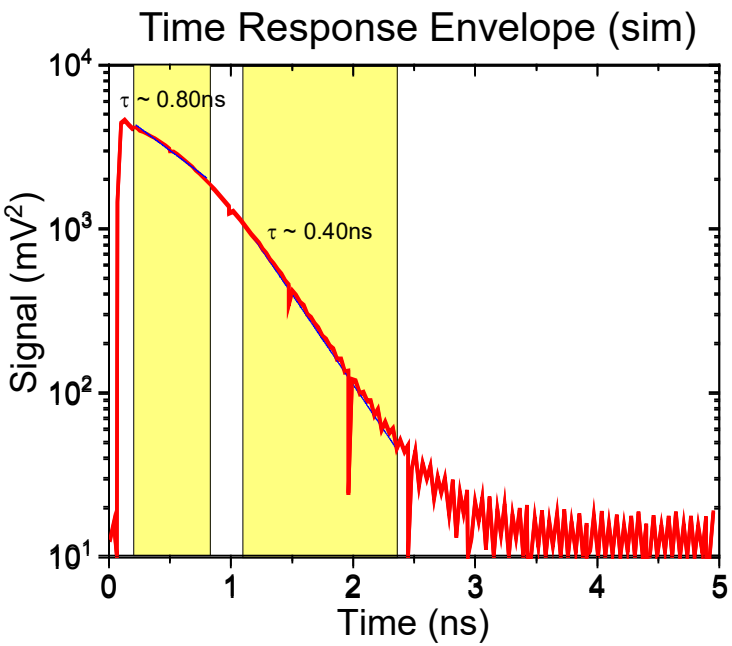
Transmission Line Model

Detector can be modeled with transmission line simulations:





RF transmission fit using model, adjusting pixel conductance and capacitance.



Preliminary time domain simulations show agreement with measurements.

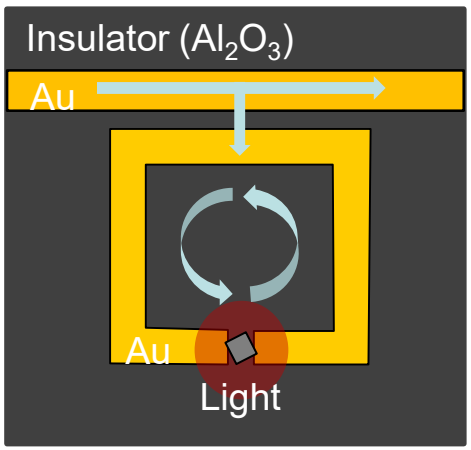
Pixel-loaded SRR is promising for high speed detection

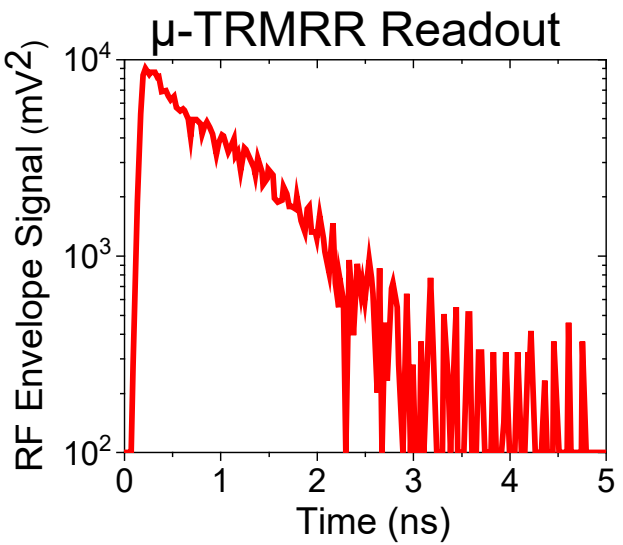
Conclusion

- InSb pixels exhibit **sub-nanosecond carrier lifetimes.**
- SRR loaded with InSb pixel allows **optical modulation of RF signal for detection**.
- This detector architecture **potentially surpasses speed limits of conventional photodetectors**.

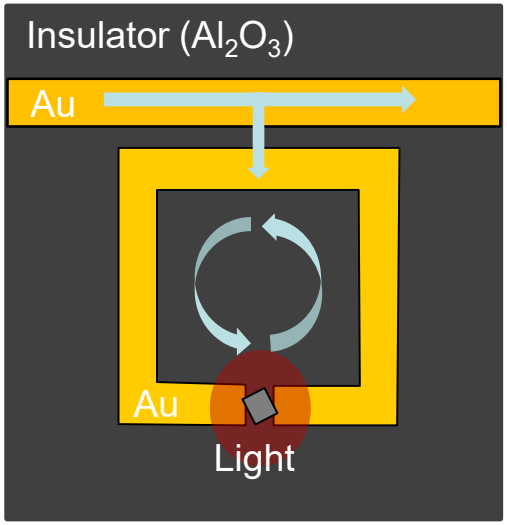
Future Work

- Investigate carrier dynamics to explain two decay regimes and integrate with transmission line model.
- Measure detector bandwidth.
- Explore applications requiring high speed IR detection, such as time-resolved photoluminescence and dual comb spectroscopy.

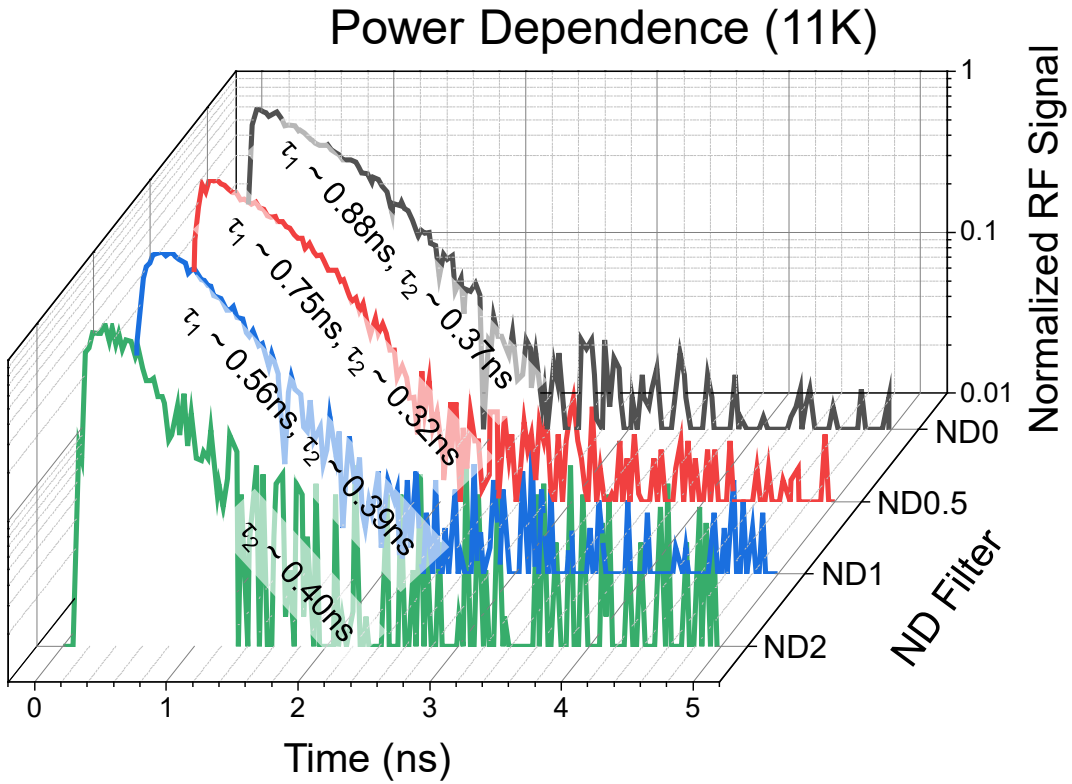


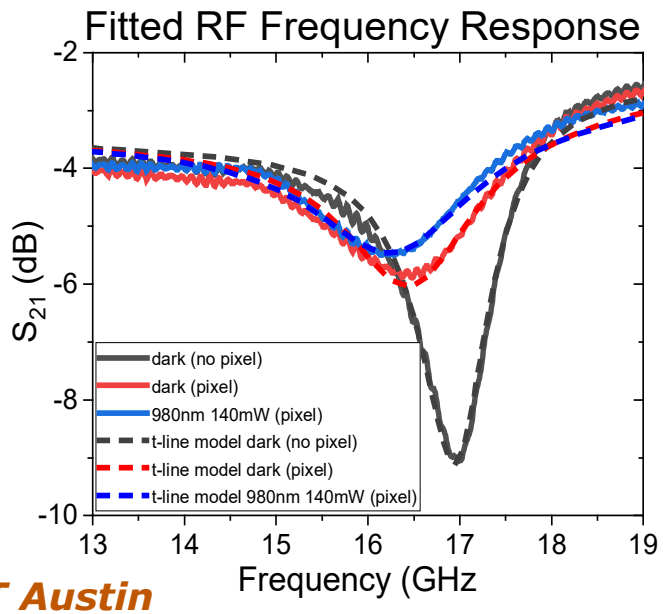


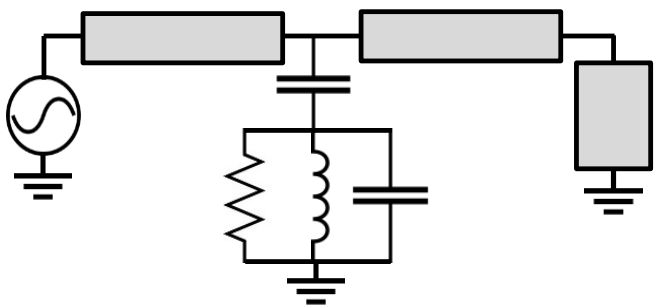
Questions



Pixel-loaded SRR responds to light, modulating RF transmission







Generic transmission line model