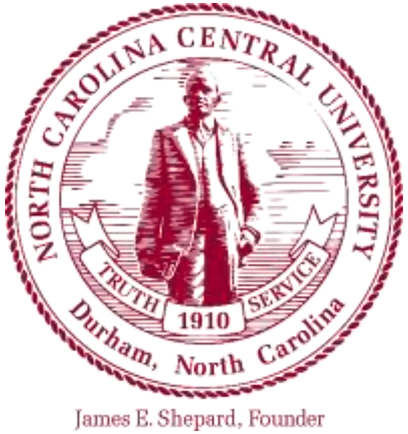
BWO and IMPATT Millimeter Wave Probing of c-Si, and Perovskite



Biswadev (Dev) Roy, A. Tsui, and B. Vlahovic

North Carolina Central University, Durham, N.C. 27707

IEEE Southeastcon, April 19-22, St. Petersburg, FL

Topics

- Millimeter wave sources
- TRmmWC experimental set up
- Brief theory slide
- Peak Voltage differences between BWO & IMPATT at various laser fluence
- BWO & CIDO transients comparison
- Summary

Various mmw & FIR Sources

SUMMARY OF ELECTROVACUUM & SS SOURCES

Source	Power range (W)	Freq. range (GHz)	λ(min-max) (mm)
BWO	**10^{-3} – $2x10^{4}$**	**30 – 1670**	**0.24 - 10**
EIO pulse	7.5 – $2x10^{3}$	100 - 246.6	1.52 - 3
TWT cw solenoid	800 – $1.25x10^{3}$	72 – 86	4.38 – 5.76
TWT cw PPM	20 – 10^{3}	40 – 70	5.76 – 9.08
Gyrotron cw	$2x10^{3}$ – $3x10^{4}$	167 – 440	0.816 – 2.48
BWO pulse	10^{5}	90.6	3.92
Magnetron pulse	$5x10^{4}$	95.33	2.54
Klystron cw	$3x10^{3}$	44	8.62
SS IMPATT	**$3x10^{-4}$ - 2.0**	**30 – 487**	**0.816 – 9.54**
TEO laser	4x10 – 0.5	30 – 126.67	2.74 – 10.0
FIR laser	0.1 – 0.5	906 – 3000	0.1 – 0.261

EIO: *extended-interaction oscillator*, PPM: *permanent periodic magnet*, TEO: *tellurium oxide*

Probing sources used: BWO and CIDO-6

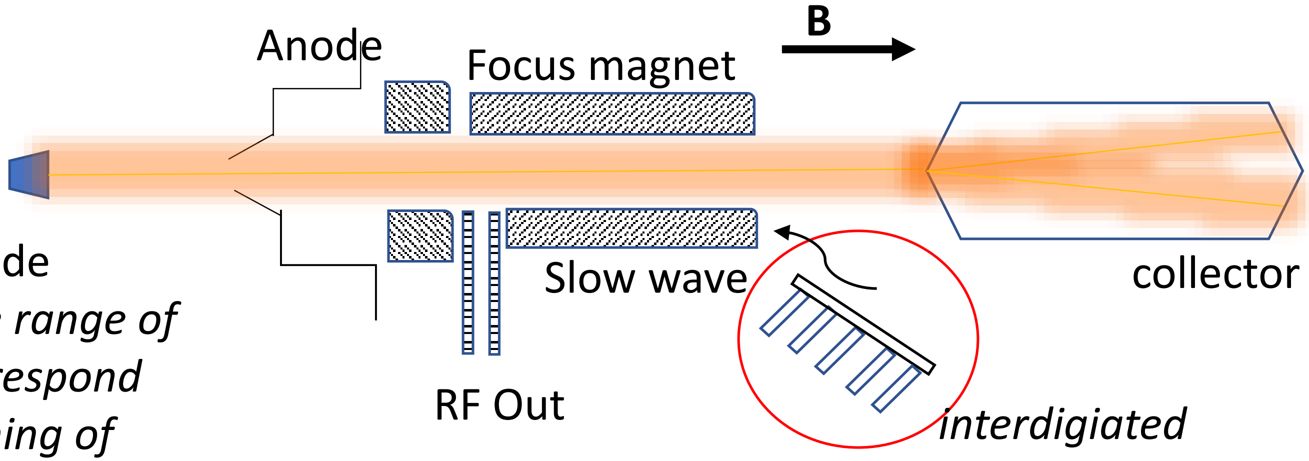
Voltage-Tunable, 110-170 GHz, resolution: 0.05GHz

- The Backward wave oscillator (BWO) operates using a vacuum tube and electron gun to generate microwaves up to the terahertz range. The system <u>generates oscillations by moving a wave against the electric field of the electron gun beam, exciting the electrons sufficiently for them to release millimeter waves.</u>
- Reason for using is able to tune to multiple frequencies, and also the beam is highly “coherent”.

Fixed at 140 GHz

- The Solid State Oscillator (CIDO) uses cavity stabilized IMPATT diode to produces waves. <u>This technique uses free electrons to impart enough energy to an atom in the cavity to cause it to lose an electron which causes a chain reaction to occur.</u> However, these only operate at a given frequency.
- Reason for using is its high power capability allowing signal to noise ratio to be reduced.

BWO: coherent mmw source

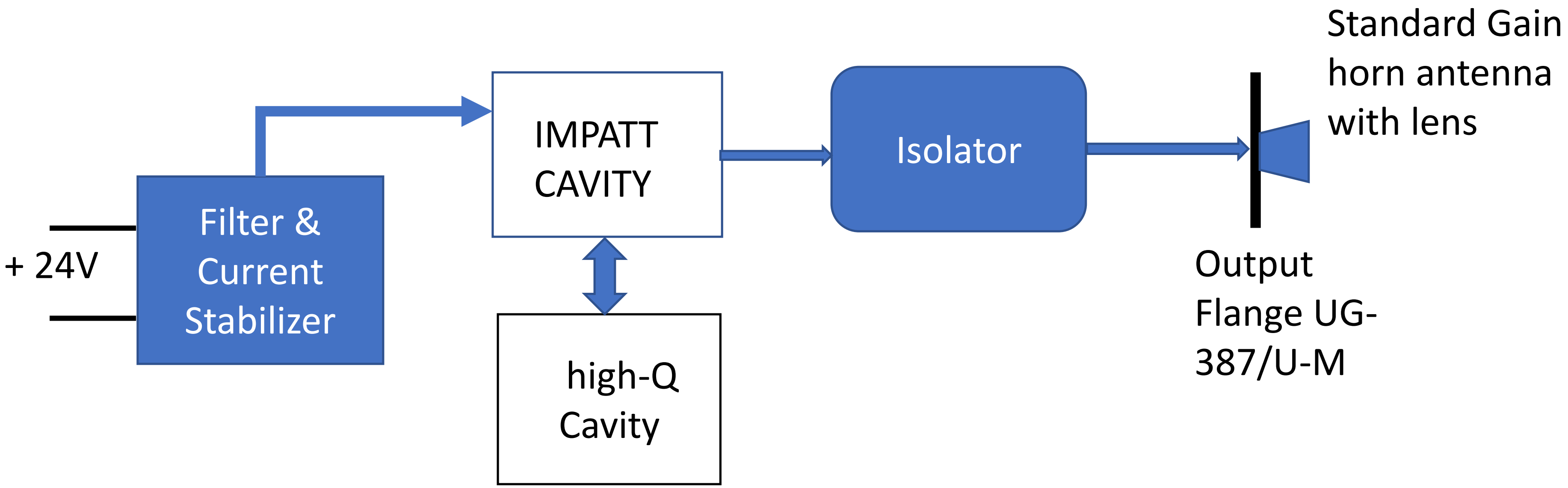


- e-beam moving through slow-wave structure
- Strong interaction when $V_{pe} \approx V_{pw}$
- Longitudinal E of slow wave introduce velocity spread of e-beam
- Part of e-beam KE is exchanges with slow wave EM energy

- Slow-wave structure with longitudinal E supports RF E field
- Phase shift varies with frequency
- Floquet's Theorem: E = ∑ harmonics; propagation constant dependent on pitch of the interdigitated slow wave structure

*IM*pact-ionization *A*valanche *T*ransit *T*ime (IMPATT) diode Oscillator

- Silicon p-n junction diode reverse biased into avalanche breakdown region *and* mounted in a cavity
- We used cavity stabilized IMPATT diode oscillator (CIDO-6)



Theory Outline

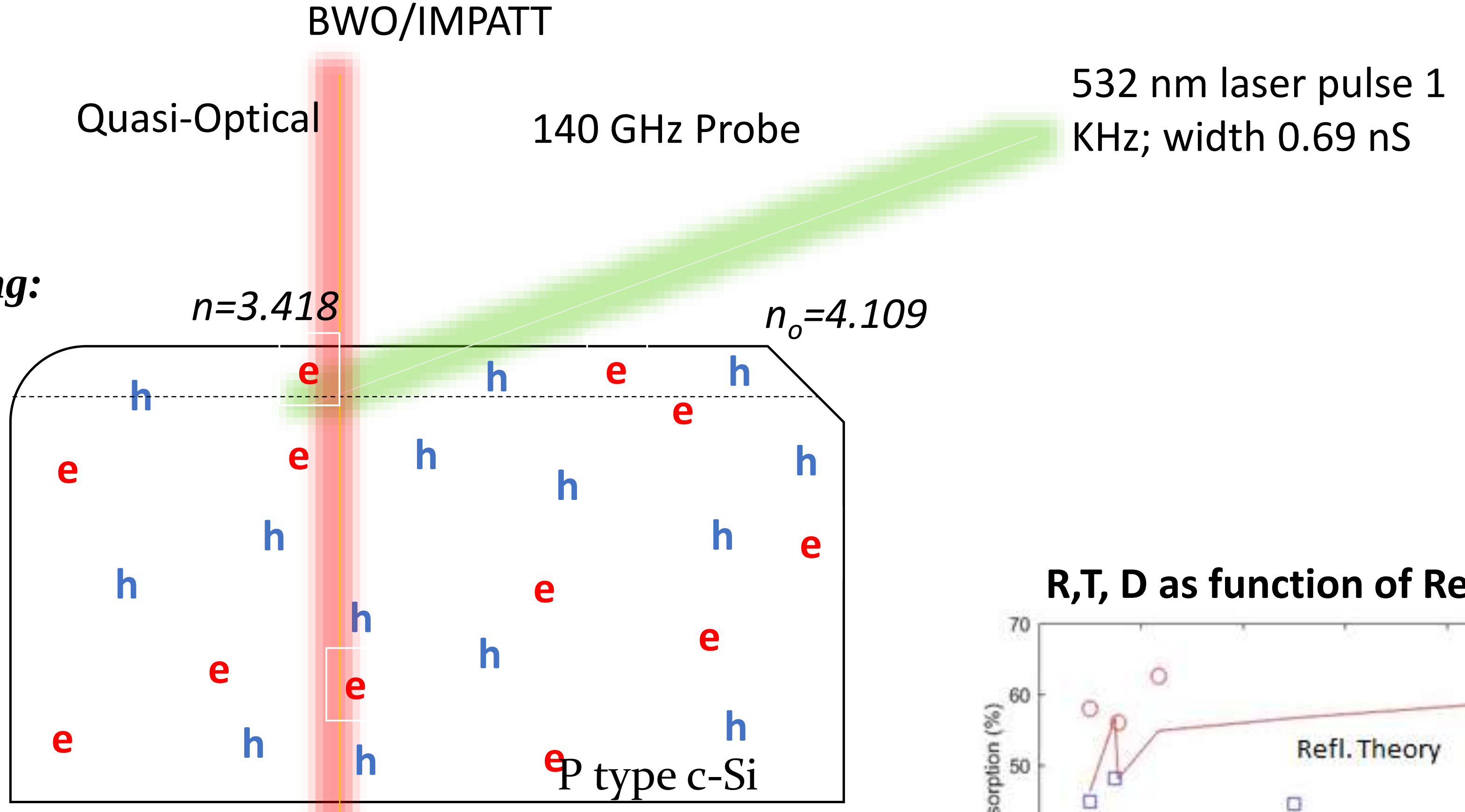
energy/sec./area: avg. ***Poynting:***

$$I_0 = \langle S \rangle = 1/2\, \varepsilon_0 c \,|E_0|^2$$

$$P_0 = I_0 A;$$

$$P_a(\sigma) = \frac{1}{2} \iiint \Delta\sigma |E_s(\sigma)|^2 dV$$

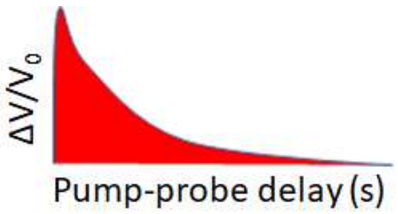
$$\Delta P_A = \sigma |E_s|^2 V = \sigma d |E_s|^2 A$$



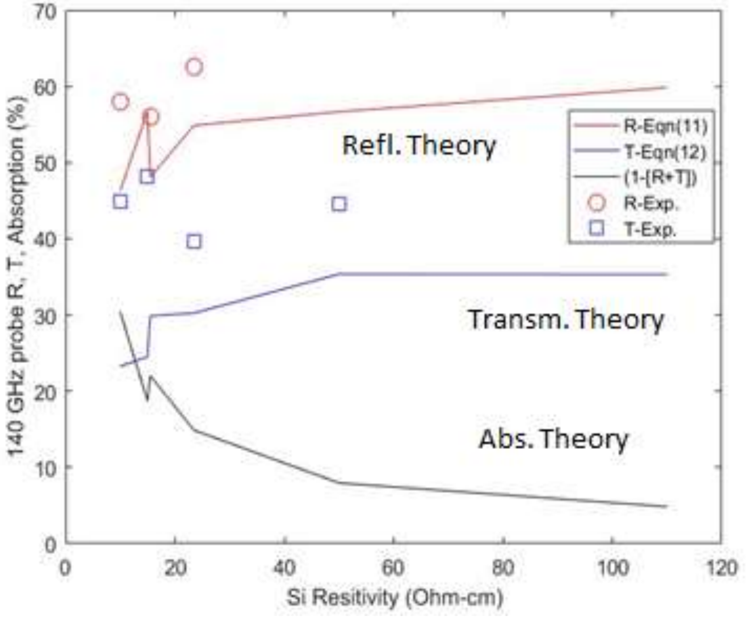
$$E_s \sqrt{n} = E_0$$

$$\frac{\Delta P_A}{P_0} = -K \frac{\sigma d}{n \varepsilon_0 c} = -KG / n\varepsilon_0 c$$

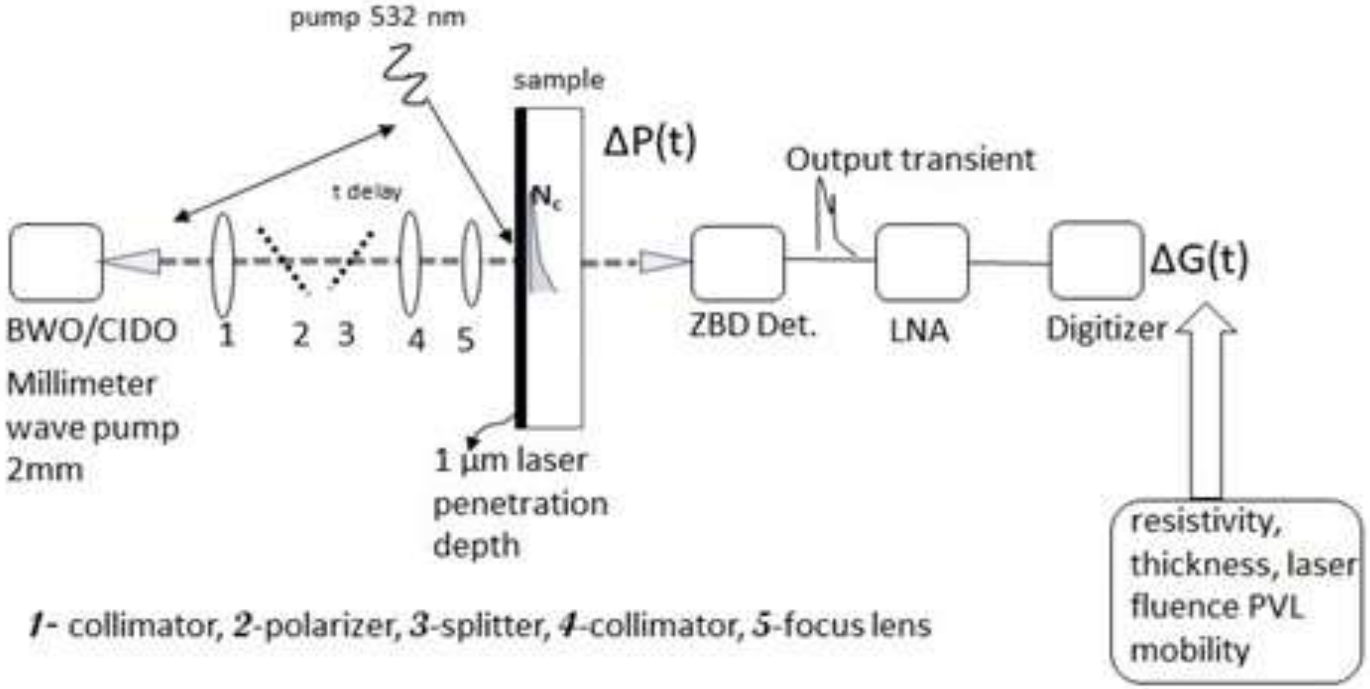
$$\Delta V / V_0 = a \Delta P / P_0$$

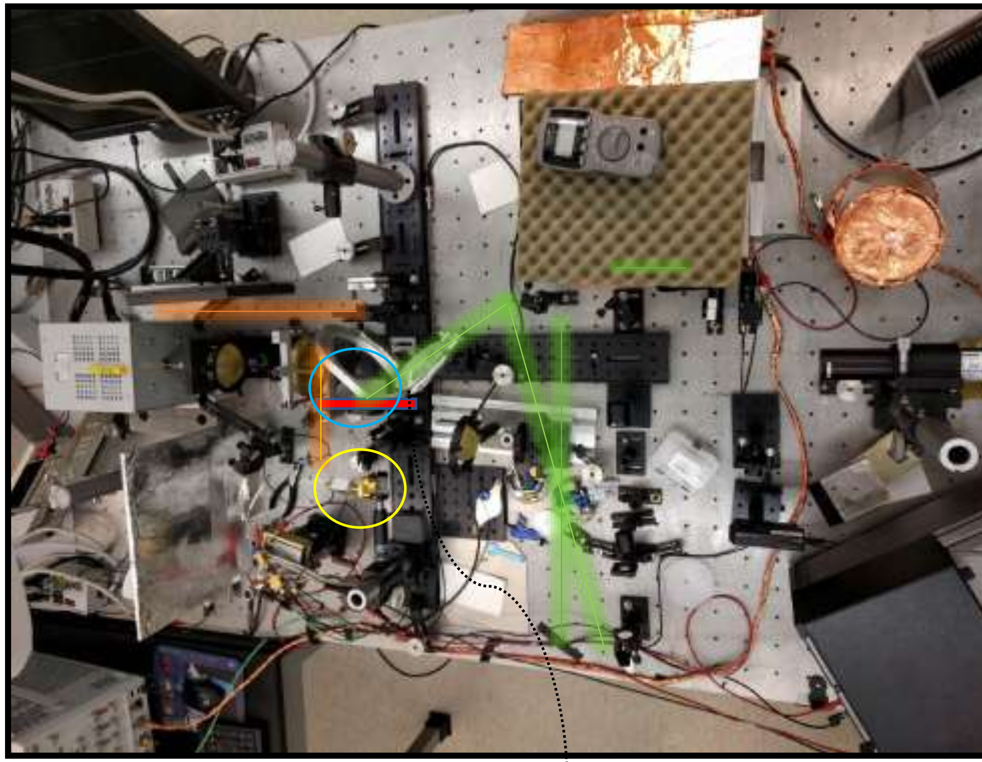


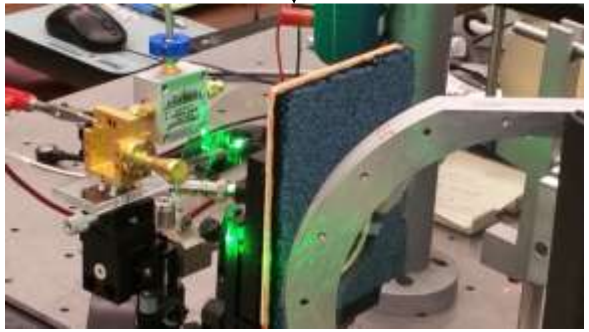
R,T, D as function of Resistivity



Differential absorption and conductivity

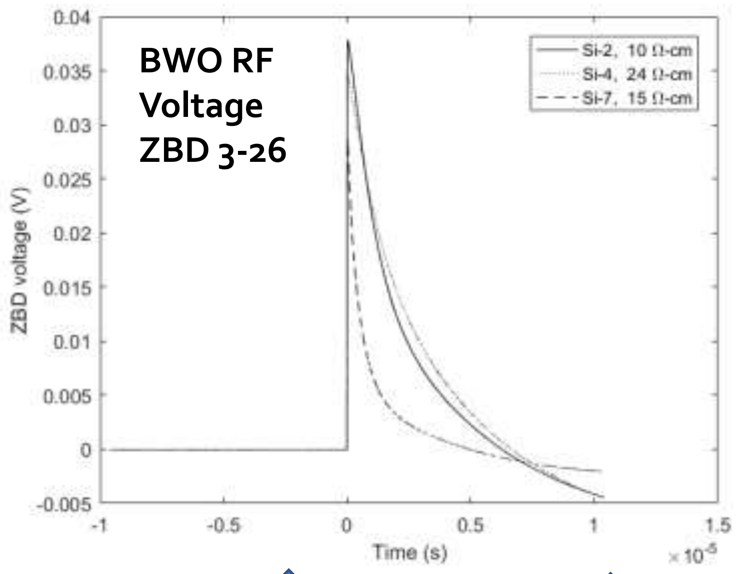


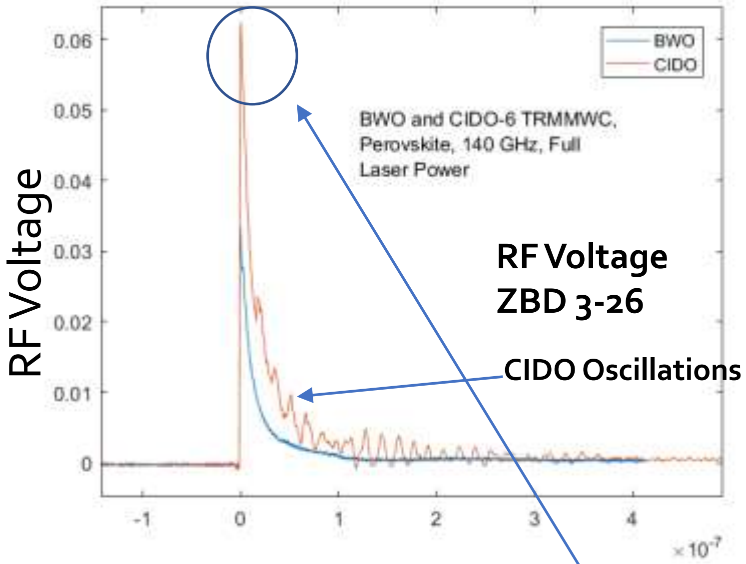




$$\frac{\Delta P_A}{P_0} = -K\frac{\sigma d}{n\varepsilon_0 c} = -KG / n\varepsilon_0 c$$

Typical TRmmWC signal using BWO and CIDO-6 probe sources: Laser ON





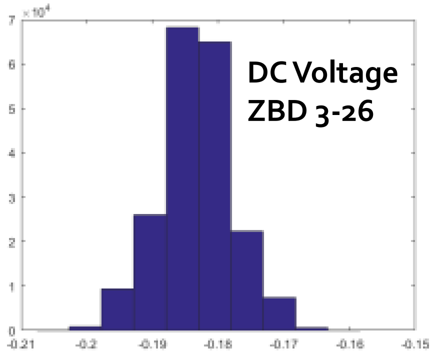
- crest-factor (dB):

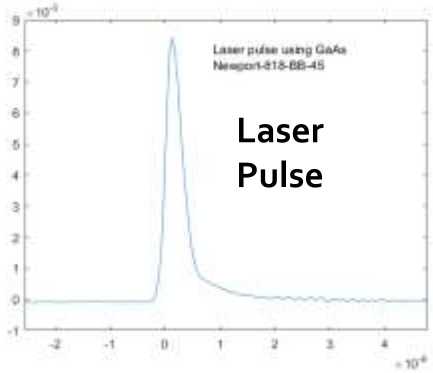
$20Log_{10}\ |V_{RF}\ |_{peak}\ /V_{RF}$ (rms)

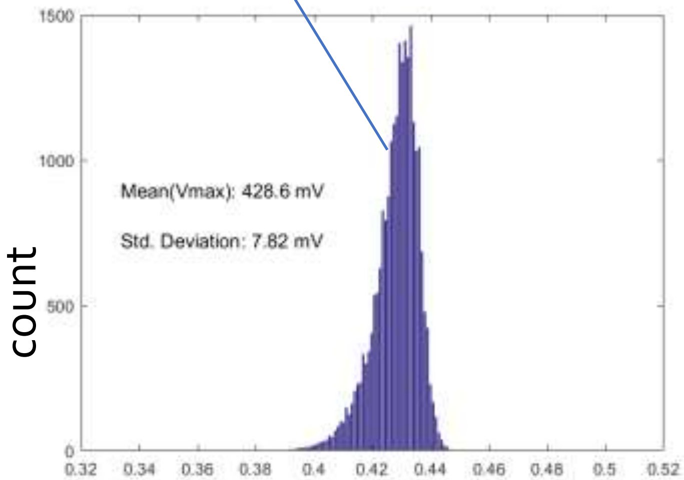
Ratio of Peak value to Effective value

- CF-BWO: 19.17 dB
- CF-CIDO: 20.64 dB

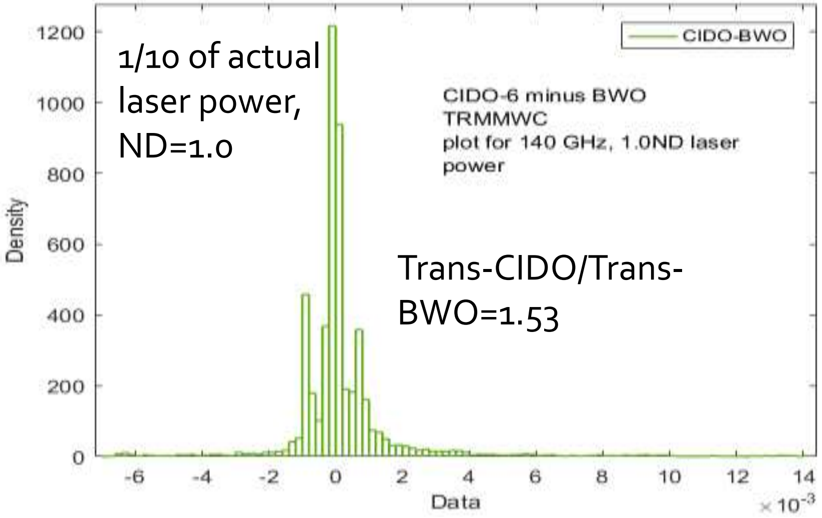
Vmax Stat







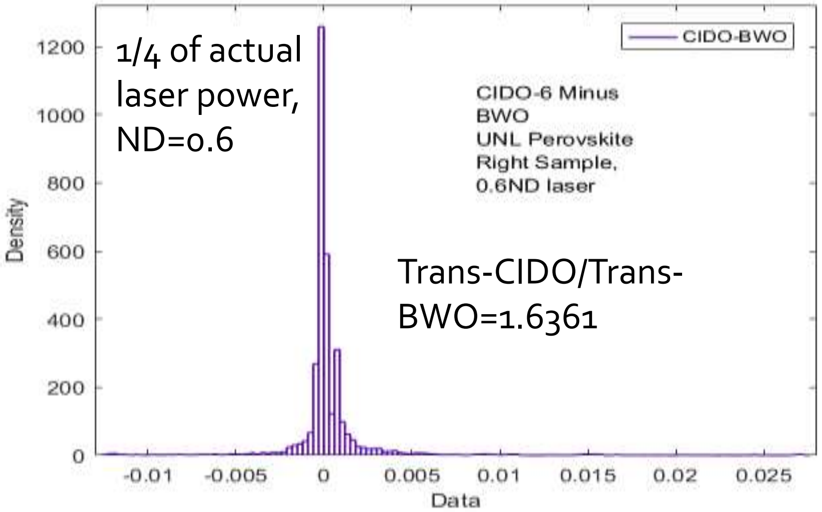
Histogram of Perovskite Sample Response, Laser ON

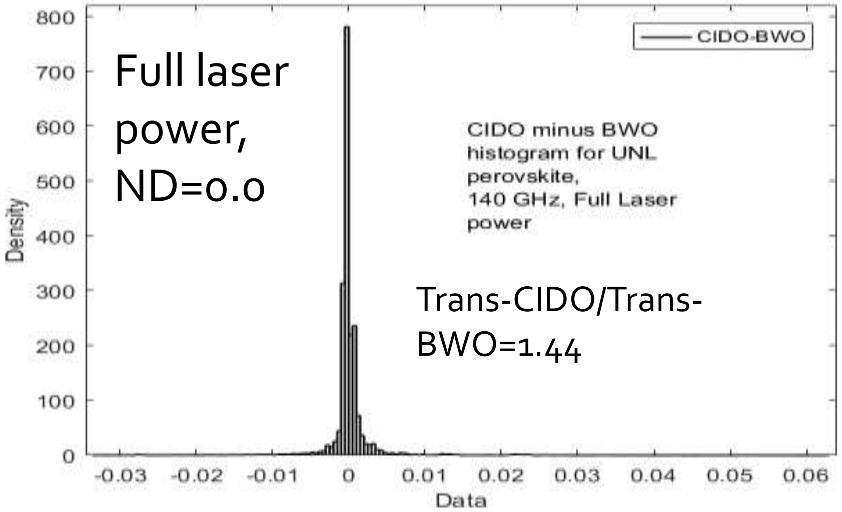


Data: BWO RF Voltage minus CIDO RF voltage for the same sample

Relative likelihood of CIDO-BWO differences

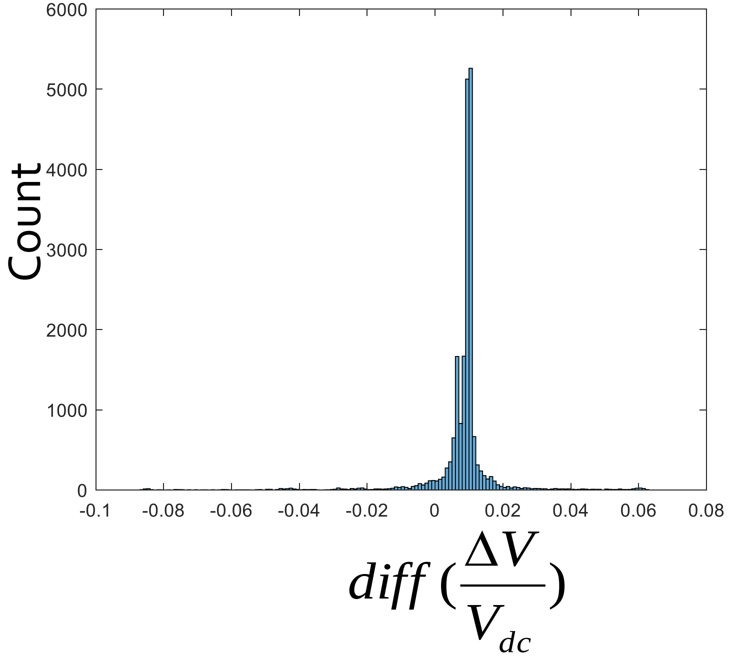
By analyzing the histograms of CIDO minus BWO RF voltages for one of the UNL Perovskite samples, the difference in noise for the two sources can be determined .This is important to select which source yields what type of response for **Neutral Density** Filter (ND) to obtain precise results.



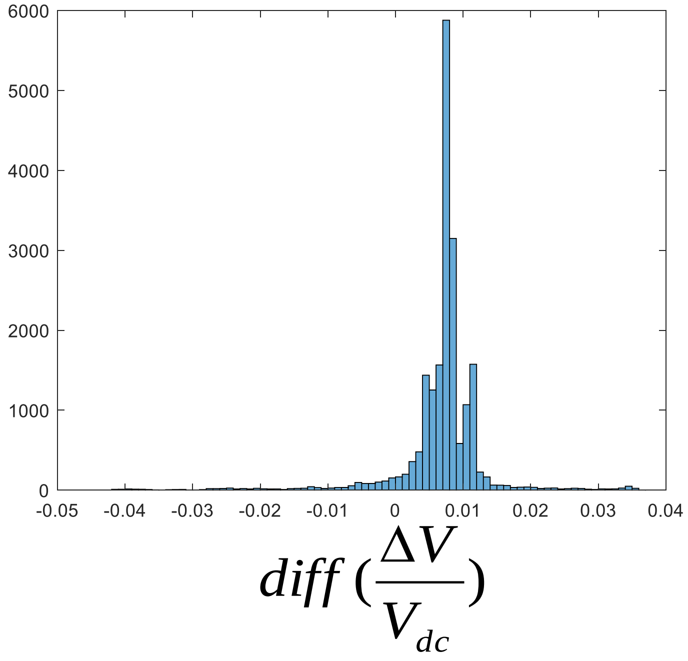


Histogram of Perovskite response with BWO and CIDO, Laser ON

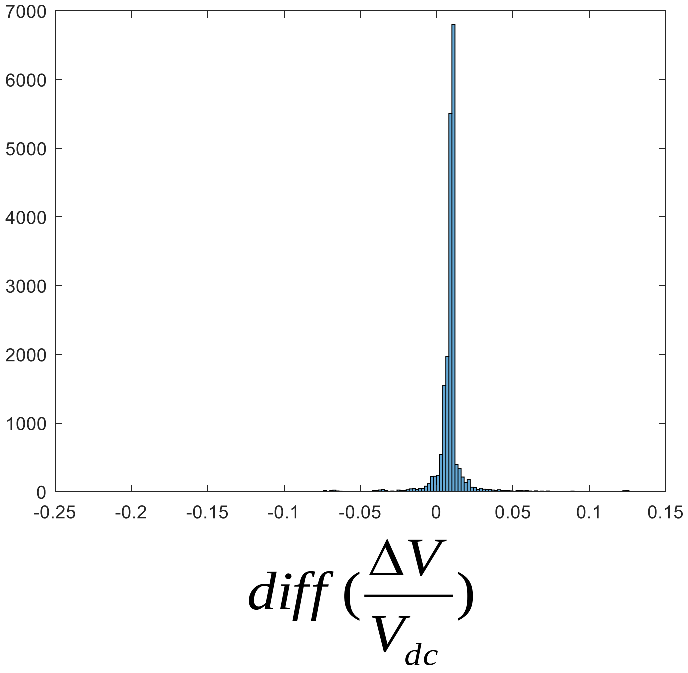
Transmissivity of CIDO-BWO for 0.6 ND



Transmissivity of CIDO-BWO for 1.0 ND

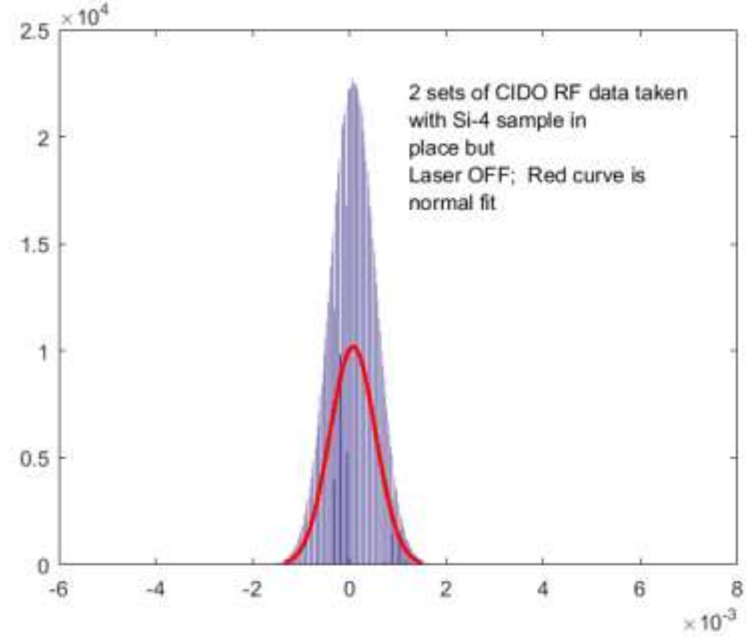


Transmissivity of CIDO-BWO for Full Laser Power



Noise in CIDO data using crystalline Si, Laser OFF

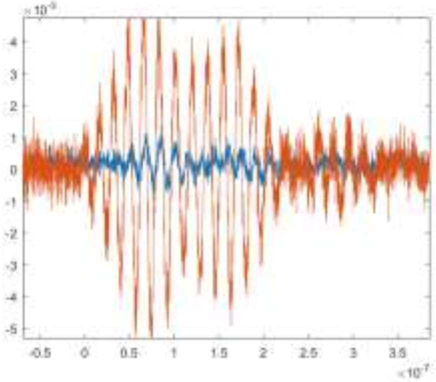
pdf using noise histogram (with no pumping: **LASER OFF**)



Random Noise

σ-set1: 0.21 mV

σ-set2: 0.42 mV



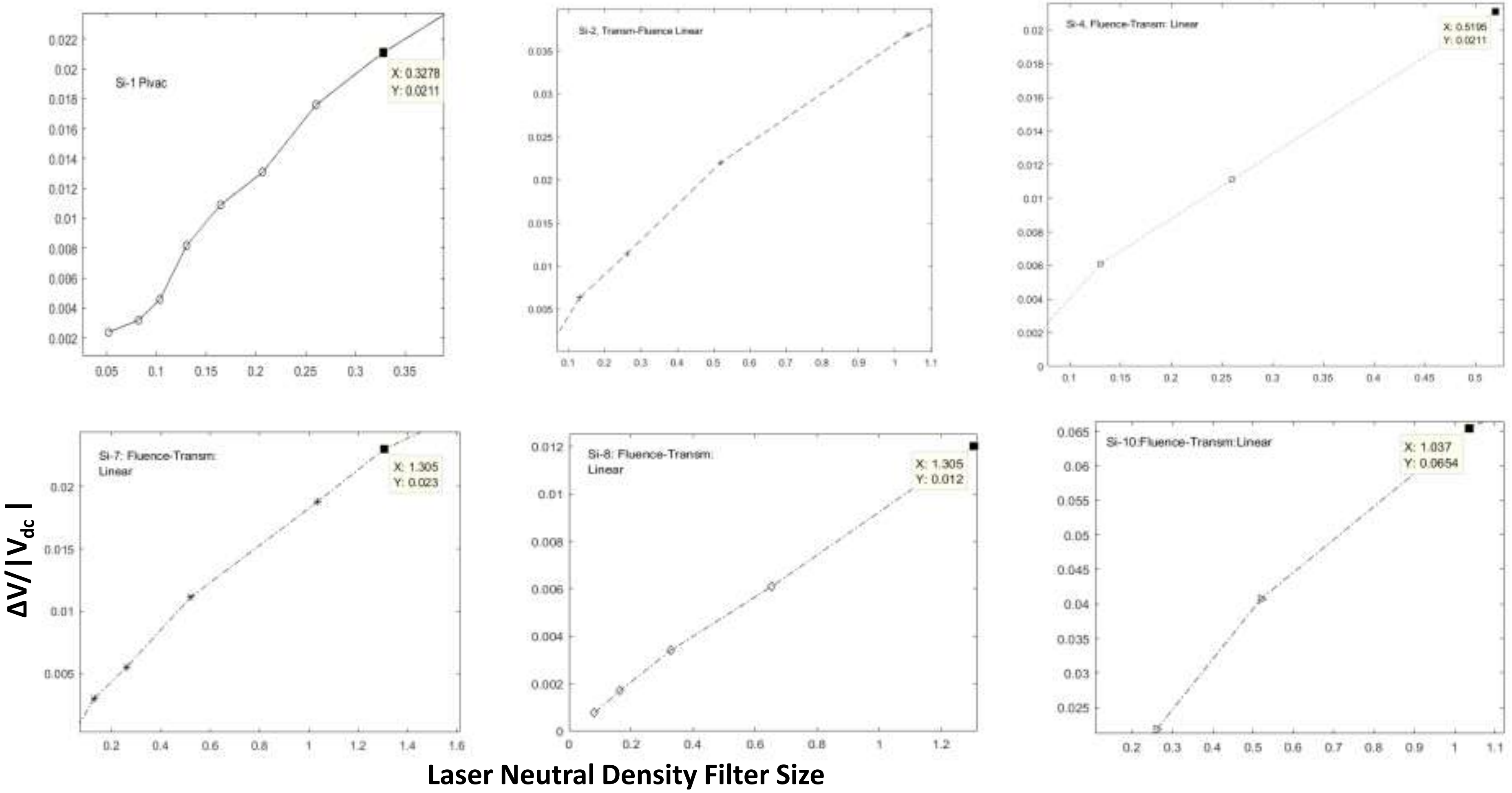
Orange CIDO set-1, Blue CIDO set-2

NOISE Sources

- RF passing through Si-4
- Environmental
- Low Noise Amplifier system incl. power supply
- Laser Power Supply (Faraday Shielded)

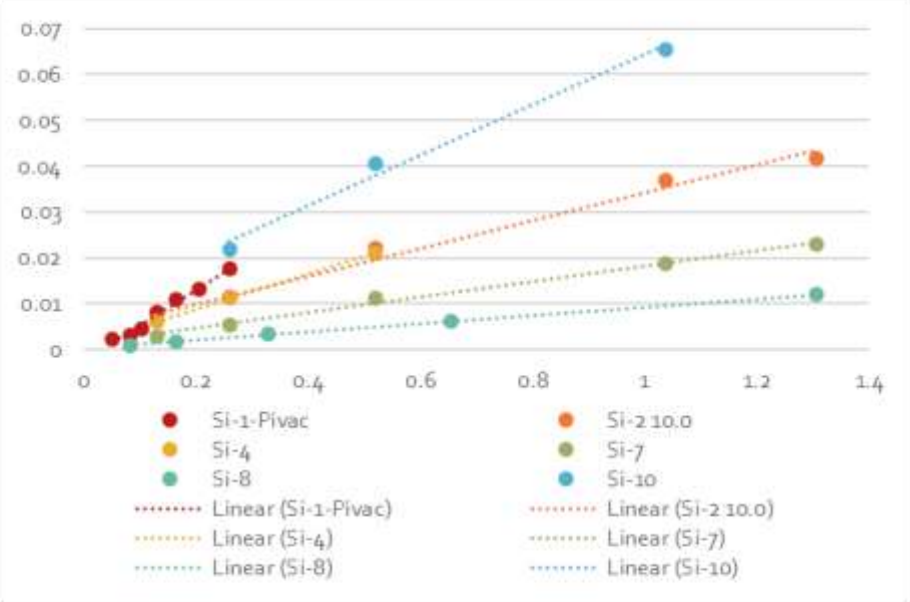
Variation of TRmmWC voltage response ratio with laser power level

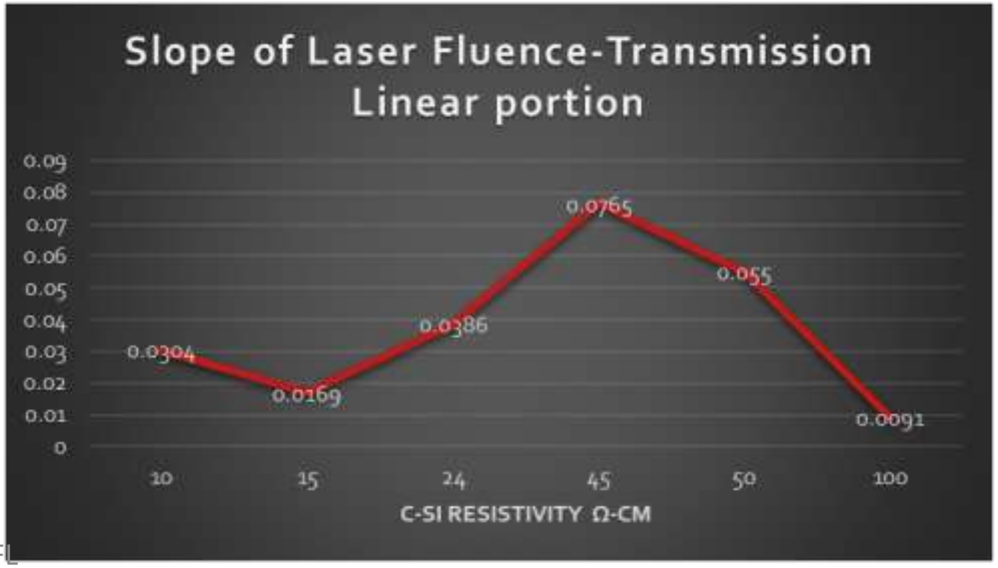
The linear portion of the graphs are the signal that we want to analyze while the nonlinear portion is noise.



We choose these linear regions for the 6 Silicon samples to study behavior of slopes with resistivity

No Systematic Relationship Between the Slope of the Transmission-Fluence Plots with RESISTIVITY was found





Conclusions

- CIDO is a solid state counterpart of BWO source and show steady performance
- Photo-decay transient signals obtained using CIDO-6 show oscillatory RF voltages which is subject to suppression by averaging for a longer period
- CIDO-6 yields normally a little higher crest-factor than BWO for the same sample: ~ 21 dB for CIDO versus 19 dB for BWO
- Mean V_{max} for CIDO is ~ 400 mV for UNL Perovskite sample with σ ~7 mV which is less than 2% (estimated signal-to-noise ratio for the peak value)
- As we decrease the laser power we see more modes appearing in the histogram of the CIDO minus BWO RF voltages; The ratio of Transmission obtained using CIDO and that of BWO increases with decrease in laser power
- There is no definite relationship for linearity of Silicon photoconductance and laser fluence to its electrical resistivity

Acknowledgements

- Prof. M. Wu, NCCU, UNC ROI principal investigator
- Prof. J. Huang, UNC, for perovskite sample
- Prof. Harald W. Ade, NCSU, UNC/ROI **Carbon Electronics** group leadership
- Prof. Charles R. Jones for the main idea
- Dr. M. Walters of SMIF, Duke U. for c-Si 4-probe resistivity
- Gilland Electronics, CA. and Elva-1, Russia, for BWO/CIDO support
- NSF for funding collaborative project with NCSU
- UNC General Administration for instruments support
- NASA grant at NCCU for summer student support: SRSP-2017