Optica Webinar
05 May 2023

Nanoscale Petahertz Electronics for Science and Technology

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Why do we want to capture subjects as they move in time?

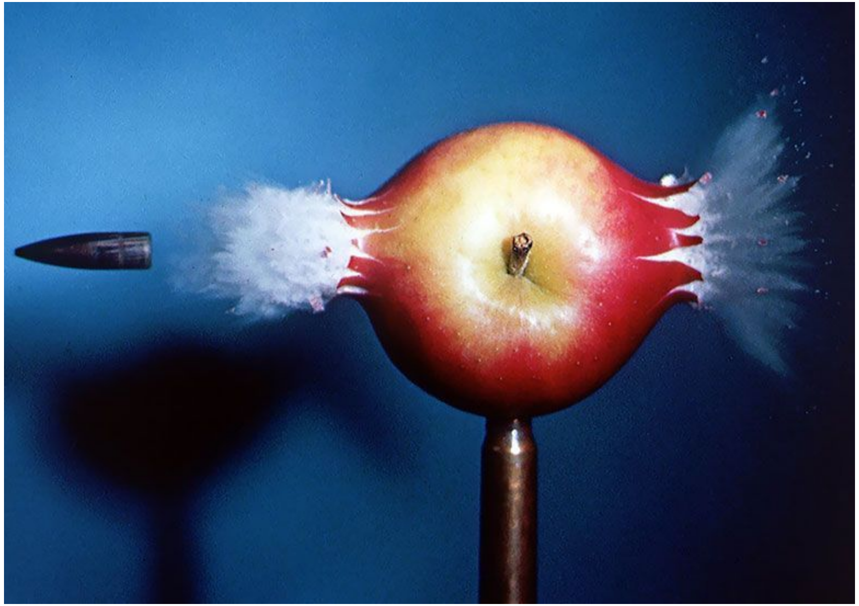
To understand *how* they move.

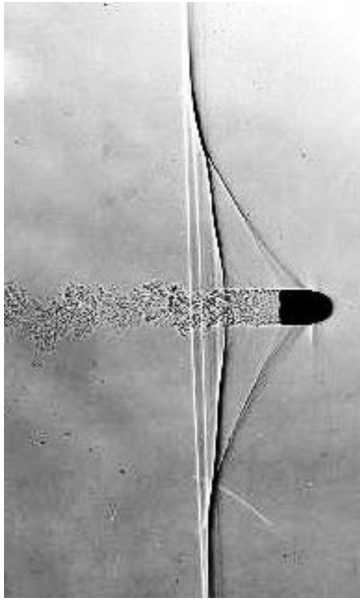
Edward Muybridge 1878

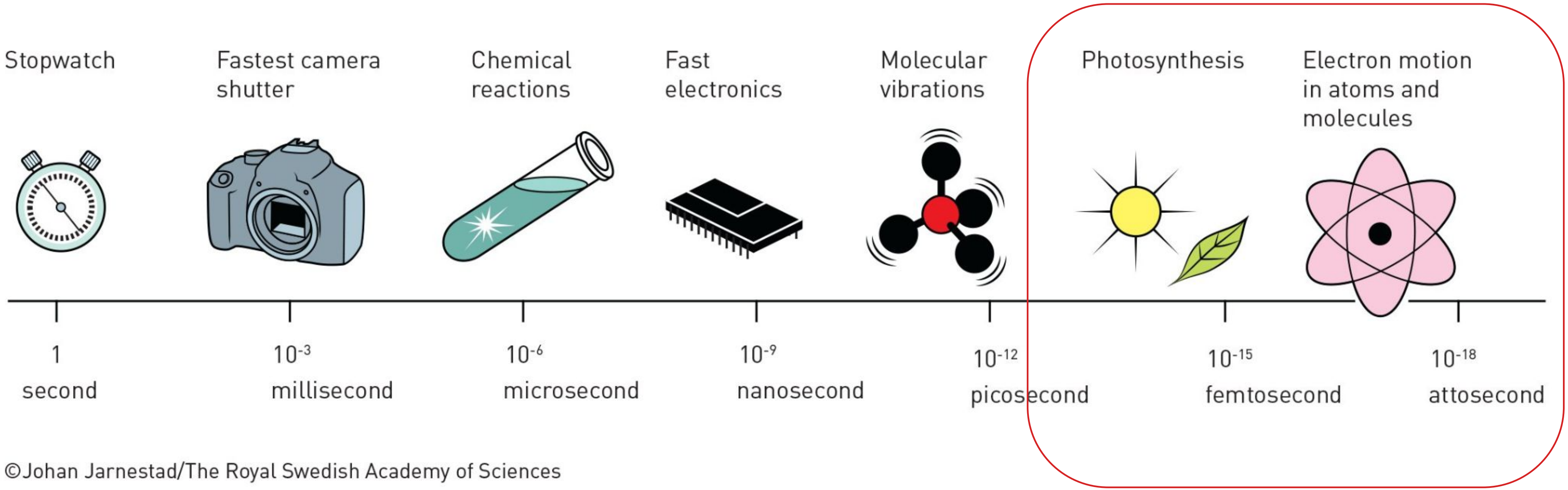
Race horses and Jockeys cross the finishing line 1850

Rebecca and Brian de Bois-Guilbert. 1828

Harold Edgerton and His Camera

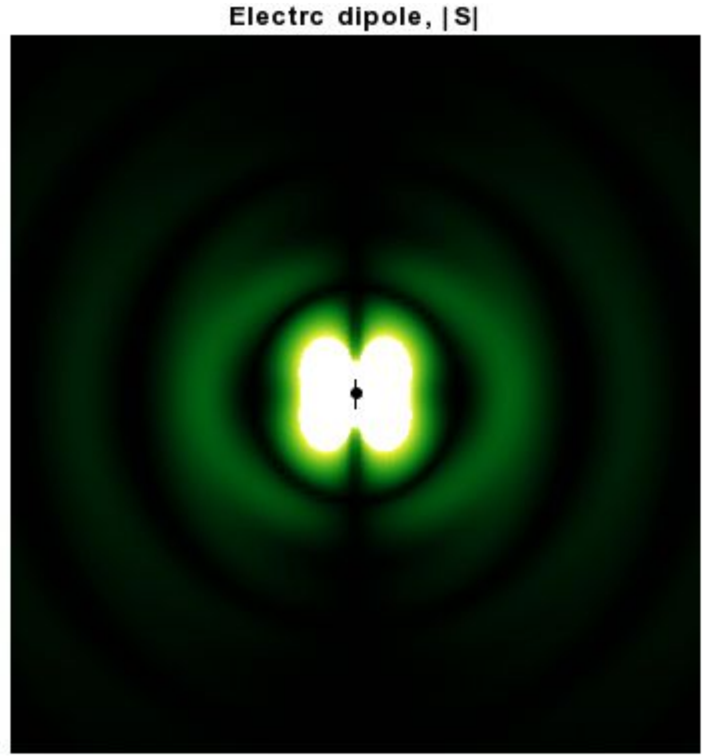




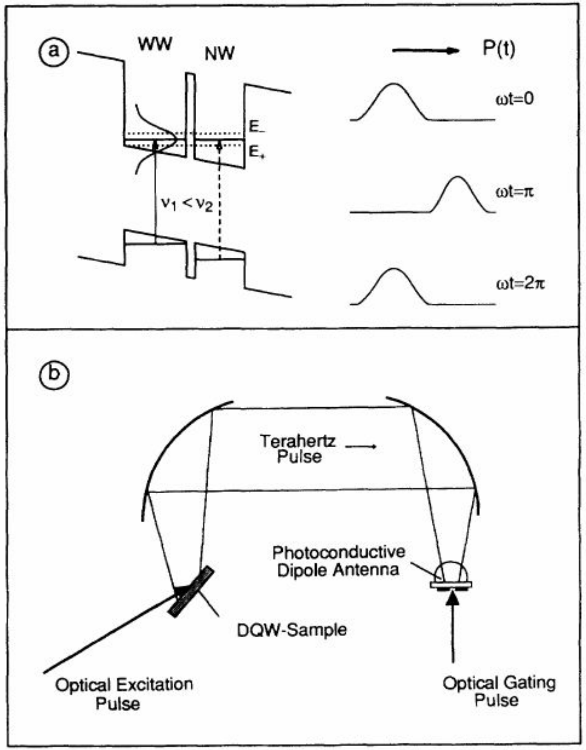

Stopwatch
Fastest camera shutter
Chemical reactions
Fast electronics
Molecular vibrations
Photosynthesis
Electron motion in atoms and molecules
1
second
10-3
millisecond
10-6
microsecond
10-9
nanosecond
10-12
picosecond
10-15
femtosecond
10-18
attosecond

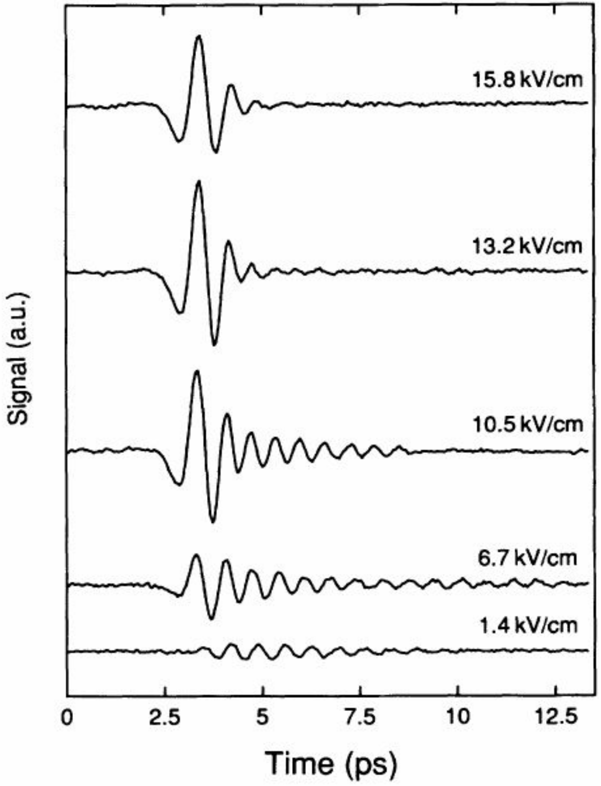
If we can measure precisely how optical fields oscillate in time,

we can understand how electrons, holes, and ions move.


Electrc dipole, |S|

Electronic Dynamics in Quantum Wells

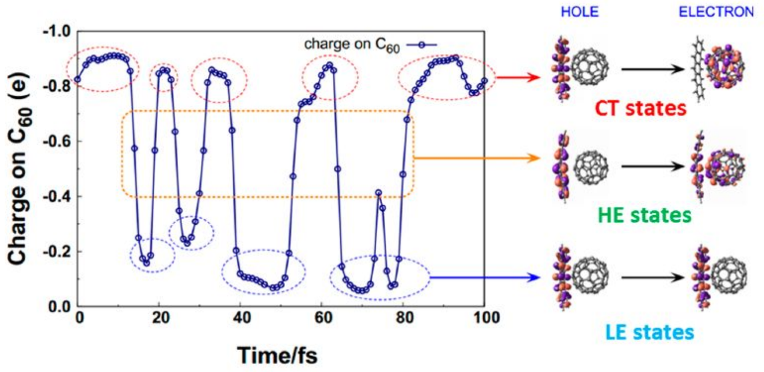




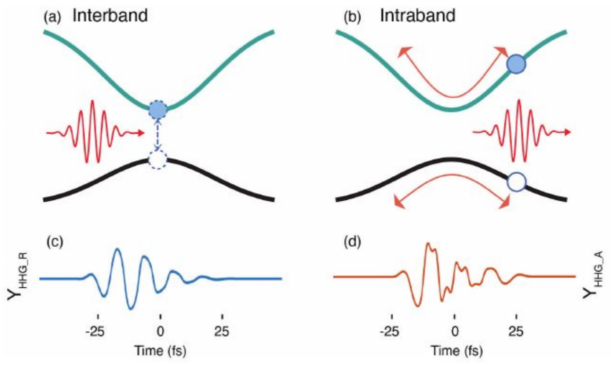
There's Plenty to Explore at Higher Frequencies!

- Exciton and charge-transfer dynamics important to photovoltaics/photosynthesis
- Dynamics behind extreme nonlinearities in molecules/solids
- Understand coherent control of chemical bonding/dissociation
- Applications in molecular sensing/analysis
- Field-resolved ultrafast dynamics of nanophotonics

Many signals of interest are often both **fast** and **weak**. Need:
- Sub- to few-fs response
- high sensitivity



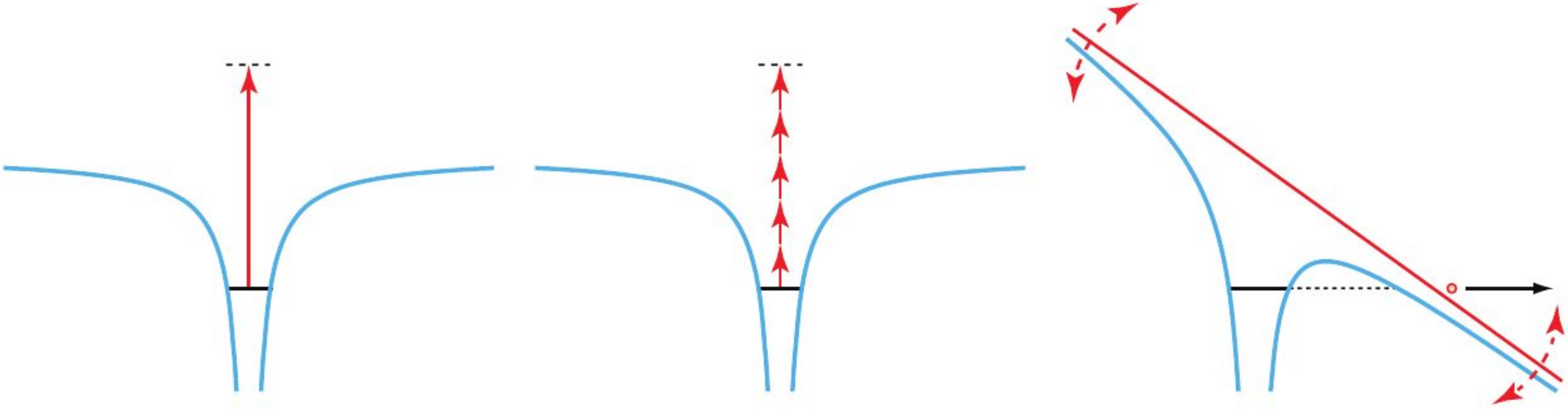
Joseph, S., *et al.* J. Phys. Chem. Lett. 8, 5171–5176 (2017).



Wang, Z. *et al.* Nat Commun 8, 1686 (2017).

Our Path

1. optical-field-driven tunneling (speed)

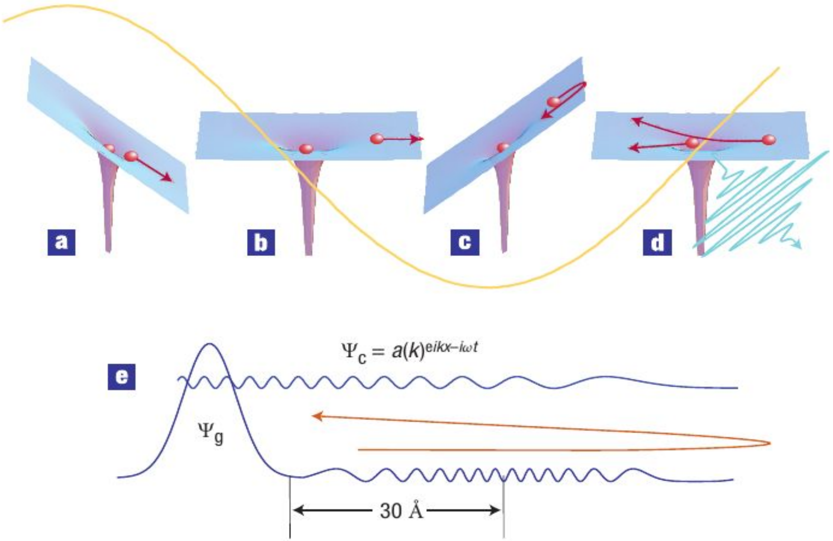


a) single-photon ionization

b) multi-photon ionization

c) tunnel ionization

Ultrafast "Flash": HHG



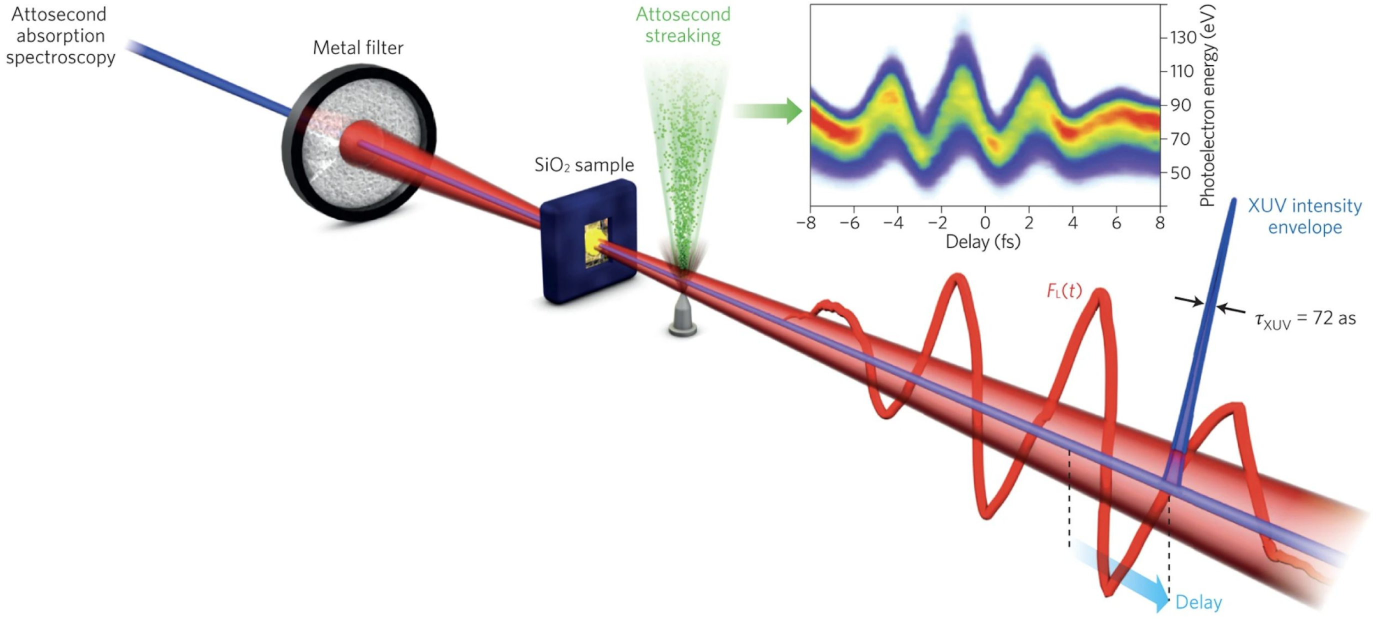
Tunneling Time $\ll$ Optical Cycle

or

$$\gamma = \sqrt{\frac{W_I}{2U_p}} \ll 1$$

$$U_p = \frac{q^2 E_0^2}{4m\omega^2}$$

Ultrafast "Flash": HHG

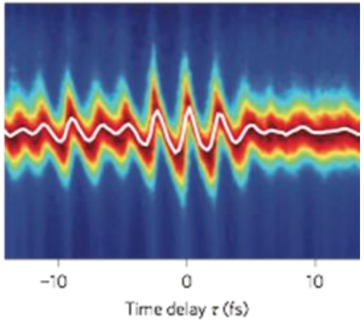


F. Krausz, M. Stockman, Nat. Photonics 8, 205 (2014).
M. Schultze, *et al.*, *Nature* 493, 75 (2013).

Ultrafast "Flash": HHG

Requires
- mJ-level lasers
- Multiple vacuum chambers
- Multiple people to operate

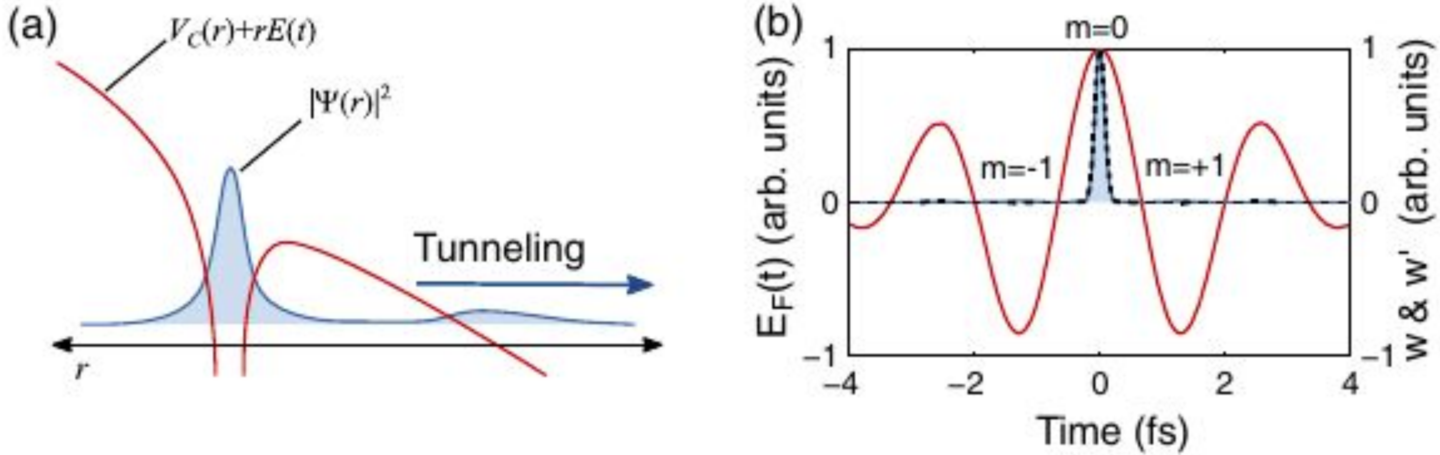
<u>*Not*</u> a viable route to compact, sensitive detection.



Top: Attosecond beamline, Polytechnico Milano.

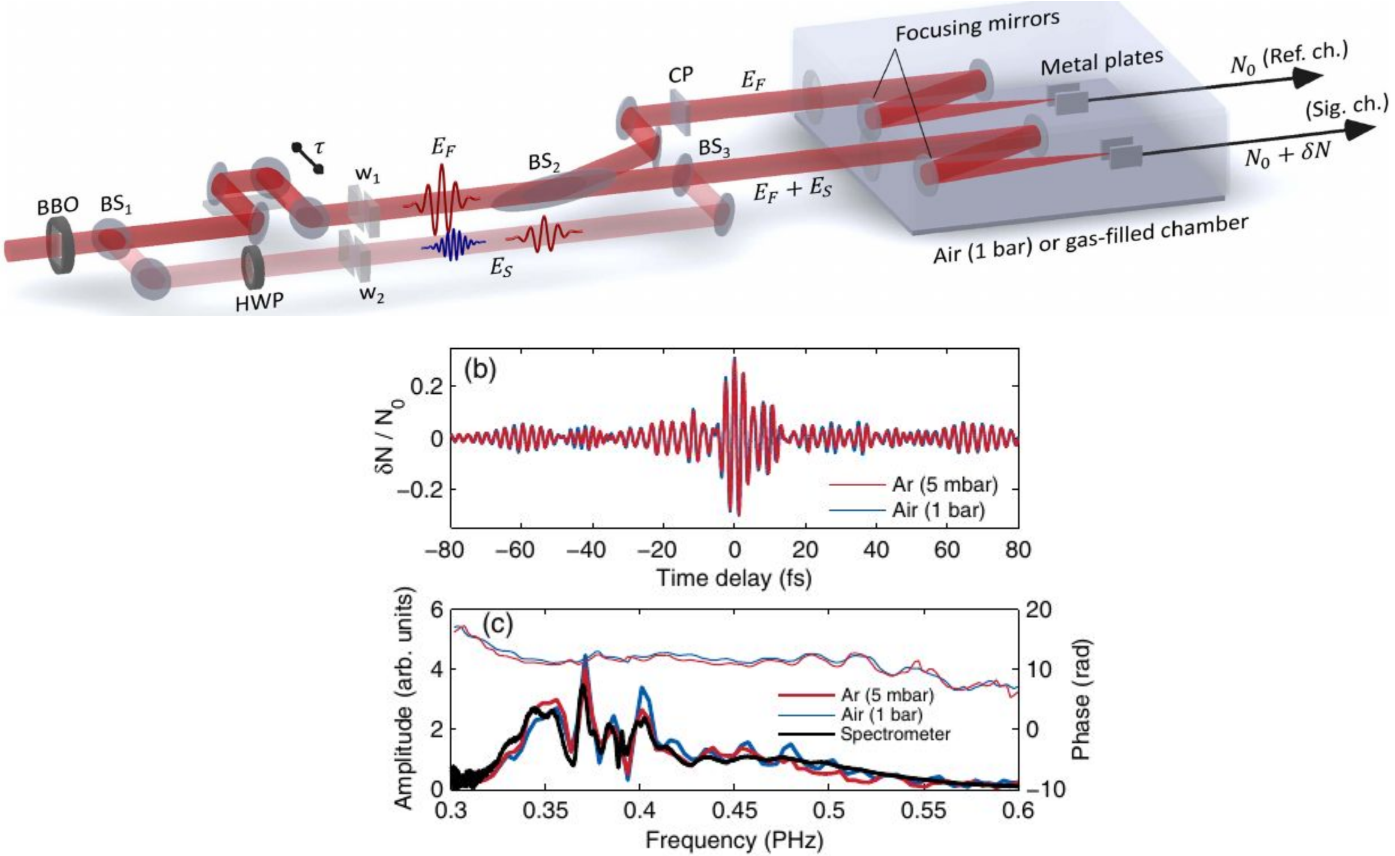
Btm: Kim *et al.*, Nat. Phot., 7, 958-962 (2013)

Sampling Light-Waves with Tunnel-Ionization: TIPTOE



Park, S. B. *et al.* Optica, OPTICA 5, 402–408 (2018).

Sampling Light-Waves with Tunnel-Ionization: TIPTOE



Park, S. B. *et al.* Optica, OPTICA 5, 402–408 (2018).

Our Path

1. optical-field-driven tunneling (speed)

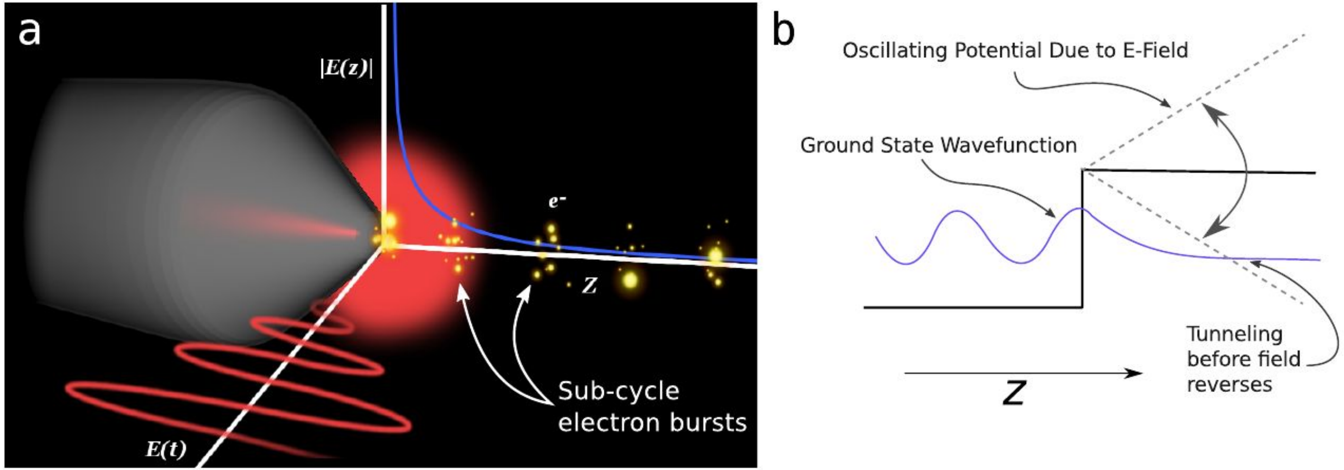
+

2. plasmonic and nanophotonic enhancement (sensitivity)

Further reducing size and energy → nano + atto

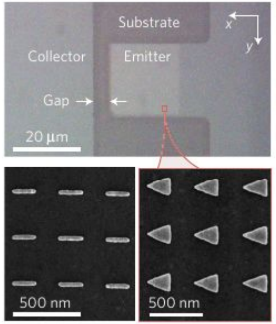
How can nanoscale structures help us?

- Field enhancement > 10x possible from nanoscale features
- Few-cycle pulse + nano field enhancement → optical tunneling without damage!
- Tunneling time < cycle time → field-sensitivity

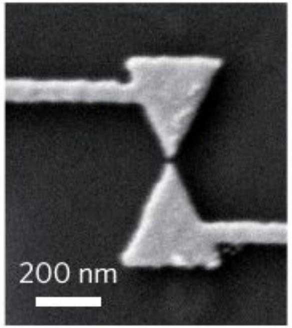


- Hommelhoff, P. et al., Phys. Rev. Lett. 97, 247402 (2006).
- Kruger, M. et al., Nature 475, 78–81 (2011).
- Herink, G. et al., Nature 483, 190–193 (2012).

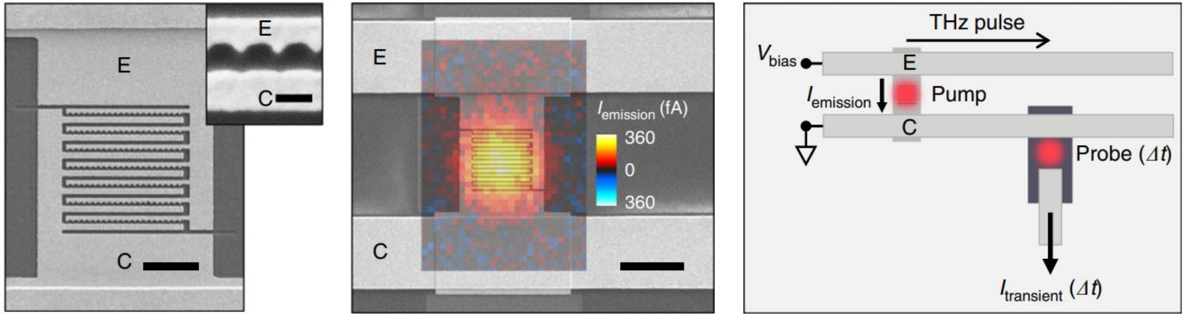
Tips on Chips for Petahertz-Scale Electronics



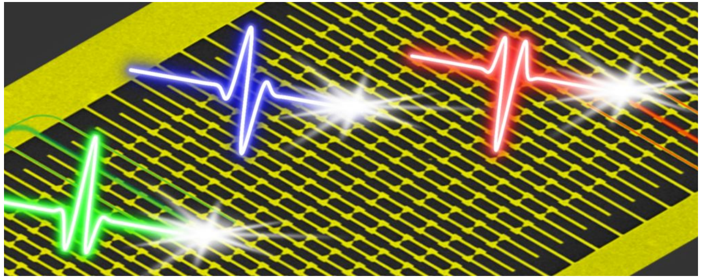
Putnam, W. P. et al., Nature Physics 13, 335–339 (2017)



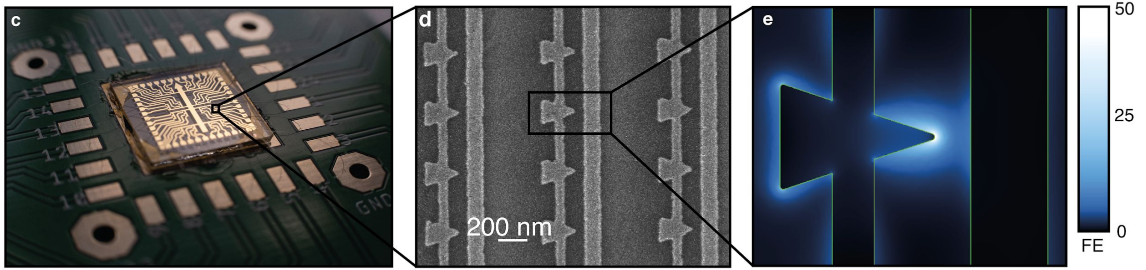
Rybka, T. et al., Nat Photon 10, 667–670 (2016)



C. Karnetzky et al. *Nature Communications* **9** (2018) 1

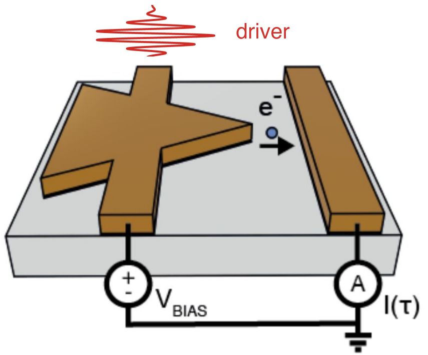


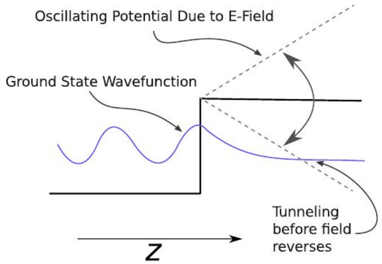
Y. Yang *et al.*, Nat. Comm. 11, 3407 (2020)

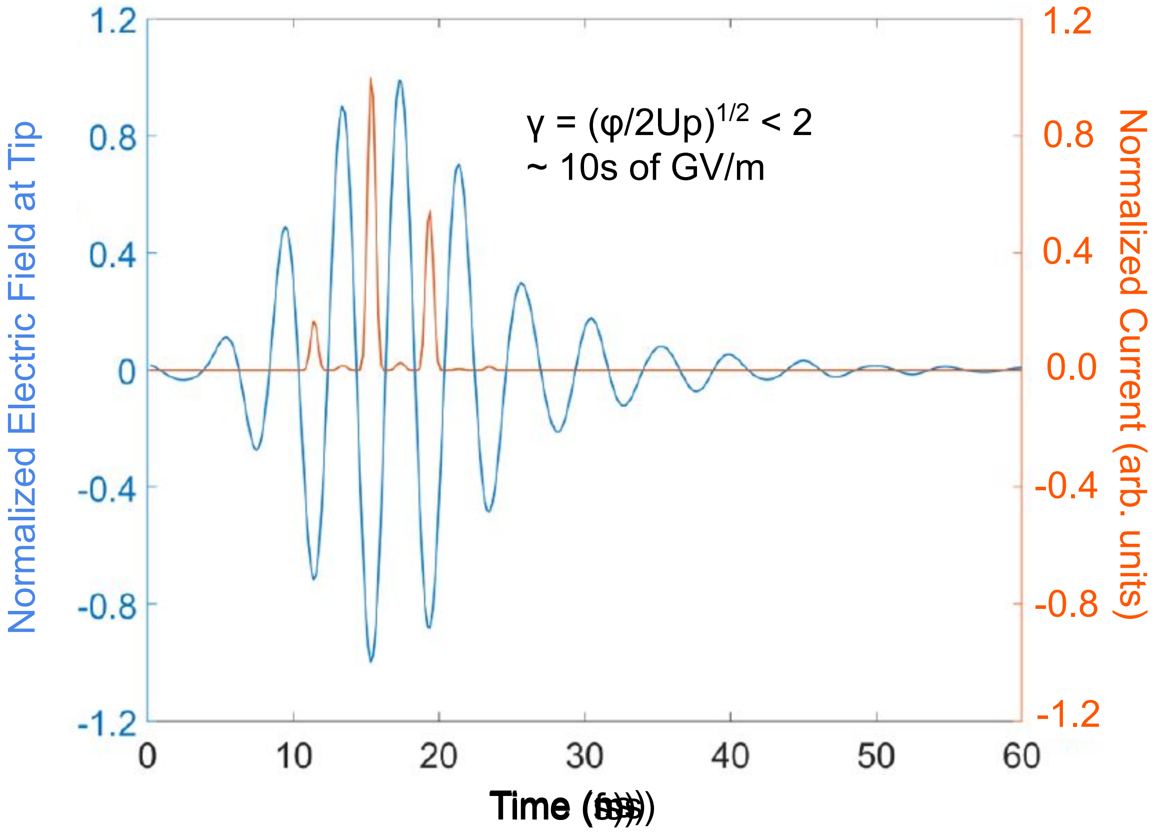


M. R. Bionta *et al. Nature Photonics* **15** (2021) 456

It’s looking more and more like electronics!

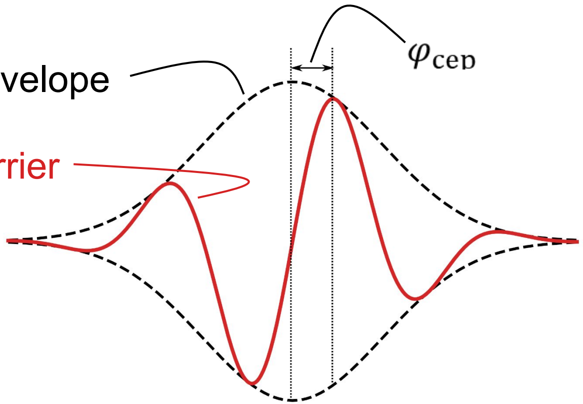




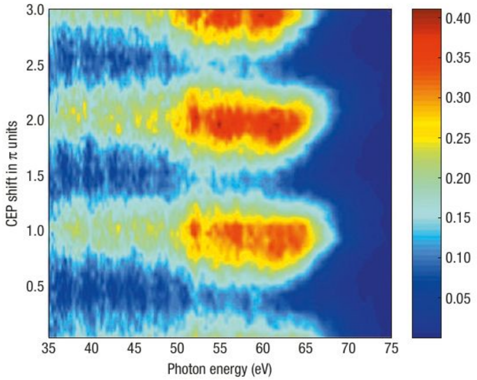


How to demonstrate optical tunneling: CEP response

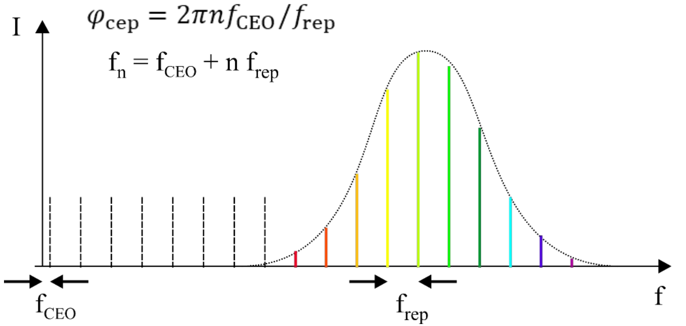
What is CEP?



- **Science**: investigate properties of optical field emission
- **Technology**
  - Stabilize optical frequency combs
    - Optical Clocks
    - Optical Ranging/GPS
  - Few-cycle field control for strong-field and attosecond science

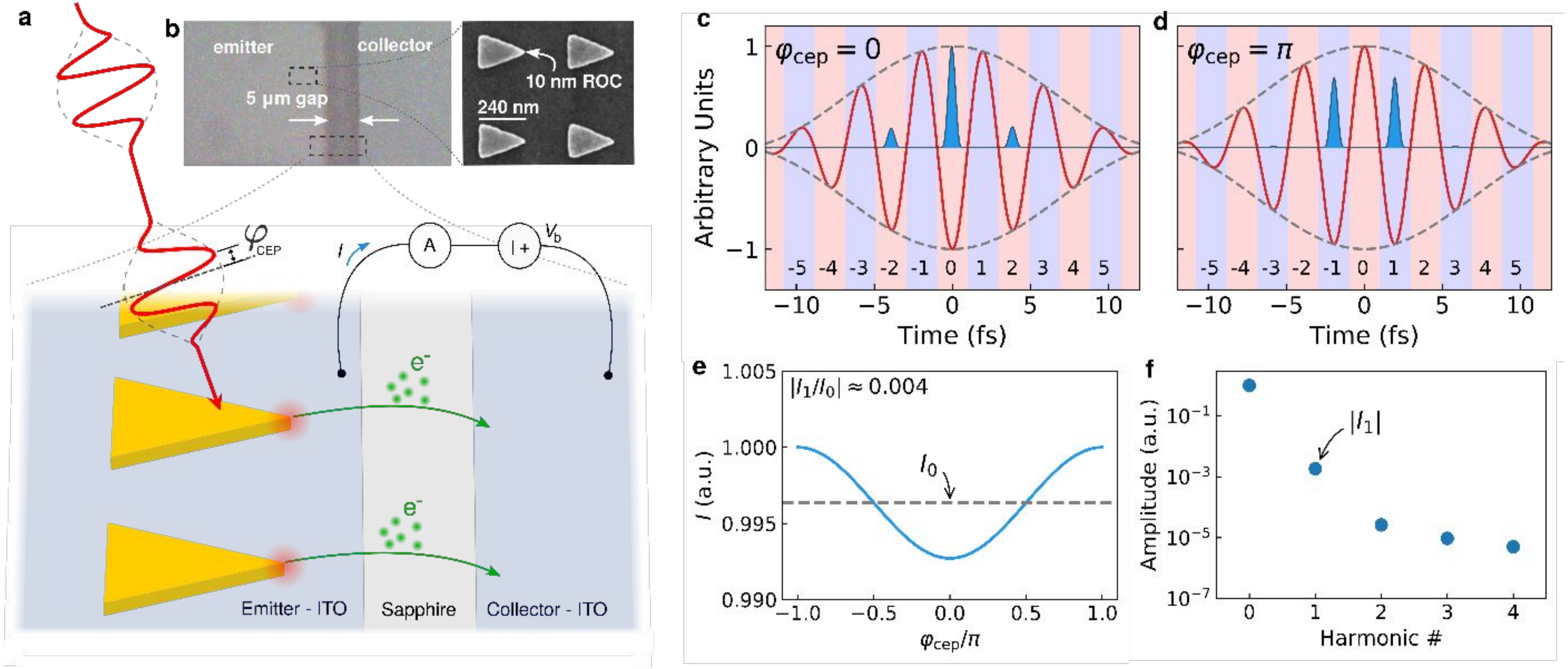


Sola, I. J. et al. Nature Physics 2, 319 (2006)



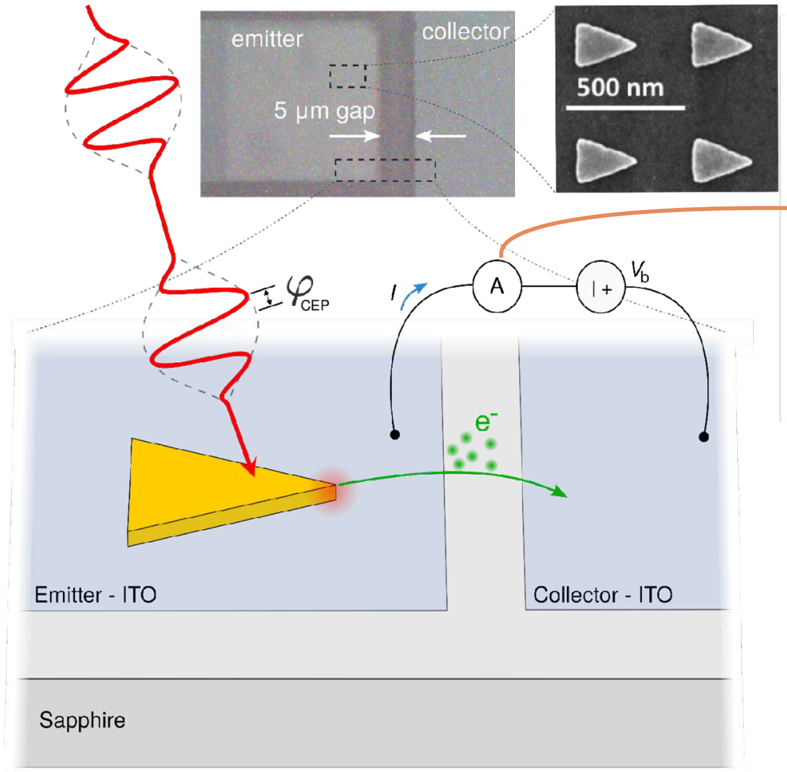
Source: Wikipedia, By User:HartmutG - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1042484

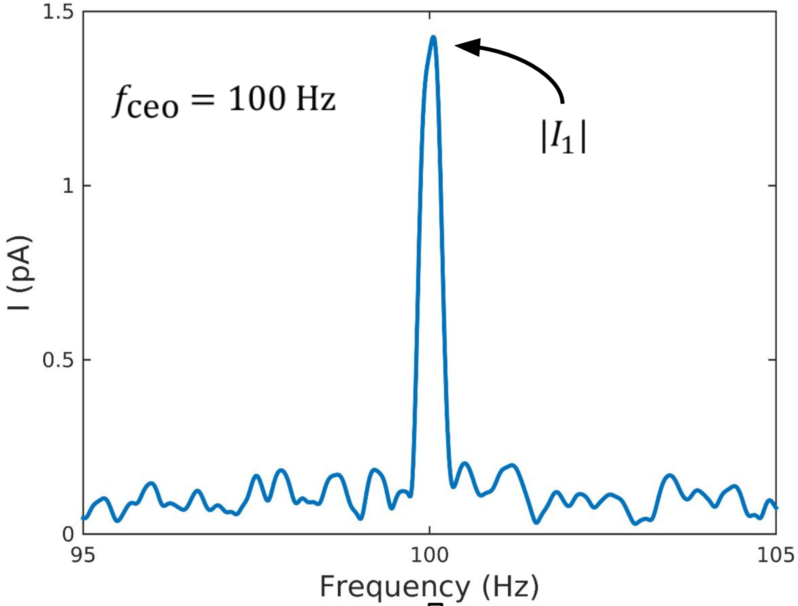
Optical-Field Sensitive Emission From Nanostructures



Keathley, P. D. et al., Nat. Phys. 15, 1128–1133 (2019).

CEP-Sensitive Photocurrent

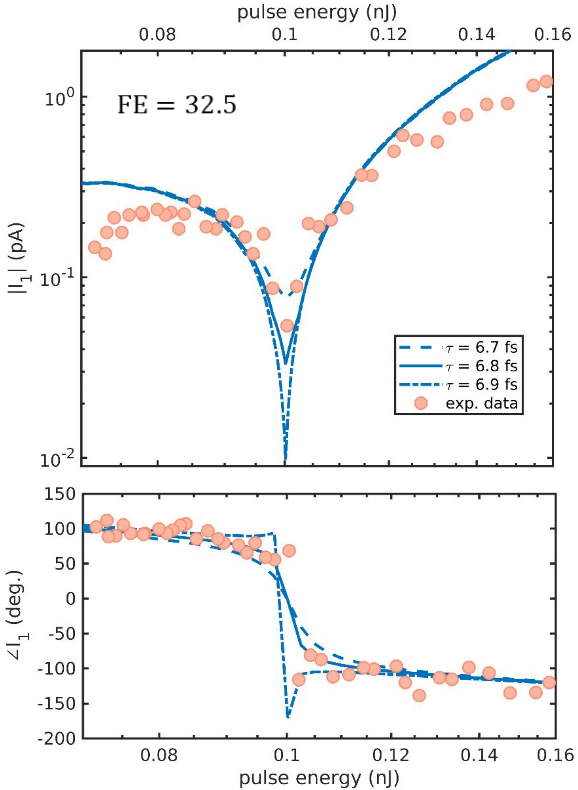


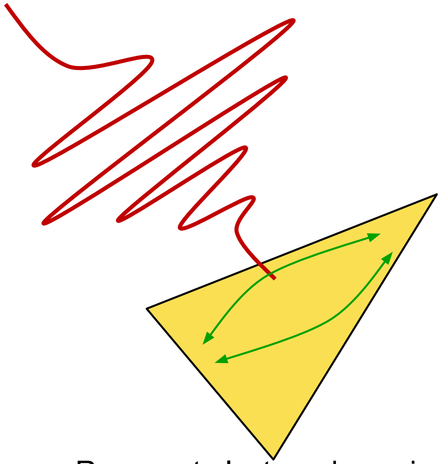


Amplitude + Phase Tracking

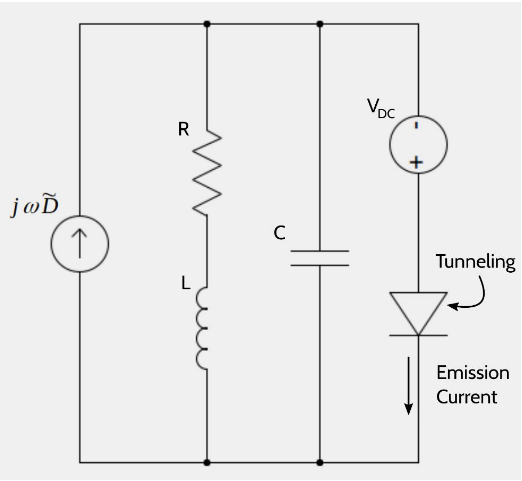
Lock-In Amplifier

In-Situ Measurement of Plasmonic Near-Fields





- Resonant electron dynamics approximated by damped harmonic oscillator
- Reshape field at surface



Extinction → Damped harmonic oscillator

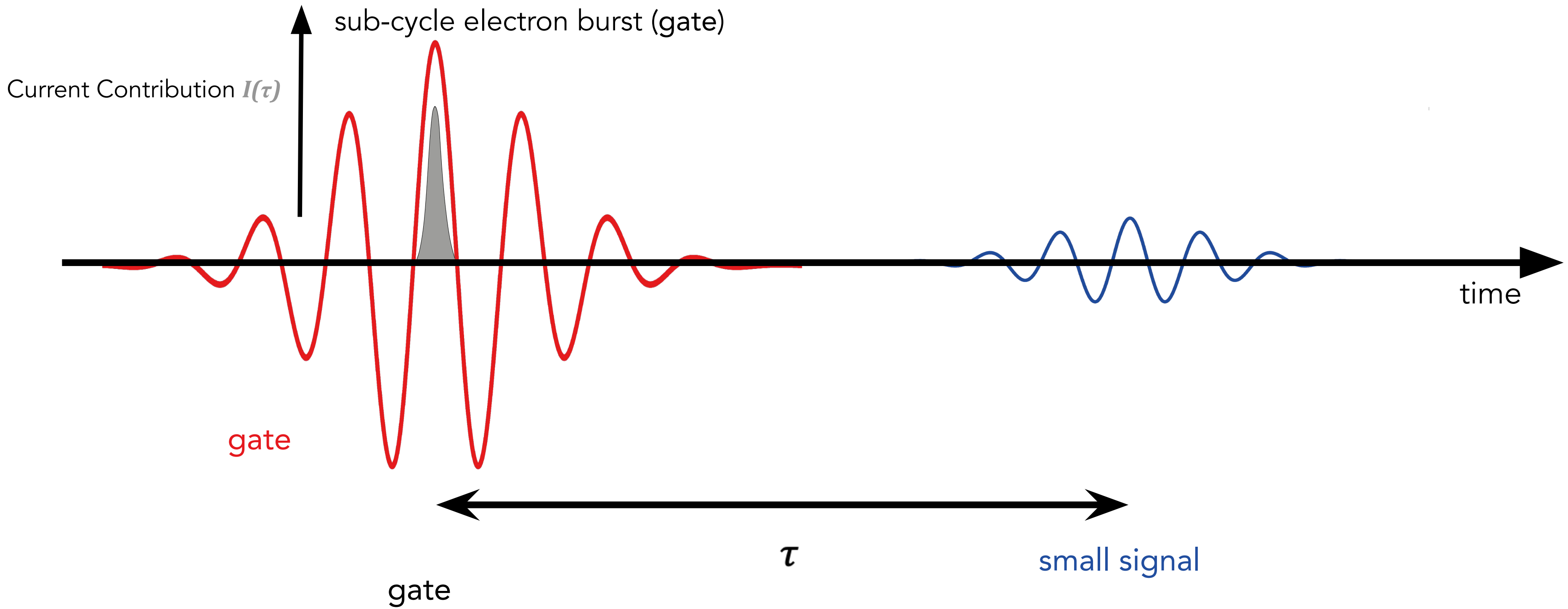
$$F_S(t) = F_0\mathcal{F}^{-1}\{\tilde{F}(\omega)\tilde{g}(\omega)\}$$

$$\tilde{g}(\omega) = \left(\omega_0^2 - \omega^2 - \frac{i\omega}{\tau}\right)^{-1}$$

F_0 → field enhancement

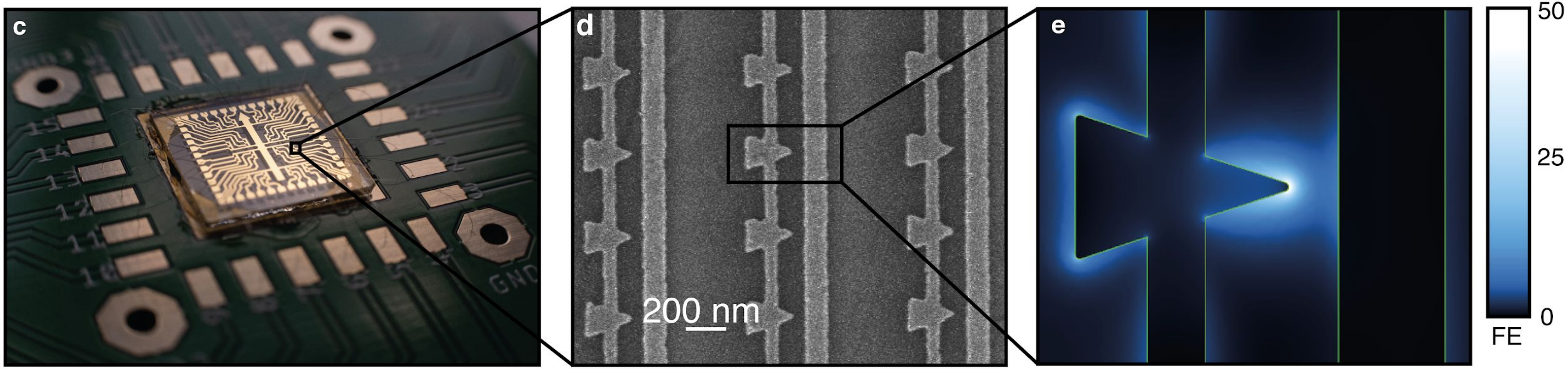
Keathley, P. D. et al., Nat. Phys. 15, 1128–1133 (2019).

How Can You Sample Fields With It?

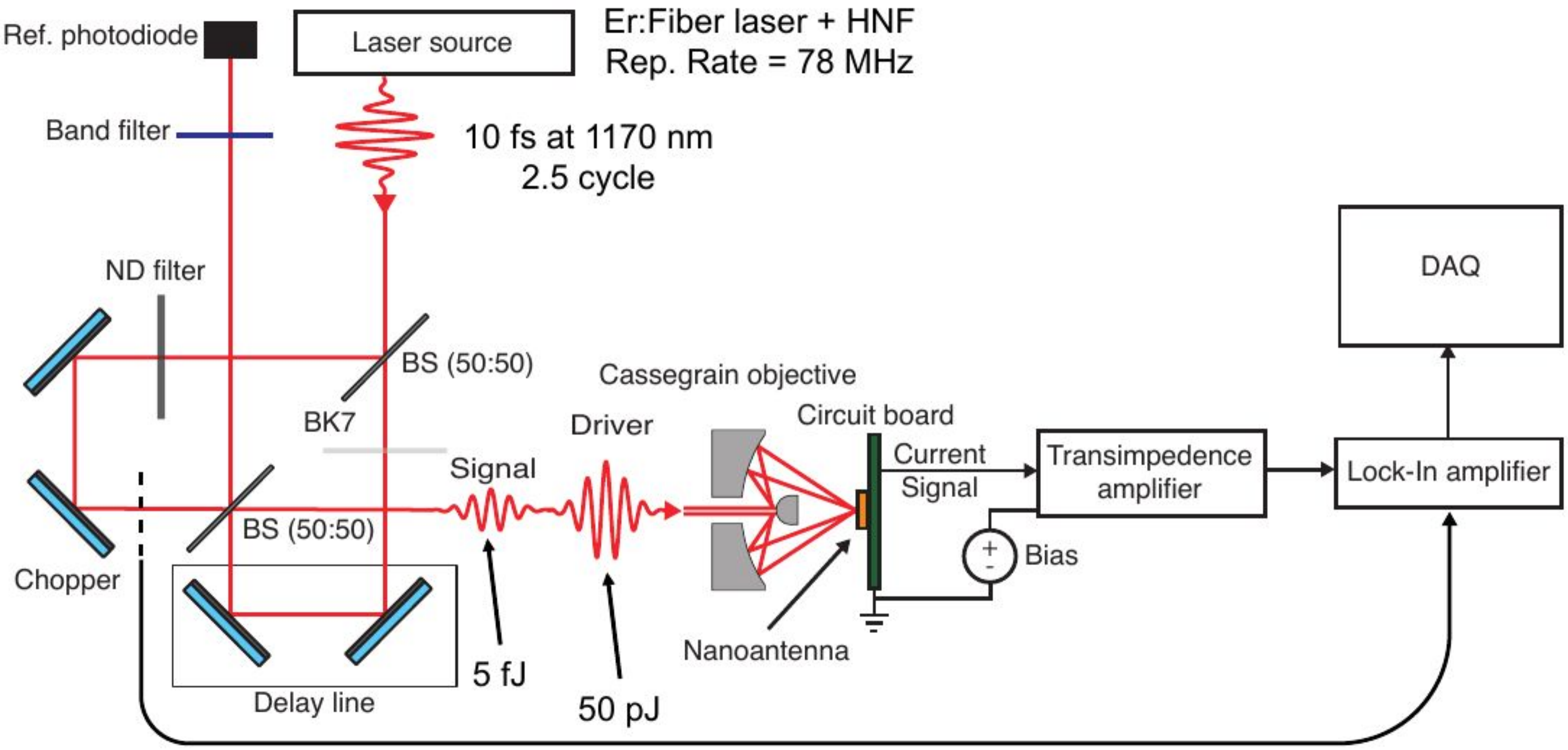


M. R. Bionta, *et al.*, Nat. Photonics 15, 456 (2021).

Fabricated devices

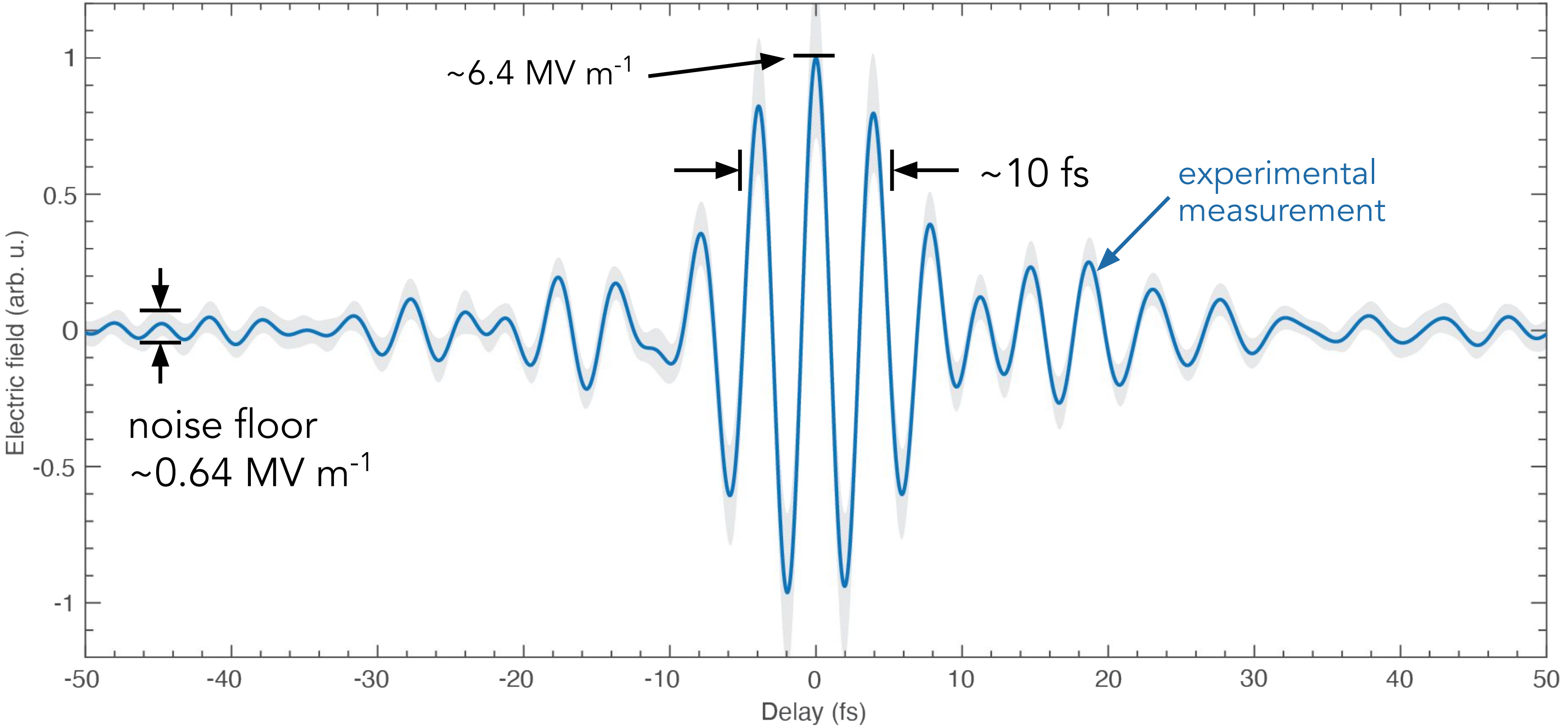


Experimental Setup



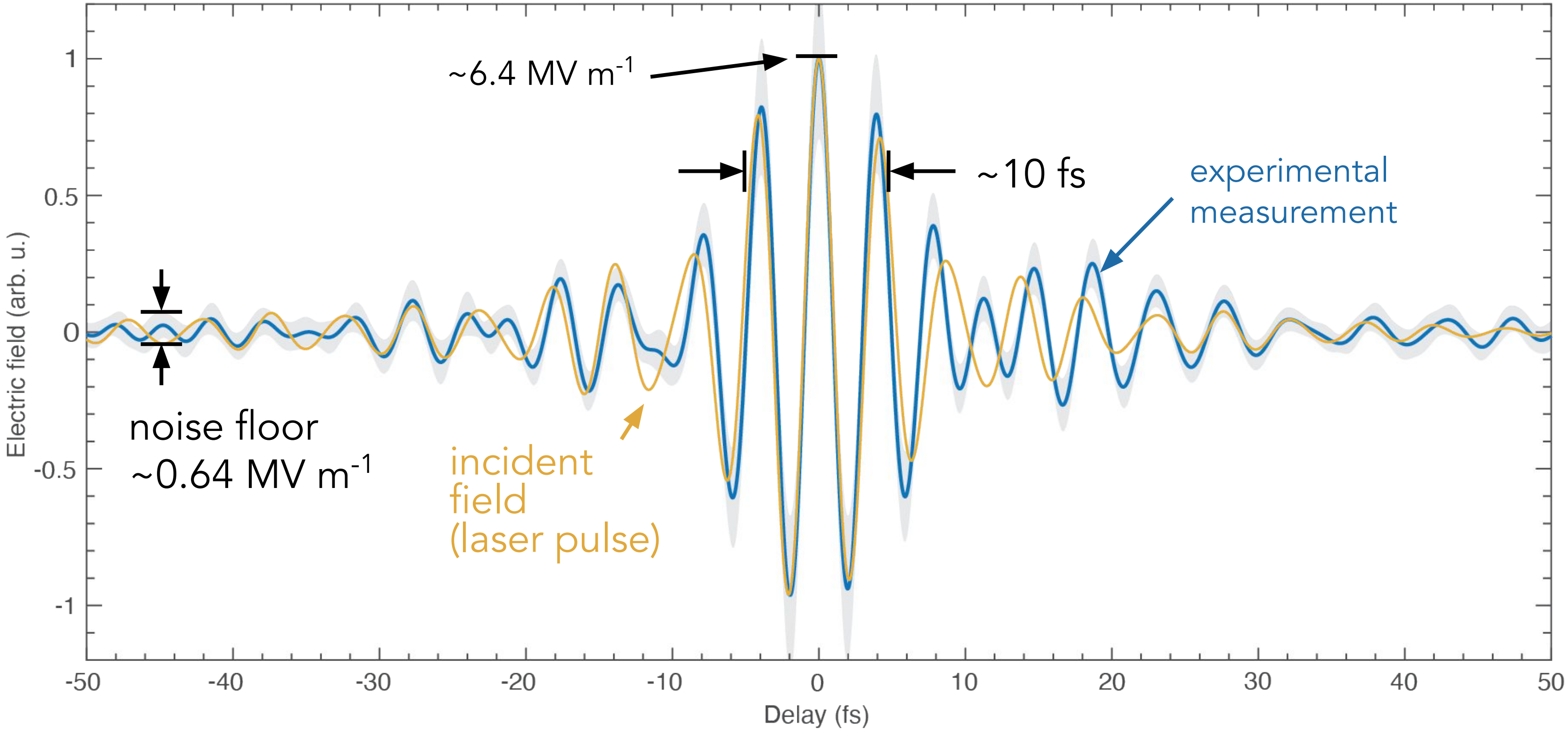
M. R. Bionta, *et al.*, Nat. Photonics 15, 456 (2021).

Time-domain measurement



M. R. Bionta, *et al.*, Nat. Photonics 15, 456 (2021).

Comparison to incident laser pulse



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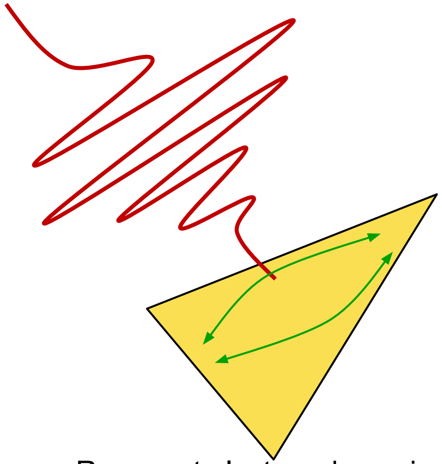
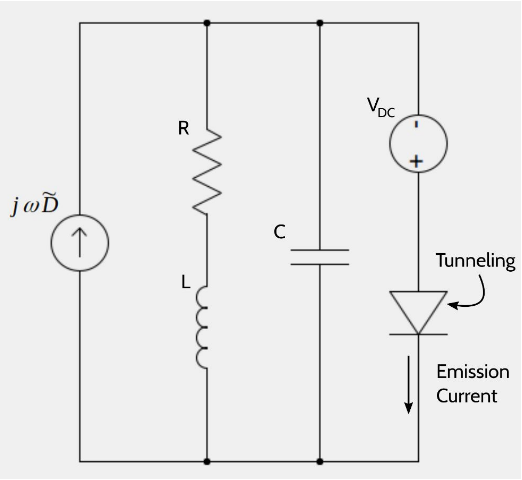
In-Situ Measurement of Plasmonic Near-Fields





- Resonant electron dynamics approximated by damped harmonic oscillator
- Reshape field at surface

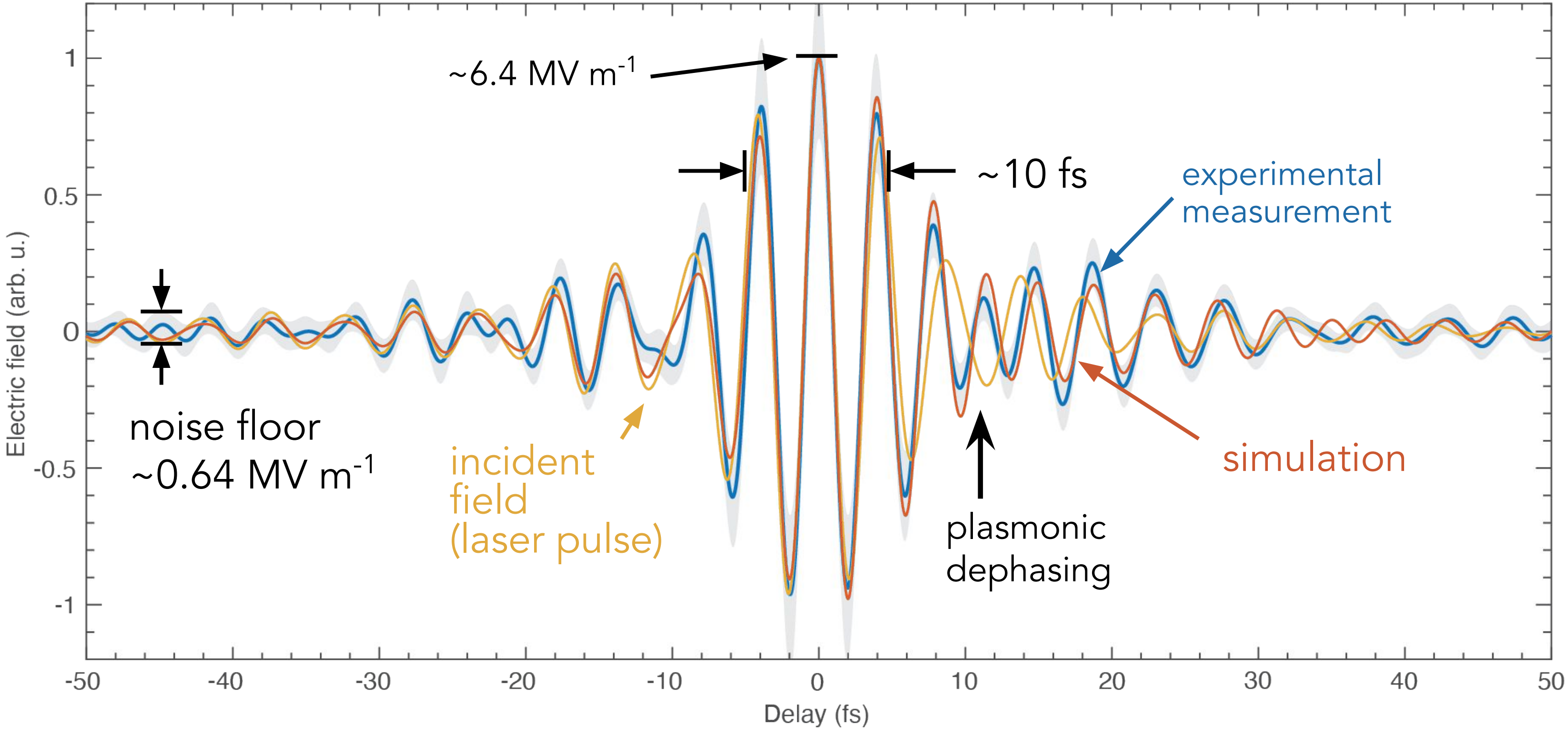
Extinction → Damped harmonic oscillator

$$F_S(t) = F_0\mathcal{F}^{-1}\{\tilde{F}(\omega)\tilde{g}(\omega)\}$$

$$\tilde{g}(\omega) = \left(\omega_0^2 - \omega^2 - \frac{i\omega}{\tau}\right)^{-1}$$

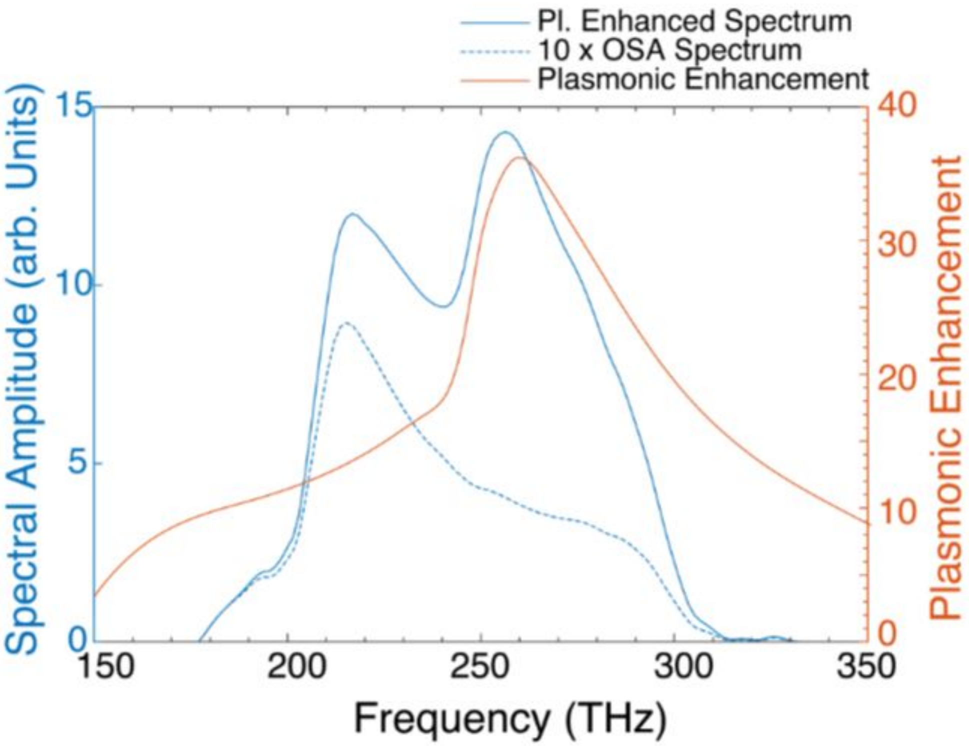
F_0 → field enhancement

Time-domain accounting for plasmonic response



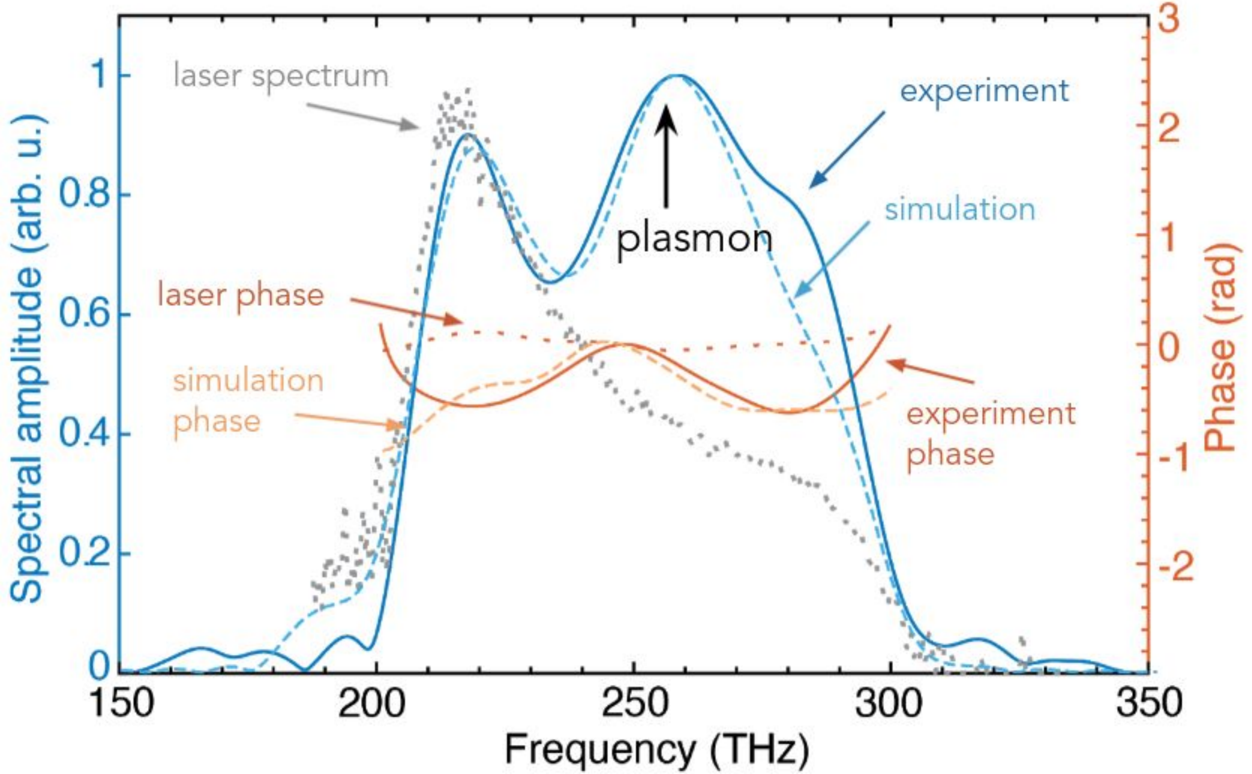
M. R. Bionta, *et al.*, Nat. Photonics 15, 456 (2021).

Accounting for plasmon reshaping of spectrum/fields



M. R. Bionta, *et al.*, Nat. Photonics 15, 456 (2021).

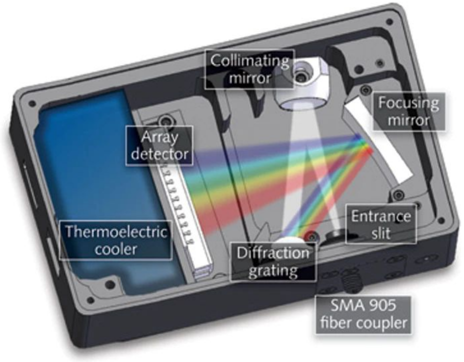
Frequency-domain accounting for plasmonic response

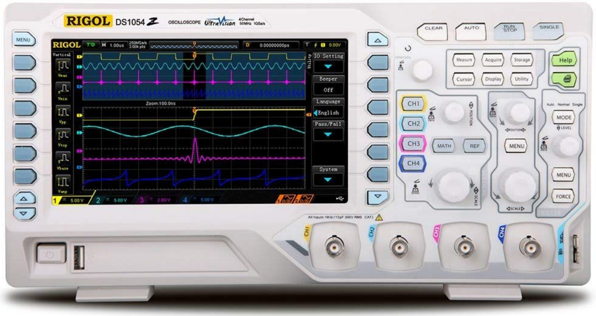


M. R. Bionta, *et al.*, Nat. Photonics 15, 456 (2021).

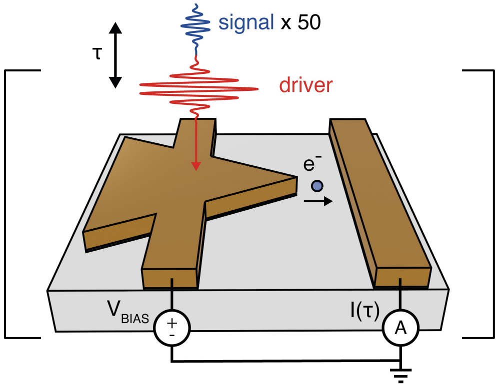
Electronics vs. Optics

Spectral Analysis



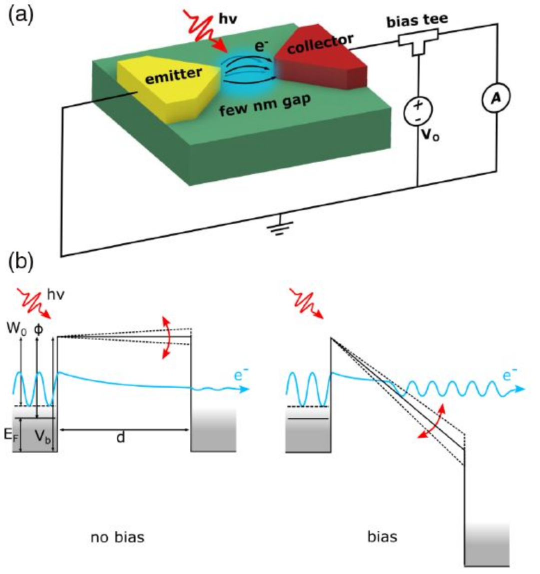


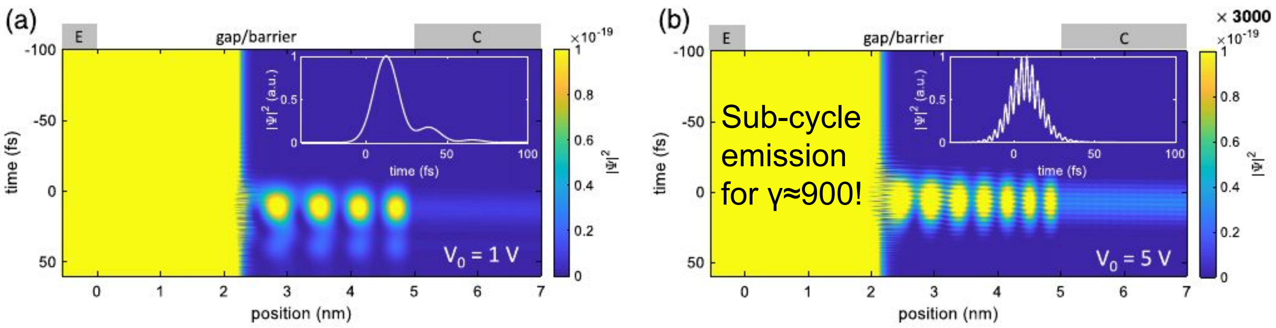
Waveform Analysis



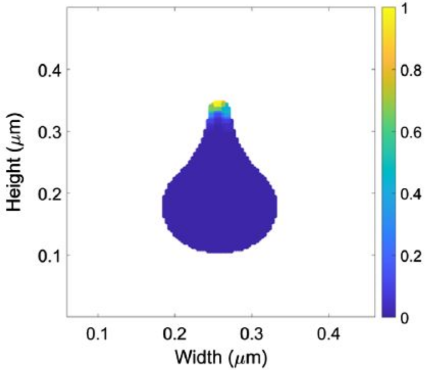
Taking Things Further

Further Improving Sensitivity





Turchetti, M. *et al.* J. Opt. Soc. Am. B 38, 1009 (2021)

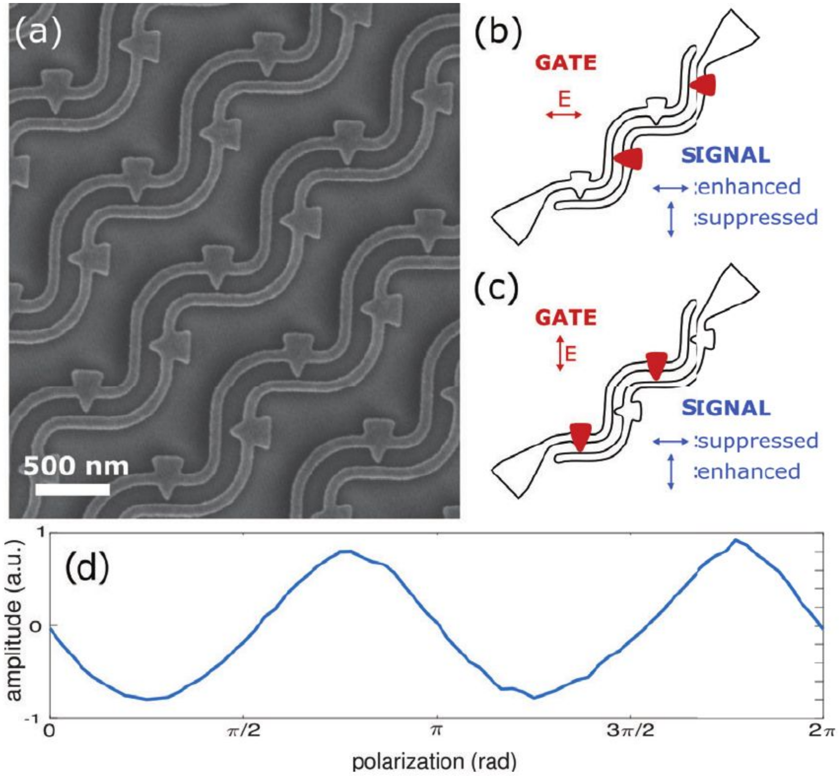


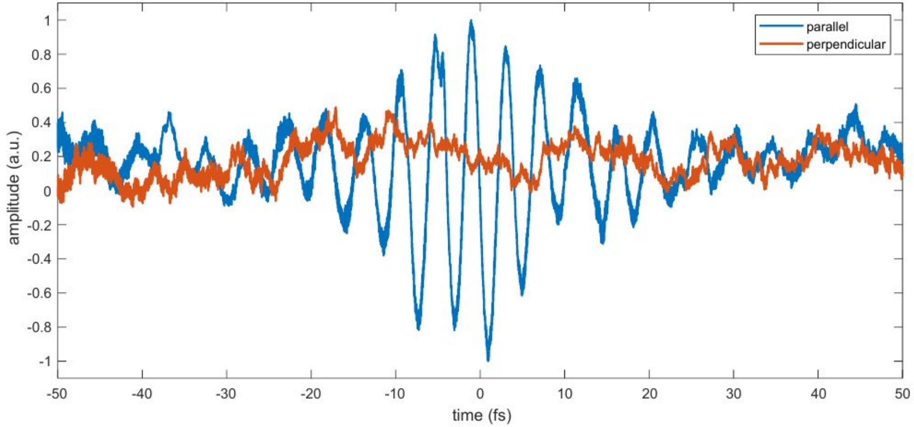
Tune geometry and resonance:

1.5× more FE
10× more CEP-sensitive current
50× more SNR!

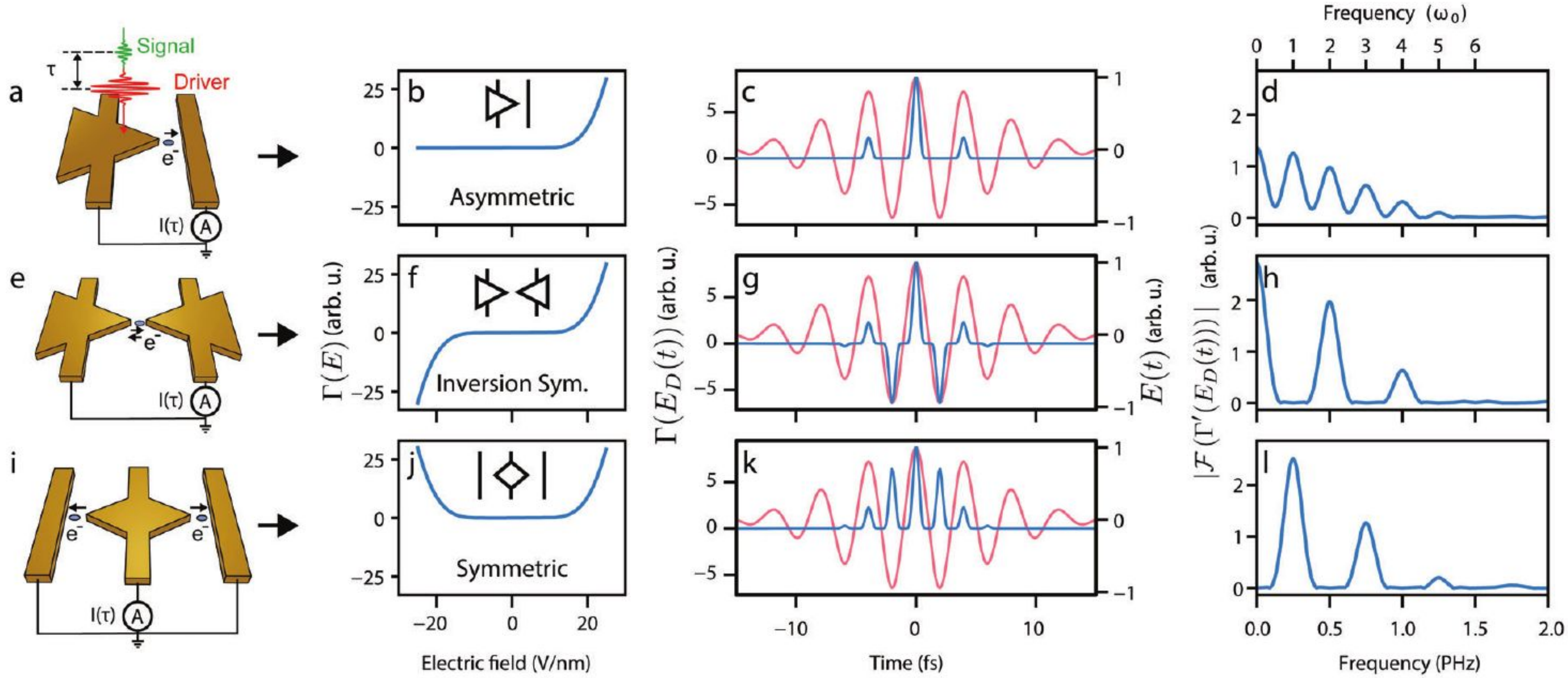
Buckley, D. *et al.* J. Opt. Soc. Am. B 38, C11 (2021)

Control Over Polarization and Frequency Response

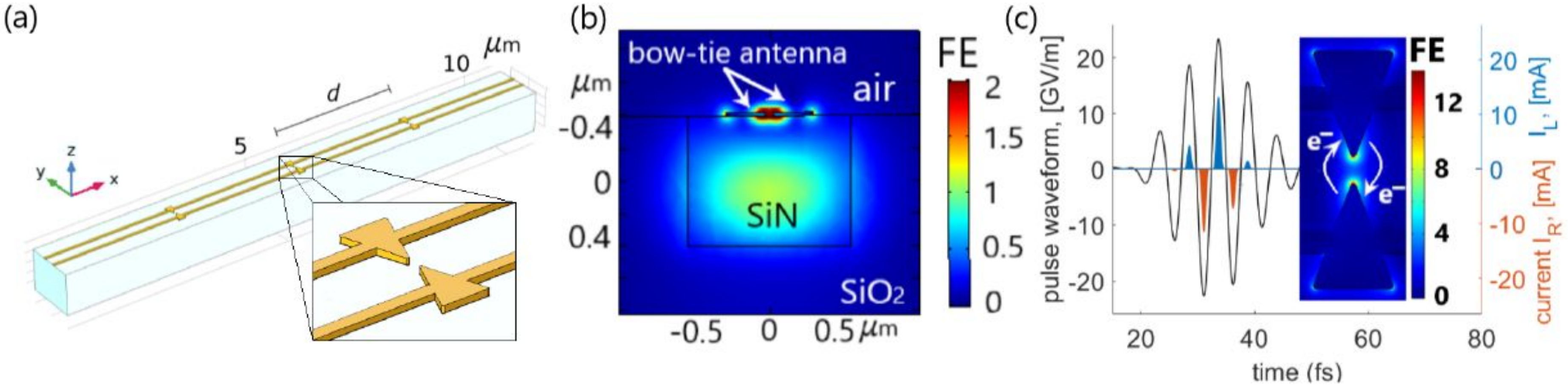




Control Over Polarization and Frequency Response

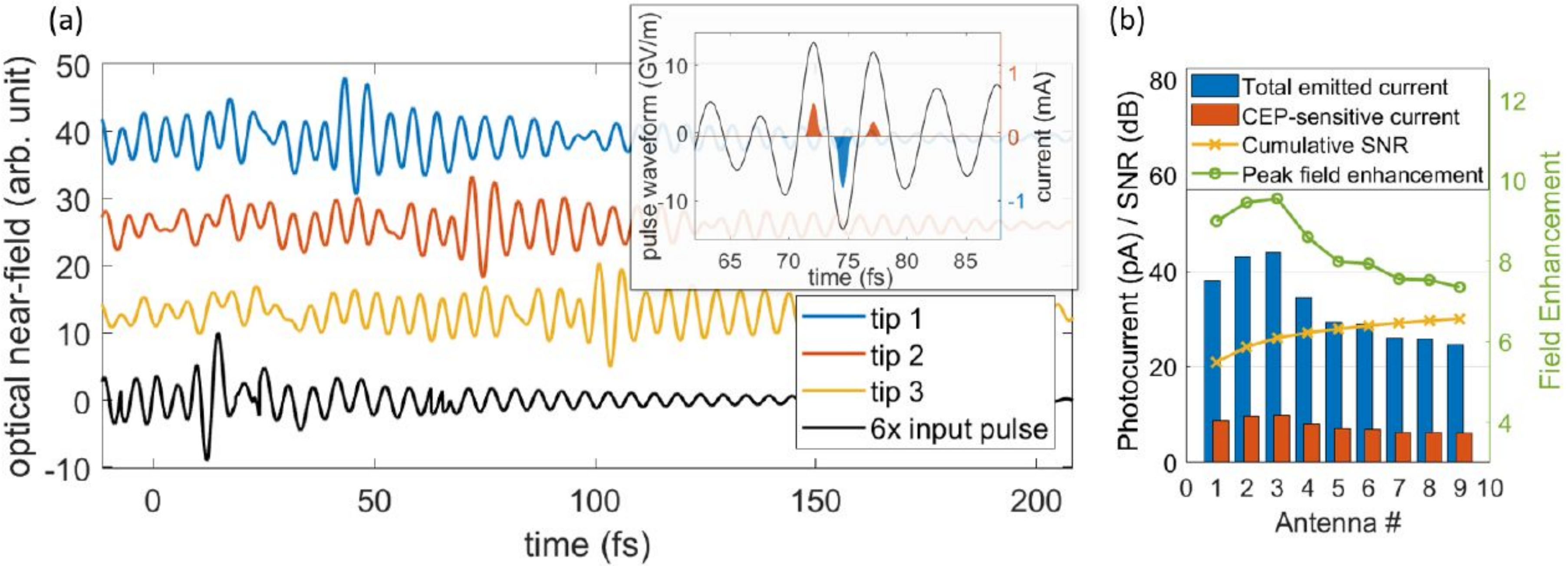


Waveguide Integration



Cattozzo Mor, D. *et al.* Journal of Lightwave Technology (2022) doi:10.1109/JLT.2022.3150246.

Waveguide Integration



Calculate CEP-Sensitive SNR of 30 dB at 50 kHz RBW

Team, Collaborators and Funding


Marco Turchetti


Dr. Mina Bionta


Felix Ritzkowsky


Prof. Karl Berggren


Dr. Yujia Yang


Matthew Yeung


Lu-Ting Chou (National Yang-Ming Univ., Taiwan)


Dario Cattozzo Mor


Alberto Nardi

<u>Not Pictured</u>

Drew Buckley

Prof. Yugu Yang-Keathley
Wentworth ECE

Prof. Franz Kärtner
DESY, U. Hamburg Physics

Prof. Luca Dal Negro
B.U. ECE

Prof. William Putnam
UC Davis ECE