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Advancing Optics and Photonics Worldwide

Nonlinear Optics Technical Group

Time-Variant Systems in Nonlinear Optics: From Frequency Conversion to Beating the Time-Bandwidth Limit

Maxim Shcherbakov, University of California, Irvine

24 September 2021

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Indian Institute of Technology

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ETH Zürich

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University of Technology Sydney

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RLE, MIT

About the Nonlinear Optics Technical Group

Our technical group focuses on the physics of nonlinear optical materials, processes, devices, & applications.

Our mission is to connect the 4000+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Webinar on High-order Dispersion Solitons and Topological Photonics in Silicon
- Transitioning into a Career in Optics Panel Discussion at FiO 2019
- Emerging Trends in Nonlinear Optics - A Review of CLEO: 2019
- Emerging Biomedical Applications of Nonlinear Optics

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.osa.org/ol
- On LinkedIn at www.linkedin.com/groups/8302249
- On Facebook at www.facebook.com/opticanonlinearoptics
- Email us at TGactivities@osa.org

Today's Speaker

Maxim Shcherbakov

University of California, Irvine

- Assistant professor with the Department of Electrical Engineering and Computer Science at the University of California, Irvine
- Received his Ph.D. in Physics from Lomonosov Moscow State University, Russia
- Joined Cornell University as a postdoctoral associate in 2016
- Main interests are artificial optical materials and their nonlinear and quantum optics applications, deep-subwavelength lithography, and augmented and mixed reality devices

UCI Samueli
School of Engineering

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Maxim Shcherbakov

Department of Electrical Engineering and Computer Science

University of California, Irvine

With groups of
Gennady Shvets (Cornell)
Igal Brenner (Sandia)
Hayk Harutyunyan (Emory)
Enam Chowdhury (Ohio State)

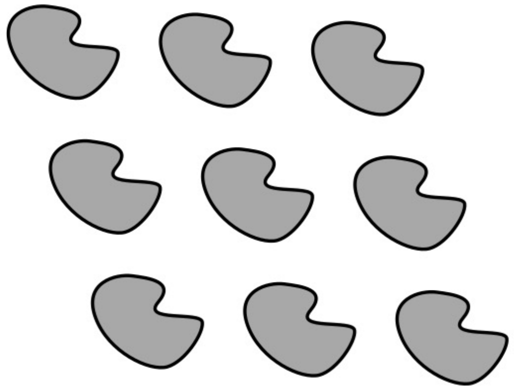
Sponsors and collaborators:

Samsung Advanced Institute of Technology
Agency for Science, Technology and Research, Singapore
The Australian National University
Ohio State
Cornell University
Department of the Navy, ONR Science & Technology
Sandia National Laboratories
Friedrich-Schiller-Universität Jena
RSF Russian Science Foundation

Nonlinear Optics Technical Group Webinar
September 24, 2021

Metamaterials: tailored spatial response

$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r}) \mathbf{E}(\mathbf{r})$$



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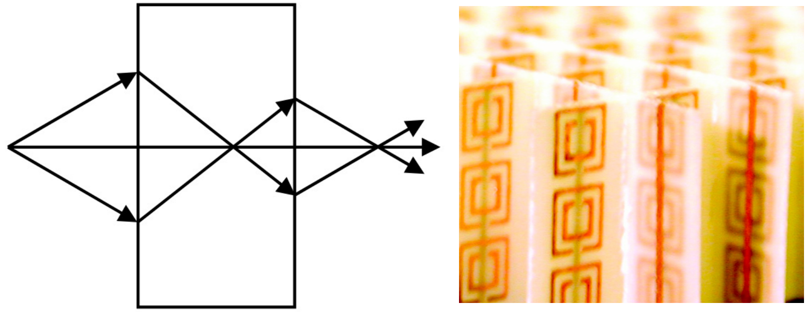

Negative refraction and LHM

Veselago, Pendry, Shelby, Smith, Schultz, Lezec, Shalaev, X Zhang, Soukoulis, Sihvola, Tretyakov, Fan

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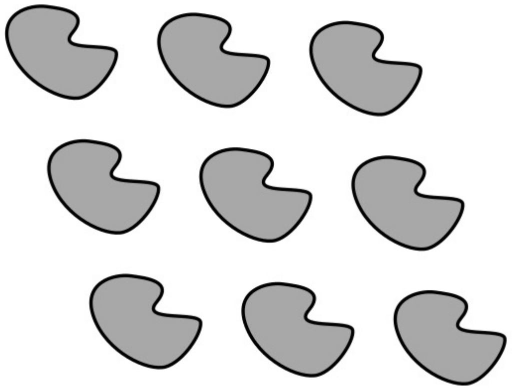

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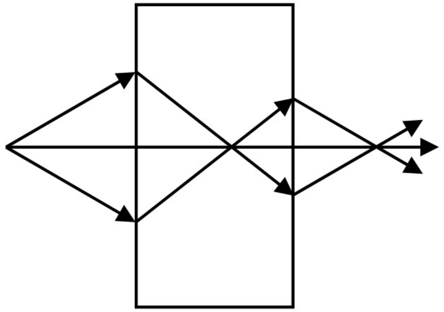

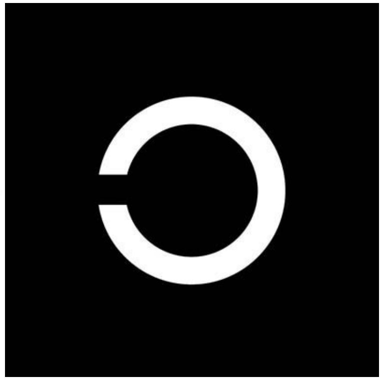

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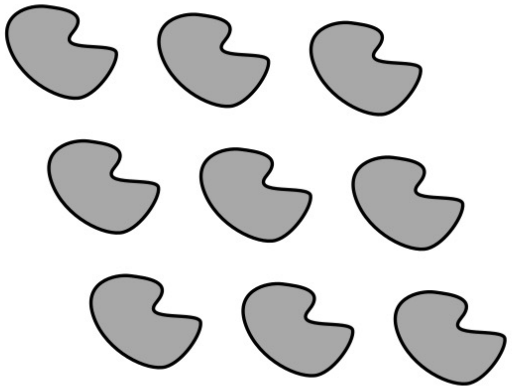

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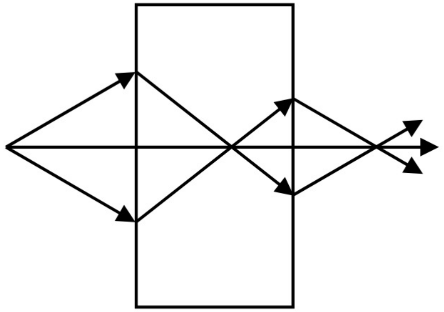
Metamaterials: tailored spatial response



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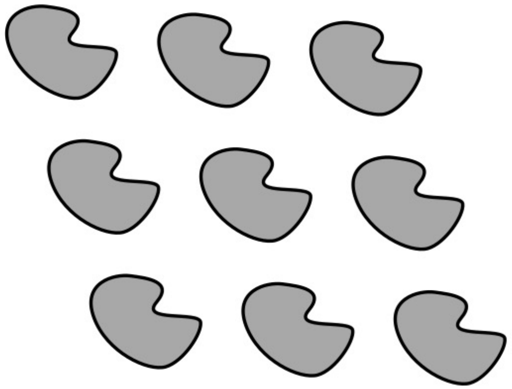

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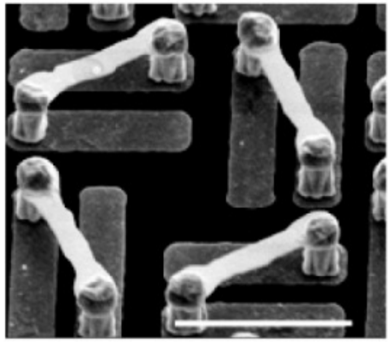

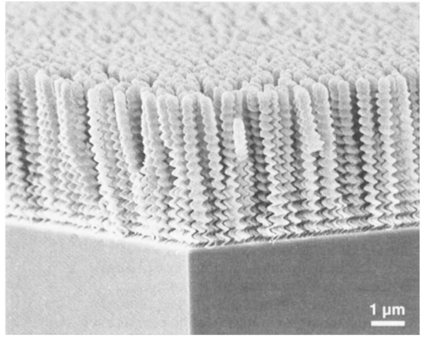

Polarization and chirality

Pendry, Lakhtakia, X Zhang, Zheludev, He, Wegener, Pertsch,
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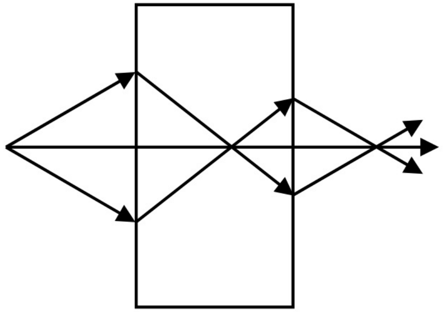
Metamaterials: tailored spatial response



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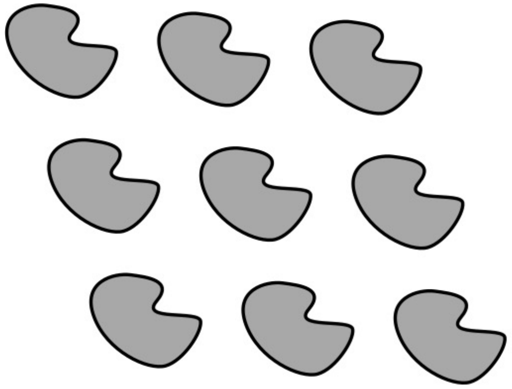

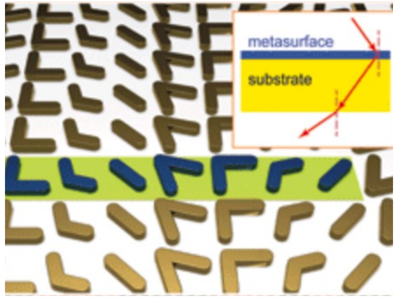

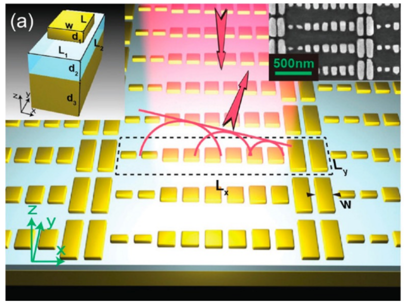

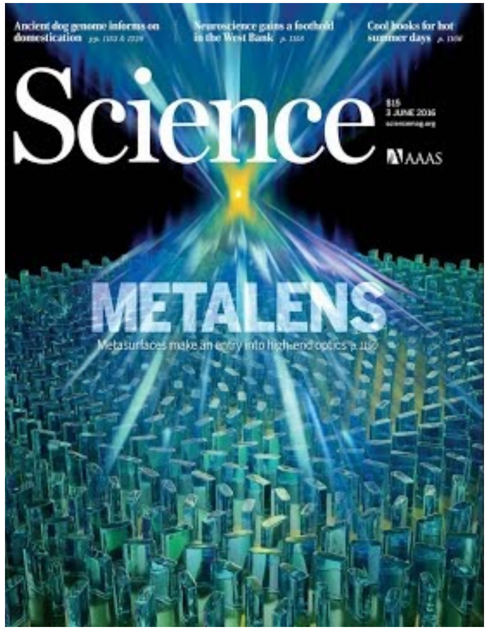

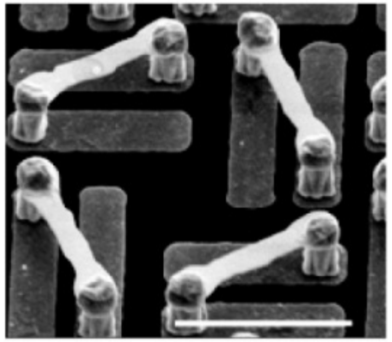

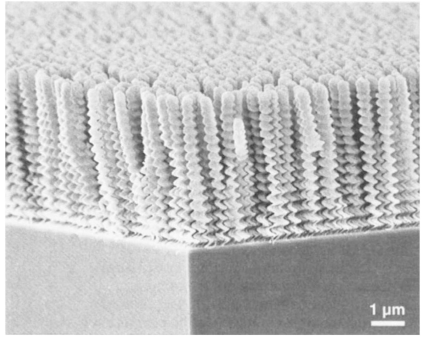

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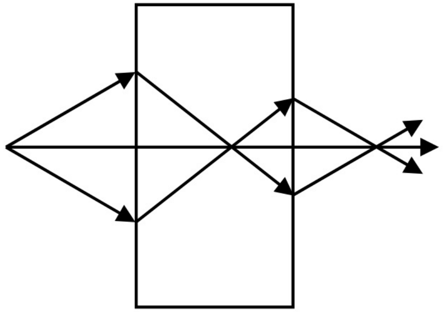
Metasurface-based devices

Capasso, Yu, Kivshar, Shalaev, Boltasseva, Brongersma, Fan,
Maier, Belov, Simovski, Zentgraf, Alu, Tsai, Bozhevolnyi,
Neshev, Cai, Faraon, Staude, Brener, many others

Metamaterials: tailored spatial response



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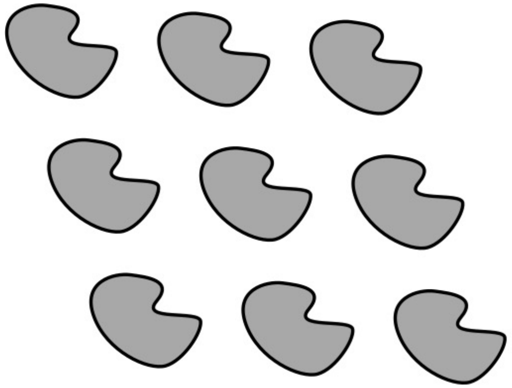

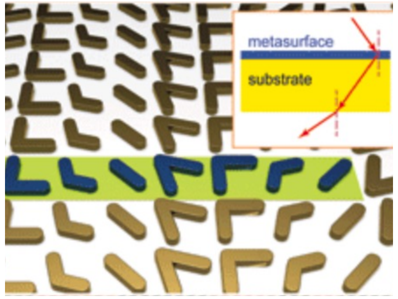

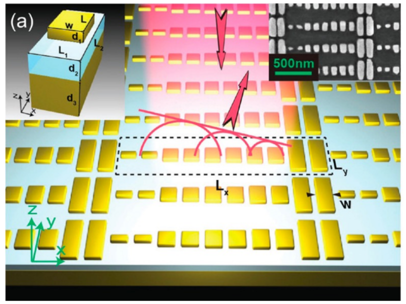

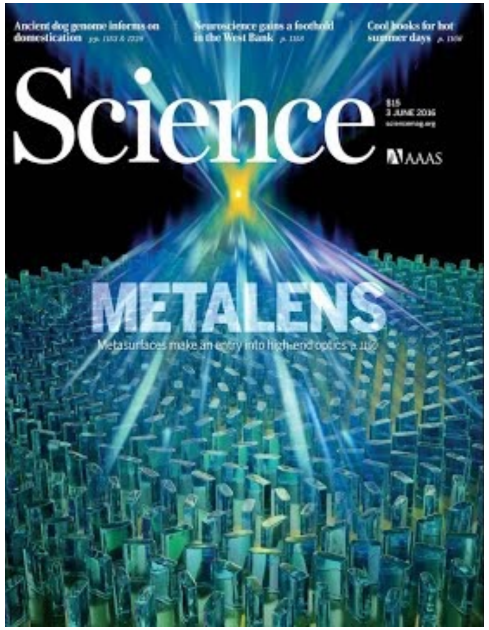

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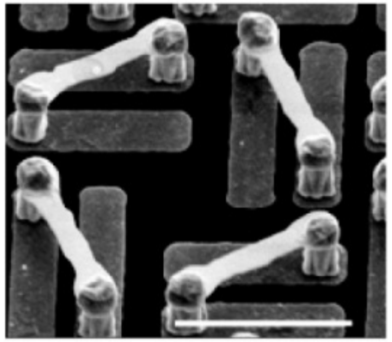

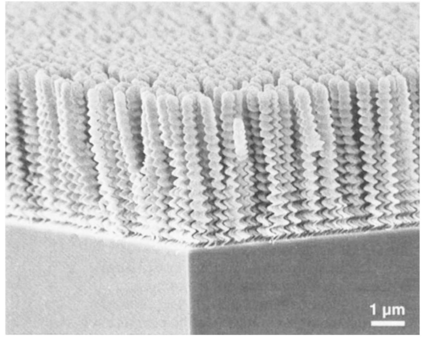

$\chi(\mathbf{r})$ defines it all

Polarization and chirality

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Metamaterials: tailored nonlinear and spatio-temporal response

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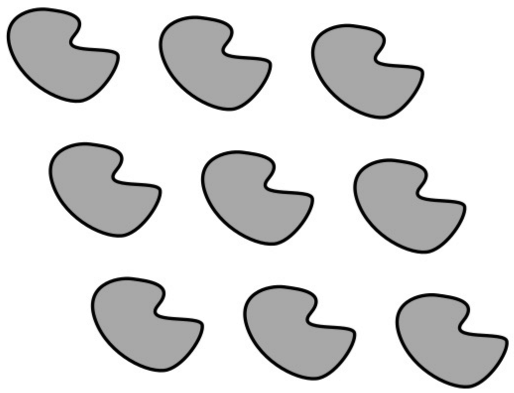

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UCI Samueli School of Engineering

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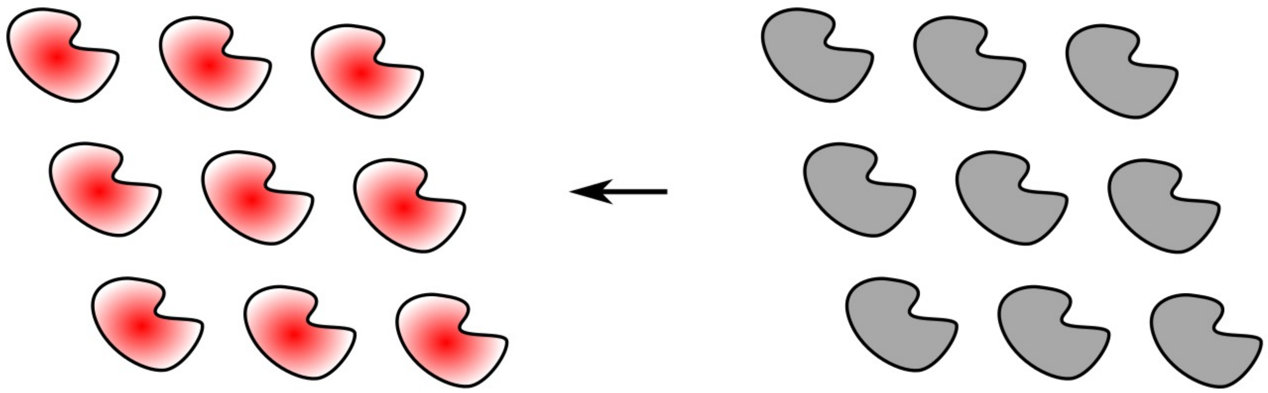
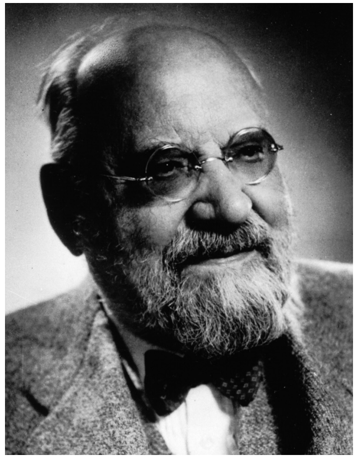
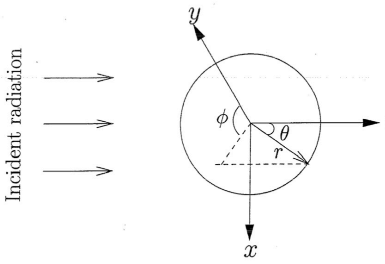


Nonlinear metamaterials

Nonlinear metasurfaces — harmonics generation

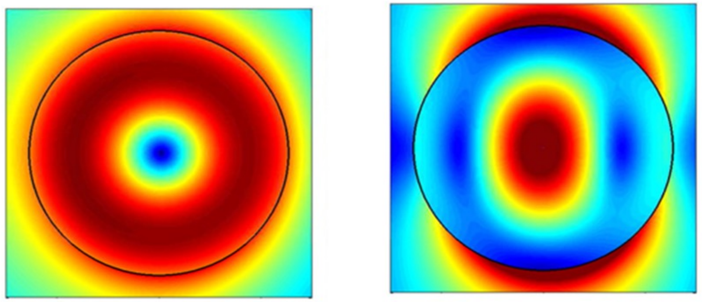


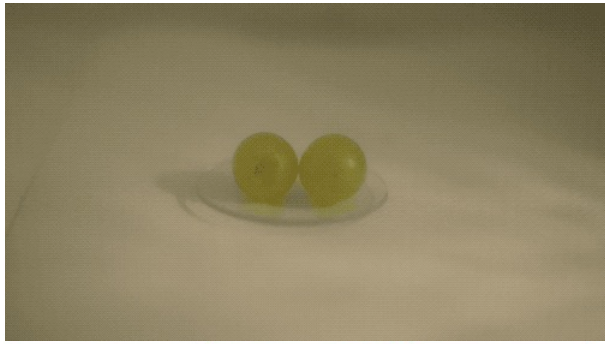
Gustav Mie
(1869 – 1957)

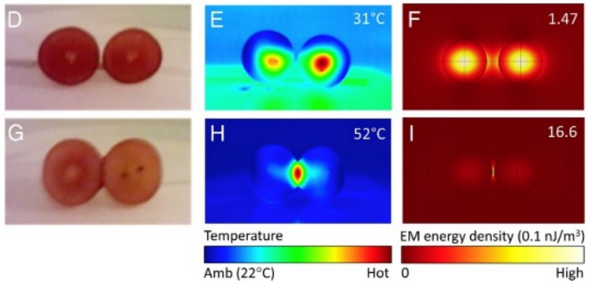


Bohren, C. F. & Huffman, D. R. *Absorption and Scattering of Light by Small Particles* Wiley Inter-Science, 1998.

$|\mathbf{E}|^2$ maps



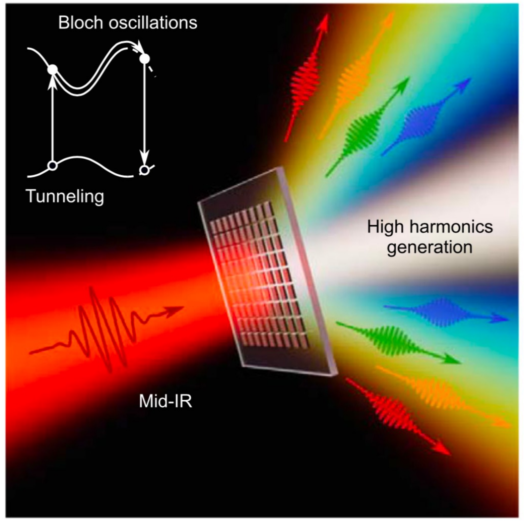


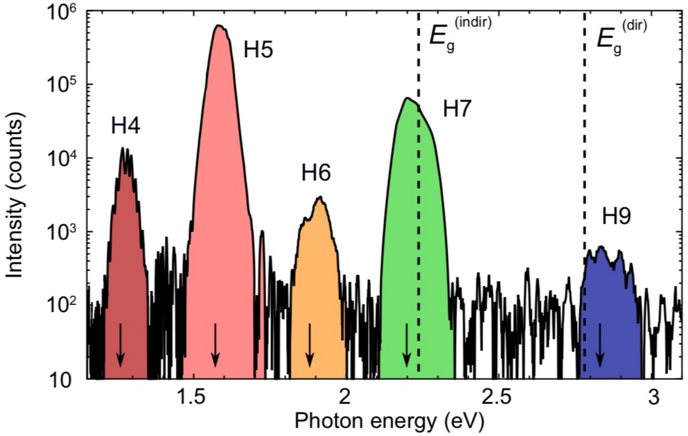


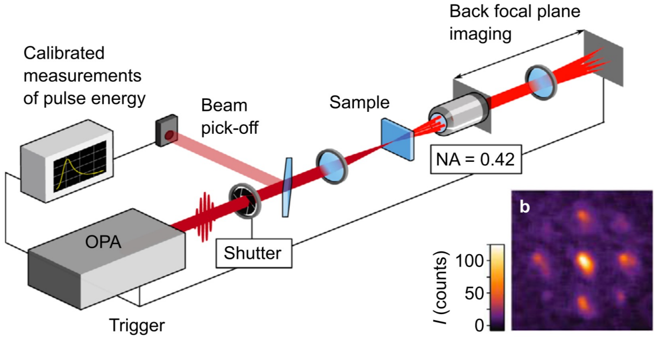
Khattak et al., *PNAS* **116**, 4000 (2019)

$$\tilde{P} = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \ldots$$

$$\tilde{E}(t) \propto e^{i\omega t} \qquad \propto e^{2i\omega t} \qquad \propto e^{3i\omega t}$$







Record-breaking conversion from an ultrathin material

Shcherbakov et al., *Nat. Commun.* **10**, 1345 (2019)

Metamaterials: tailored nonlinear and spatio-temporal response

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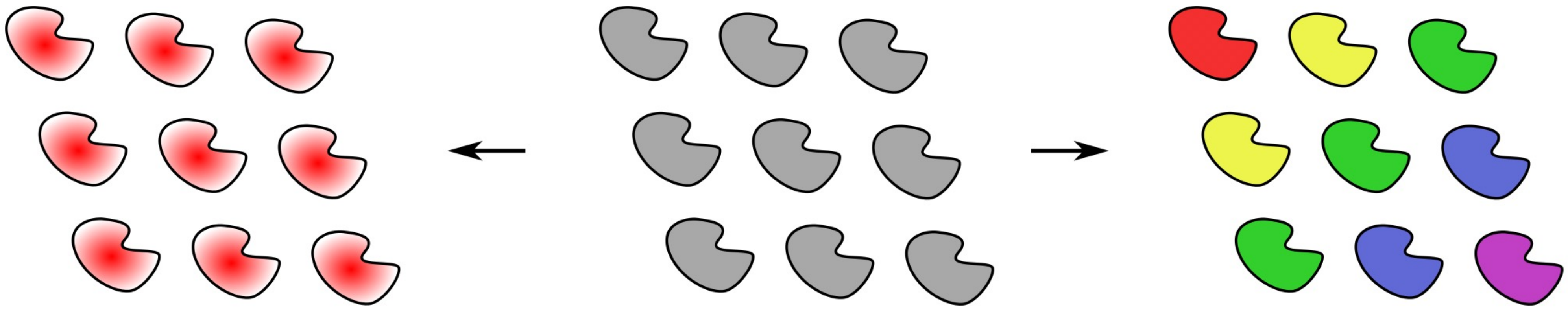
$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r})\mathbf{E}(\mathbf{r})$$

$$\mathbf{P}(\mathbf{r},t) = \varepsilon_0 \int d\mathbf{r}' \int dt' \, \chi(\mathbf{r},t,\mathbf{r}',t')\mathbf{E}(\mathbf{r}-\mathbf{r}',t-t')$$



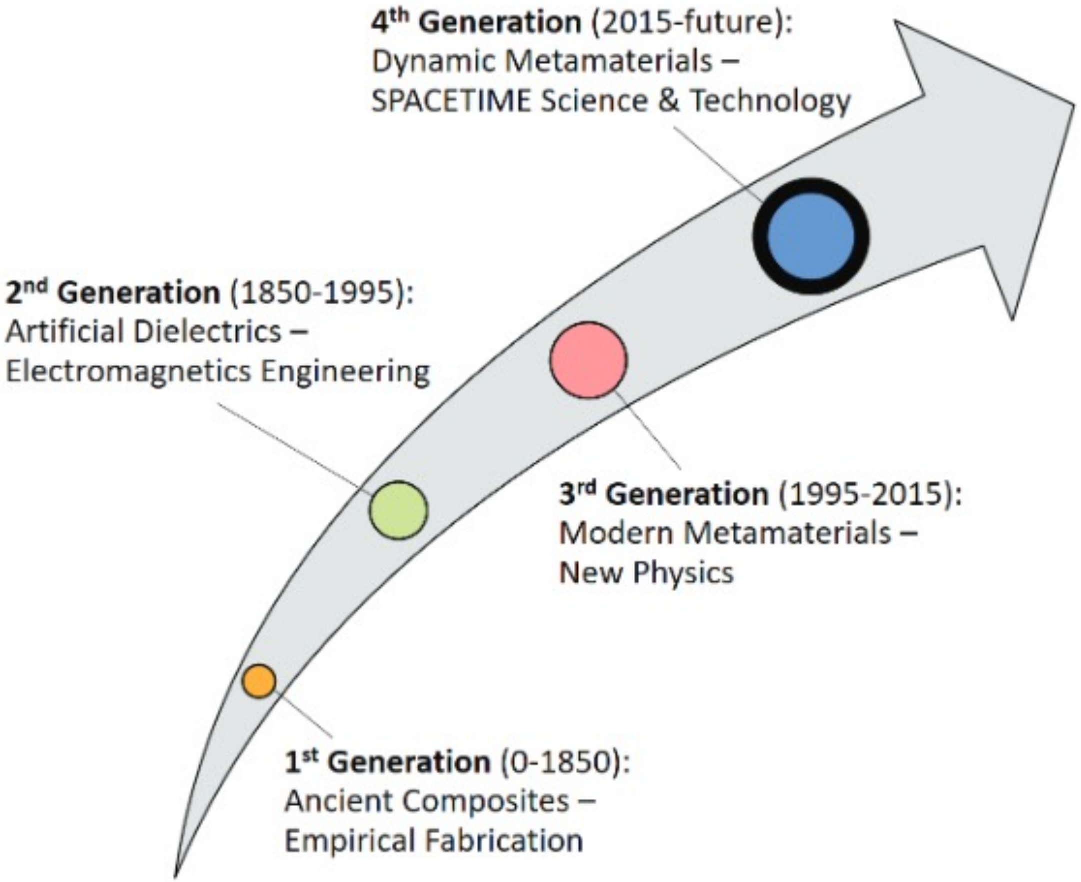
Nonlinear metamaterials

Nano Letters **14**, 6488 (2014)
ACS Photonics **2**, 578 (2015)
Nano Letters **15**, 6985 (2015)
Nano Letters **16**, 4857 (2016)
Nature Communications **8**, 17 (2017)
Nature Communications **10**, 1345 (2019)

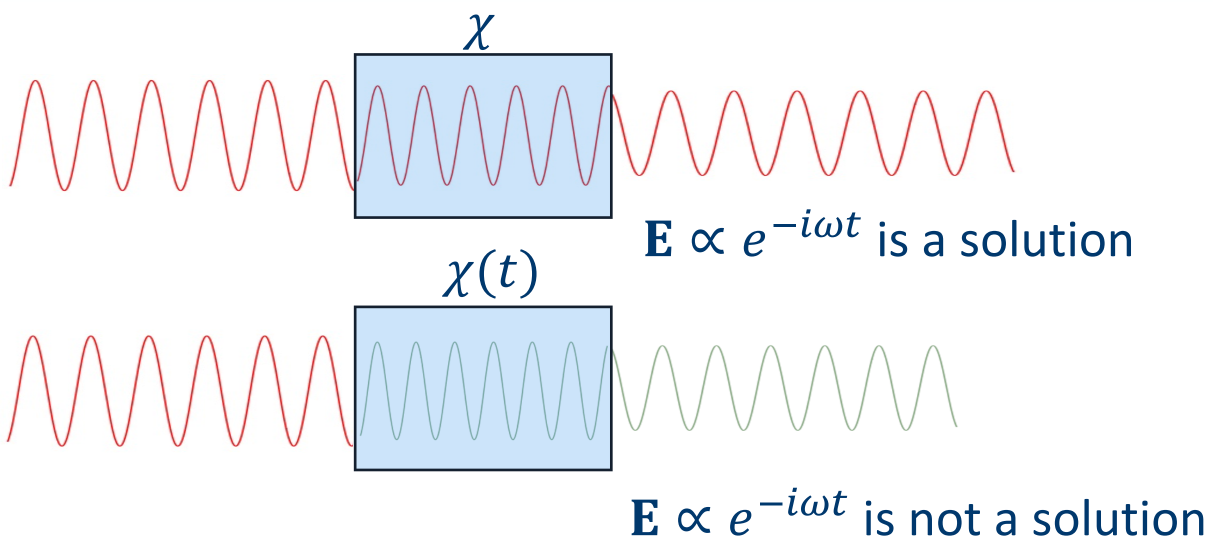
Time-variant metamaterials

Nature Communications **10**, 1345 (2019)
Optica (Memorandum) **6**, 1441 (2019)
Physical Review A **100**, 063847 (2019)
Nano Letters **20**, 7052 (2020)
APL Materials **9**, 060701 (2021)

Time-variant metasurfaces



Caloz and Deck-Leger, *IEEE Trans Ant Propag* **68**, 1569 (2020)



Caloz, Tretyakov, Boyd, Pendry, Engheta, Alu, Segev, Shadrivov, Huidobro, Boltasseva, Shalaev, Brongersma, Kinsey, Halevi, Khurgin, Caglayan, Faccio, Nassar, Narimanov, Monticone, Sapienza, Fleury, Rodriguez, Lurie, Ramezani, Ramaccia
many others

Focus of this talk:
Aperiodic modulation in resonators

Time-variant semiconductor metasurfaces. Outline

- Frequency conversion
- Breaking the time-bandwidth limit
- Discussion: Time-variant ∈ nonlinear?
- Conclusion

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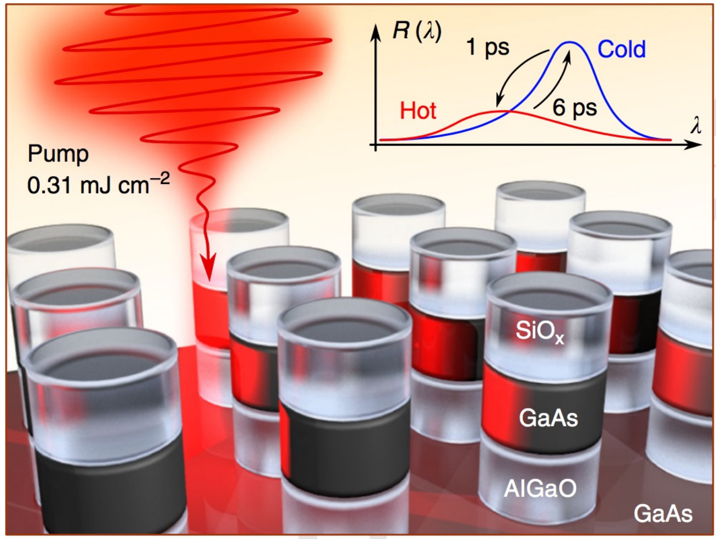
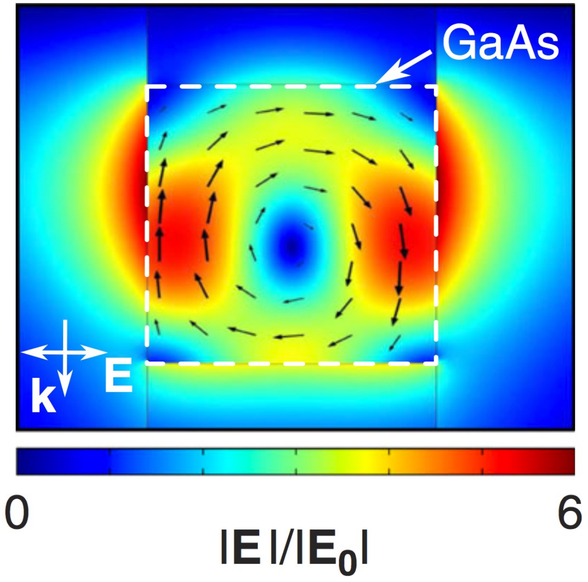
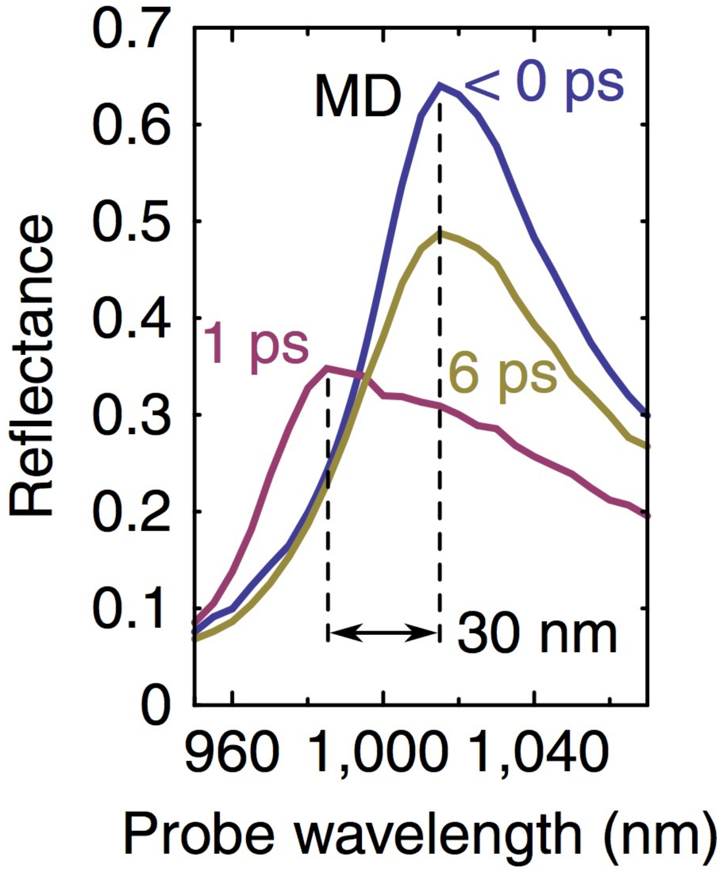
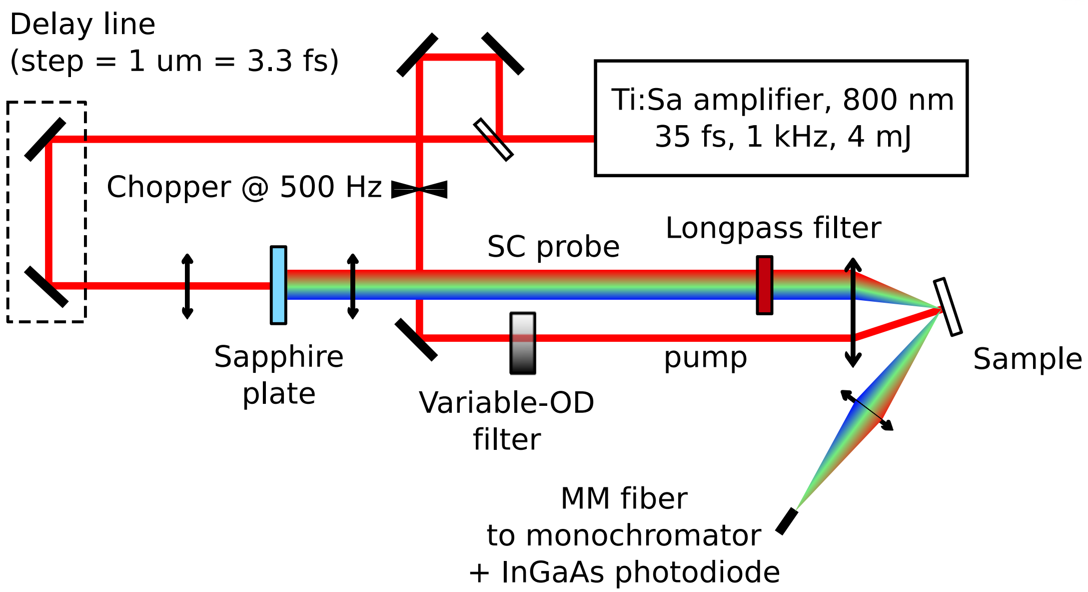
Time-variant metasurfaces – how to?



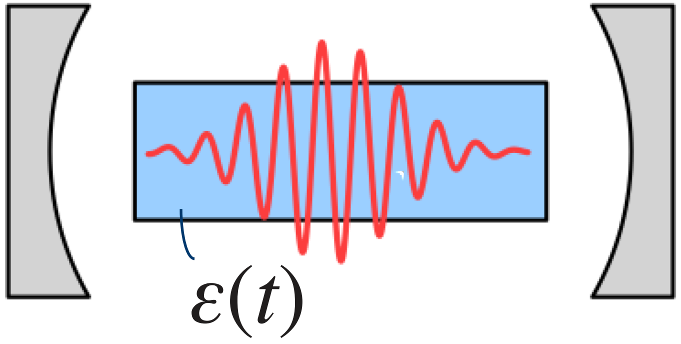






Shcherbakov et al., *Nat. Commun.* **8**, 17 (2017)

Light in time-modulated cavities



J. T. Mendonca, *Theory of Photon Acceleration* (Institute of Physics Publishing, Bristol and Philadelphia, 2000)

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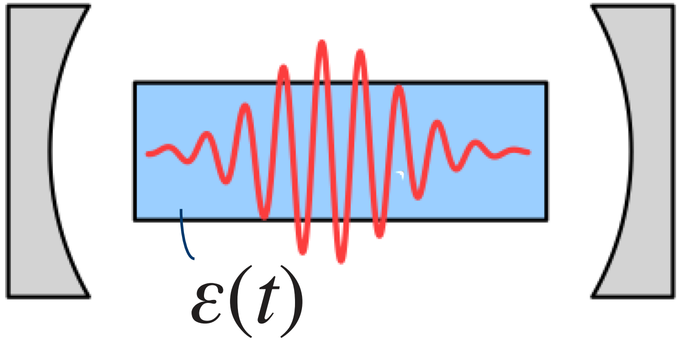

$$\ddot{a} + \frac{\dot{\varepsilon} + \sigma}{\varepsilon}\dot{a} + \frac{k^2}{\varepsilon\mu_0}a = 0$$

Time-dependent damping

Time-dependent frequency

J. T. Mendonca, *Theory of Photon Acceleration* (Institute of Physics Publishing, Bristol and Philadelphia, 2000)

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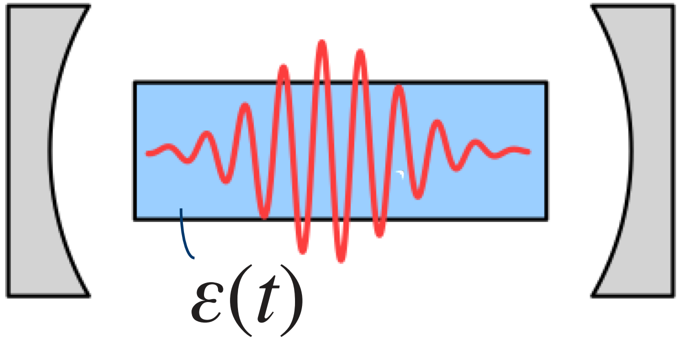

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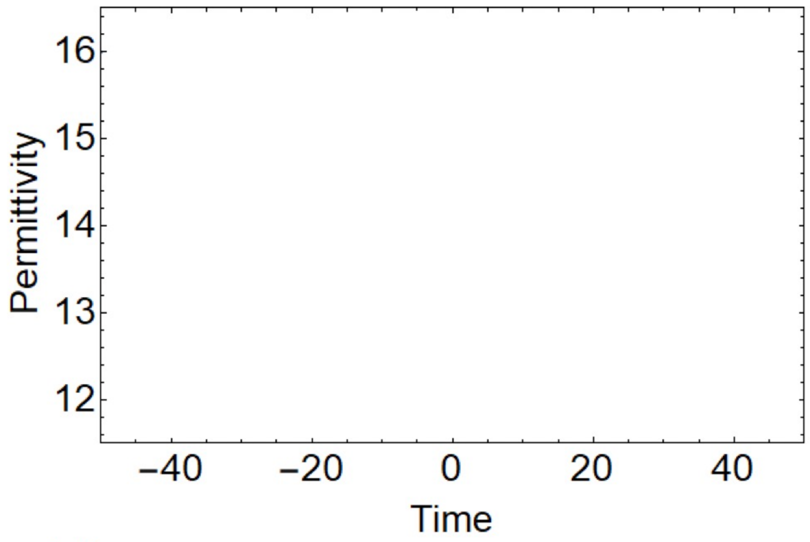

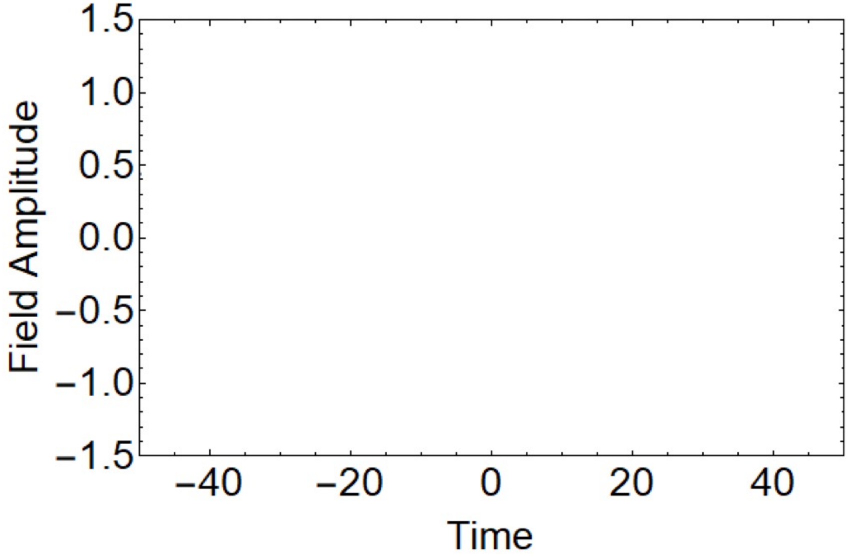

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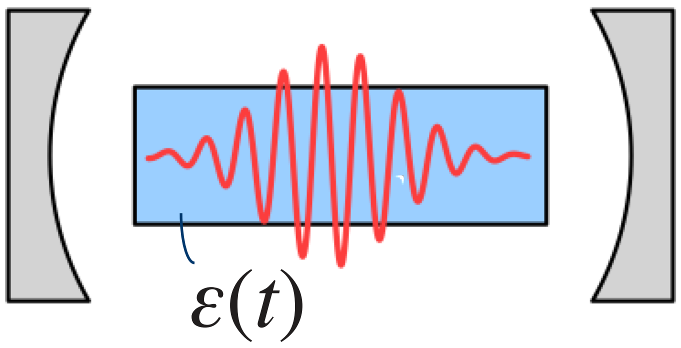

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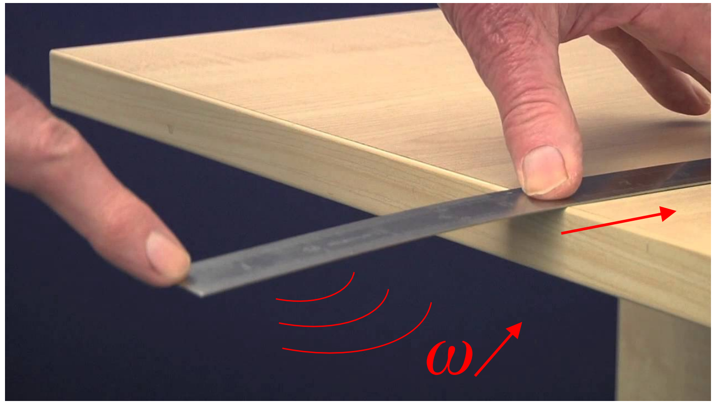

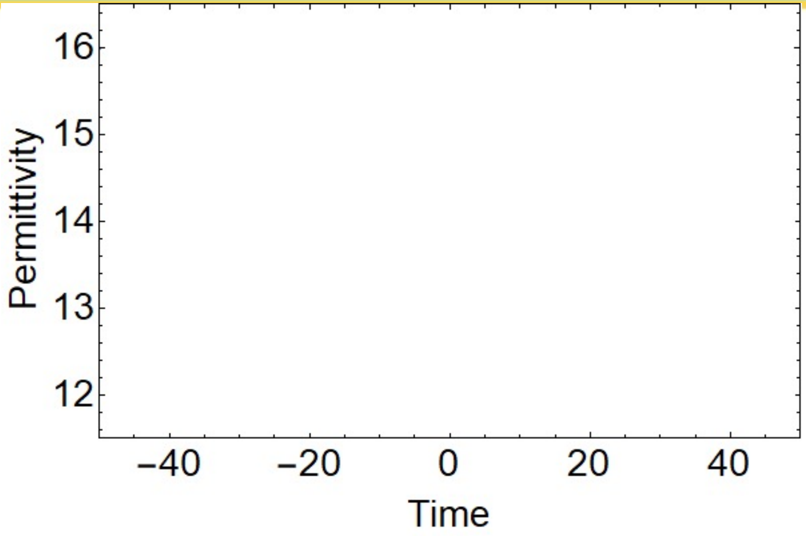

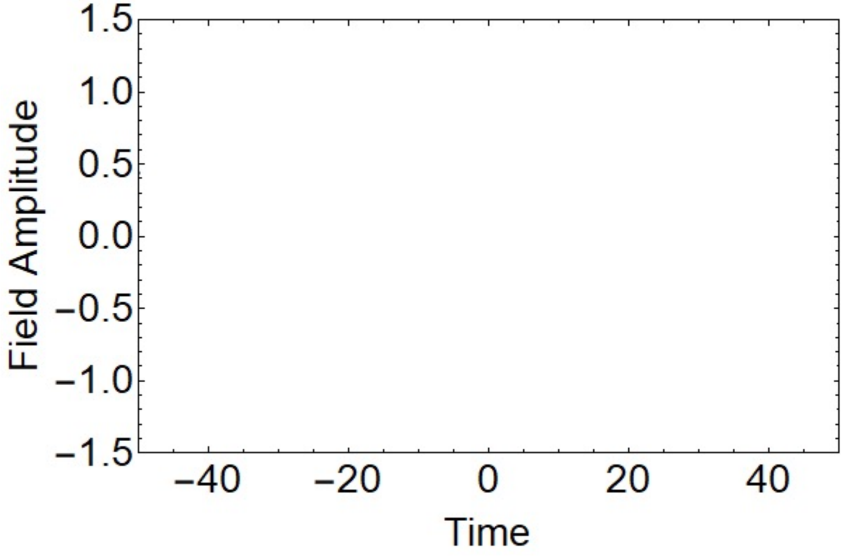

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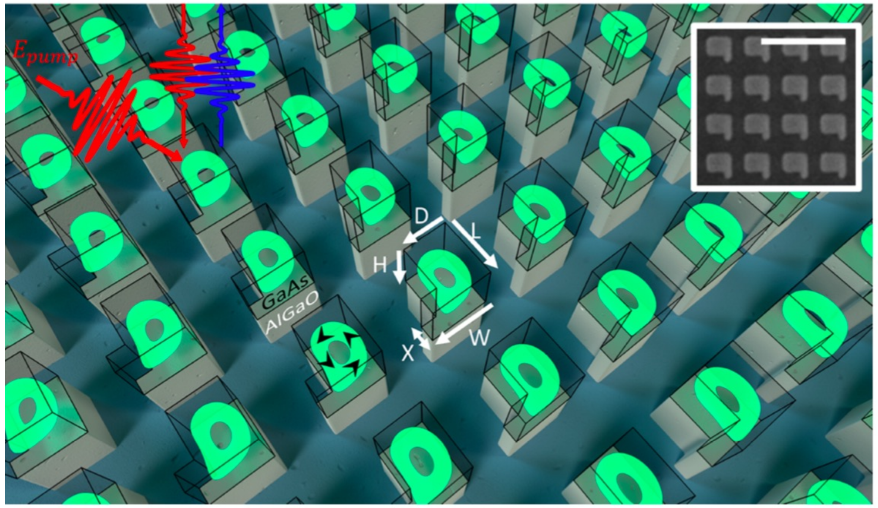
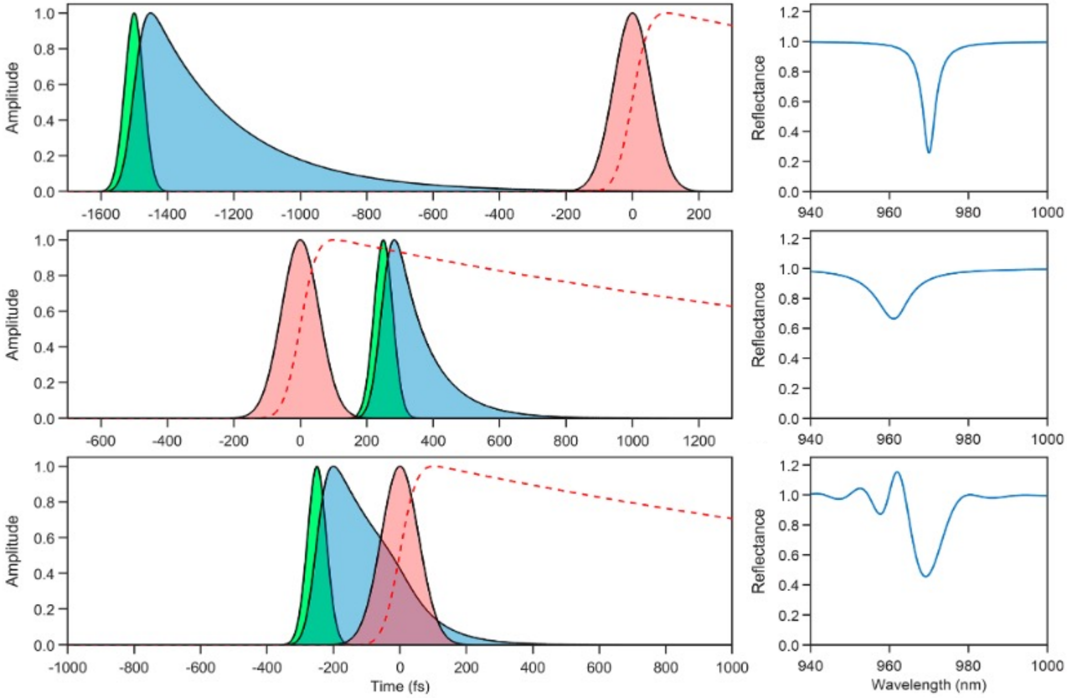
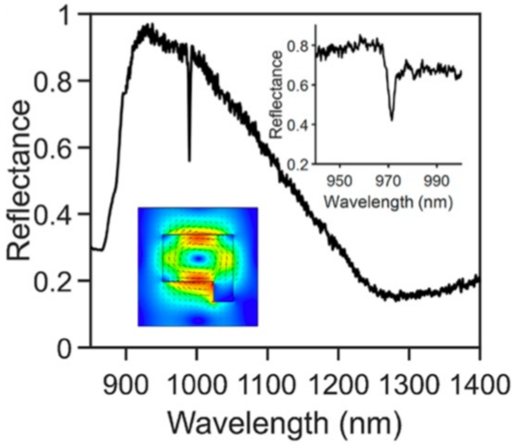
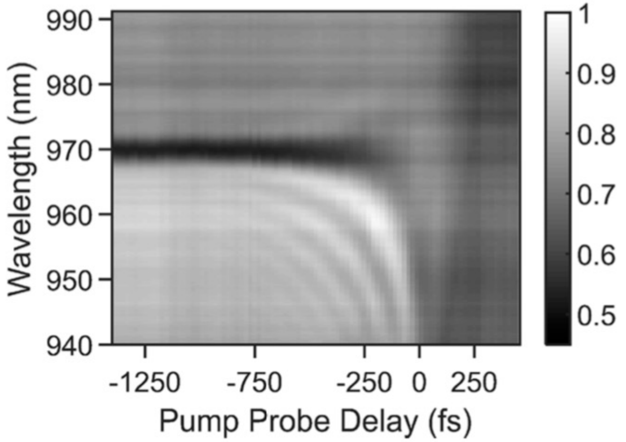
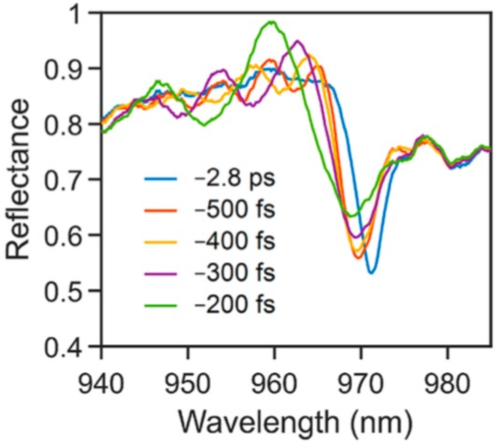
Tuning the color of light











Karl et al., *Nano Lett.* **20**, 7052 (2020)

Early demonstrations:
Lipson, Muskens, Agrawal,
Tanabe/Kuramochi, others

Frequency conversion by dynamic losses

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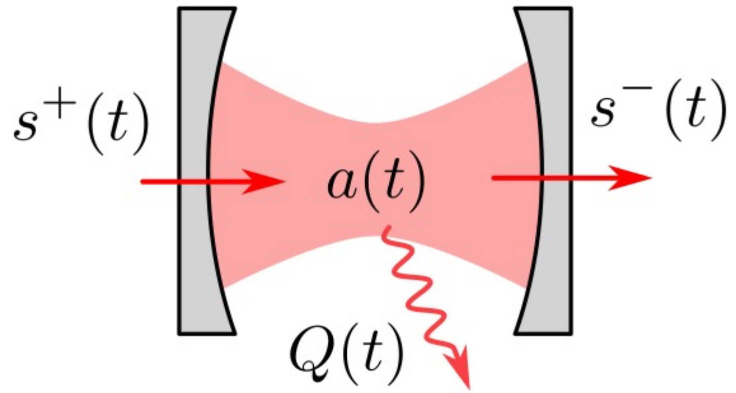
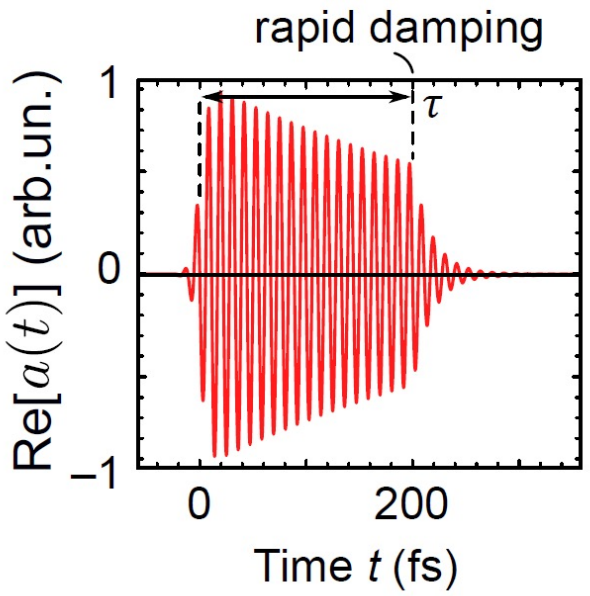
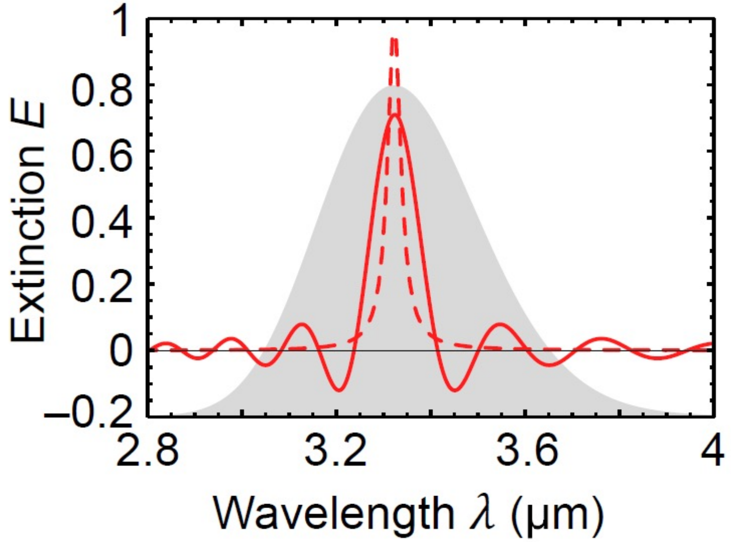
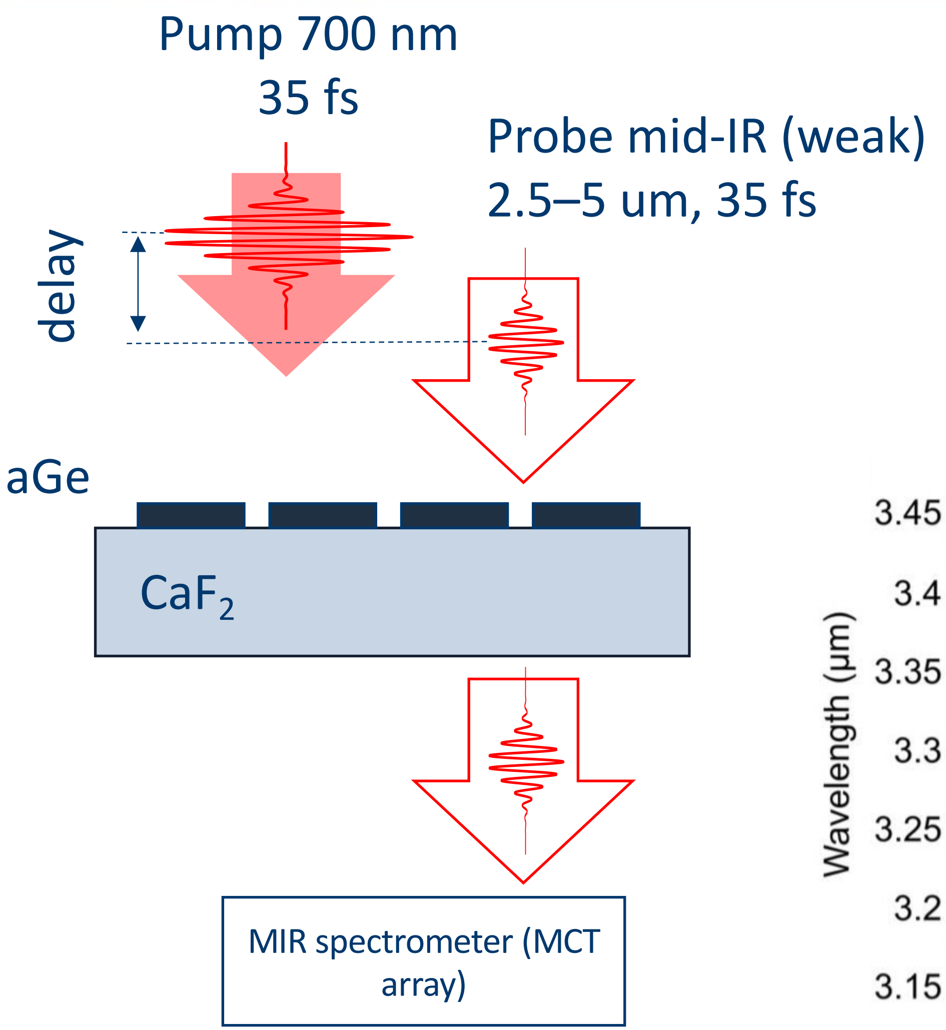
$$\dot{a}(t) + i\omega_0 a(t) + [\gamma_\mathrm{r} + \gamma_\mathrm{nr}(t)]a(t) = \sqrt{\gamma_\mathrm{r}}s^+(t),$$

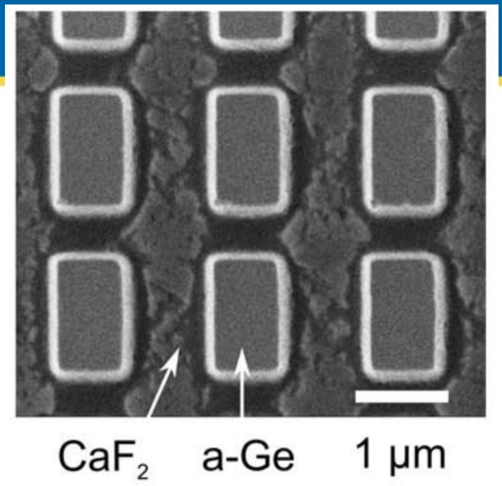
$$s^-(t) = s^+(t) - \sqrt{\gamma_\mathrm{r}}a(t)$$

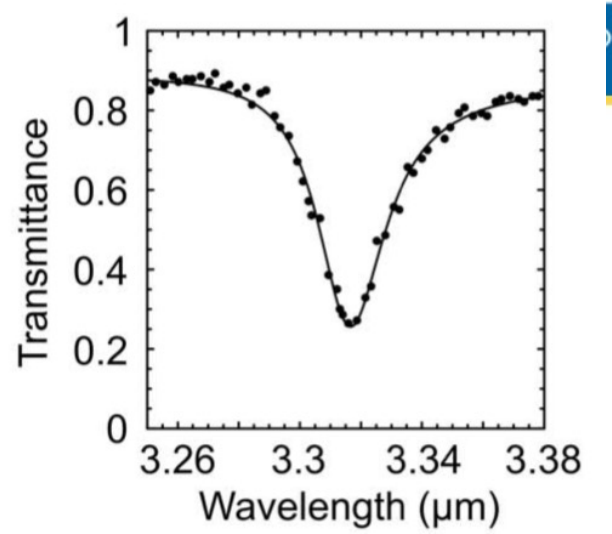


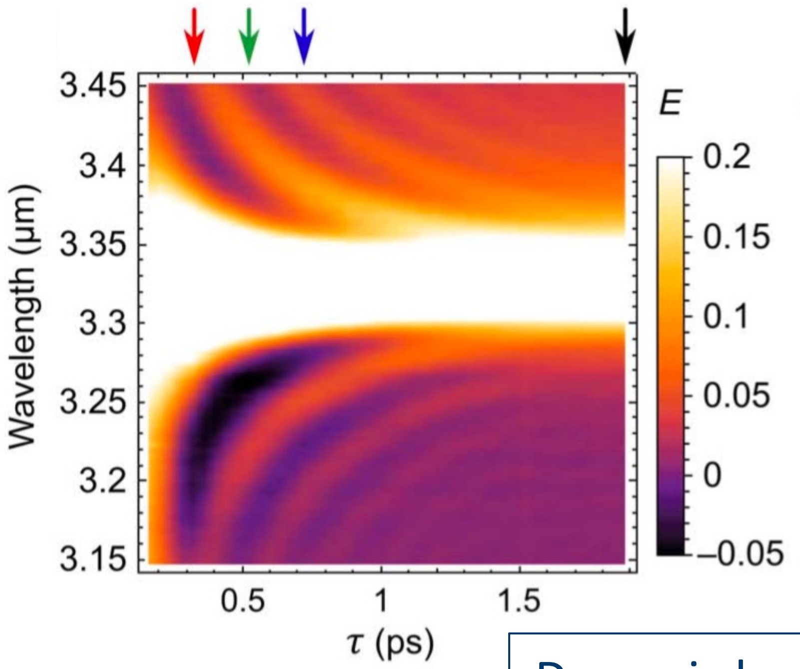


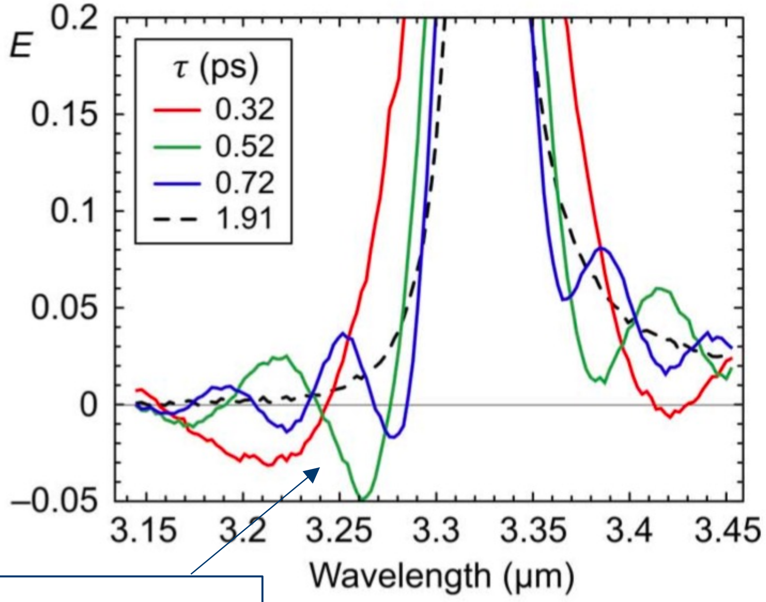










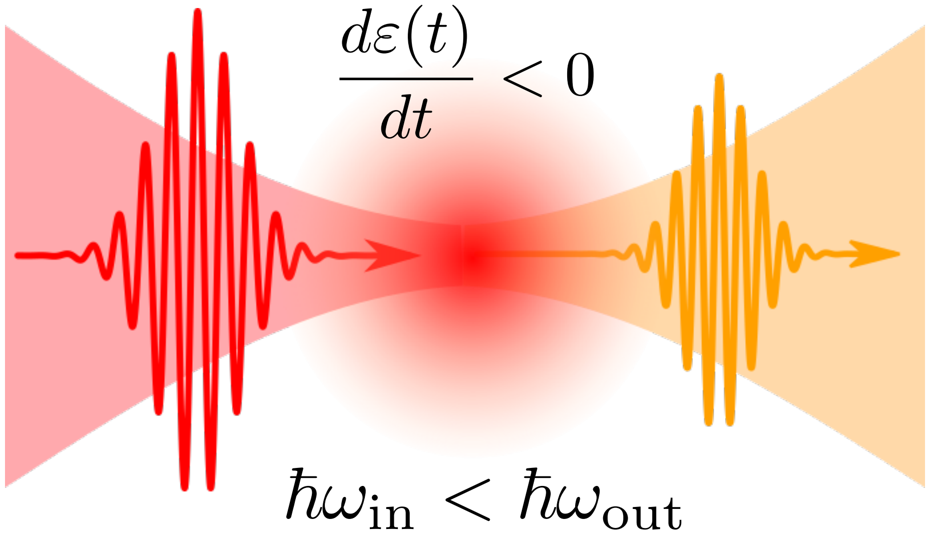


Dynamic loss-induced negative extinction

Shcherbakov et al., *Optica* **6**, 1441 (2019)

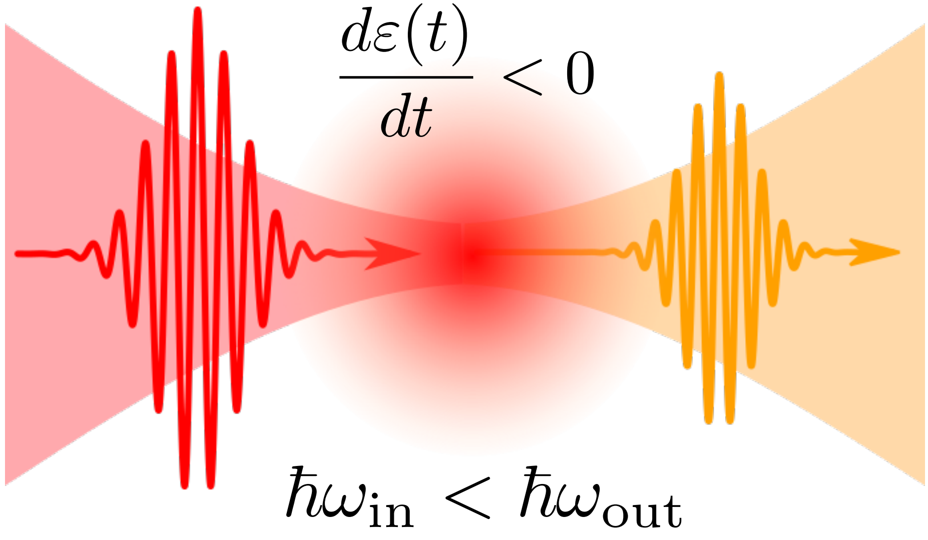
See also: Bruck et al., *Nat. Photonics* **8**, 54 (2014) – microresonators

Photon acceleration by dynamic plasma



Photon acceleration by dynamic plasma

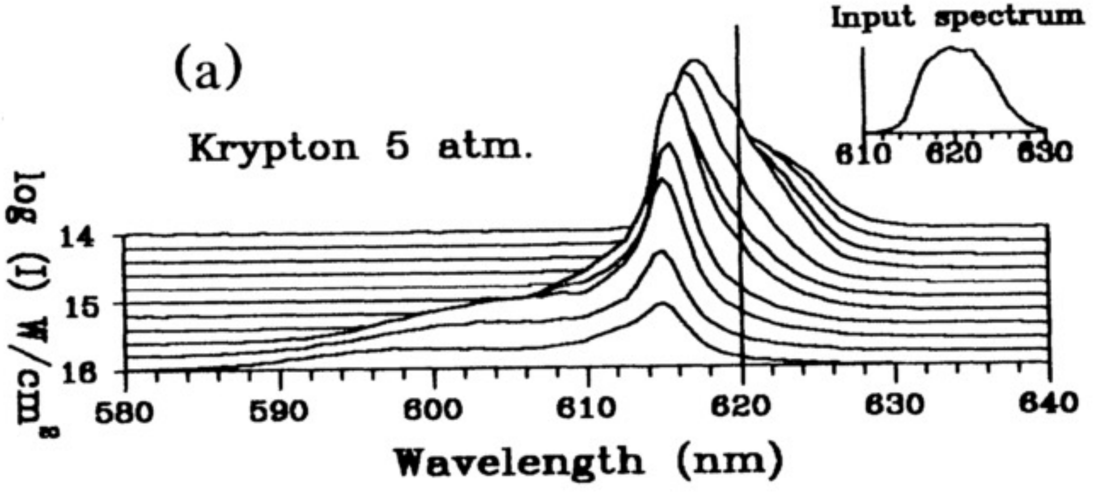
UCI Samueli School of Engineering



VOLUME 62, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 1989

Photon Accelerator

S. C. Wilks,[1] J. M. Dawson,[1] W. B. Mori,[1] T. Katsouleas,[1] and M. E. Jones[2]
[1] *Department of Physics, University of California, Los Angeles, California 90024*
[2] *Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
(Received 22 February 1989)



Theory:

[1] L. B. Felsen and G. M. Whitman, IEEE Trans. Antennas Propag. AP-18, 242 (1970).

Experiments:

[2] S. Kuo, Phys. Rev. Lett. **65**, 1000 (1990).

[3] C. Joshi, C. Clayton, K. Marsh, D. Hopkins, A. Sessler, and D. Whittum, IEEE Trans. Plasma Science **18**, 814 (1990).

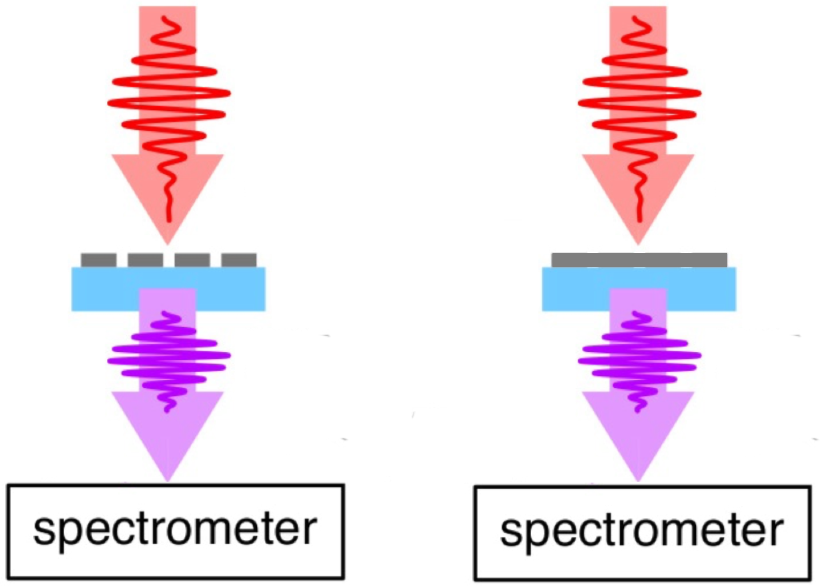
[4] E. Yablonovitch, Phys. Rev. Lett. **31**, 877 (1973).

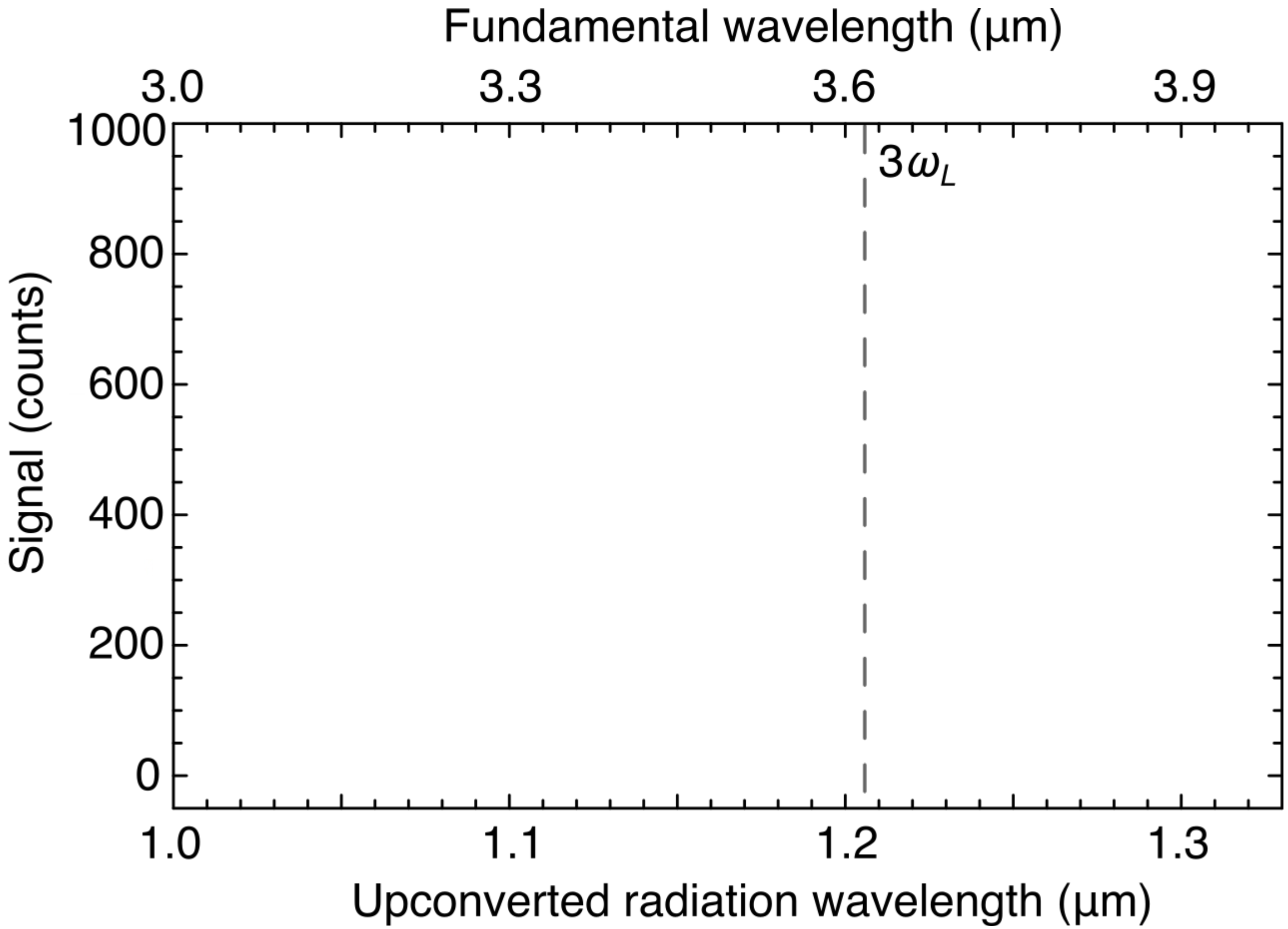
[5] V. Mironov, A. Sergeev, E. Vanin, G. Brodin, and J. Lundberg, Phys. Rev. A **46**, 6178 (1992).

[6] B. M. Penetrante, J. N. Bardsley, W. M. Wood, C. W. Siders, and M. C. Downer, J. Opt. Soc. Am. B **9**, 2032 (1992).

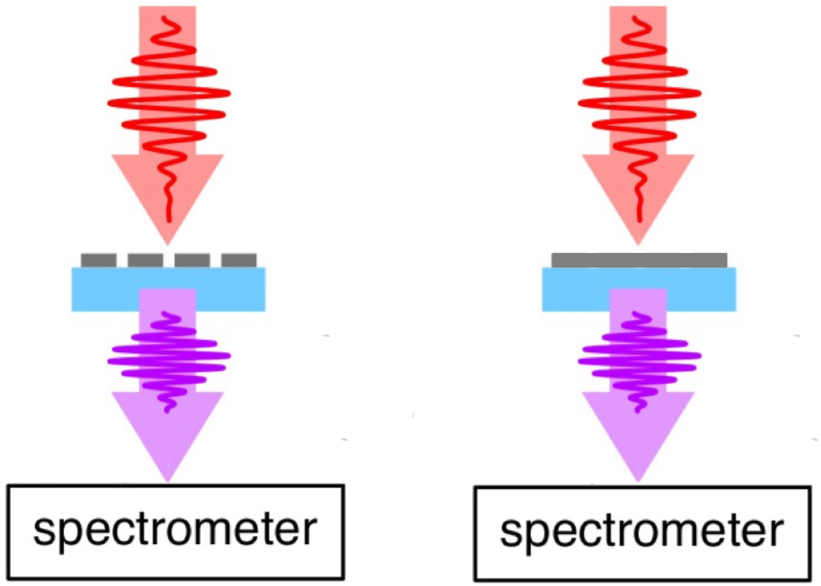
[7] W. Wood, C. Siders, and M. Downer, Phys. Rev. Lett. **67**, 3523 (1991).

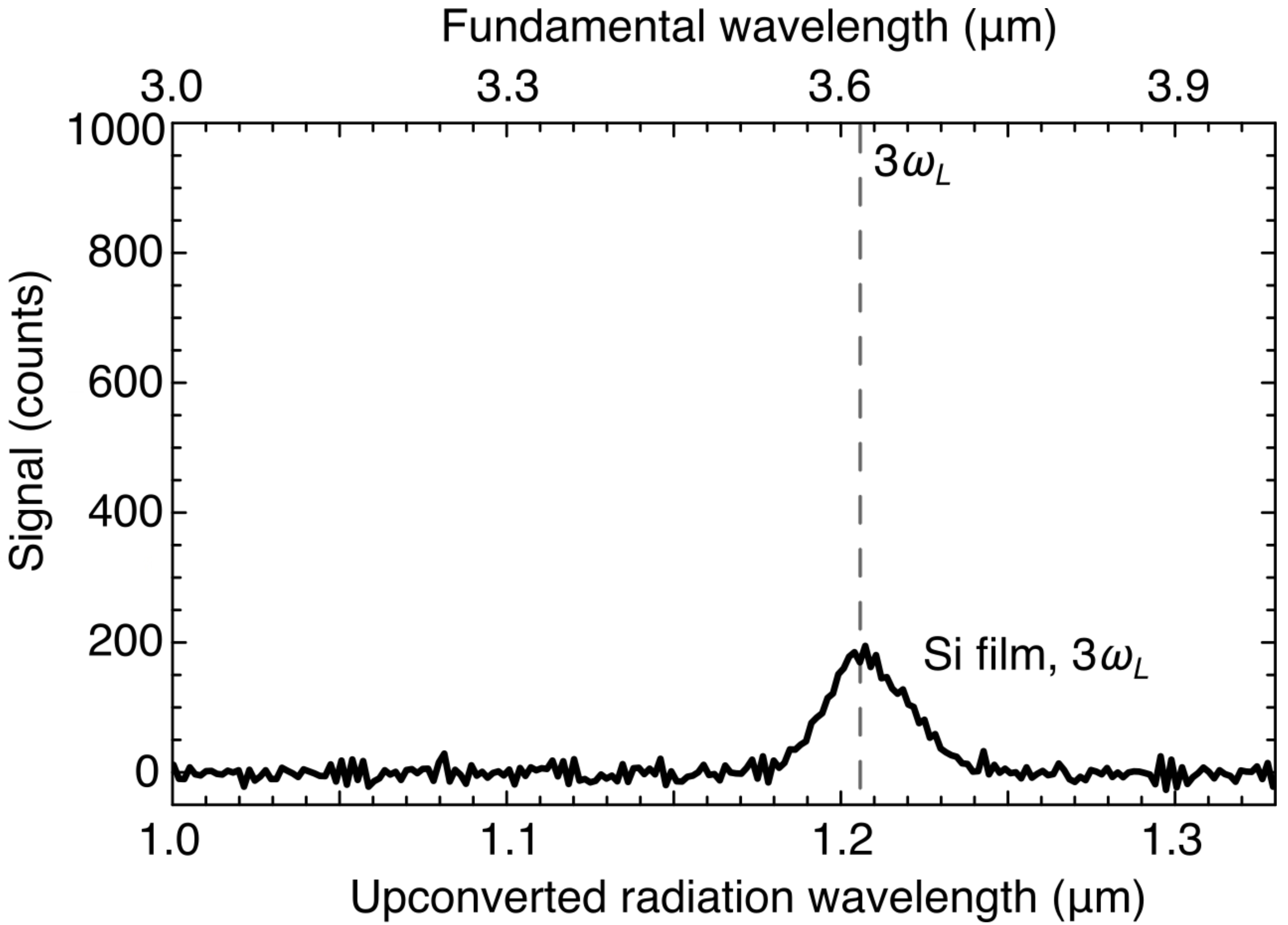
Photon acceleration probed by THG



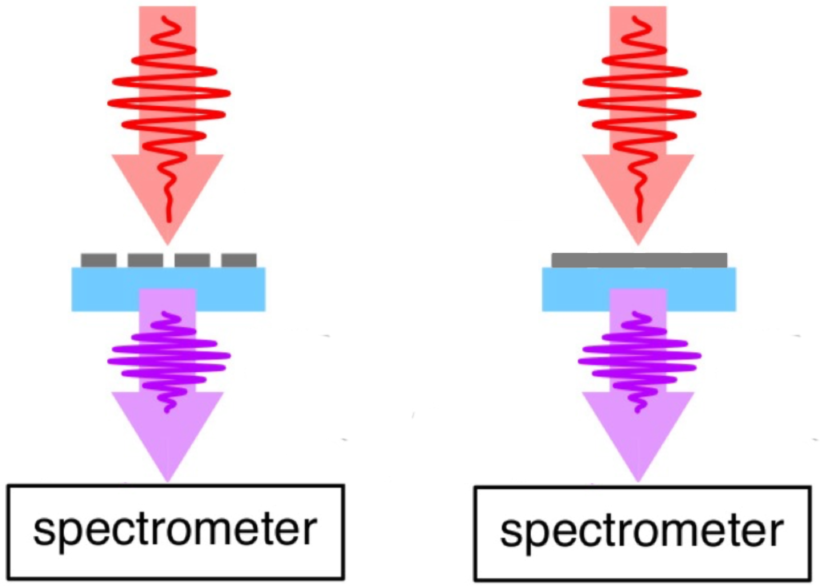


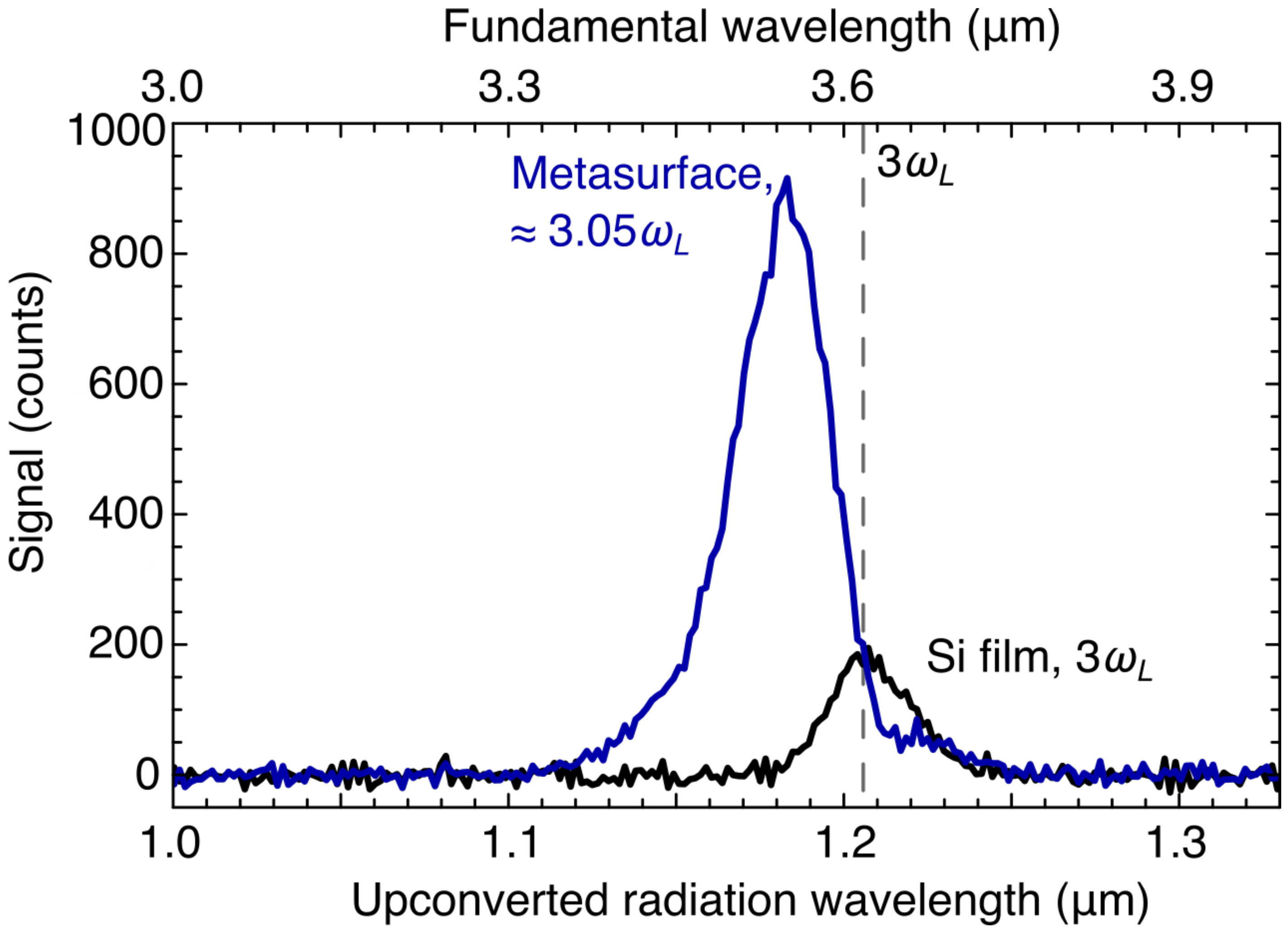
Photon acceleration probed by THG



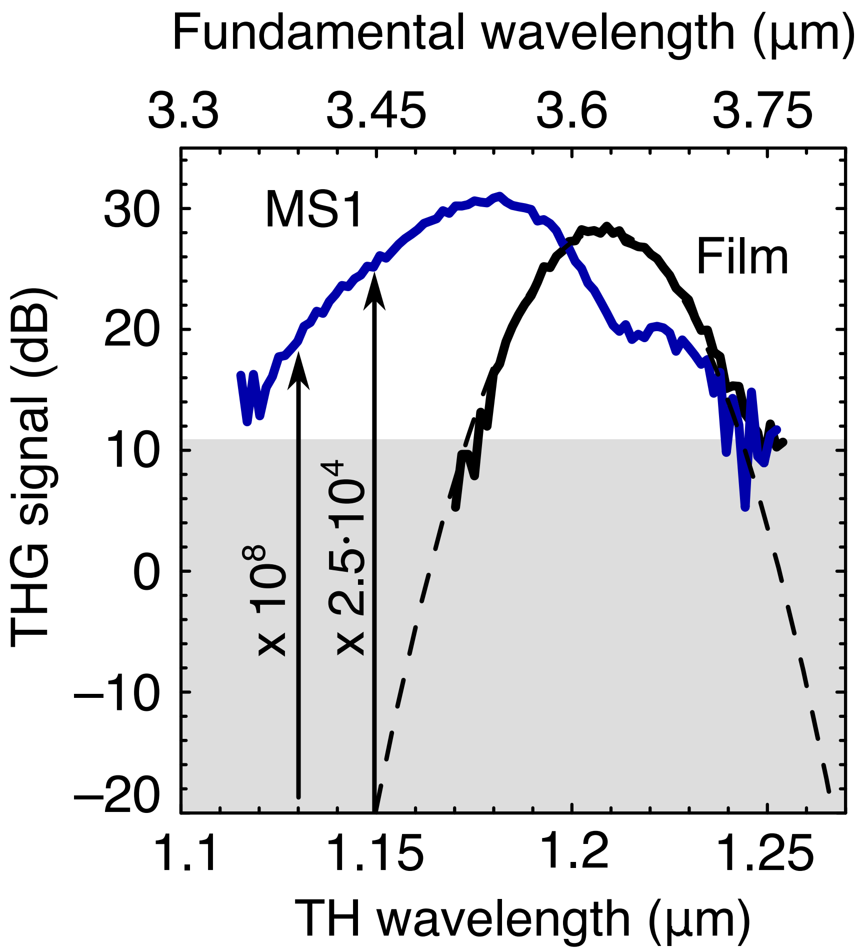


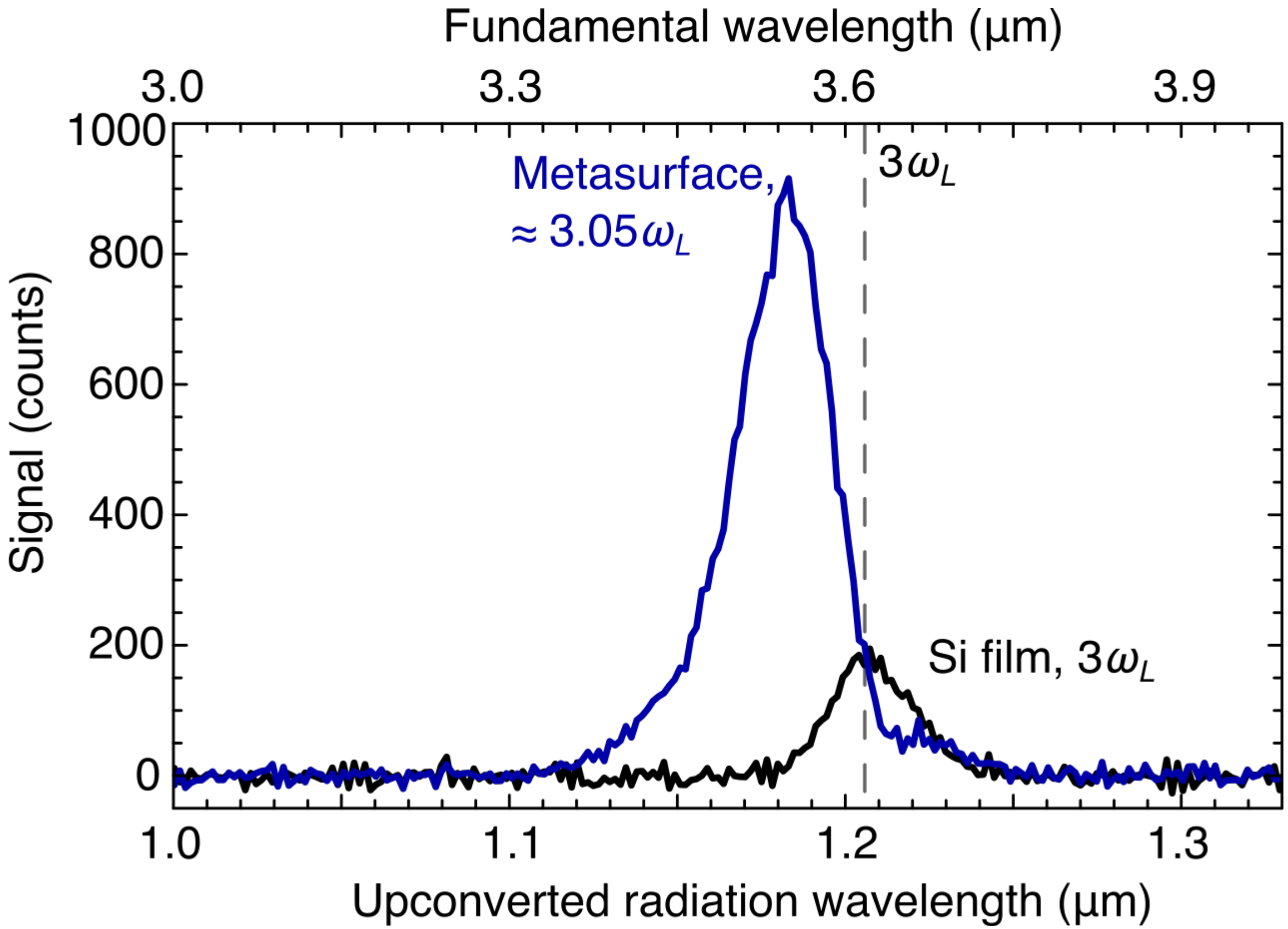
Photon acceleration probed by THG



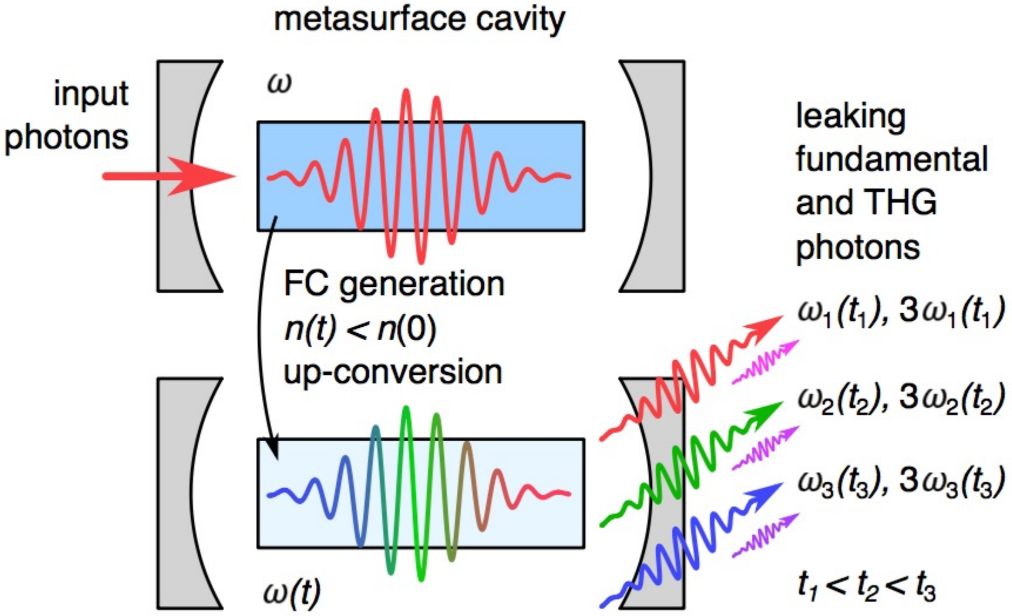


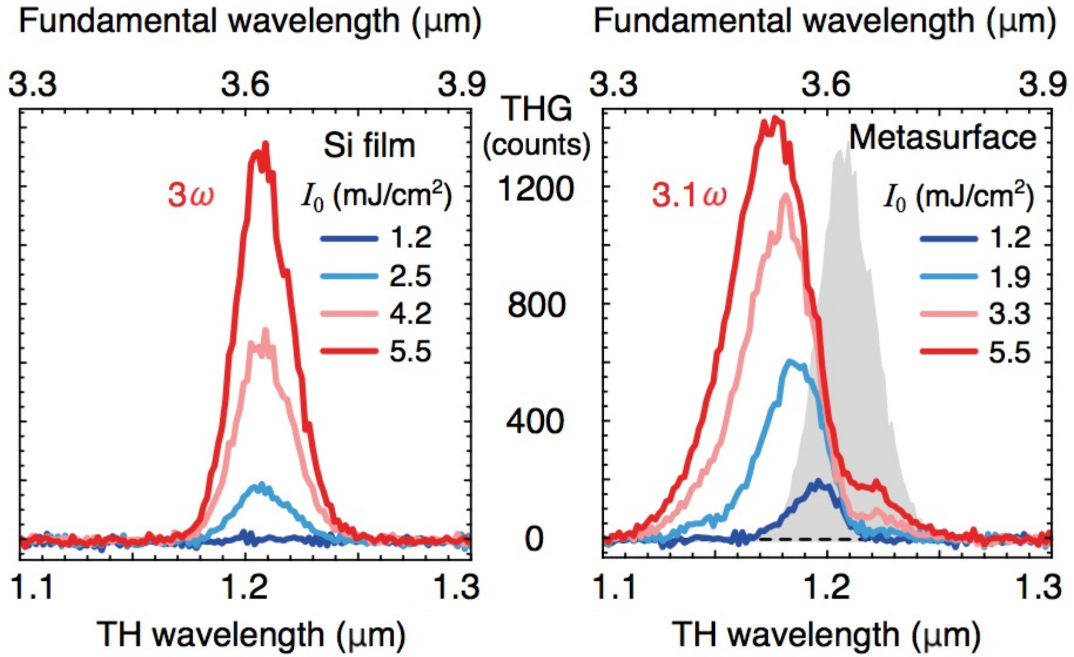
Photon acceleration probed by THG

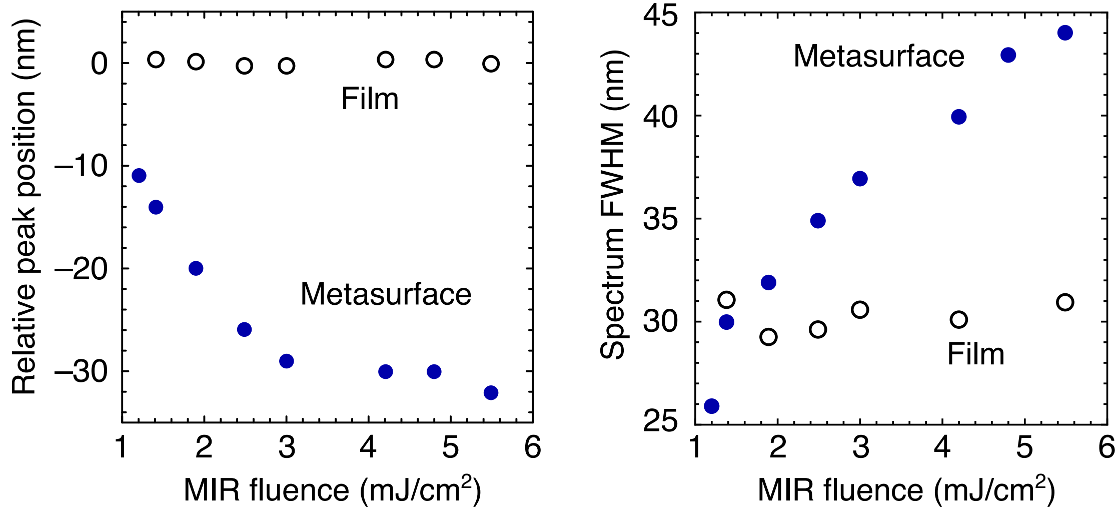




Photon acceleration probed by THG







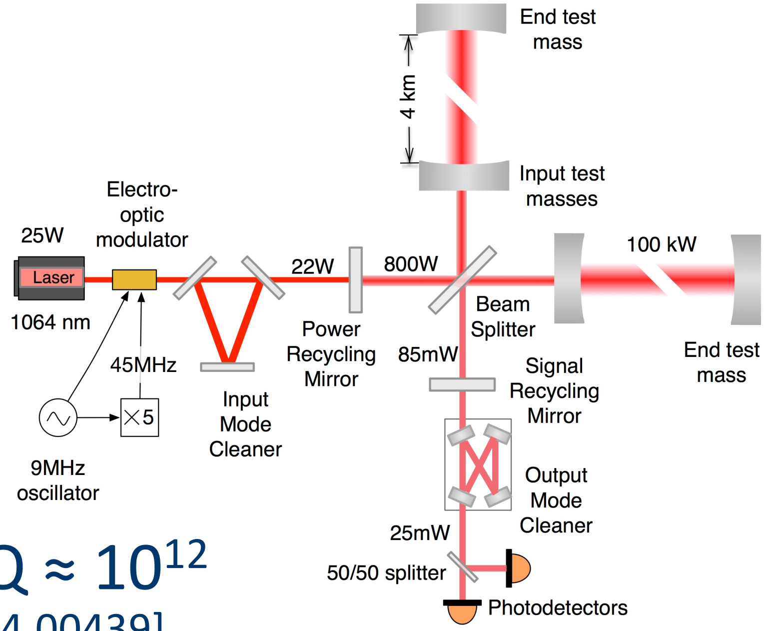
Photon acceleration
at $10^{-4}\times$ intensity
and $10^{-3}\times$ thickness
of that in gases

Shcherbakov et al., *Nat. Commun.* **10**, 1345 (2019)

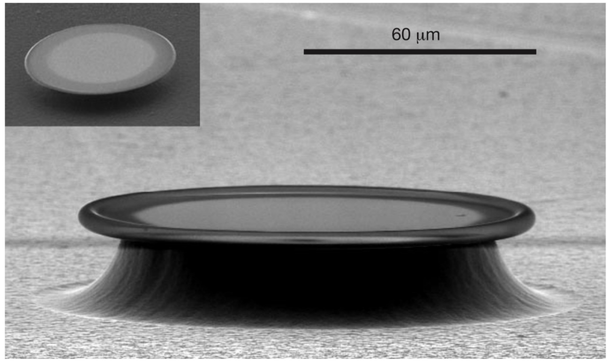
Time-variant semiconductor metasurfaces. Outline

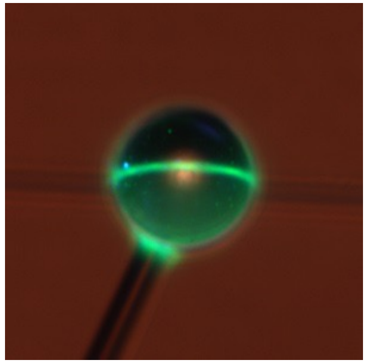
- Frequency conversion
- Breaking the time-bandwidth limit
- Discussion: Time-variant ∈ nonlinear?
- Conclusion

Resonators and the time-bandwidth limit



LIGO: Q ≈ 10^{12}
[arXiv:1604.00439]



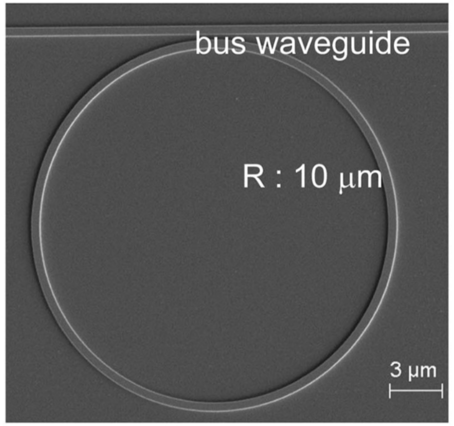


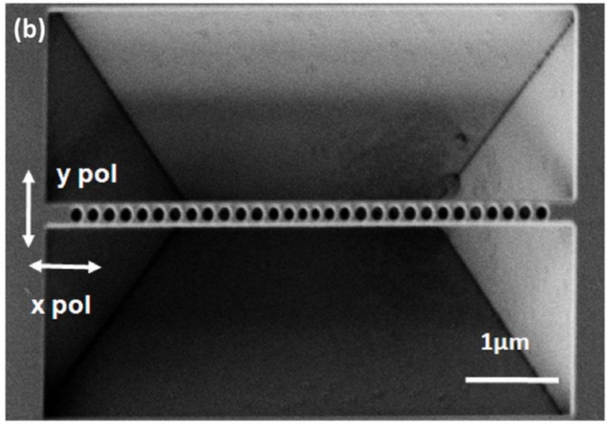
WGM resonators: Q ≈ $10^{(8-10)}$
[Vahala, Kippenberg, Gorodetskiy, Oraevsky,…]

The time-bandwidth limit:

$$\Delta t \times \Delta f \geq 1$$

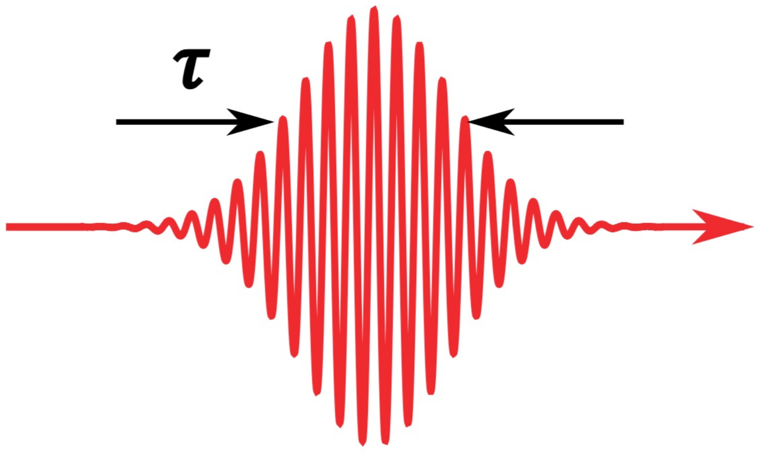
(Kupfmuller principle)





On-chip cavities: Q ≈ $10^{(4-7)}$
[Lipson, Gaeta, Loncar, Crozier, Painter…]

Problem: broad pulses, narrow resonances



Assume a standard Ti:Sapphire pulse:

τ = 85 fs, λ_c = 800 nm

FWHM bandwidth = 10 nm

Resonators with $Q \gtrapprox 100$
do not take advantage
of the full pulse bandwidth

Chirped pulse + time-varying cavity

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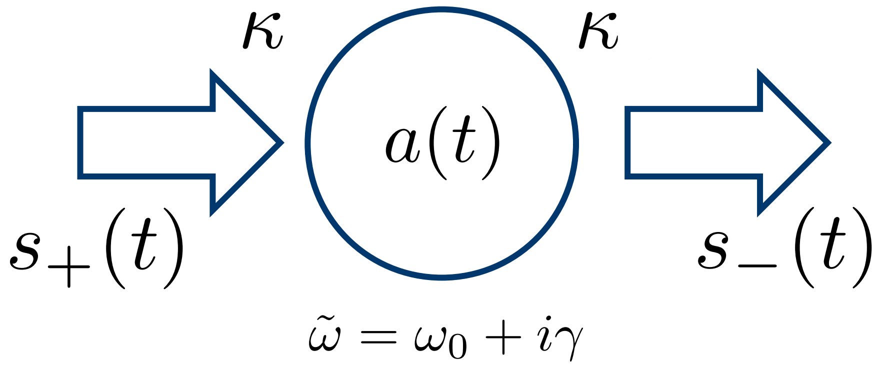
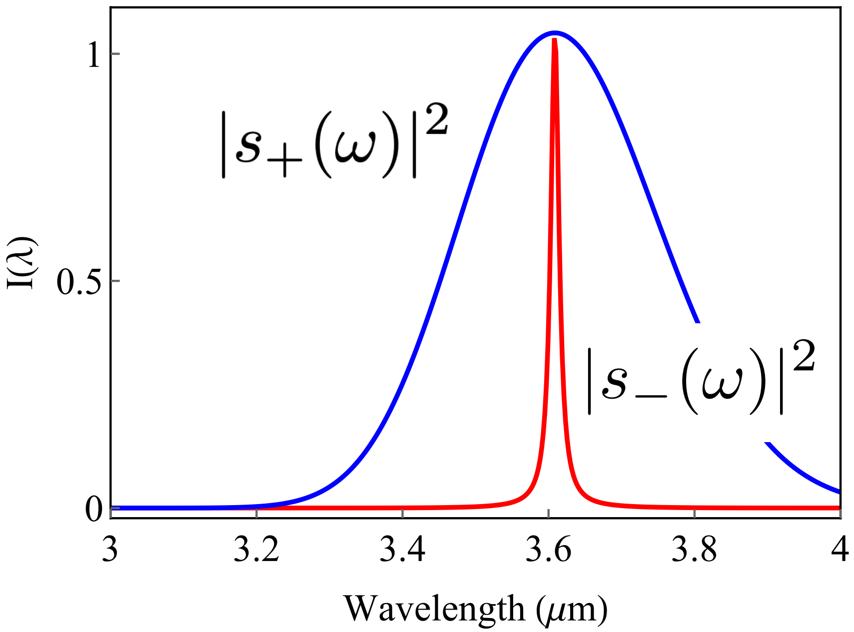


$$\dot{a}(t) + i\tilde{\omega}(t)a(t) = \kappa s_+(t)$$

$$s_+(t) = s_0 e^{-i\omega\left(1+\frac{t\delta}{2}\right)t - \frac{t^2}{\tau^2}}$$

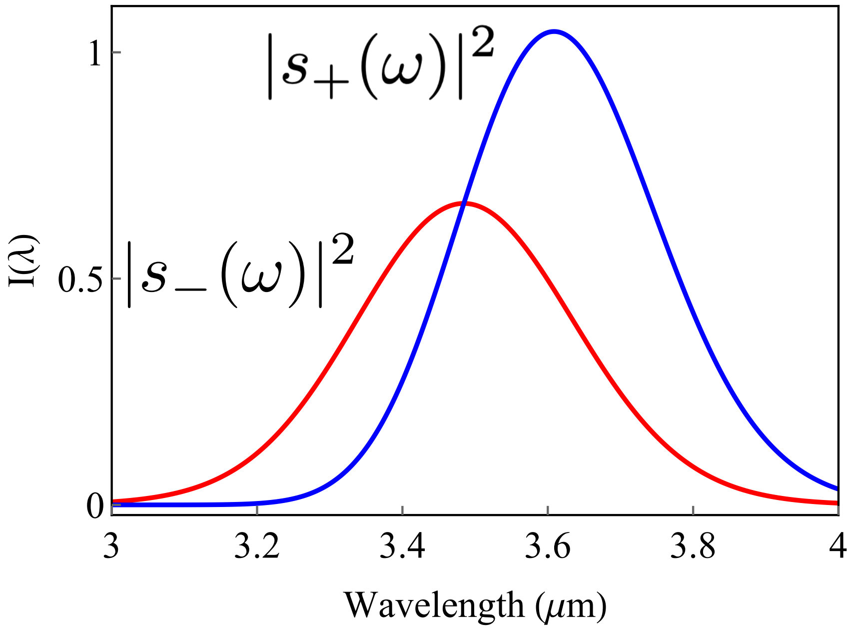
$$s_-(t) = \kappa a(t)$$

Case 1: ω_0 fixed

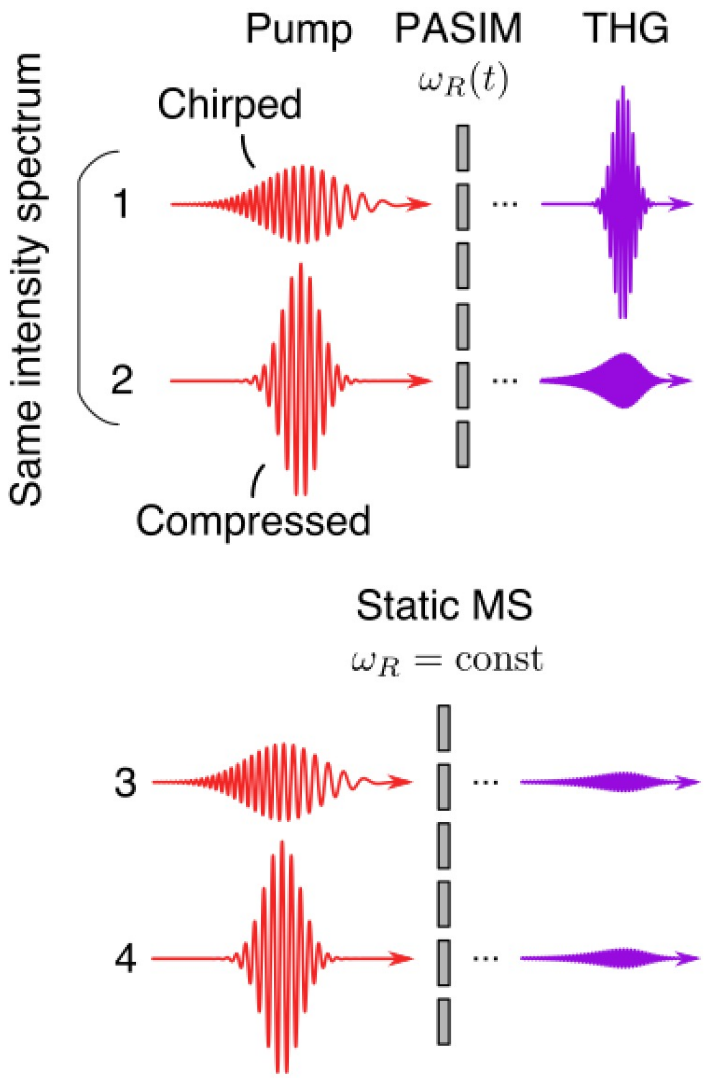


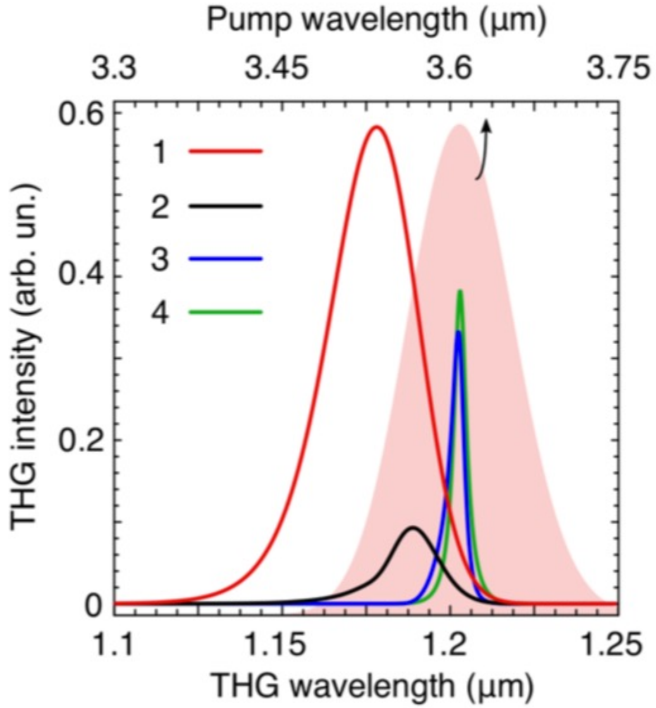
T = 0.06

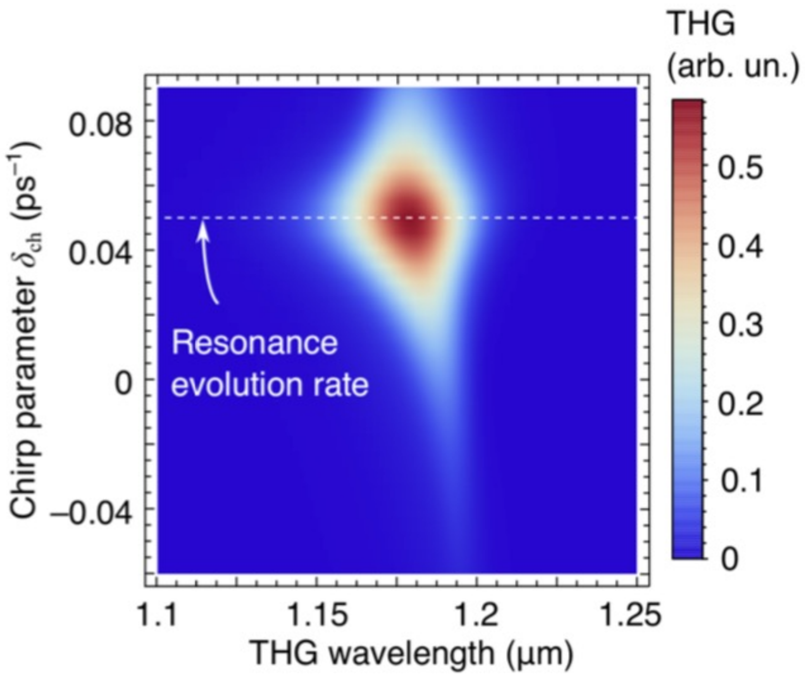
Case 2: $\omega_0 = \omega_0(0)(1 + \alpha t), \alpha = \delta$



T = 0.77







Broadband nonlinear response

from a narrowband (= resonant) cavity

Theory: *Nat. Commun.* **10**, 1345 (2019)

Numerical verification: *PRA* **100**, 063847 (2019)

Time-variant semiconductor metasurfaces. Outline

- Frequency conversion
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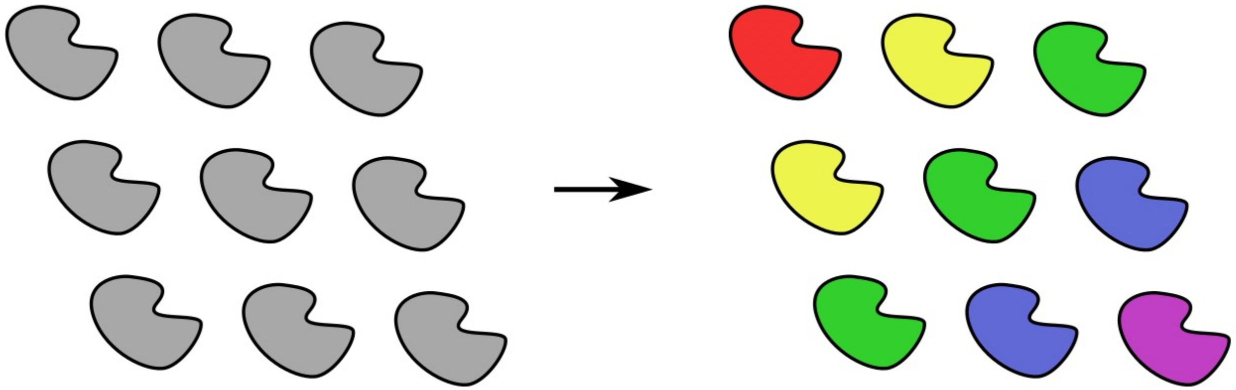
- Discussion: Time-variant ∈ nonlinear?
- Conclusion

Time-variant: also, linear?

$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r})\mathbf{E}(\mathbf{r}) \qquad \mathbf{P}(\mathbf{r},t) = \varepsilon_0 \int d\mathbf{r}' \int dt'\, \chi(\mathbf{r},t,\mathbf{r}',t')\mathbf{E}(\mathbf{r}-\mathbf{r}',t-t')$$



Opinion 1. *Obviously so*: polarization is linear is E!

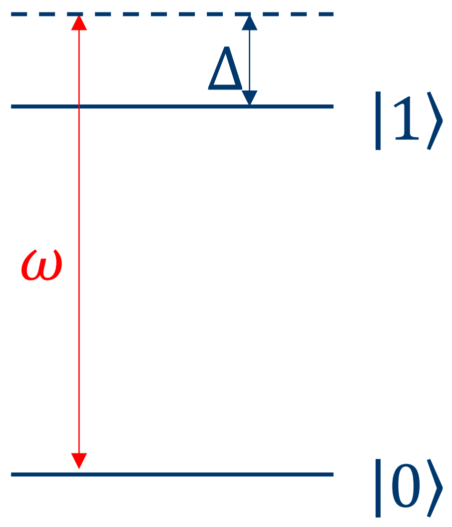
Jayathurathnage et al., arxiv:2011.00262v3 (2020) – Sergey Tretyakov's Group; Lee et al., "Linear frequency conversion via sudden merging of meta-atoms in time-variant metasurfaces," Nature Photonics 12, 765 (2018) – Bumki Min's Group; predominantly from RF community

Opinion 2. *Obviously not*: $\chi(\mathbf{r},t,t')$ is driven by an external source, which is mixing with E and generating new frequencies! See, e.g., Raman/Brillouin sidebands.

See QM-description of optical nonlinearities, including Raman, FC-induced blueshift etc.

FCD + NLSE: Zhou et al., *Light Sci. App.* **6**, e17008 (2017);

Two-level system revisited: time-variant detuning

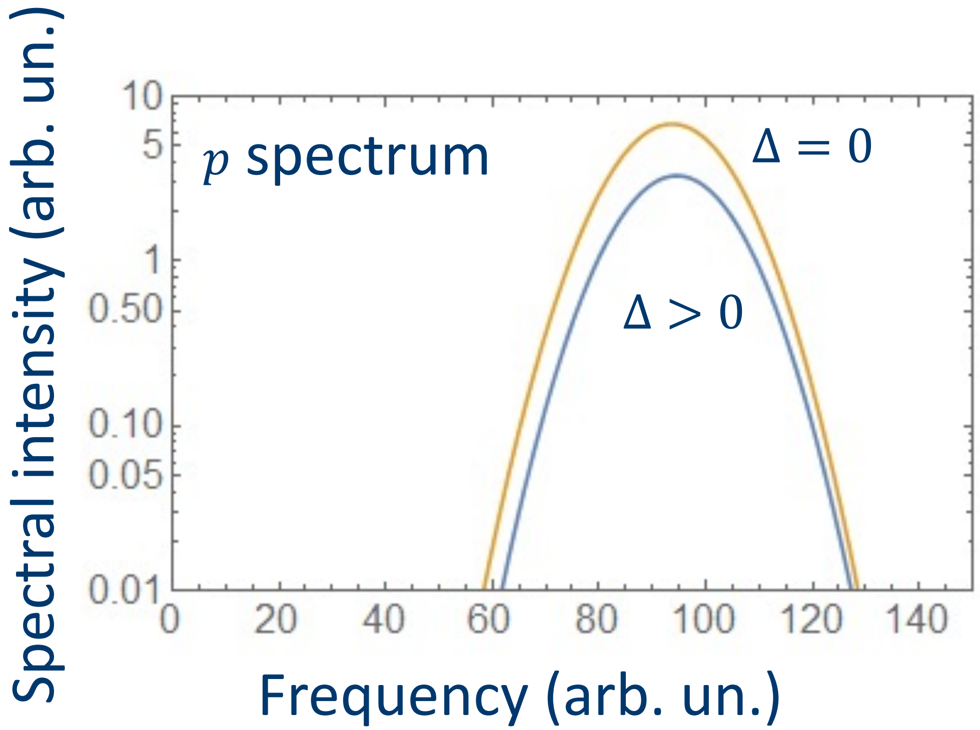


$$\dot{p} = \left(i\Delta - \frac{1}{T_2}\right)p - \frac{i}{\hbar}|\mu|^2 E w$$

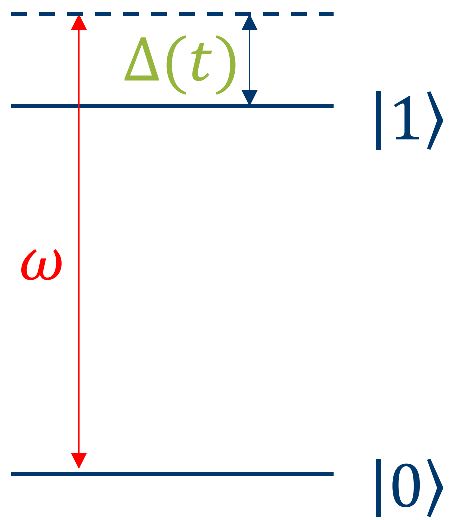
$$\dot{w} = -\frac{w+1}{T_1} - \frac{2i}{\hbar}(pE^* - p^*E)$$

Pulsed excitation:

$$E = E_0 e^{-i\omega t - t^2/\tau^2}$$



Boyd *Nonlinear Optics* (6.6)



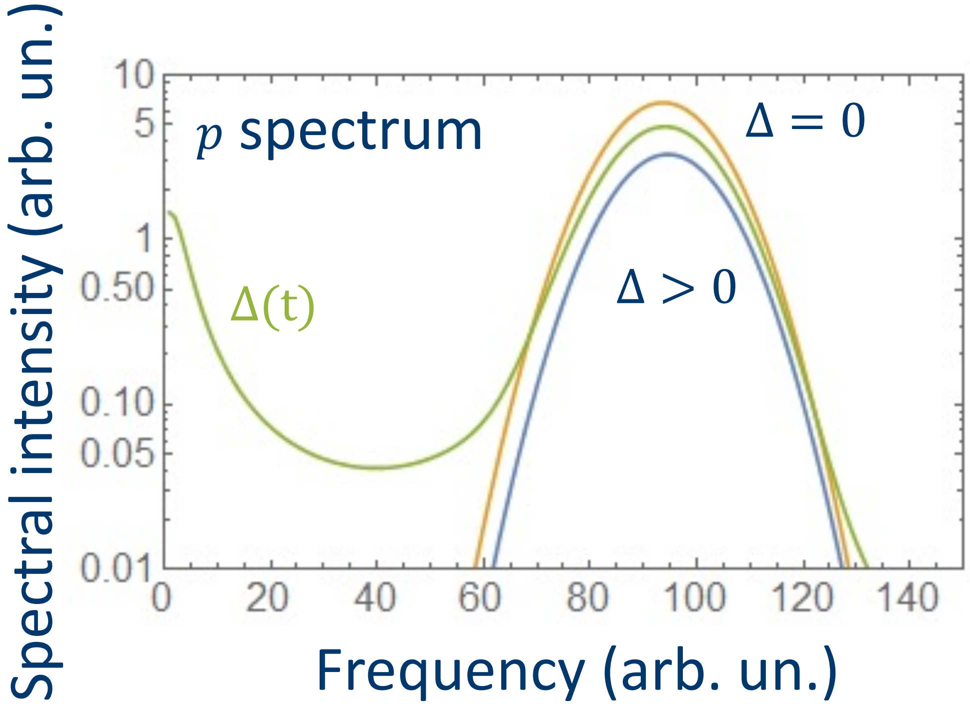
E.g., AC Stark shift

$$\dot{p} = \left(i\Delta(\mathrm{t}) - \frac{1}{T_2}\right)p - \frac{i}{\hbar}|\mu|^2 E w$$

$$\dot{w} = -\frac{w+1}{T_1} - \frac{2i}{\hbar}(pE^* - p^*E)$$

Pulsed excitation:

$$E = E_0 e^{-i\omega t - t^2/\tau^2}$$

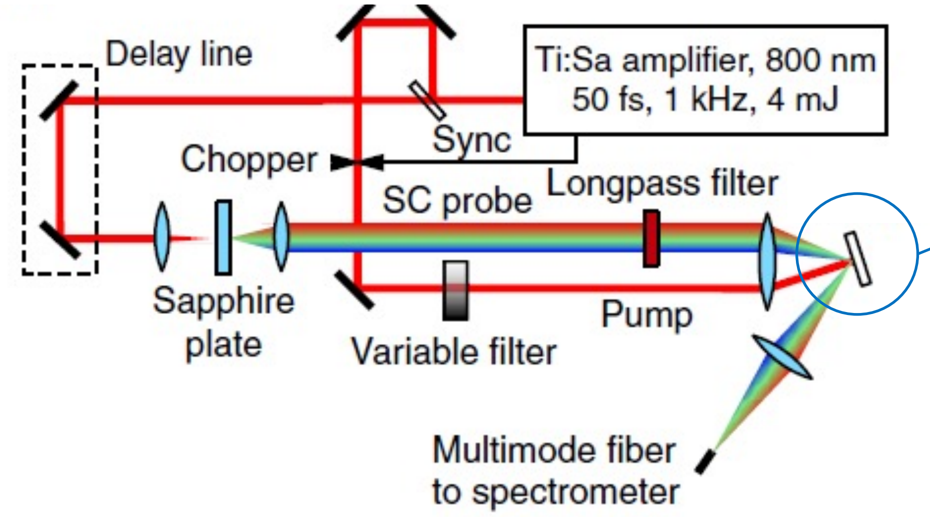


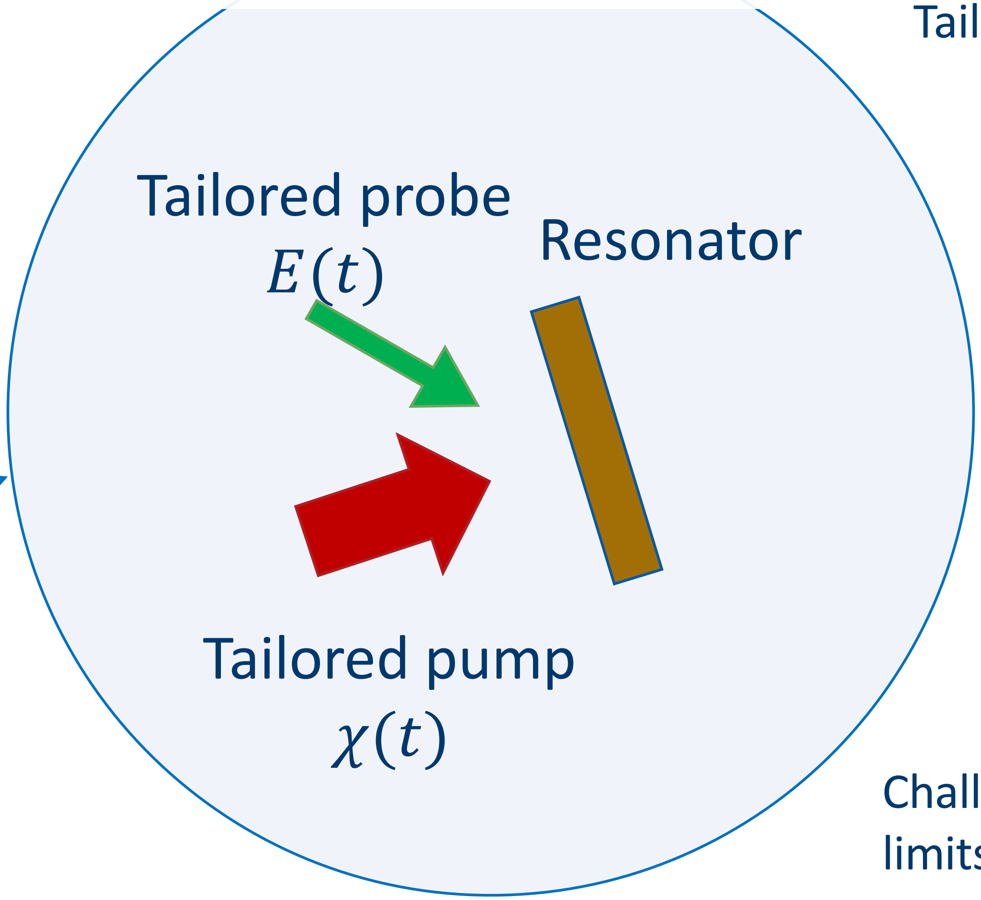
Nonlinear? Yes.
Perturbative? No.
No effective parameters —
Full QM description needed!

Boyd *Nonlinear Optics* (6.6)

Platform for spacetime EM

Utility Embracing the temporal degree of freedom in metamaterials to advance the *fundamental understanding* of light-matter interactions and *applications* in active photonic devices





- Tailoring single-photon spectrum
- Frequency conversion*
- Space-time crystals
- Waveform engineering*
- Non-adiabatic processes*
- Challenging the fundamental limits of electromagnetism*

Time-variant metasurfaces. Summary

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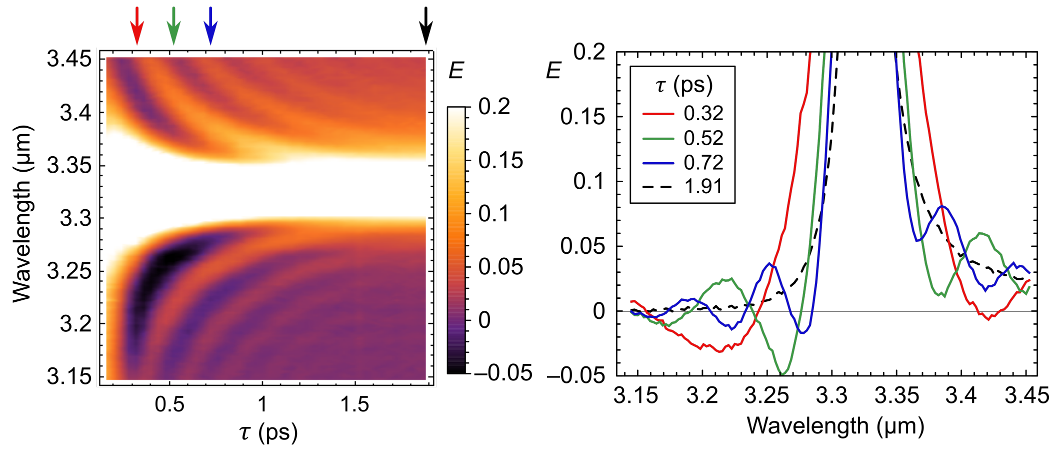
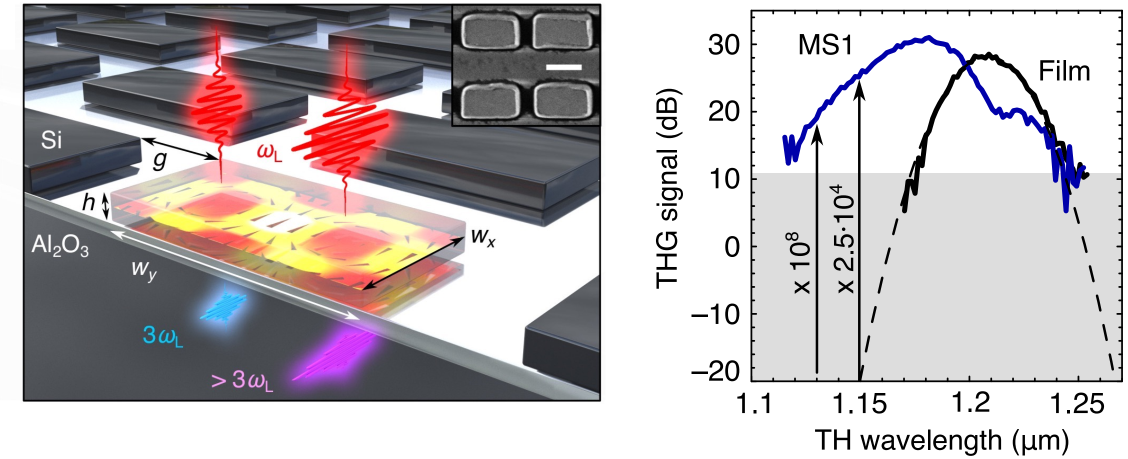
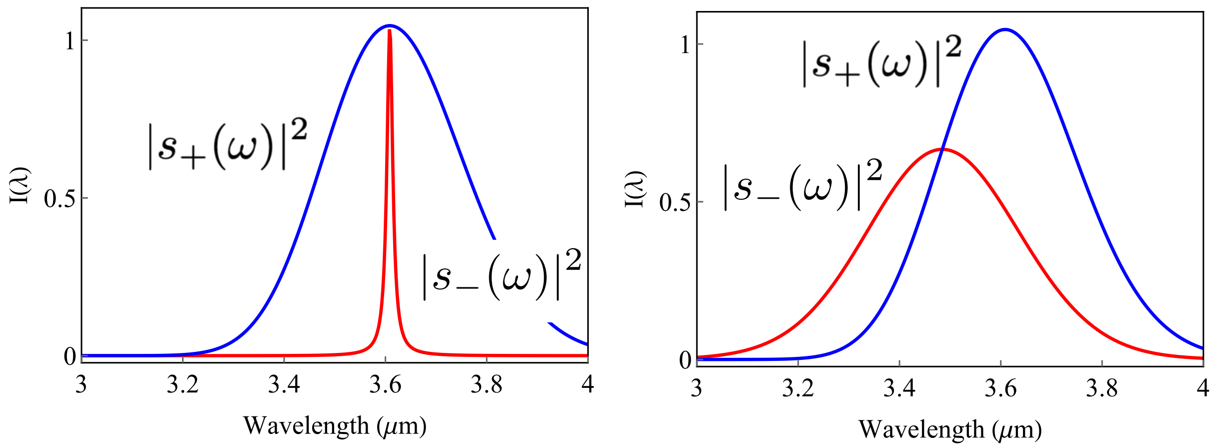
Frequency conversion



Photon acceleration (self-conversion)



Broadband resonant light-matter interactions



Nat. Commun. **8**, 17 (2017)

Nat. Commun. **10**, 1345 (2019)

Phys. Rev. A **100**, 063847 (2019)

APL Materials **9**, 060701 (2021)

arXiv:2008.03619 (2020)

arXiv:2012.06604 (2020)

Optica **6**, 1441 (2019)

My group @ UC Irvine EECS is hiring

Email: maxim.shcherbakov@uci.edu

Website: shcherbakov.eng.uci.edu

Cluster and graph states in frequency domain

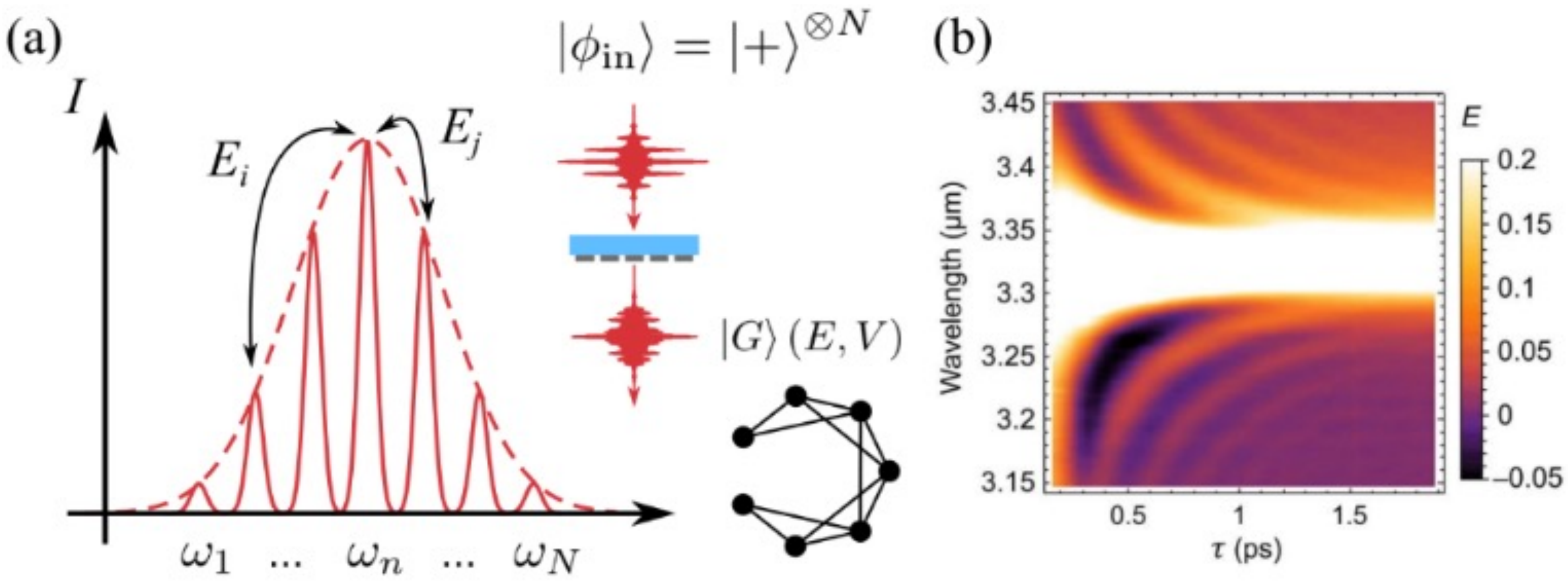


Fig. 5. Quantum networks based on graph states in time-variant resonators. (a) The input spectrally shaped laser pulse serves as a set of vertices V for the future graph state. The vertices are entangled in a time-variant metasurface to form a graph state with edges E. The prepared state $|G\rangle$ can serve a basis for one-way quantum computing. (b) Preliminary results: classical-optical analog of frequency entanglement with mid-infrared photons [Shcherbakov et al., Optica 2019].