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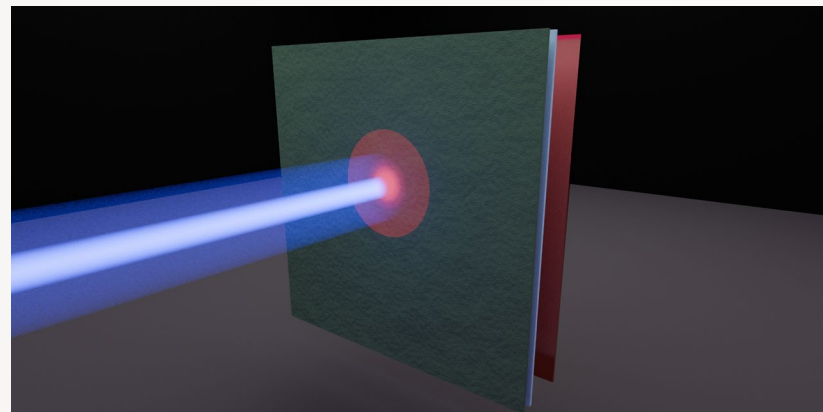
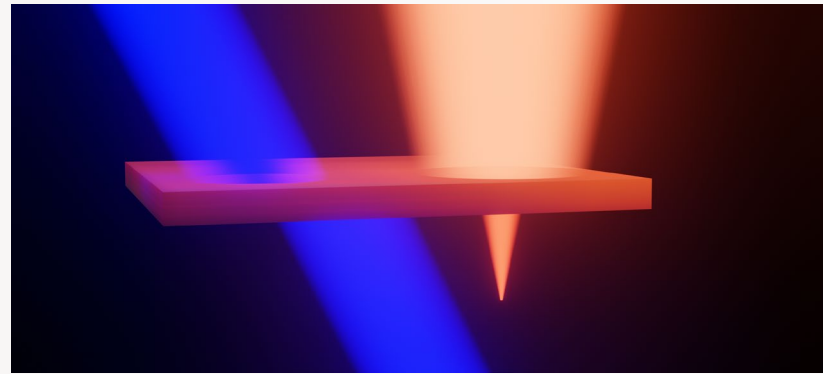
Nonlocal and Time-Varying Metasurfaces and Meta-structures

Francesco Monticone

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Cornell University, NY 14850, USA

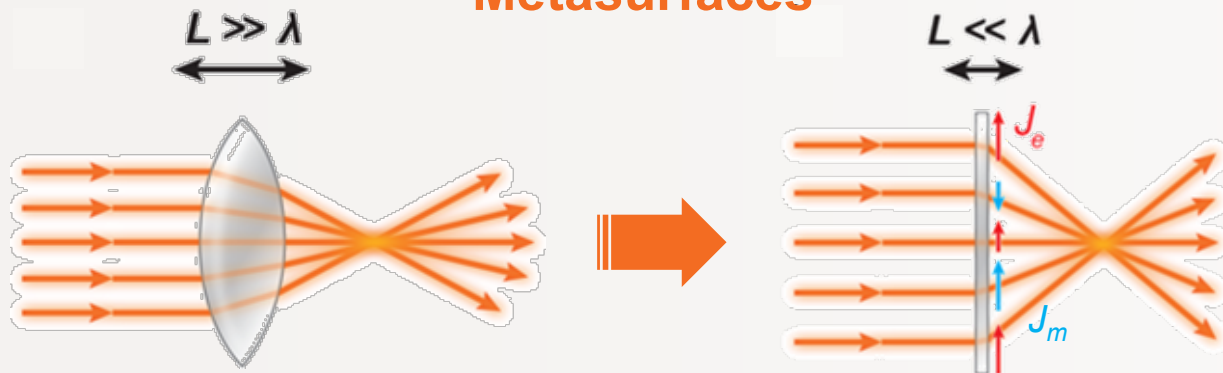
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<http://monticone.ece.cornell.edu/>



Metasurfaces

Metasurfaces



Alù, Andrea. "Wave-shaping surfaces." *Physics* 6 (2013): 53.

The New York Times

CURRENTS

These Materials Could Make Science Fiction a Reality

Metamaterials, which could improve smartphones and change how we use other technology, allow scientists to control light waves in new ways.



Editorial

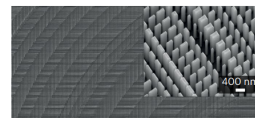
Focus on metasurfaces

<https://doi.org/10.1038/s41566-022-01137-1>

Metasurfaces go mainstream

Check for updates

Early research towards bulk metamaterials and exotic properties has been supplanted by work on thin metasurfaces ripe for commercialization, as outlined in this Focus issue.



in length, and single-digit dollars per square metre, with tens-of-nanometres accuracy". The company has also announced a large contract with a GIO central bank to produce security features for bank notes. In the interview Palikaras explains their plans from aerospace and automotive to healthcare, with frequency regimes

BBC Sign in Home News Sport Reel Worklife Travel Futu

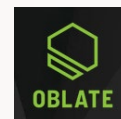
NEWS

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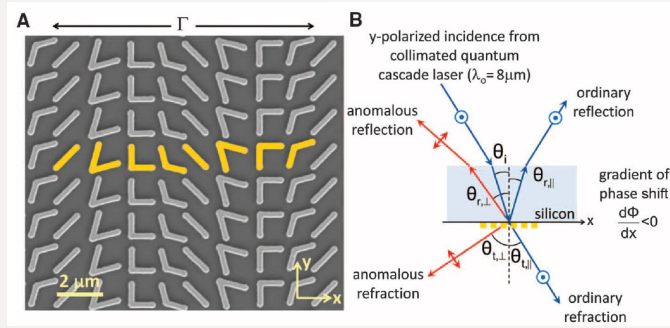
Business Market Data New Economy New Tech Economy Companies Entrepreneurship Technology of Business E

Smaller and better smartphone cameras are on the way

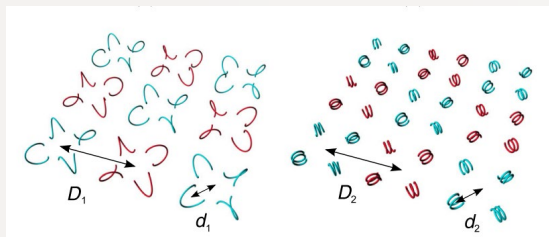
By David Silverberg
Technology of Business reporter



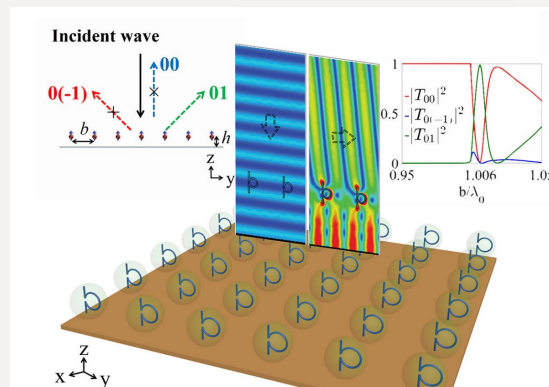
Metasurfaces



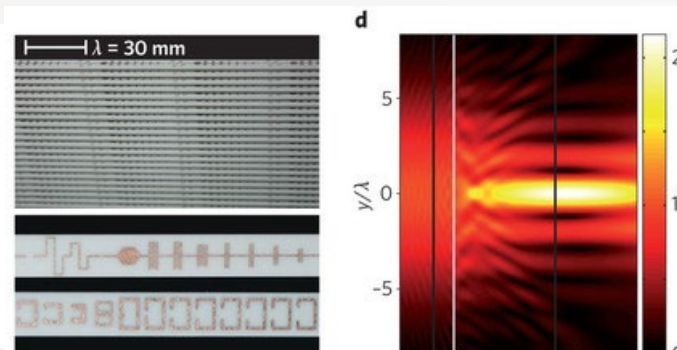
N. Yu, ..., F. Capasso, Science 334, 333-7 (2011).



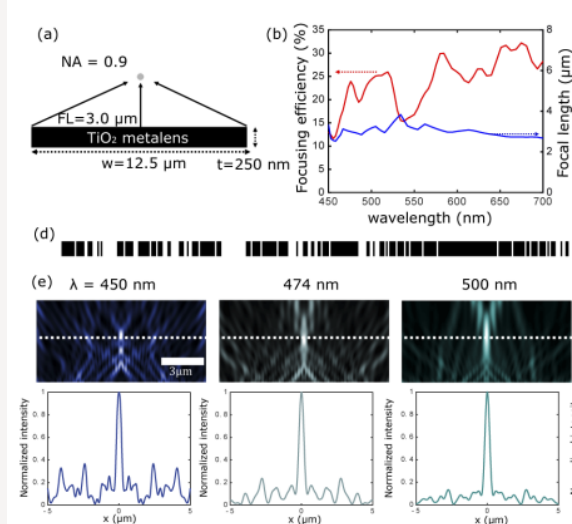
Asadchy, ..., Tretyakov, Physical Review X 5 (3), 031005 (2015)



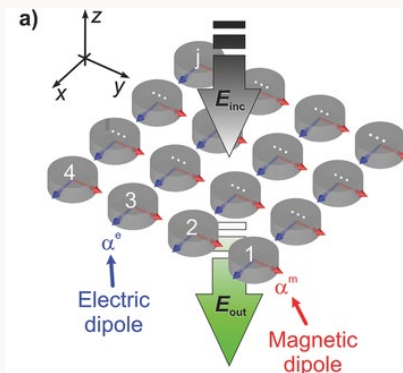
Radi, Sounas, Alu, Phys. Rev. Lett. 19 (2017)



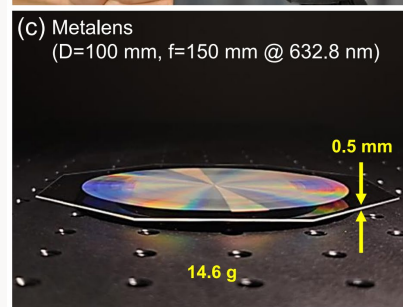
C. Pfeiffer and A. Grbic, Phys. Rev. Lett. 110 197401 (2013)



H. Chung and O. D. Miller, Optics Express 28, 6945-6965 (2020)



M. Decker ... Y. Kivshar Adv. Opt. Mater. 3 813-20 (2015)



Capasso's group @Harvard (2023)



What's Next?

Harnessing new degrees of freedom!

- ❑ **Breaking the assumption of spatial locality**

→ Strong dependence on the incident wavevector (linear momentum, angle of incidence, spatial frequency)

- ❑ **Breaking the assumption of time invariance**

→ Time as a new design parameter

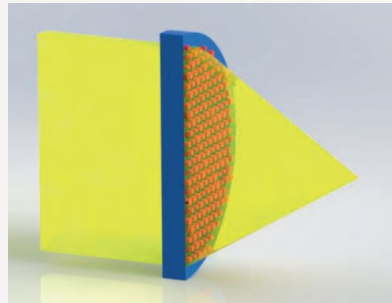


Local Metasurfaces

“Local” devices: Wave transmission/reflection is manipulated as a function of transverse position (locally and pointwise) based on a transversely inhomogeneous structure

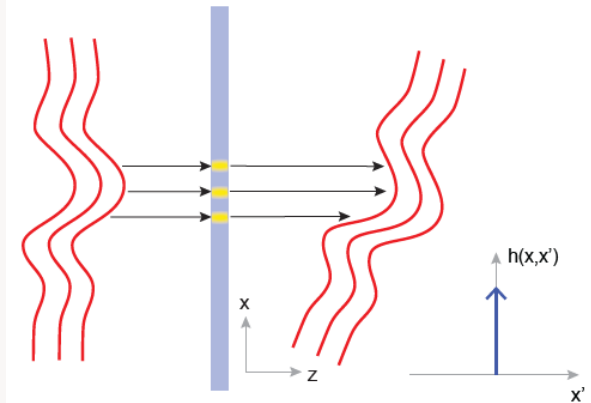
Position-dependent response

$$\varphi(r) = -\frac{\omega}{c} \left(\sqrt{F^2 + r^2} - F \right)$$

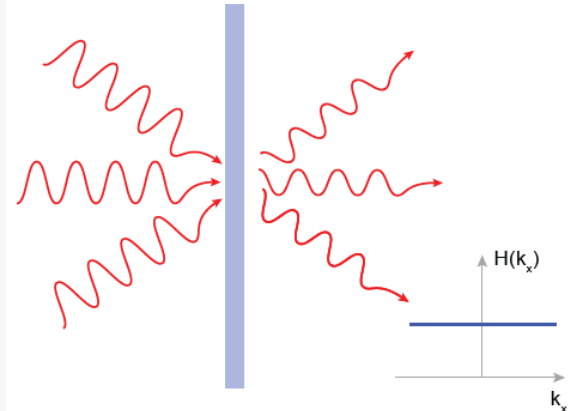


In the ideally local case, the electromagnetic response at a certain point only depends on the applied field at a single point, namely, the spatial impulse response is a delta function.

Local flat optic (Real Space)



Local flat optic (Momentum Space)



Nonlocal Metasurfaces

In a **nonlocal metasurface**, the electromagnetic response (wave transmission, reflection, etc.) at each point depends on the applied field in an extended spatial region.

In spatial Fourier space, this corresponds to a **strongly wavevector-dependent response** (i.e., dependent on the transverse momentum, spatial frequency, angle)

Property also known as **spatial dispersion**.

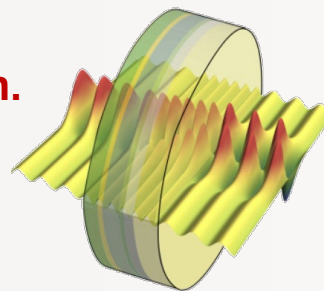
$$A(k_t) \propto -k_t^2$$

Second-order spatial differentiation

Wave-Based Analog Computing

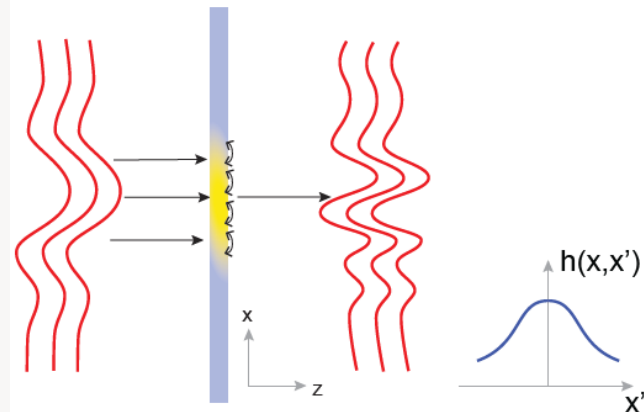
$$\varphi(k_t) = L\sqrt{k_0^2 - k_t^2}$$

“Space compression”

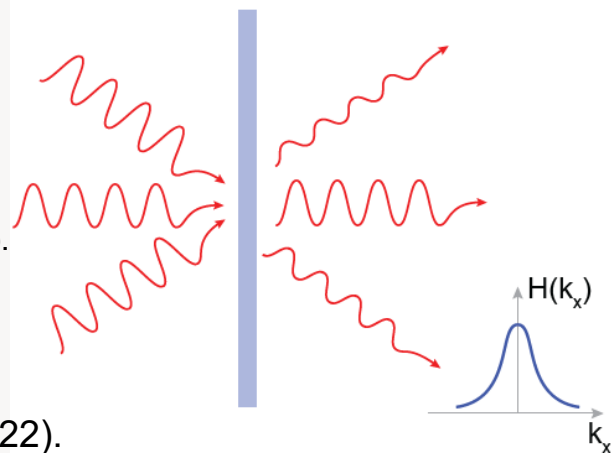


A. Silva, F. Monticone, et al.
Science 343, 160–163 (2014).

Nonlocal flat optic (Real Space)



Nonlocal flat optic (Momentum Space)



K. Shastri and F. Monticone, “**Nonlocal flat optics**,” Nat. Photonics (2022).

A. Overvig, and A. Alù. “**Diffraction nonlocal metasurfaces**.” Laser & Photonics Reviews 16, no. 8 (2022).



Nonlocal Flat Optics

nature photonics

Review Article

<https://doi.org/10.1038/s41566-022-01098-5>

Nonlocal flat optics

Received: 29 June 2022

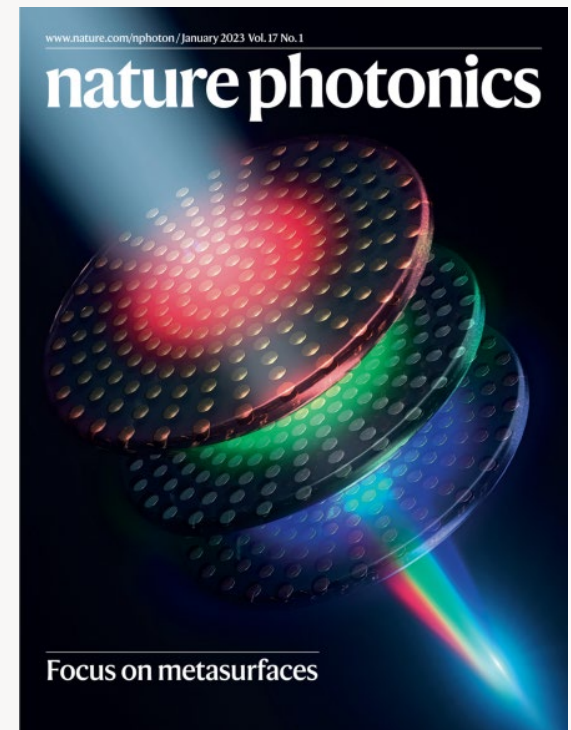
Accepted: 5 October 2022

Published online: 22 December 2022

 Check for updates

Kunal Shastri  & Francesco Monticone  

In electromagnetics and photonics, ‘nonlocality’ refers to the phenomenon by which the response/output of a material or system at a certain point in space depends on the input field across an extended region of space. Although nonlocal effects and the associated wavevector/momentum dependence have often been neglected or seen as a nuisance in the context of metasurfaces, the emerging field of nonlocal flat optics seeks to exploit strong effective nonlocality to enrich and enhance their response. Here we summarize the latest advances in this field, focusing on its fundamental principles and various applications, from optical computing to space compression. The convergence of local and nonlocal flat optics may open exciting opportunities in the quest to control light, in real and momentum space, using ultra-thin platforms.

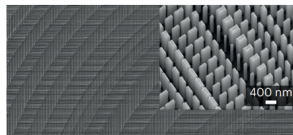



Editorial

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LASER & PHOTONICS REVIEWS

Perspective

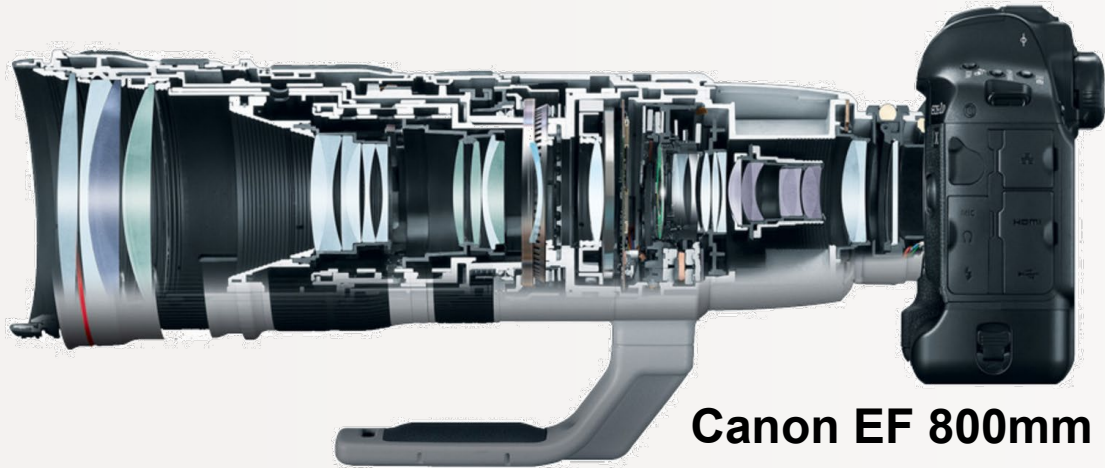
Diffraction Nonlocal Metasurfaces

Adam Overvig, Andrea Alù 

First published: 03 July 2022 | <https://doi.org/10.1002/lpor.202100633>

Space Compression - Spaceplates

Can nonlocal flat optics help further miniaturize optical systems?



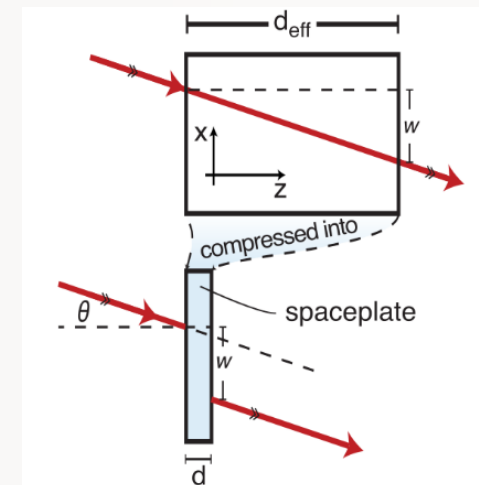
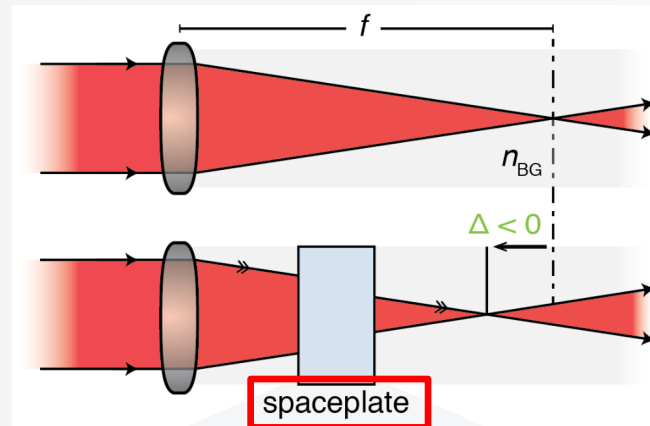
Canon EF 800mm

What's inside?

- ❑ Combinations of **optical elements** → Their miniaturization is the goal of local metasurfaces
- ❑ **Free space** between elements! (e.g., necessary to allow waves to acquire an angle-dependent phase and achieve focusing)

How to further miniaturize this system?

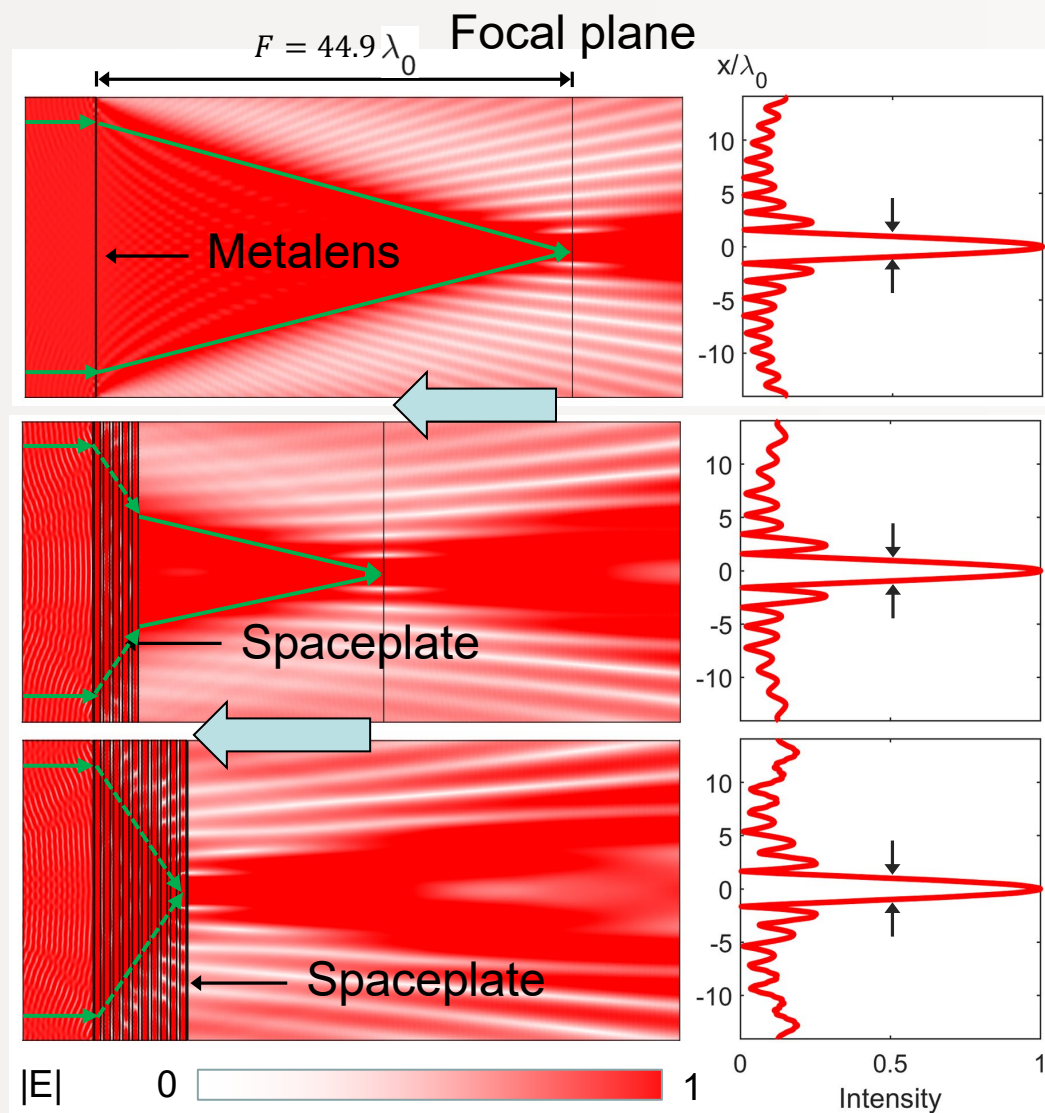
Need to design an optical element that **mimics the optical phase response of a free space volume** over a much smaller length!



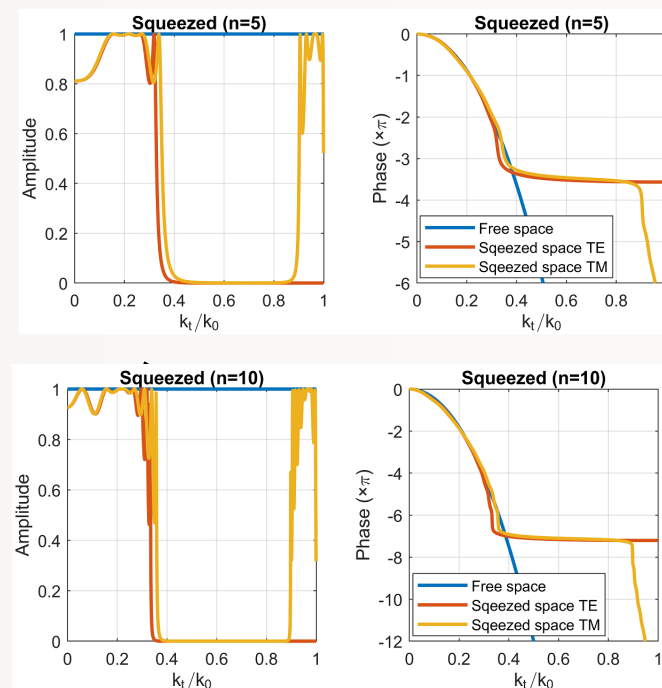
- O. Reshef, ..., **R. W. Boyd**, and **J. S. Lundeen**, "Towards ultra-thin imaging systems: an optic that replaces space," Nature Communications (2020).
C. Guo, H. Wang, and **S. Fan**, "Squeeze free space with nonlocal flat optics," Optica 7, 1133–1138 (2020).
A. Chen and **F. Monticone**, "Dielectric Nonlocal Metasurfaces for Fully Solid-State Ultrathin Optical Systems," ACS Photonics 8, 5, 1439–1447 (2021).

Space Compression - Spaceplates

$$\varphi(k_t) = L\sqrt{k_0^2 - k_t^2}$$



Angular response of spaceplate



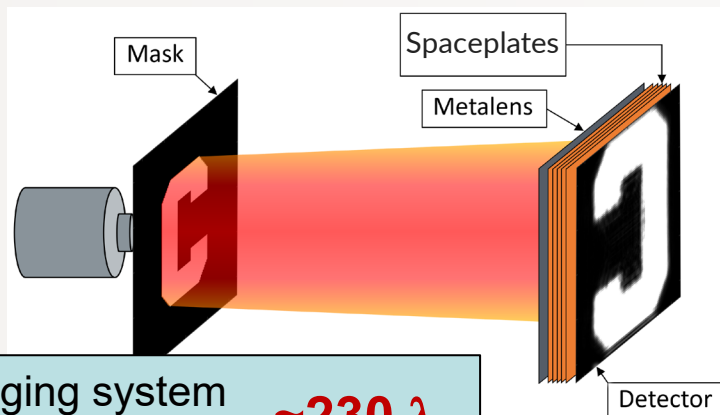
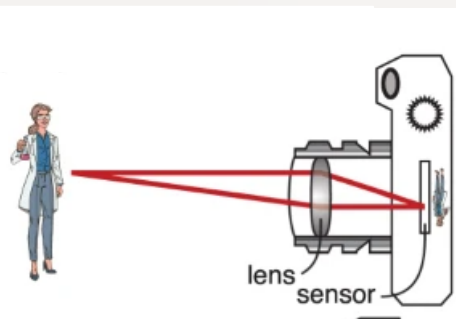
**Focusing is obtained
at a shorter distance...**

**... but the focal length
of the lens and other
metrics are unaltered!**

Space Compression - Spaceplates

Same functionality (for example magnification)
with a drastically shorter propagation length!

Ultra-compact, planar, electromagnetic and optical systems!



- ❑ Initial length of the imaging system (from lens to image plane): $\sim 230 \lambda_0$
- ❑ Length **with spaceplate** ($n = 50$) $\sim 45 \lambda_0$
- ❑ **Ultimate thickness limit:** $\sim 30 \lambda_0$

RESEARCH ARTICLE

OPTICS

Why optics needs thickness

David A. B. Miller*

Science, vol. 379, no. 6627, Jan. 2023.

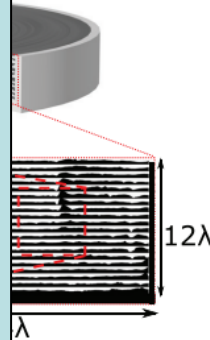
OPTICS

Toward ultrathin optics

Function determines the minimum thickness of an optical system

By Francesco Monticone

Photonics 8,



. Lett. 118,

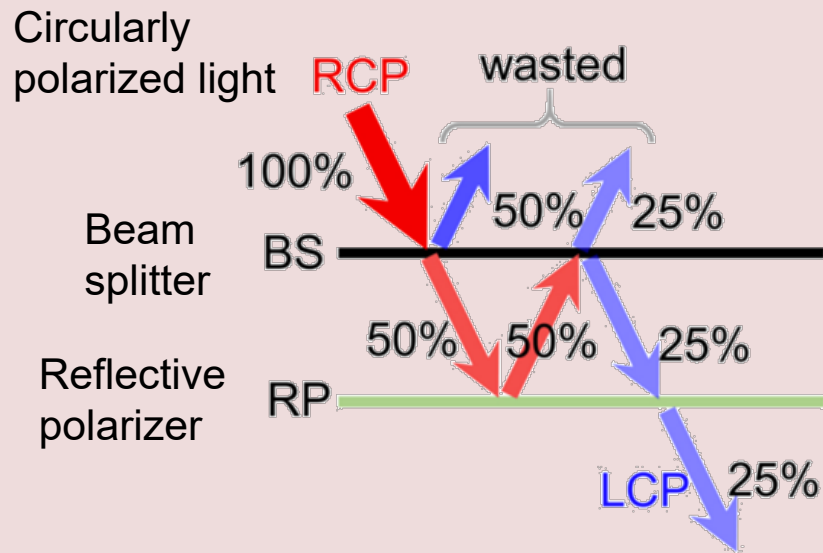
Ultra-thin cameras,
microscopes,
telescopes, wave-
based processors,
lens antennas, etc.!

C. Guo, H. Wang, and S. Fan, Optica 7, 1133-1138 (2020)

Mrnka, M., Hendry, E., Láčik, J., Barr, L. E. & Phillips, D. B. APL Photonics 7, 076105 (2022)

Comparison to “Pancake Optics”

“Pancake optics”

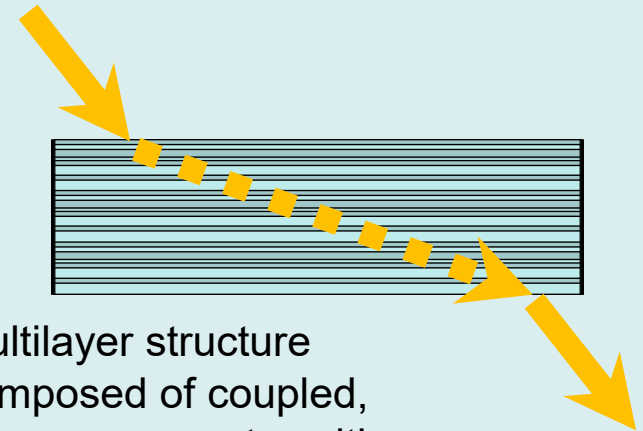


Spaceplate

Any polarization,
multiple colors?

Multilayer structure
composed of coupled,
planar, resonant cavities

~100%



Space Compression: Bandwidth

What about bandwidth?

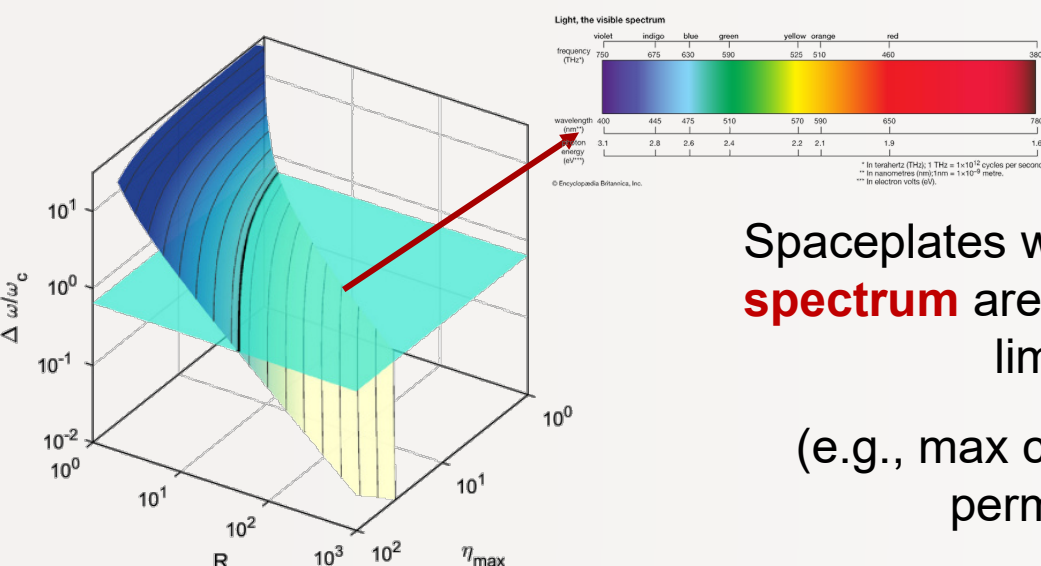
- Space-compression effects are typically narrowband because are based on **resonances**.



General expression for the fundamental bandwidth limits of any spaceplate!

$$\frac{\Delta\omega}{\omega_c} \leq \frac{1}{2\pi} \frac{\kappa}{L/\lambda_c} \frac{\sqrt{1 - (\text{NA}/n_b)^2} v_{gx}/c}{R \cdot \text{NA}/n_b - v_{gx}/c}$$

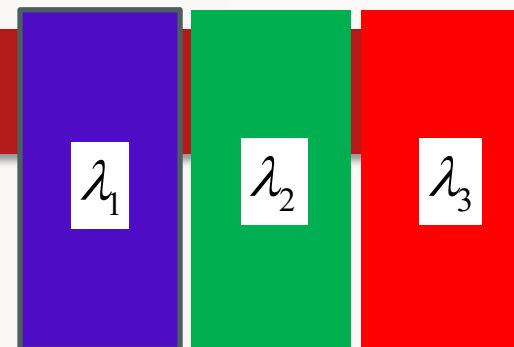
$$\kappa = \frac{\pi}{\sqrt{3}} \frac{L}{\lambda_c} \frac{|\varepsilon(z, \omega)/\varepsilon_b - 1|_{\max}}{\cos(\alpha)}$$



Spaceplates working over the **entire visible spectrum** are theoretically possible but with limited performance!

(e.g., max compression ratio **C=2**, for a permittivity contrast of 3)

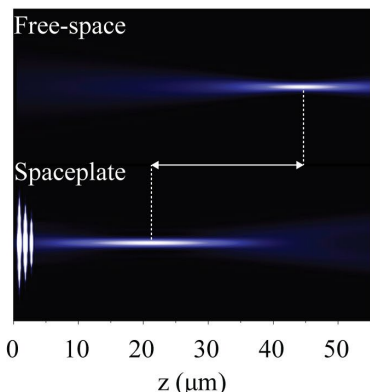
Multi-Color Spaceplates



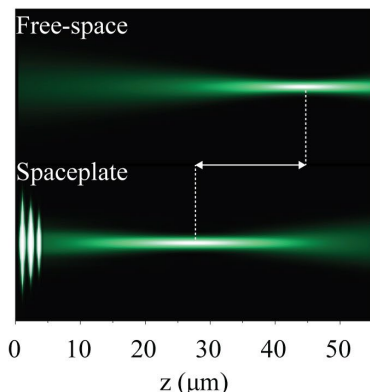
Alternative solutions?

- ❑ Fundamental limit only applies to *continuous* bandwidths
- ❑ We can bypass this limit by designing multi-frequency (multi-color) spaceplates

Could we just stack monochromatic spaceplates?

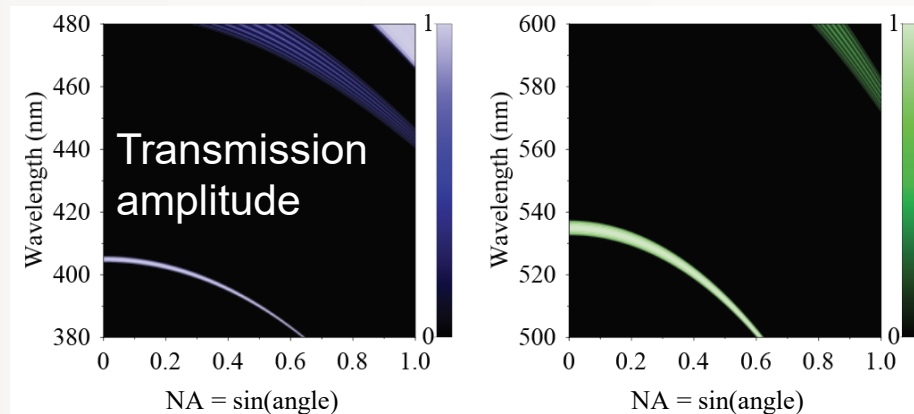


C=9.2



C=5.4

Different compression ratios



Not mutually transparent

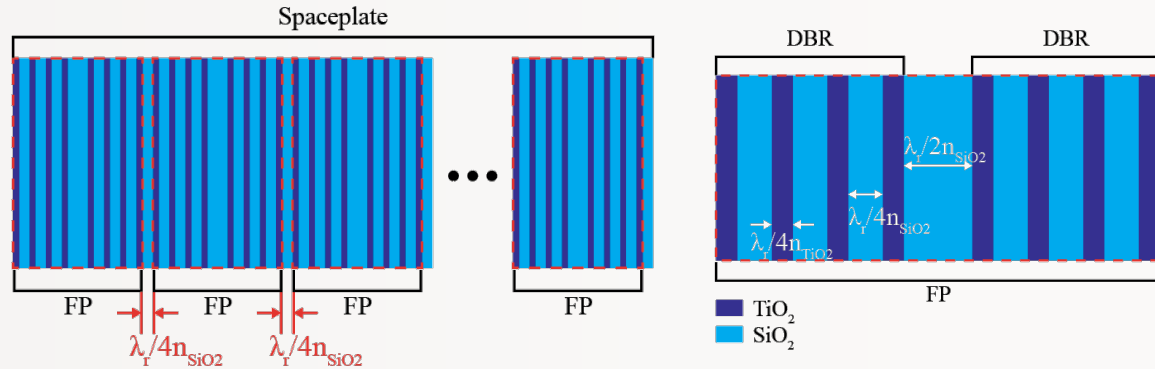
- ❑ Main design challenges:

1. **Transparency** at multiple discrete wavelengths
2. **Achromatic performance** (equal compression ratio)

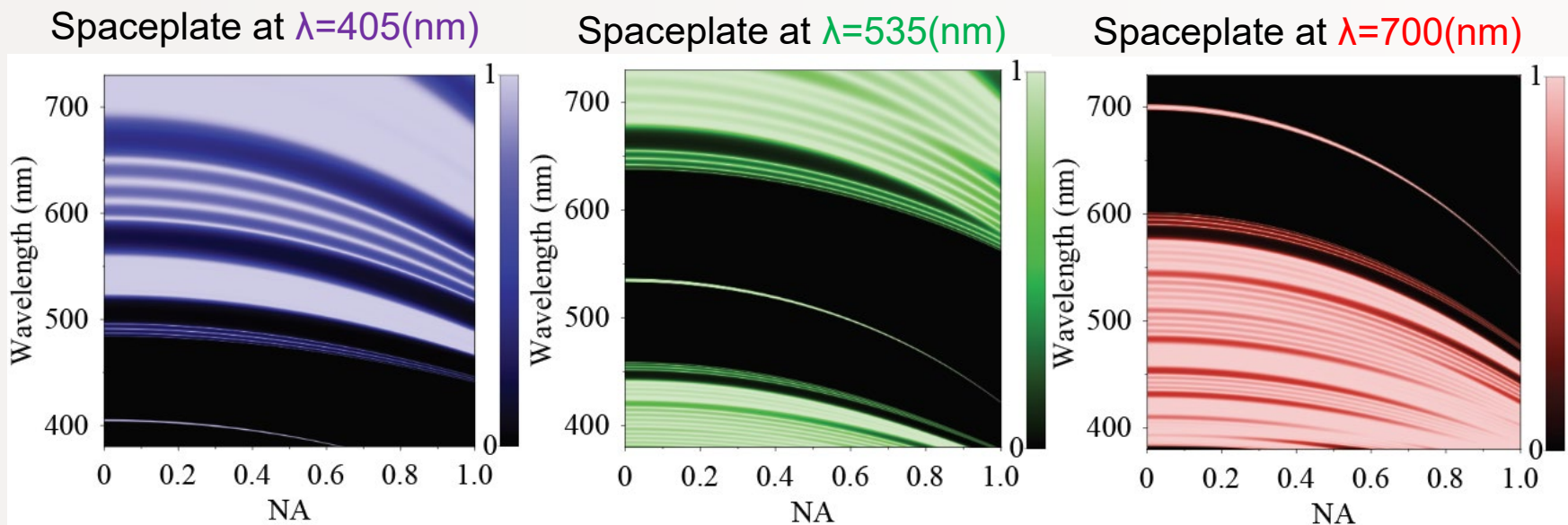
Multi-Color Spaceplates

❑ Our solution: **dispersion-engineered combination of monochromatic spaceplates**

❑ **Scalable structure and realistic dielectric materials,** transparent in the visible range and commonly used in the field of meta-optics



1. **Transparency:** Use higher-order resonances, such that each of the design wavelengths falls within the transparency window of the other monochromatic spaceplates



Achromatic Space Compression

2. Achromatic performance

- Define a “**compression matrix**,” whose element $C_{i,j}$ is the compression factor of the individual monochromatic spaceplate designed for $\lambda = j$ nm when light with wavelength $\lambda = i$ nm passes through it.

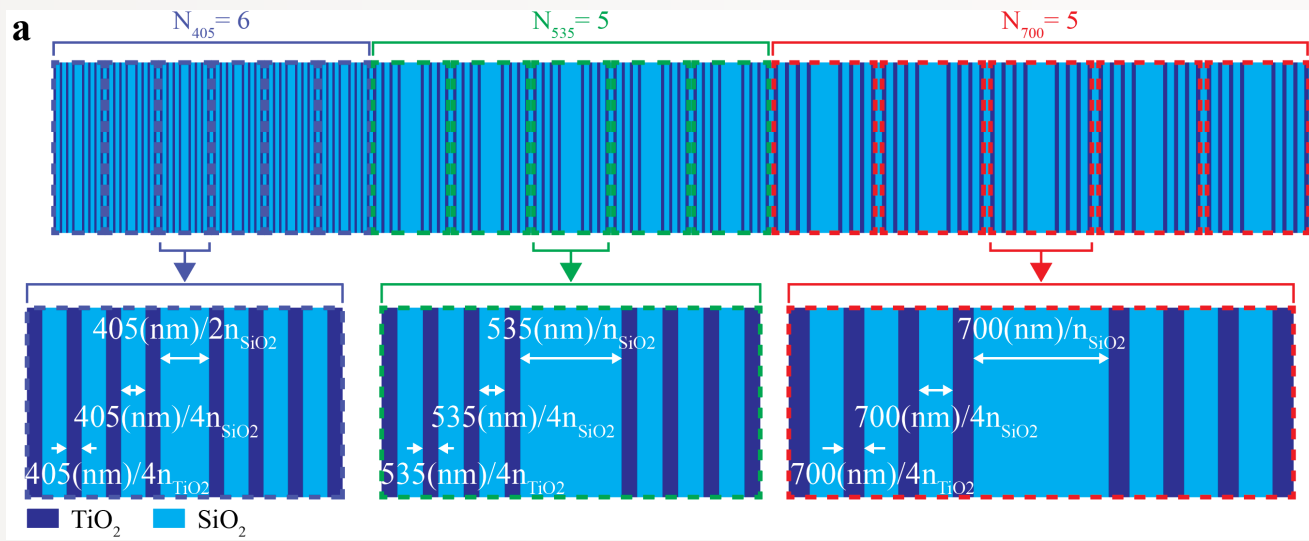
$$C = \begin{bmatrix} C_{405,405} = 9.13 & C_{535,405} = 0.67 & C_{700,405} = 0.58 \\ C_{405,535} = 0.67 & C_{535,535} = 7.22 & C_{700,535} = 0.61 \\ C_{405,700} = 0.59 & C_{535,700} = 0.67 & C_{700,700} = 5.8 \end{bmatrix}$$

While each monochromatic spaceplate performs **space-compression** near its resonance wavelength ($C_{i,j} > 1$, for $i = j$), at other wavelengths the refraction of light through the structure introduces a “**space-expansion**” effect ($C_{i,j} < 1$, for $i \neq j$).

Achromatic condition

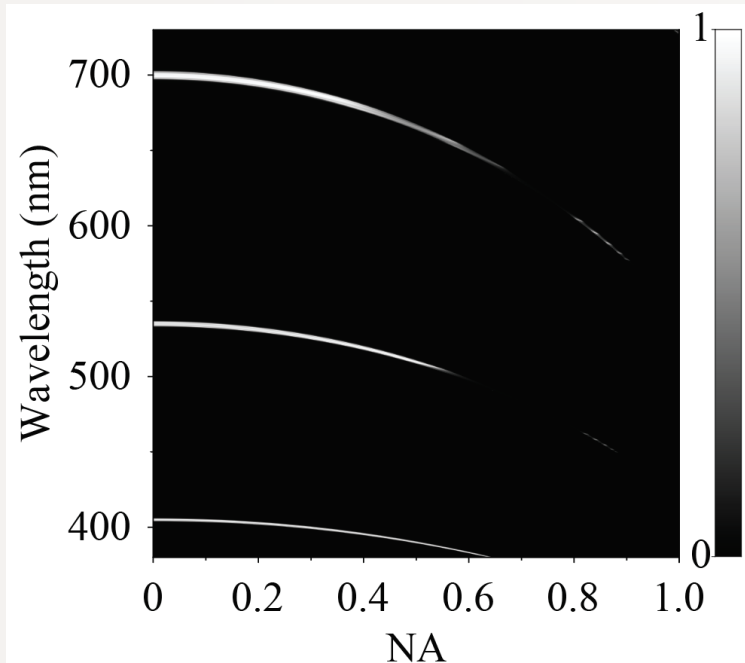
$$\sum_{j=405,535,700} L_j C_{405,j} = \sum_{j=405,535,700} L_j C_{535,j} = \sum_{j=405,535,700} L_j C_{700,j}$$

- The achromatic condition can be met by adjusting L_j through the number of resonant cavities N_j in each monochromatic spaceplate.

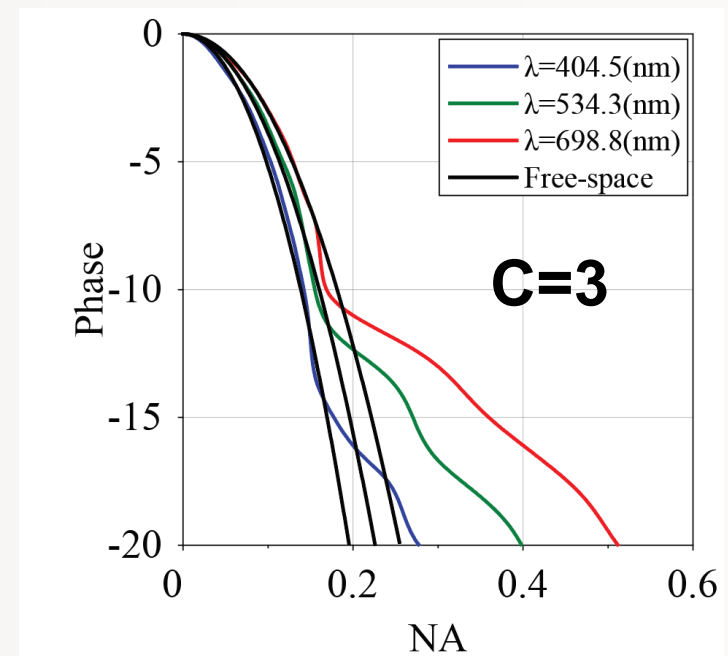


Multi-Color Space Compression: Results

Transmission amplitude, as a function of wavelength and incident angle [numerical aperture $NA = \sin(\text{angle})$]



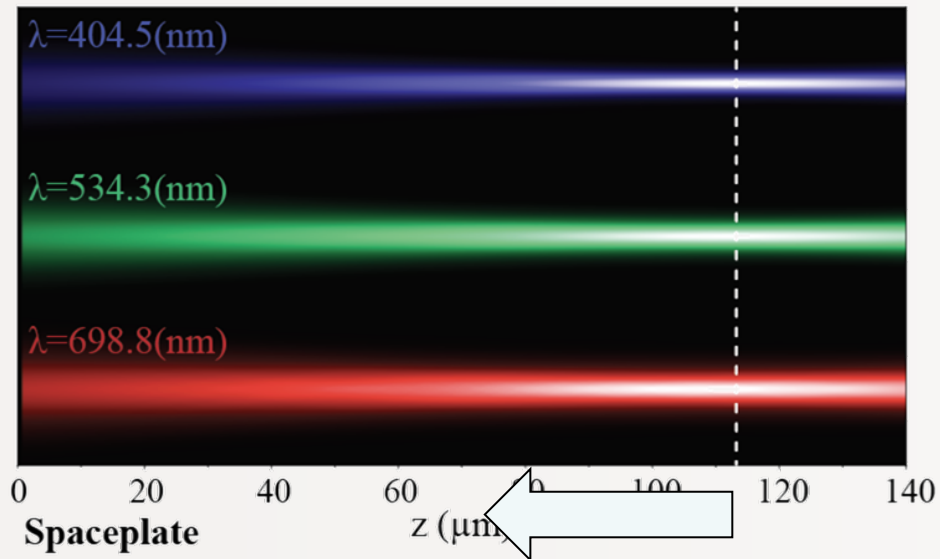
Transmission phase, matching the angular response of a (longer) free-space volume at multiple wavelengths



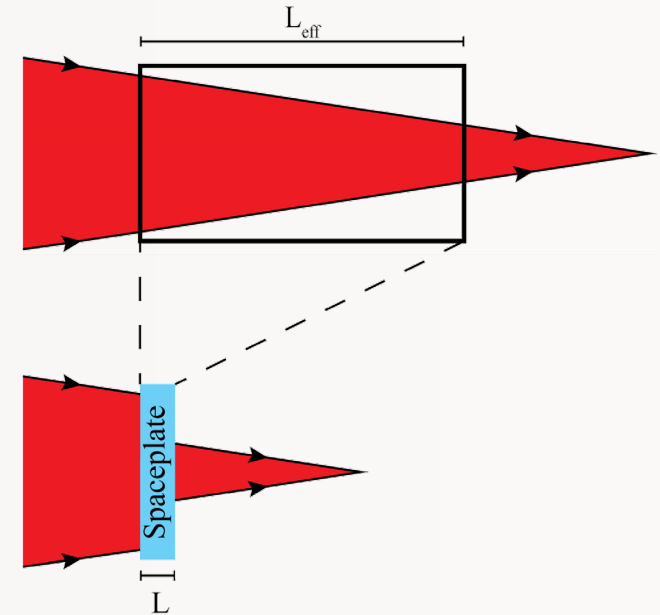
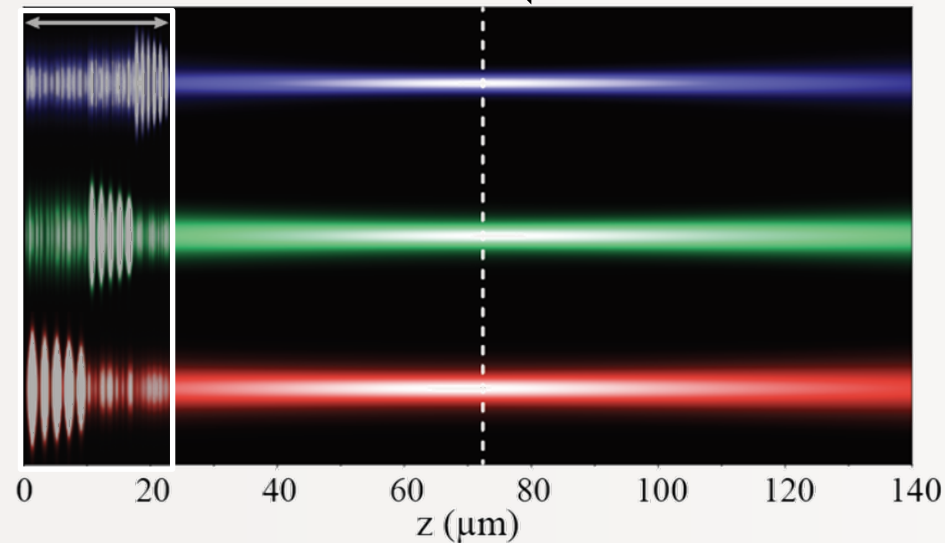
M. Pahlevaninezhad, F. Monticone, "**Multi-color spaceplates in the visible**", ACS Nano (2024).

Multi-Color Space Compression: Results

Free-space

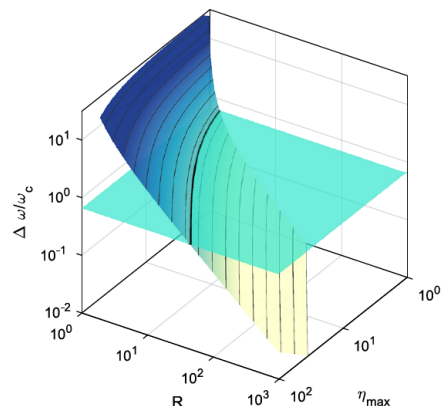


Spaceplate



Multi-color space compression: The focal plane is shifted backward, equally and with minimized distortions, at three different wavelengths.

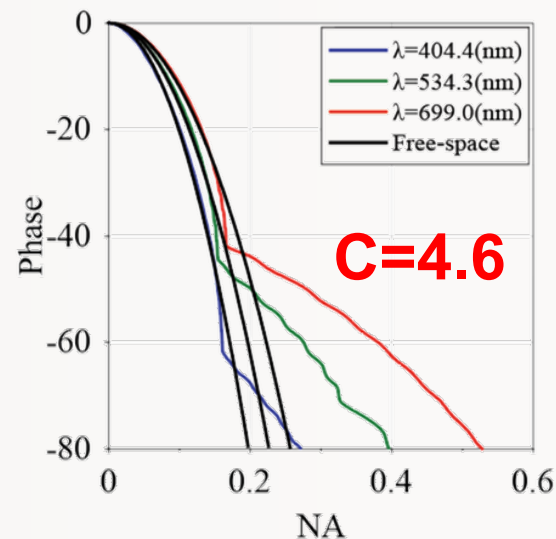
Another Example



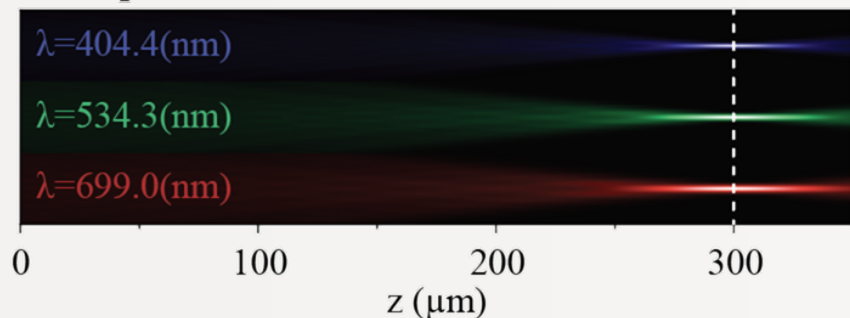
Maximum possible compression ratio for a **continuously** broadband spaceplate covering the same visible-light colors, using the **same permittivity contrast**:

$$C_{\max} = 2.8$$

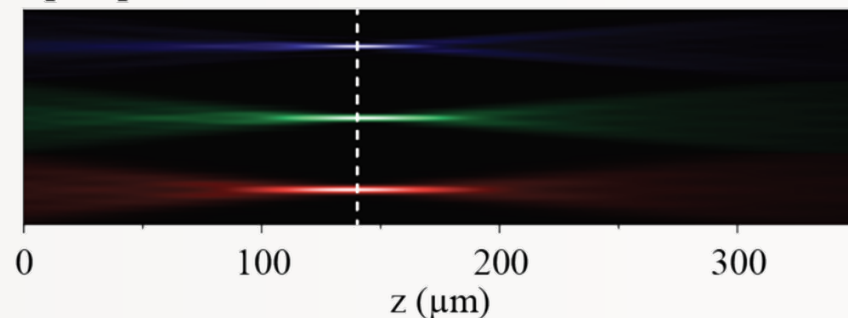
K. Shastri, et al & F. Monticone. Optica 9, 738 (2022).



Free-space



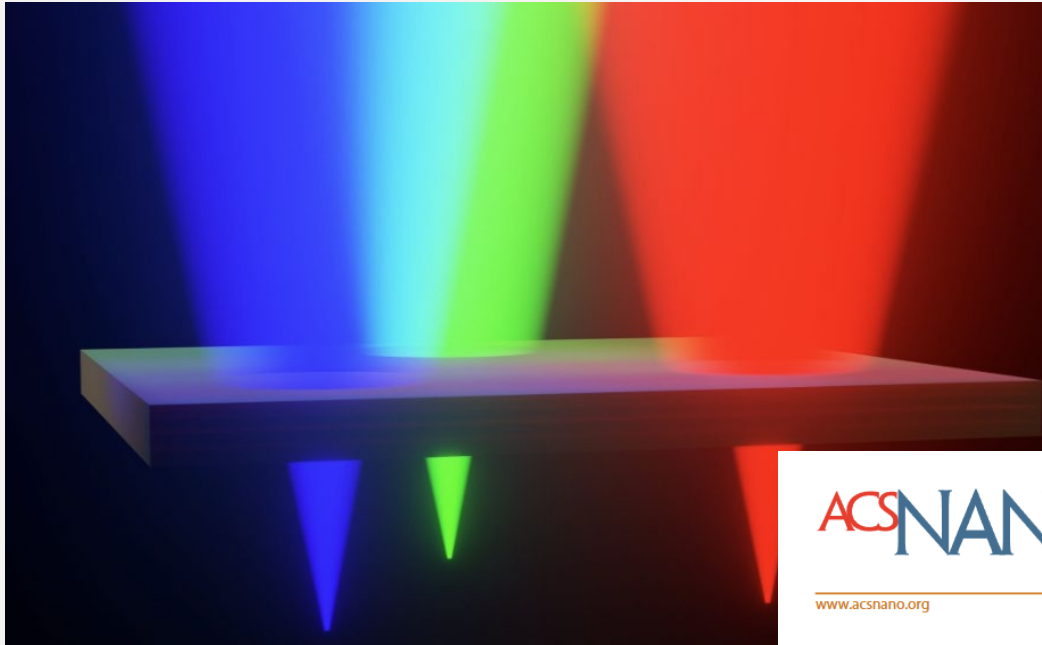
Spaceplate



M. Pahlevaninezhad, F. Monticone, "Multi-color spaceplates in the visible", ACS Nano (2024).



Multi-Color Spaceplates



- ❑ High transmission efficiency
- ❑ Replaces a large volume of free-space
- ❑ Multi-color operation over the visible spectrum
- ❑ Achromatic space compression
- ❑ Practically feasible

M. Pahlevaninezhad, F. Monticone, "Multi-color spaceplates in the visible", **ACS Nano** (2024).

F. Monticone, and M. Pahlevaninezhad "Multi-Color Spaceplate," **US Patent App. 63/542,235**, 2024.

ACS NANO

www.acsnano.org

Multi-Color Spaceplates in the Visible

Masoud Pahlevaninezhad and Francesco Monticone*

Cite This: *ACS Nano* 2024, 18, 28585–28595

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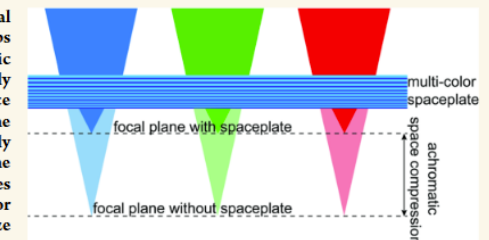
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Metrics & More

Article Recommendations

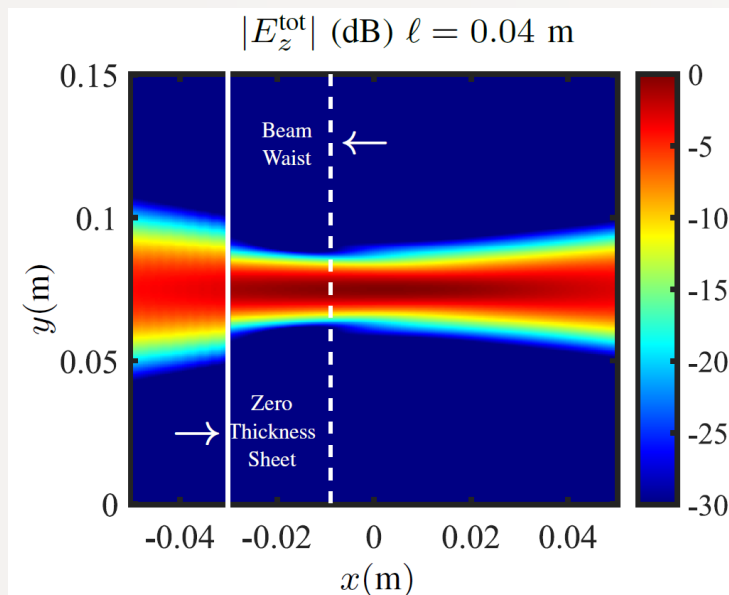
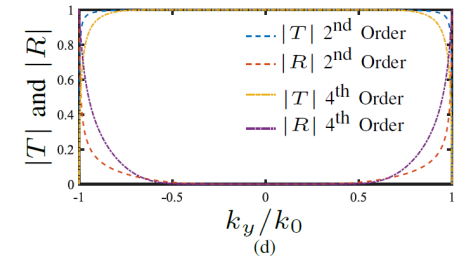
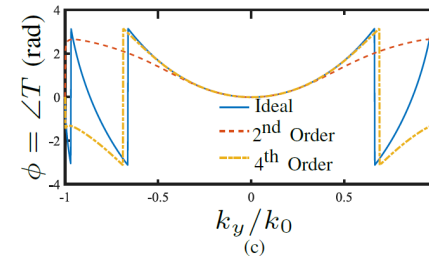
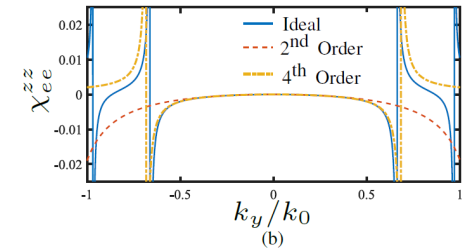
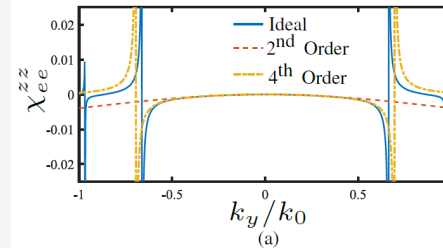
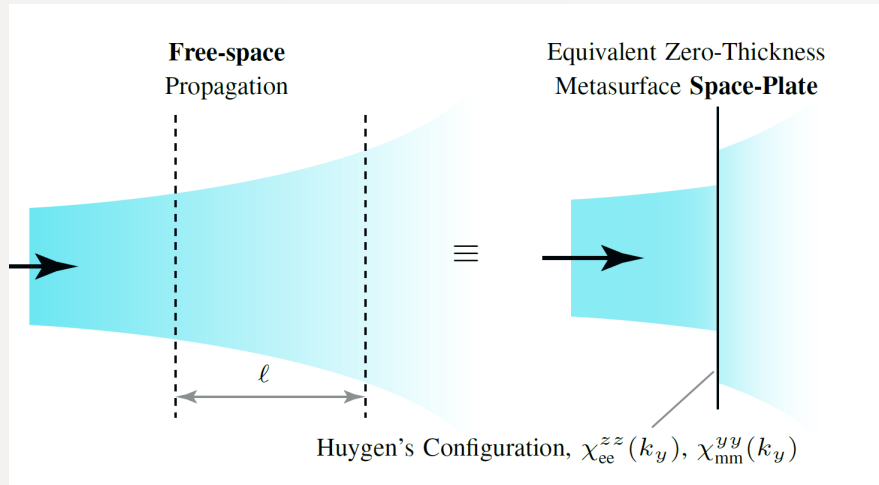
Supporting Information

ABSTRACT: The ultimate miniaturization of any optical system relies on the reduction or removal of free-space gaps between optical elements. Recently, nonlocal flat optic components named “spaceplates” were introduced to effectively compress space for light propagation. However, space compression over the visible spectrum remains beyond the reach of current spaceplate designs due to their inherently limited operating bandwidth and functional inefficiencies in the visible range. Here, we introduce “multi-color” spaceplates performing achromatic space compression at three distinct color channels across the visible spectrum to markedly miniaturize color imaging systems. In this approach, we first design monochromatic spaceplates with high compression factors and



Nonlocal Metasurfaces – A New Modeling Method

New analytical method to model spatially dispersive metasurfaces as angle-dependent surface susceptibilities imposing **higher-order spatial boundary conditions**.



Surface Susceptibility Synthesis of Spatially Dispersive Metasurfaces for Space Compression and Spatial Signal Processing

Jordan Dugan, Tom J. Smy, Francesco Monticone
and Shulabh Gupta *Senior Member, IEEE*

Available on TechRxiv

Abstract—An analytical method is proposed to synthesize the angle-dependent surface susceptibilities, χ of spatially dispersive or non-local zero-thickness metasurfaces. The proposed method is based on the extended Generalized Sheet Transition Conditions

spatial frequency domain. This allows for the implementation of signal processing operations in situ, at the speed of light and with lower power consumption than digital methods. For these

J. Dugan, T. J. Smy, F. Monticone, and S. Gupta, "Surface Susceptibility Synthesis of Spatially Dispersive Metasurfaces for Space Compression and Spatial Signal Processing," IEEE TAP (2024).

What's Next?

Harnessing new degrees of freedom!

❑ Breaking the assumption of spatial locality

→ Strong dependence on the incident wavevector (linear momentum, angle of incidence, spatial frequency)

❑ Breaking the assumption of time invariance

→ Time as a new design parameter

Time-Modulated (Meta)Materials

Very active area of research in electromagnetics, optics, acoustics!



❑ **Waves in linear time-varying media** have been studied for decades

Morgenthaler, F. R. *IRE Transactions on microwave theory and techniques*, 6(2), 167 (1958).

Cassedy, E. S., & Oliner, A. A. *Proceedings of the IEEE*, 51(10), 1342 (1963).

Fante, R. *IEEE Transactions on Antennas and Propagation*, 19(3), 417 (1971).

Jiang, C. L. *IEEE Transactions on Antennas and Propagation*, 23(1), 83 (1975).

❑ Recent surge of interest motivated by opportunities to **overcome long-standing performance limits of time-invariant systems** with engineered temporal (and spatio-temporal) modulations

❑ **Reciprocity constraints in electromagnetics and photonics**

Sounas, D. L., & Alù, A. *Nature Photonics*, 11(12), 774 (2017).

❑ **Breaking symmetries for light emission/absorption** (Kirchhoff's law of thermal radiation)

❑ **Delay-bandwidth constraints and dispersion engineering**

Yanik, M. F., & Fan, S. *Physical review letters*, 92(8), 083901 (2004).

Tucker, R. S., Ku, P. C., & Chang-Hasnain, C. J. *JLT*, 23(12), 4046 (2005).

Hayran, Z., & Monticone, F. *ACS Photonics*, 8(3), 813 (2021).

❑ **Limits on antennas:** e.g., Chu limit on the bandwidth of small antennas

Manteghi, M. *IEEE Antennas and Propagation Society International Symposium* (2009).

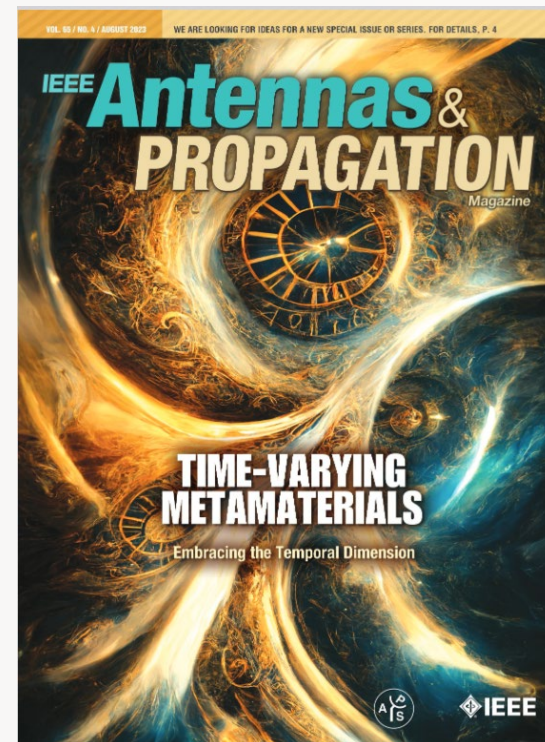
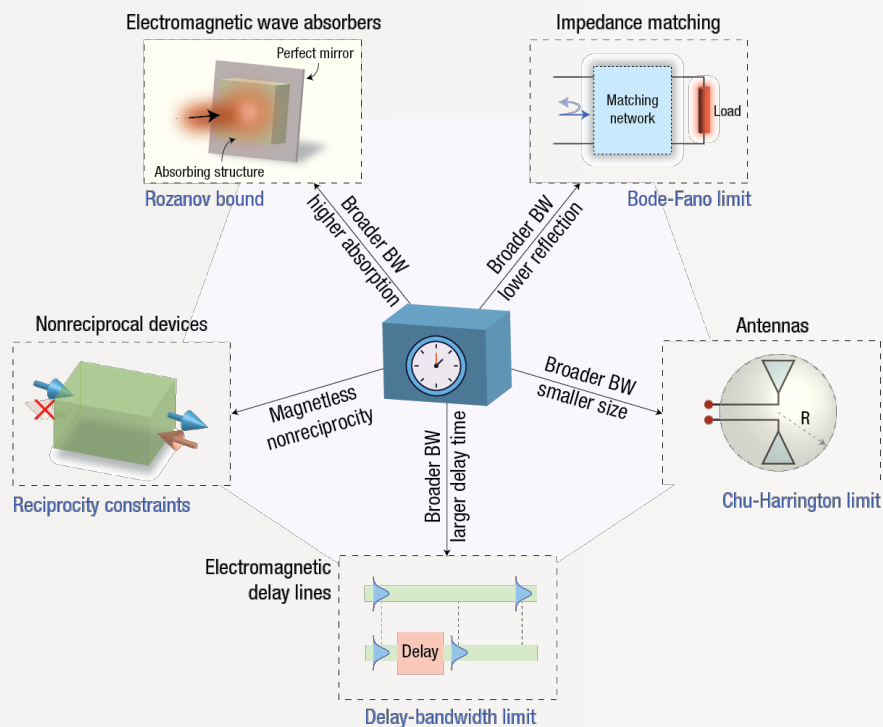
Li, H., Mekawy, A., & Alù, A. *Physical review letters*, 123(16), 164102 (2019).

❑ **Limits on absorption and scattering reduction:** Rozanov bound (impedance matching through absorption) and Bode-Fano limit (impedance matching through interference)

Shlivinski, A., & Hadad, Y. *Physical review letters*, 121(20), 20430 (2018).

Li, H., & Alù, A. *Optica*, 8(1), 24 (2021).

Sievenpiper, Monticone, and others!



Using Time-Varying Systems to Challenge Fundamental Limitations in Electromagnetics

Zeki Hayran, Francesco Monticone, *Member, IEEE*

School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA

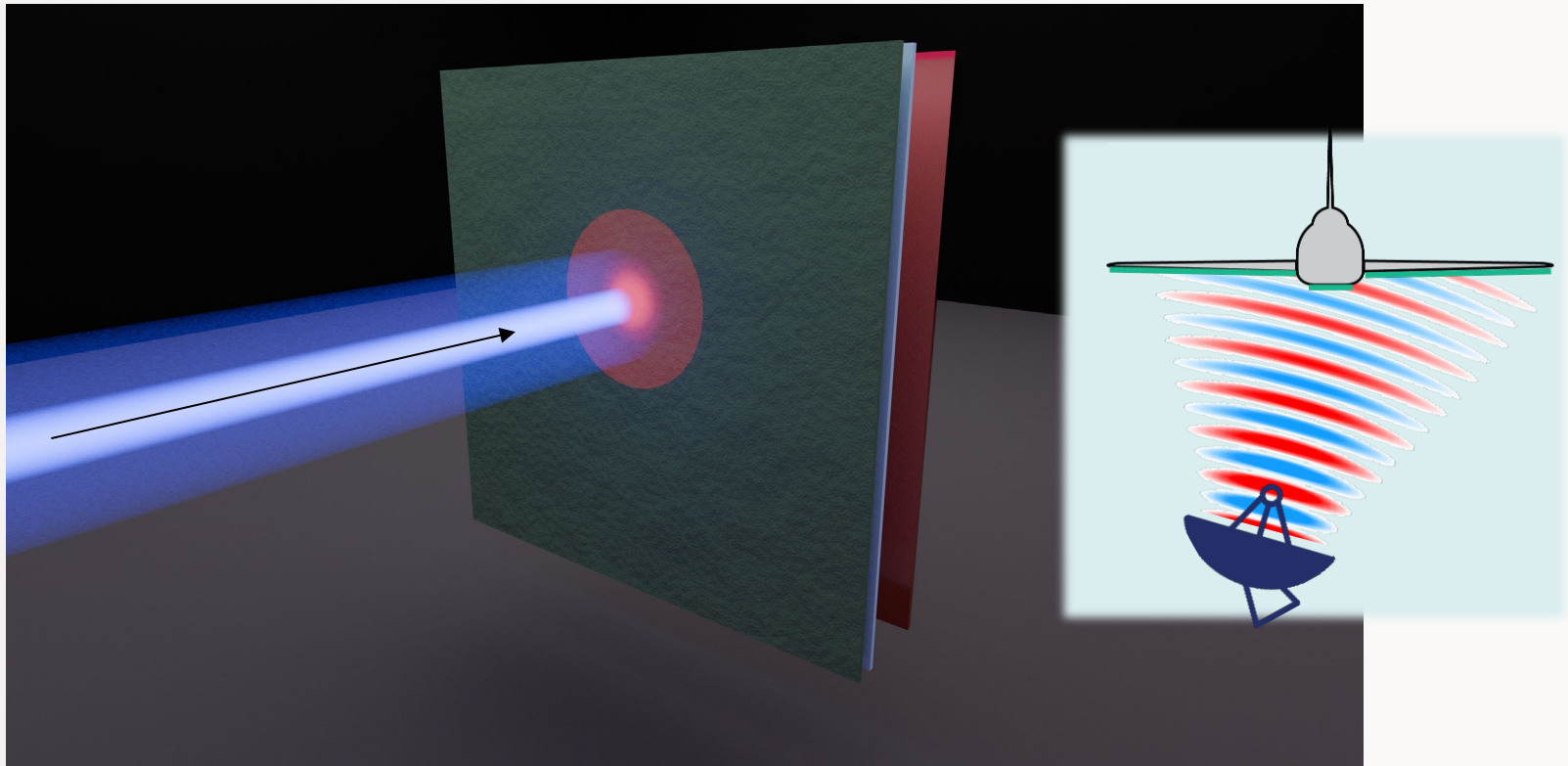
Time-varying media, dispersion, and the principle of causality [Invited]

THEODOROS T. KOUTSERIMPAS AND FRANCESCO MONTICONE*

School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA

*francesco.monticone@cornell.edu

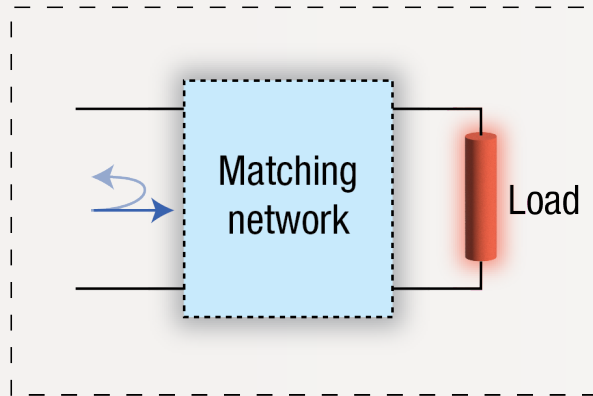
Wave Absorption



Can we design an ultra-thin (e.g., deeply subwavelength) metasurface able to absorb as much incident electromagnetic energy as possible over an ultra-wide bandwidth?

Bode-Fano and Rozanov Limits on Reflection Reduction

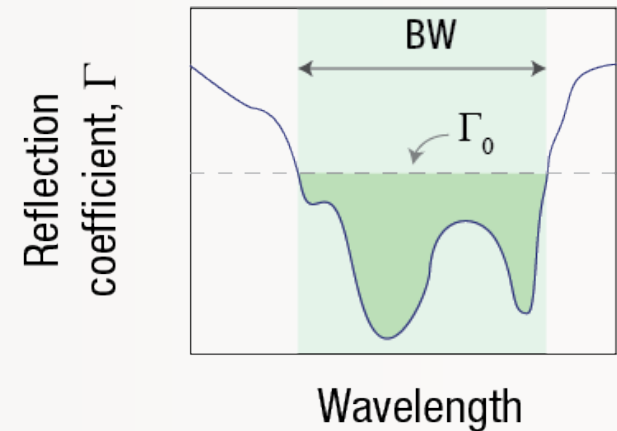
Impedance matching



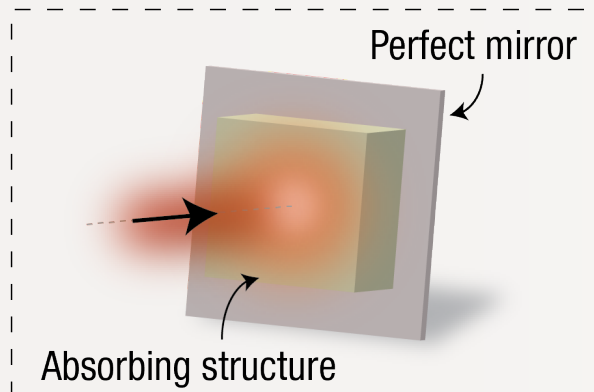
Bode-Fano Limit

$$\left| \int_0^\infty \omega^n \ln |\Gamma(\omega)| d\omega \right| \leq \kappa(n, \text{load})$$

Fano, R. M. (1950), Theoretical limitations on the broadband matching of arbitrary impedances, Journal of the Franklin Institute, 249(1), 57–83



Electromagnetic wave absorbers



Rozanov bound ("causality limit" in acoustics)

$$\left| \int_0^\infty \ln |\Gamma(\lambda)| d\lambda \right| \leq 2\pi^2 \mu_s d$$

Assumptions:

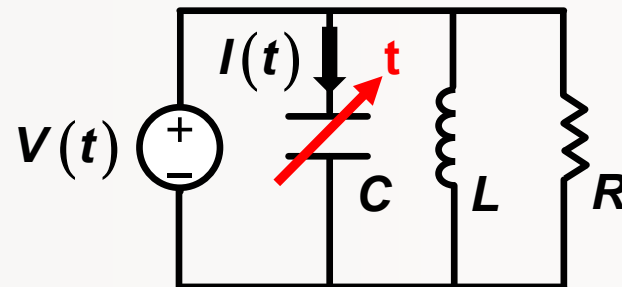
- ☐ Causality
- ☐ Linearity
- ☐ Passivity
- ☐ Time-invariance

K. N. Rozanov, "Ultimate thickness to bandwidth ratio of radar absorbers," IEEE Trans. on Antennas Propag. 48, 1230–1234 (2000).

Modulating Reactance

What features of linear time-varying systems may allow breaking these bounds?

What are the options available?



❑ **Modulating a reactance** (e.g., the real part of the permittivity of material) **New term**

Lossless time-varying capacitor
$$I(t) = \frac{dC(t)V(t)}{dt} = C(t) \frac{dV(t)}{dt} + V(t) \frac{dC(t)}{dt}$$

Energy dissipated or gained
$$E = \int_{-\infty}^{\infty} V(t)I(t)dt = \frac{1}{2} \int_{-\infty}^{\infty} V(t)^2 (dC(t) / dt) dt$$

❑ **Energy exchange** with the external modulator

$$C(t) = C_0 + C_m \cos(\omega_m t + \phi)$$

❑ If modulation is periodic with $\omega_m = 2\omega_s$:

❑ **Parametric gain or parametric absorption**

$$Z(\omega) = \frac{V(\omega)}{I(\omega)} = -i \left(\frac{1}{\omega C_0} + \frac{1}{\omega C_m} 2e^{i\phi} \right)$$

for $\omega_m \approx 2\omega$

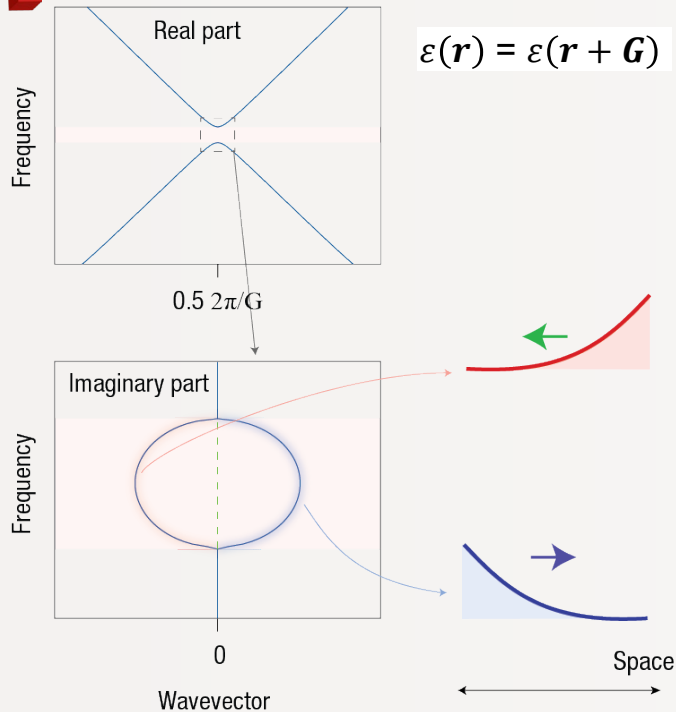
❑ Coupling between **positive to negative frequencies**

❑ **Change of impedance dispersion**

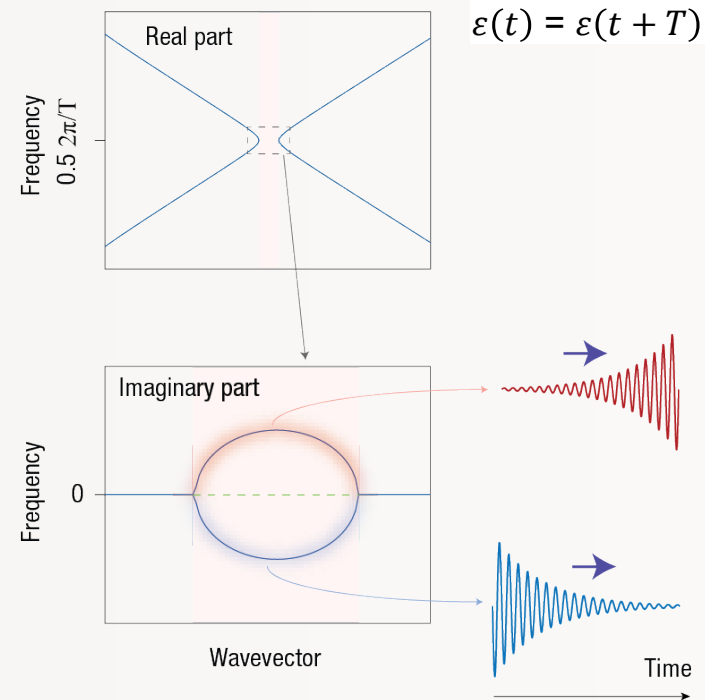
❑ For propagating modes: Opening of **momentum bandgaps**

Photonic Crystals vs. Photonic Time Crystals

Space-periodic media



Time-periodic media



Wave Propagation in a Medium with a Progressive Sinusoidal Disturbance*

A. HESSEL†, MEMBER, IRE, AND A. A. OLINER†, FELLOW, IRE

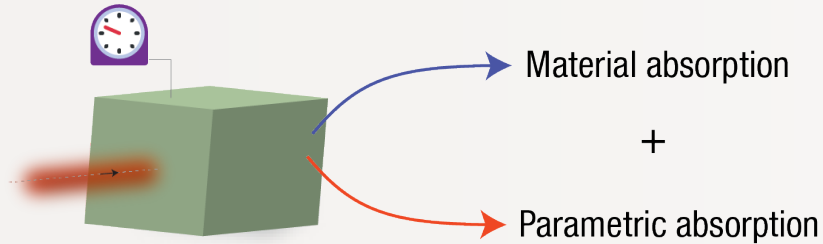
Dispersion Relations in Time-Space Periodic Media: Part I—Stable Interactions*

E. S. CASSEDY†, SENIOR MEMBER, IEEE, AND A. A. OLINER†, FELLOW, IEEE

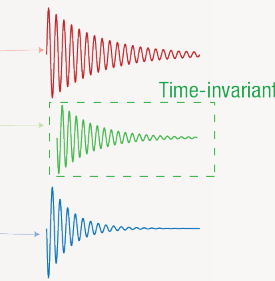
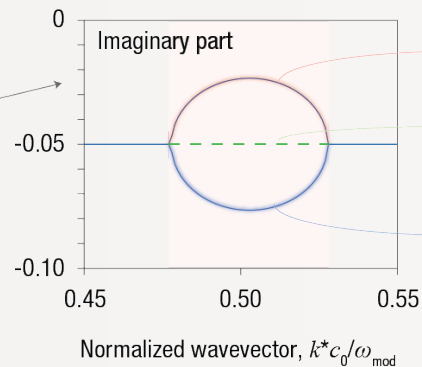
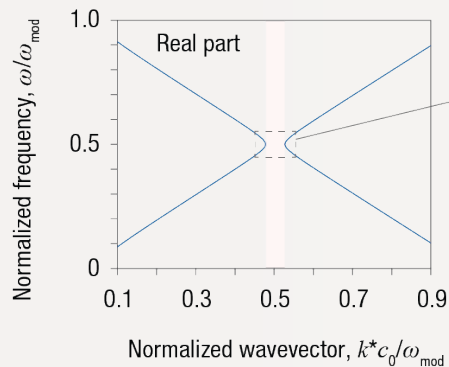
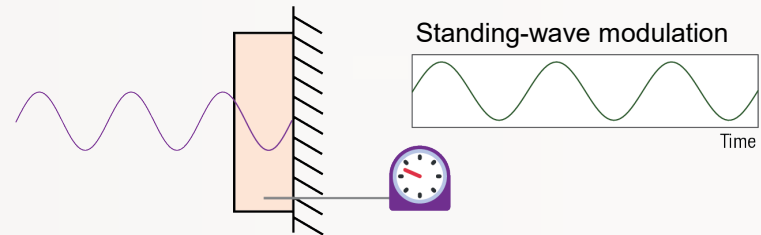
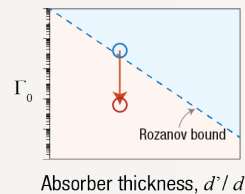


Lossy Periodic Time Modulation

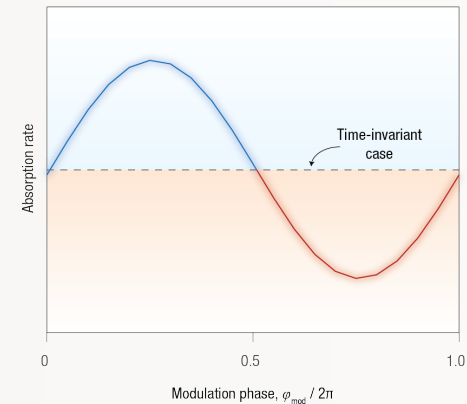
Can this be used to break bounds on the reflection coefficient, such as the Rozanov bound for absorbers?



Lossy periodically time-modulated material



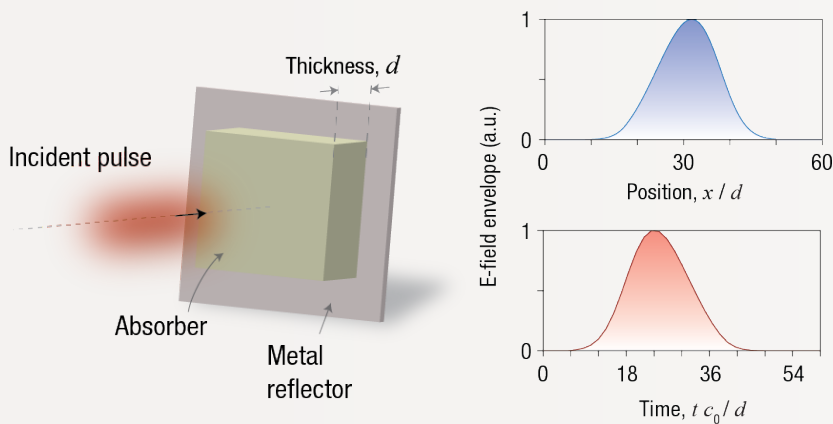
$$\omega_{\text{mod}} > \omega_{\text{p0}}^2 / (\sqrt{3}\gamma)$$



Z. Hayran, and F. Monticone, "Beyond the Rozanov Bound on Electromagnetic Absorption via Periodic Temporal Modulations," Phys. Rev. Applied 21, 044007 (2024).



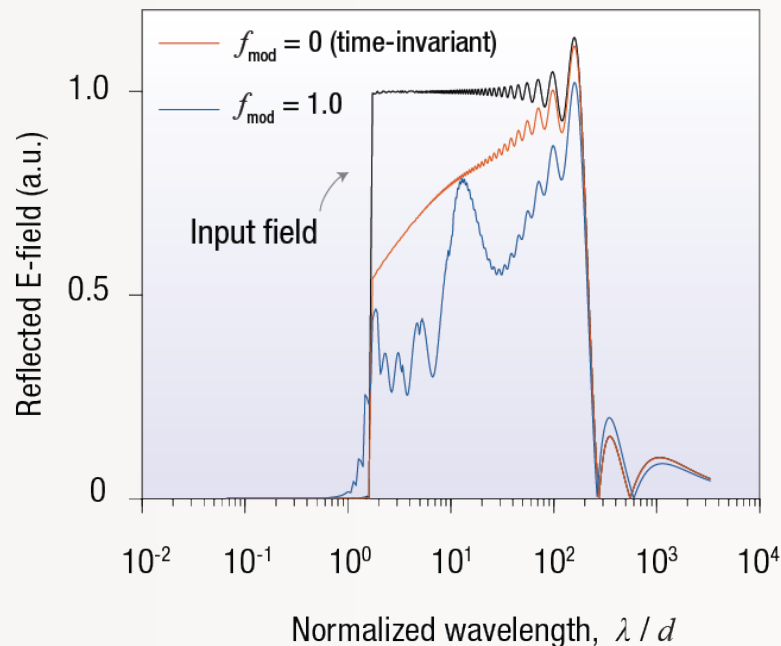
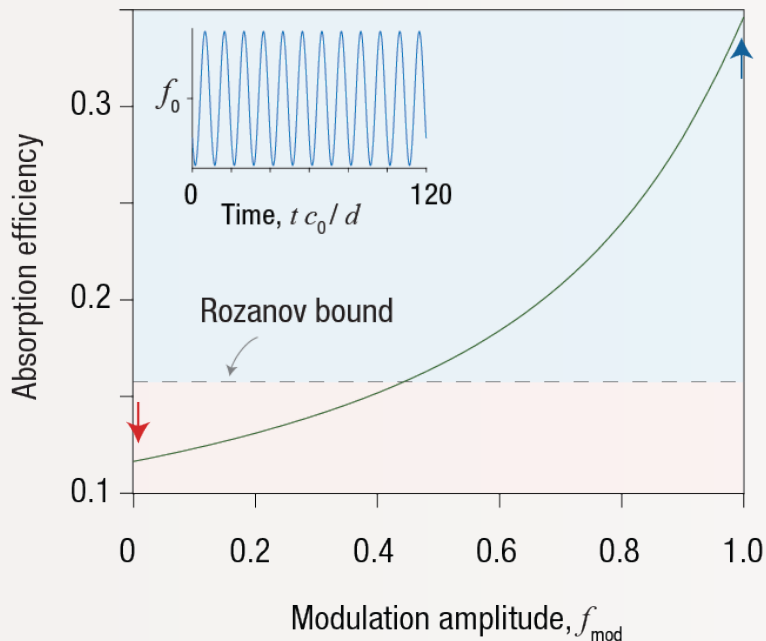
Parametric Absorption to Overcome the Rozanov Bound



Lossy dispersive plasmonic medium with time-modulated plasma frequency:

$$\omega_p^2(t) = \omega_{p0}^2 (1 + f_{\text{mod}} \sin(\omega_{\text{mod}} t + \varphi_{\text{mod}}))$$

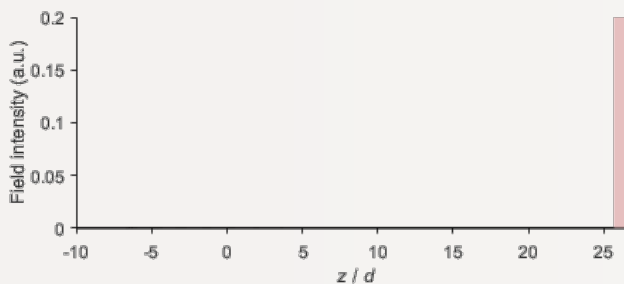
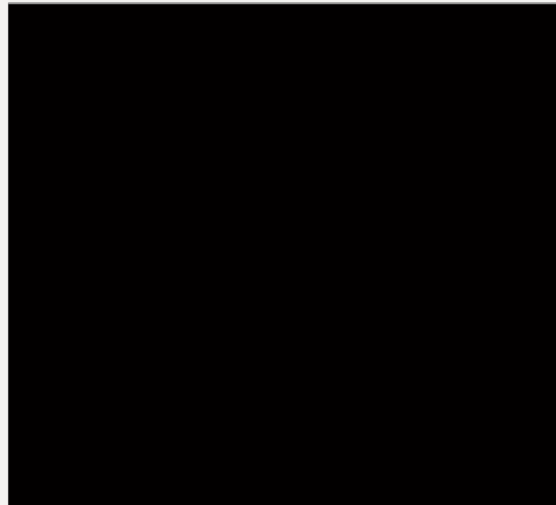
$$AE = 1 - \frac{\int_{-\infty}^{\infty} |E_{\text{ref}}(f)|^2 df}{\int_{-\infty}^{\infty} |E_{\text{inc}}(f)|^2 df}$$



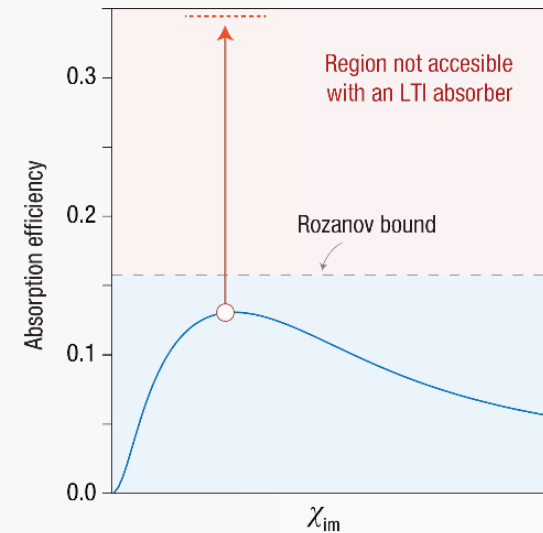
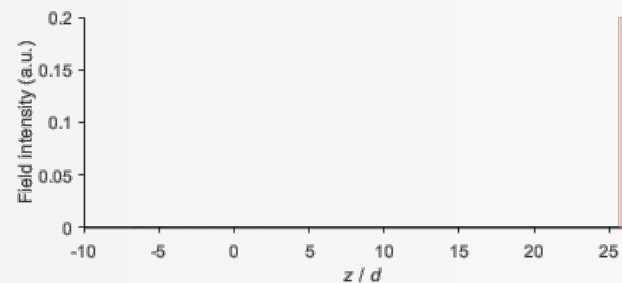
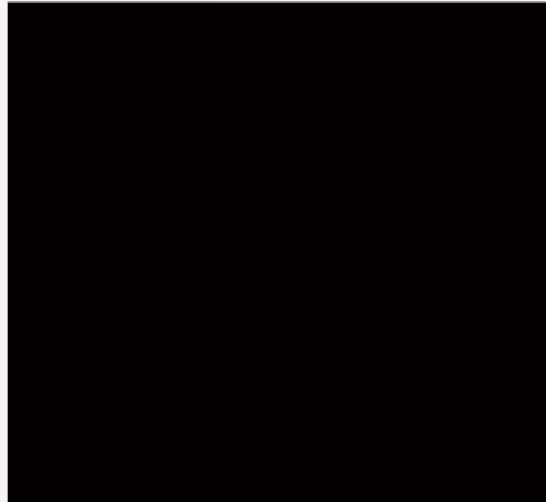
Absorption performance significantly enhanced beyond the Rozanov bound!

Going Beyond the Rozanov Bound

Time-invariant



With temporal modulation

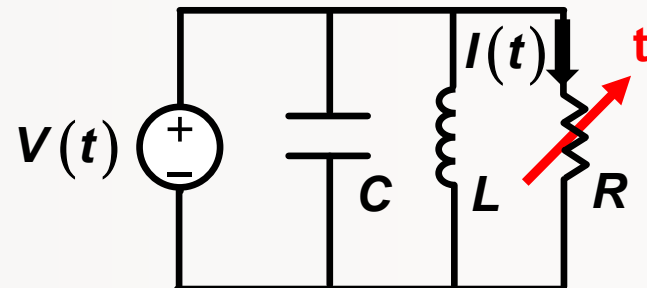


Z. Hayran, and F. Monticone, "Beyond the Rozanov Bound on Electromagnetic Absorption via Periodic Temporal Modulations," Phys. Rev. Applied 21, 044007 (2024).



Modulating Resistance

- ❑ **Modulating a resistance** (e.g., conductivity of an imperfect conductor)



Time-varying resistor $V(t) = R(t)I(t)$ **Ohm's Law remains unchanged!**

- ❑ **No energy exchange** with modulator
- ❑ Modulation still generates **harmonics**
- ❑ Energy **dissipated** on the resistor can change

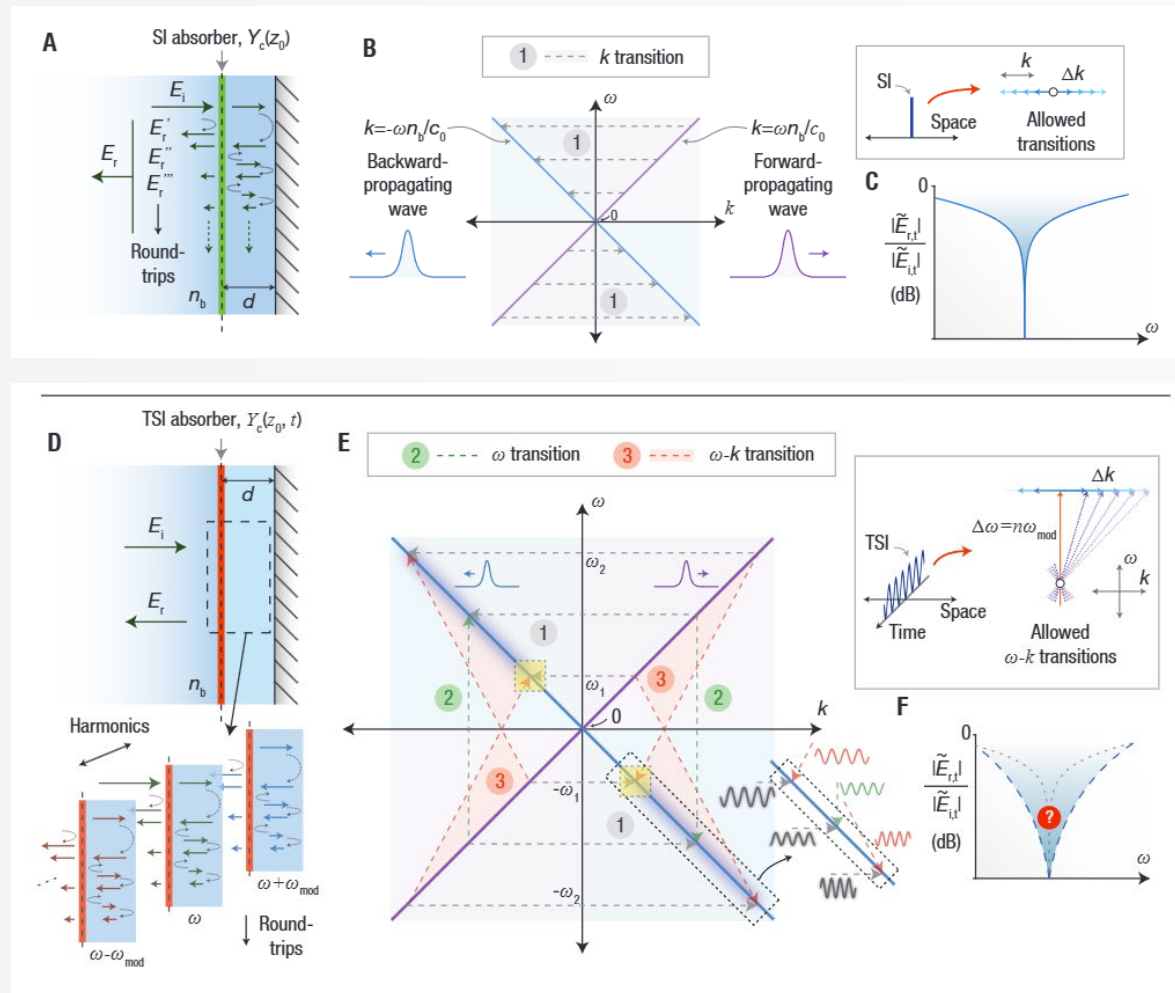
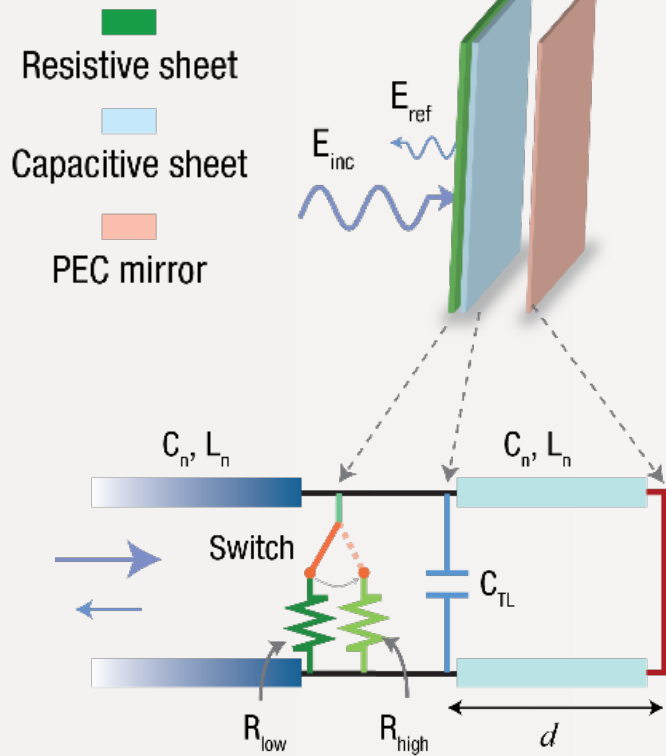
Energy dissipated
$$E = \int_{-\infty}^{\infty} V(t)I(t)dt = \frac{1}{2} \int_{-\infty}^{\infty} V(t)^2 / R(t) dt$$

Can this still be used to break the Rozanov bound for absorbers?

Yes, through destructive interference between harmonics

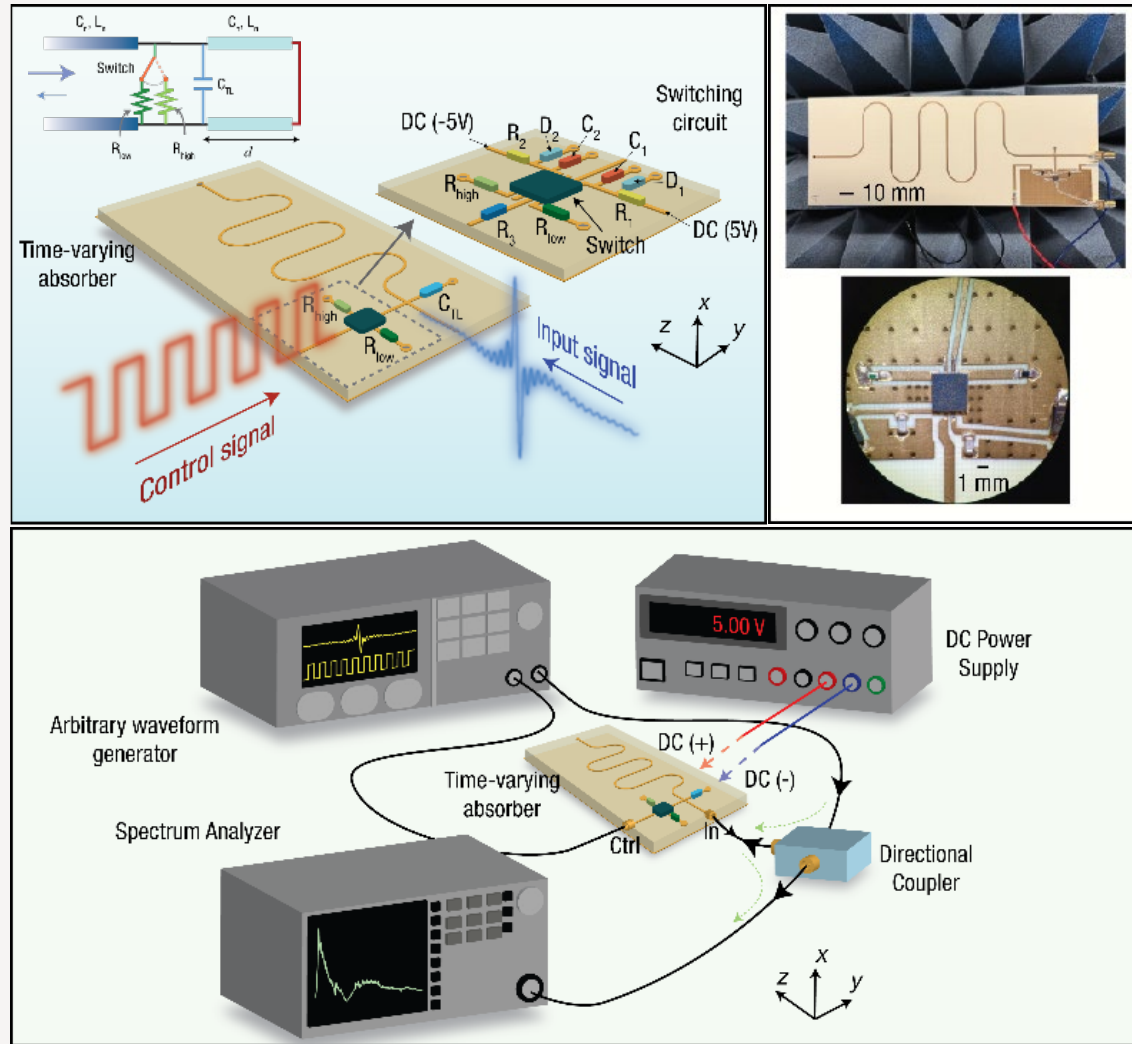
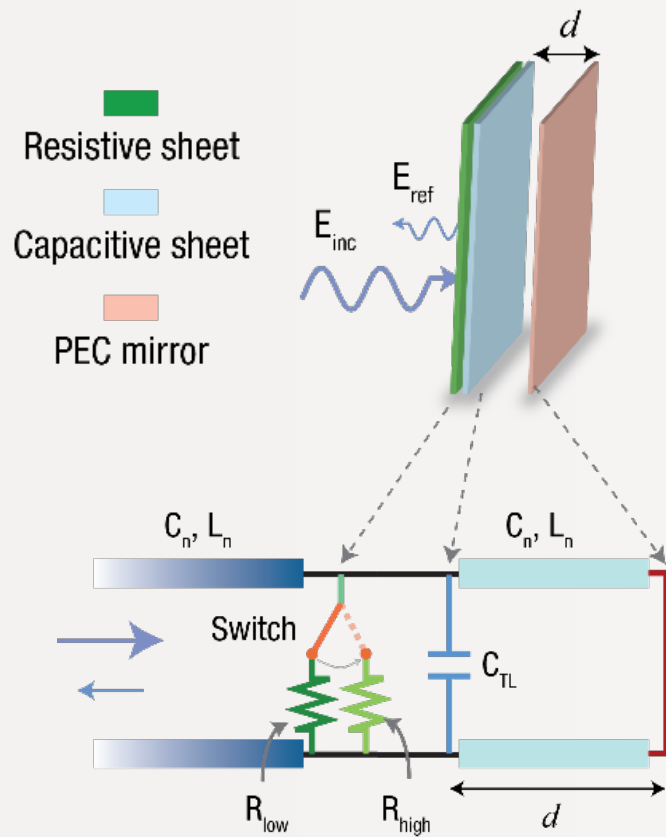
Destructive interference between harmonics

Destructive interference between partial reflections



Destructive interference between harmonics

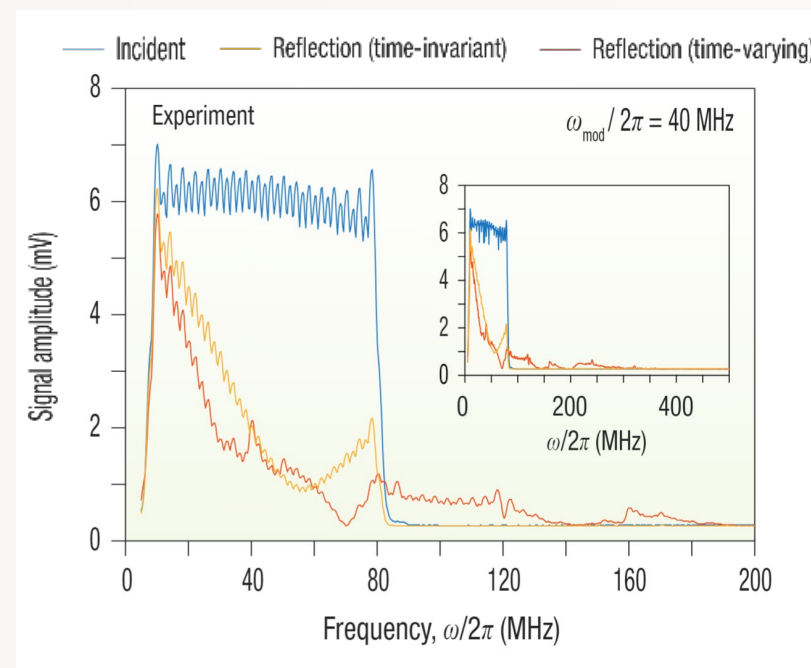
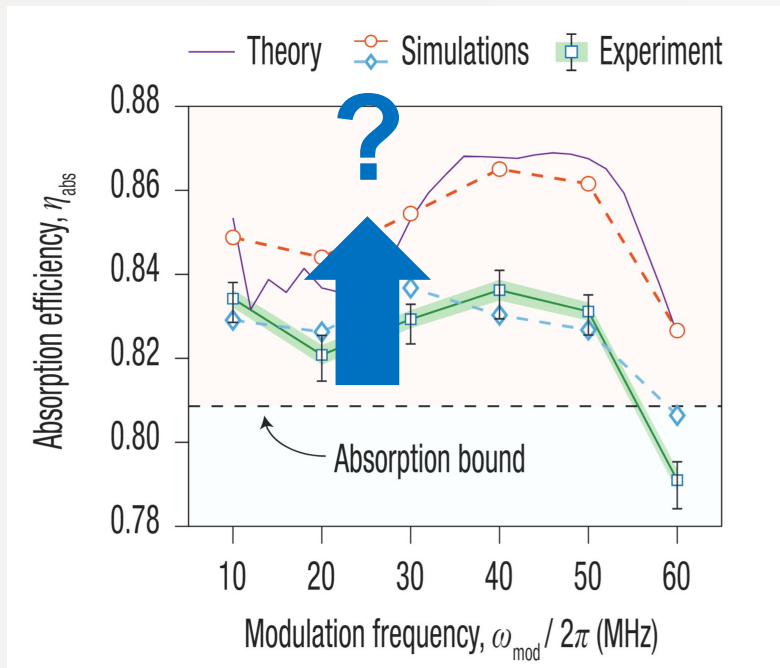
Experimental Demonstration



M. Ciabattini, Z. Hayran, and F. Monticone, "Observation of broadband super-absorption of electromagnetic waves through space-time symmetry breaking," **Science Advances**, in press, 2024. arXiv preprint, arXiv:2408.14679



Experimental Results



First experimental demonstration of electromagnetic absorption performance beyond the Rozanov limit using periodic temporal modulations

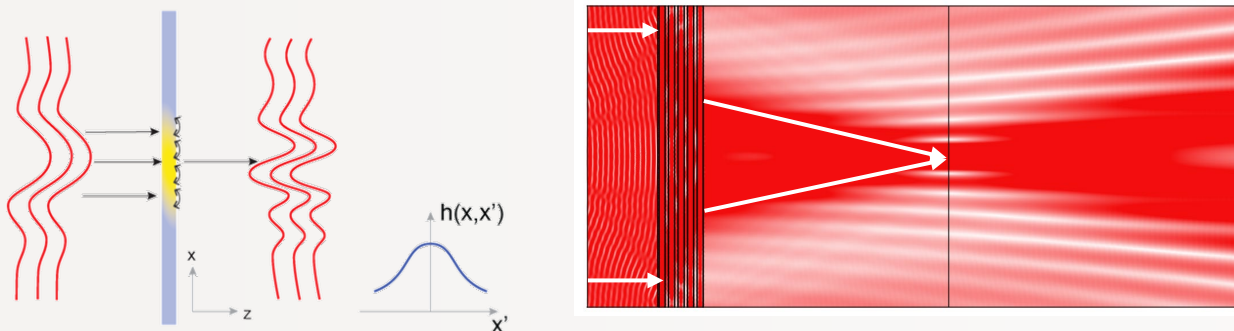
- ❑ Very **broadband** absorption enhancement.
- ❑ Absorber is **thinner** than the width of the incident pulse.
- ❑ Destructive interference between harmonics
→ **More energy is actually dissipated** in the resistor
- ❑ Next steps:
 - Self-tuning mechanisms to automatically adjust the mod **phase**
 - Implement and test in **metasurface** form.

Conclusion

Harnessing new degrees of freedom!

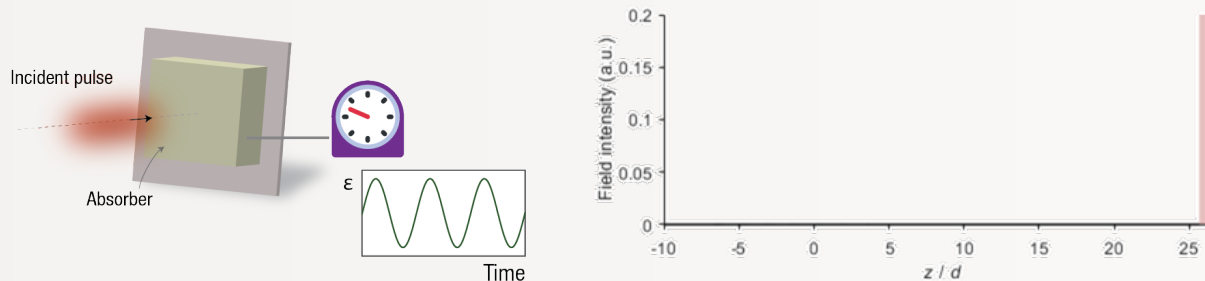
❑ Breaking the assumption of spatial locality

→ Strong dependence on the incident wavevector (linear momentum, angle of incidence, spatial frequency)



❑ Breaking the assumption of time invariance

→ Time as a new design parameter



Acknowledgements

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Thanks for Your Attention

Questions



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