Omni-Resonance in Cavities and Space–Time Wave Packets

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Overview

Introducing precise correlations between the degrees of freedom of an optical field leads to dramatic changes in the free propagation of such fields and their interaction with photonic devices. When this concept is applied to the spatial *and* temporal degrees of freedom of the field, a new realm of phenomena and applications that we call '***space-time optics and photonics***' emerges. We denote coherent pulses incorporating such structure '***space-time (ST) wave packets***', or more generally '***ST fields***'.

Potential applications

1. Diffraction-free, dispersion-free pulsed beams in free space
2. Self-healing after obstructive objects
3. Controlling the group velocity in free space and in optical materials
4. Long-distance propagation
5. Incoherent fields
6. Accelerating wave packets
7. Localized tunable modes in planar waveguides
8. ***Omni-resonance in planar cavities***

OPN, May 2019

"Do not all charms fly
At the mere touch of cold philosophy?
There was an awful rainbow once in heaven:
We know her woof, her texture; she is given
In the dull catalogue of common things.
Philosophy will clip an Angel's wings,
Conquer all mysteries by rule and line,
Empty the haunted air, and gnomed mine—
Unweave a rainbow ..."
J. Keats, 'Lamia' 1820

Timeline

1983 Brittingham focused wave mode (FWM; (luminal $v_g = c$))

Diffraction-free luminal pulses

1978 McKinnon nondispersive wavepacket (subluminal $v_g < c$)

Subluminal diffraction-free beams

1979 Berry-Balasz accelerating (1+1)D Airy wavepacket

No 1D diffraction free beams

1980's Strategic Defense Initiative ('Star wars')

1987 Durnin *et al.*, Bessel beam (precursors: 1908 Whittaker, Stratton)

1991 X-waves in ultrasonics (superluminal $v_g > c$)

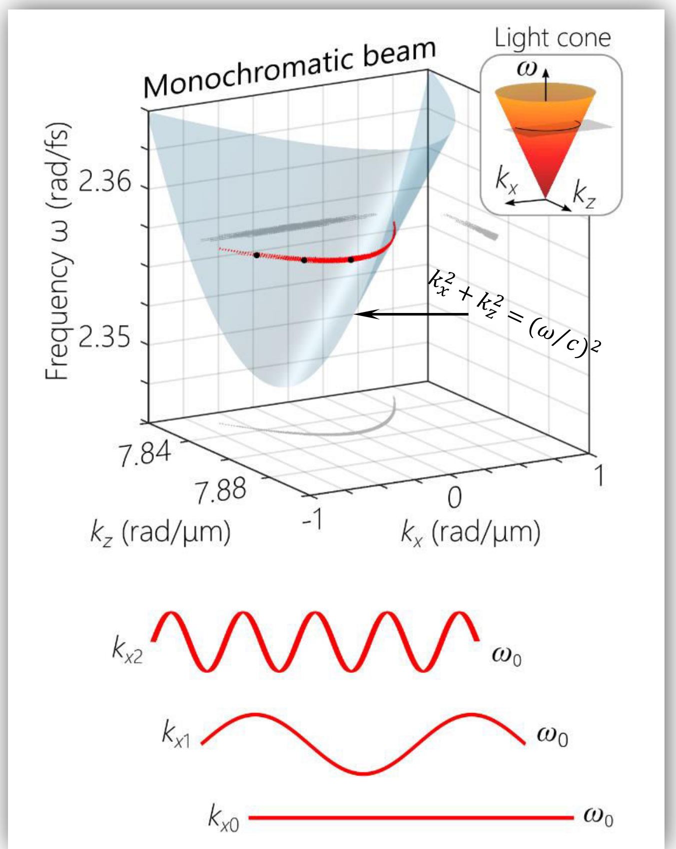
1997 Saari, Optical X-waves (Bessel-X pulses)

2007 Accelerating optical Airy beams

2010 Airy pulses and Airy-Bessel bullets

Monochromatic and pulsed beams

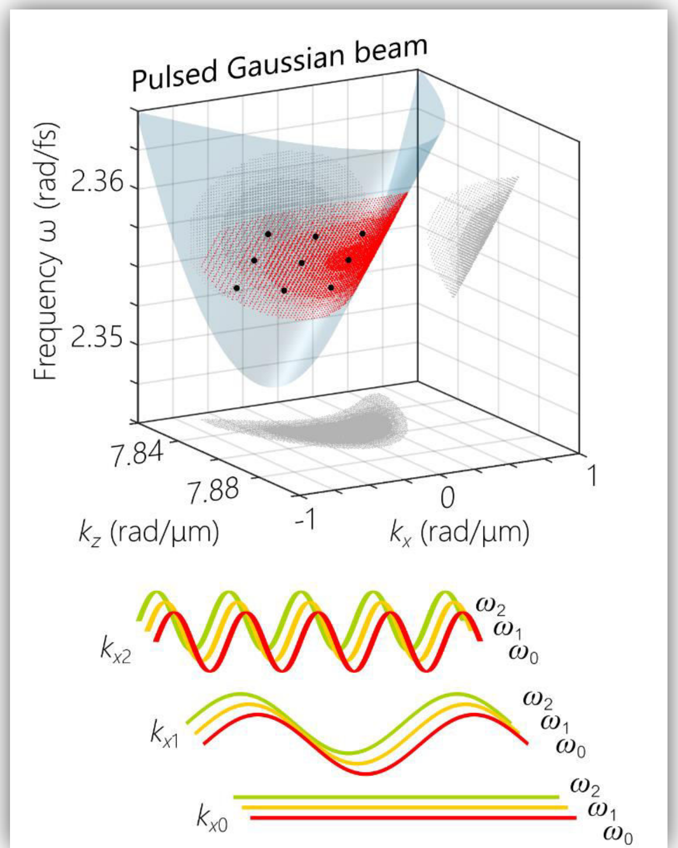
Monochromatic beams



The spatial spectra of all ***monochromatic beams*** lie on the circle at the intersection of the light-cone $k_x^2 + k_z^2 = (\omega/c)^2$ with a horizontal plane.

$$E(x,z;t) = e^{-i\omega t}\int dk_x \tilde{E}(k_x) e^{i(k_x x + k_z z)}$$

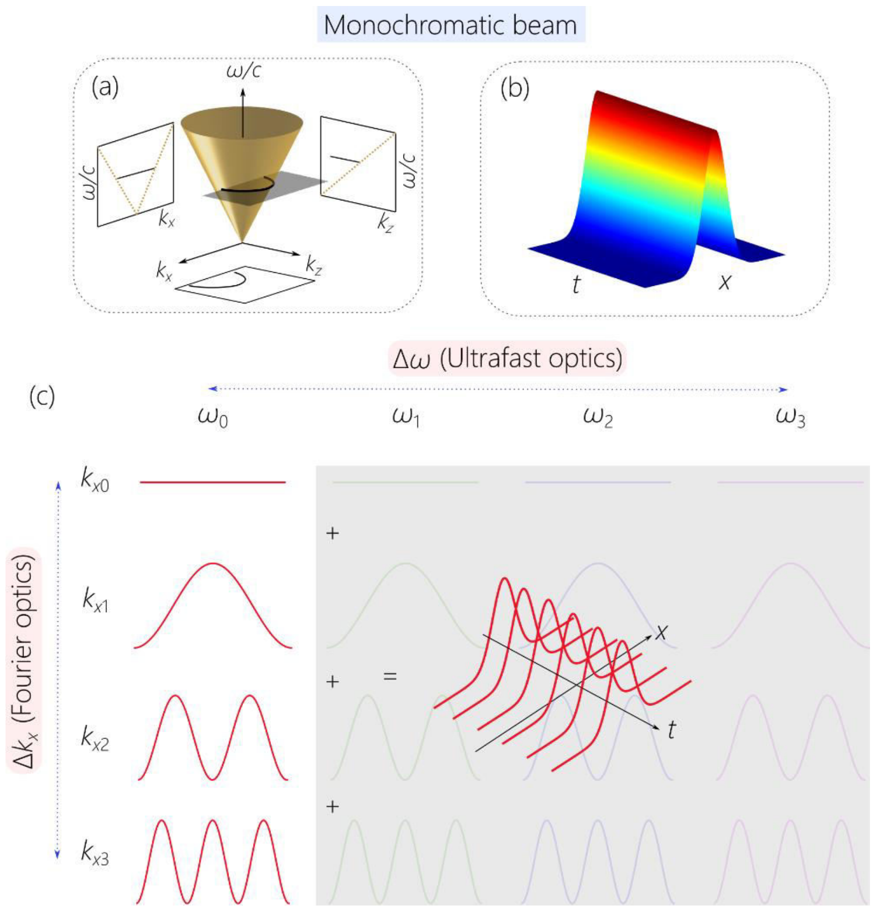
Pulsed beams

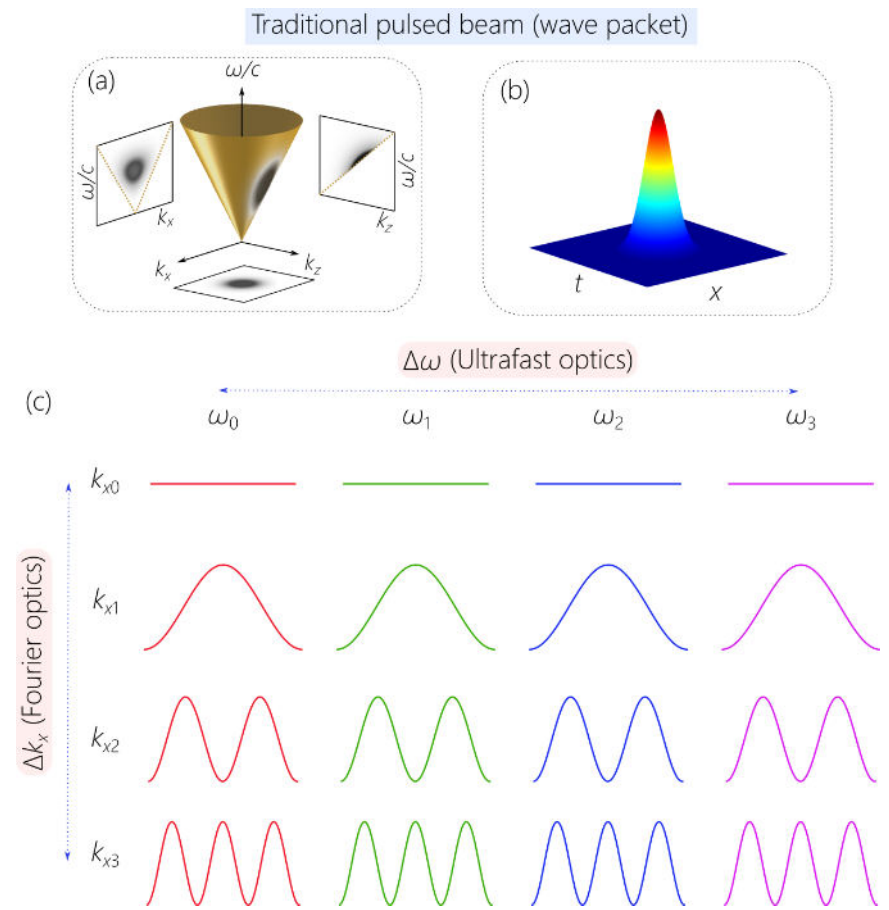


The spatio-temporal spectra of ***pulsed beams*** in general cover a patch on the light-cone.

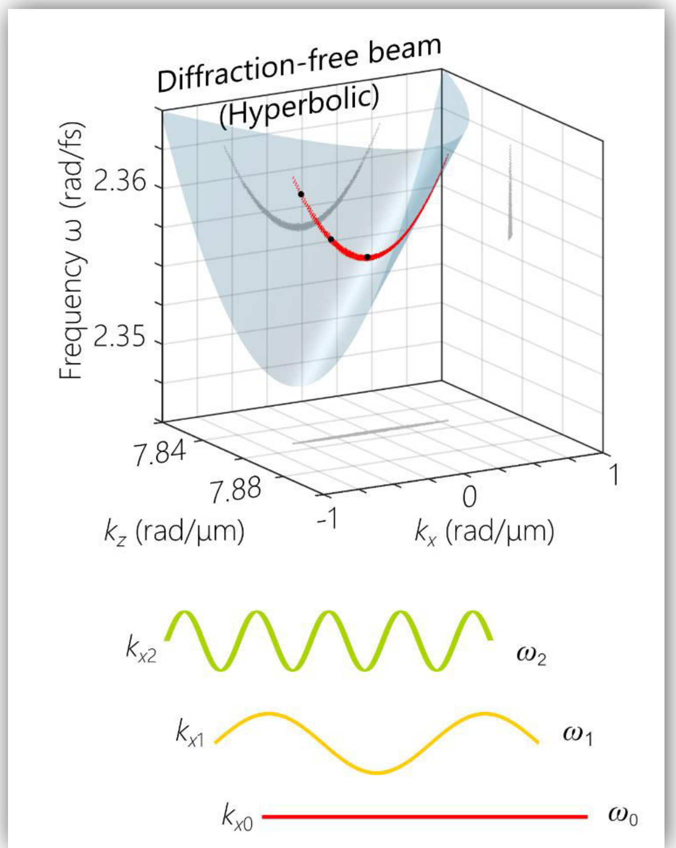
$$E(x,z;t) = \iint dk_x d\omega \tilde{E}(k_x, \omega) e^{i(k_x x + k_z z - \omega t)}$$

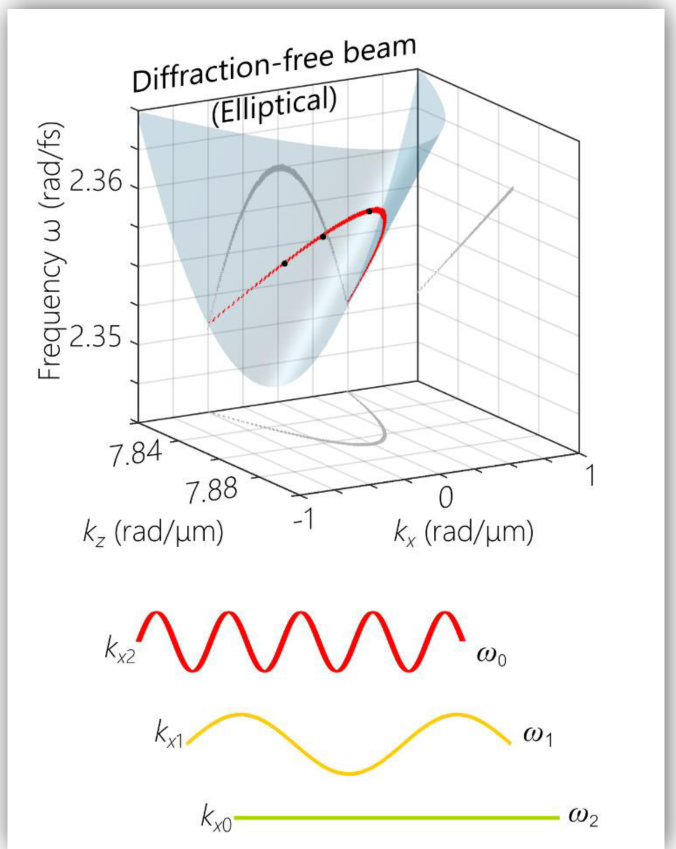
Monochromatic and pulsed beams





Diffraction-free and dispersion-free beams

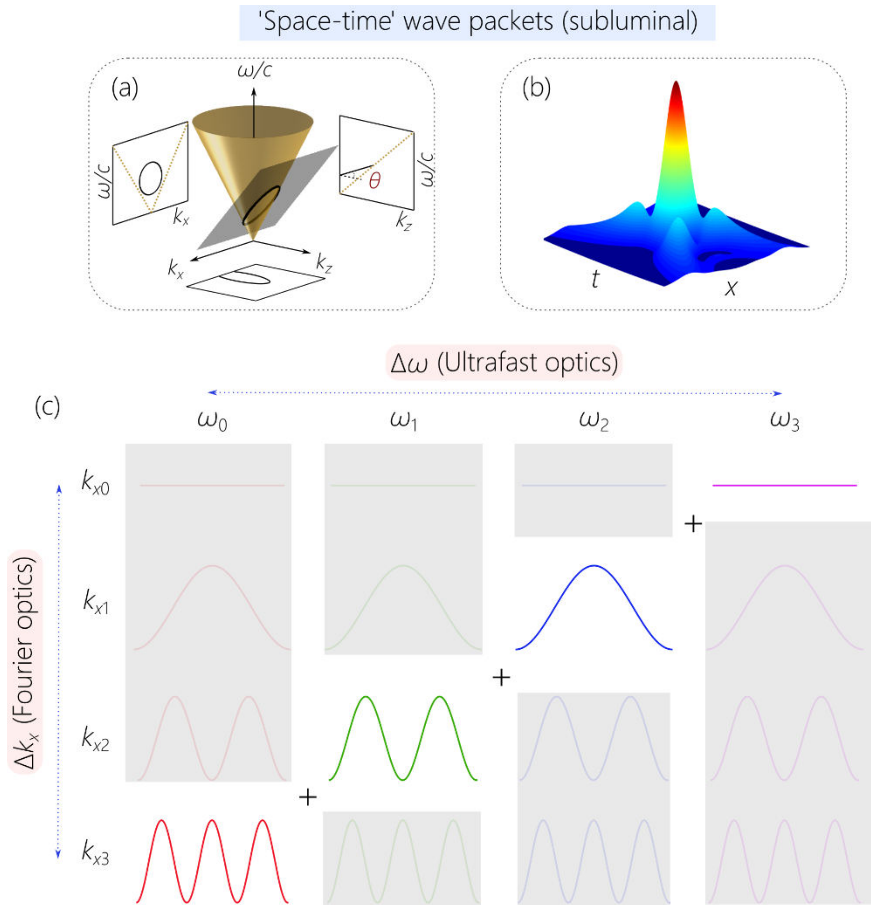


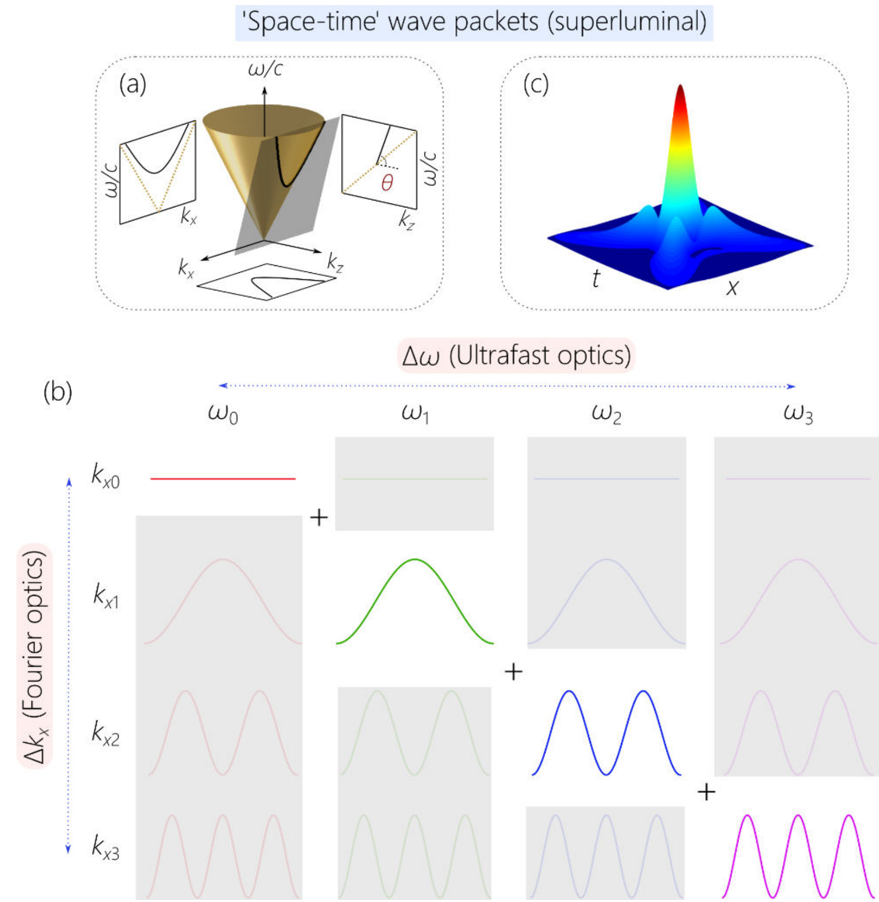


The spatio-temporal spectra of all diffraction-free, dispersion-free pulsed beams lie on the conical sections at the intersection of the light-cone and planes. We call such beam in which the spatial and temporal degrees of freedom are tightly intertwined *space-time beams*.

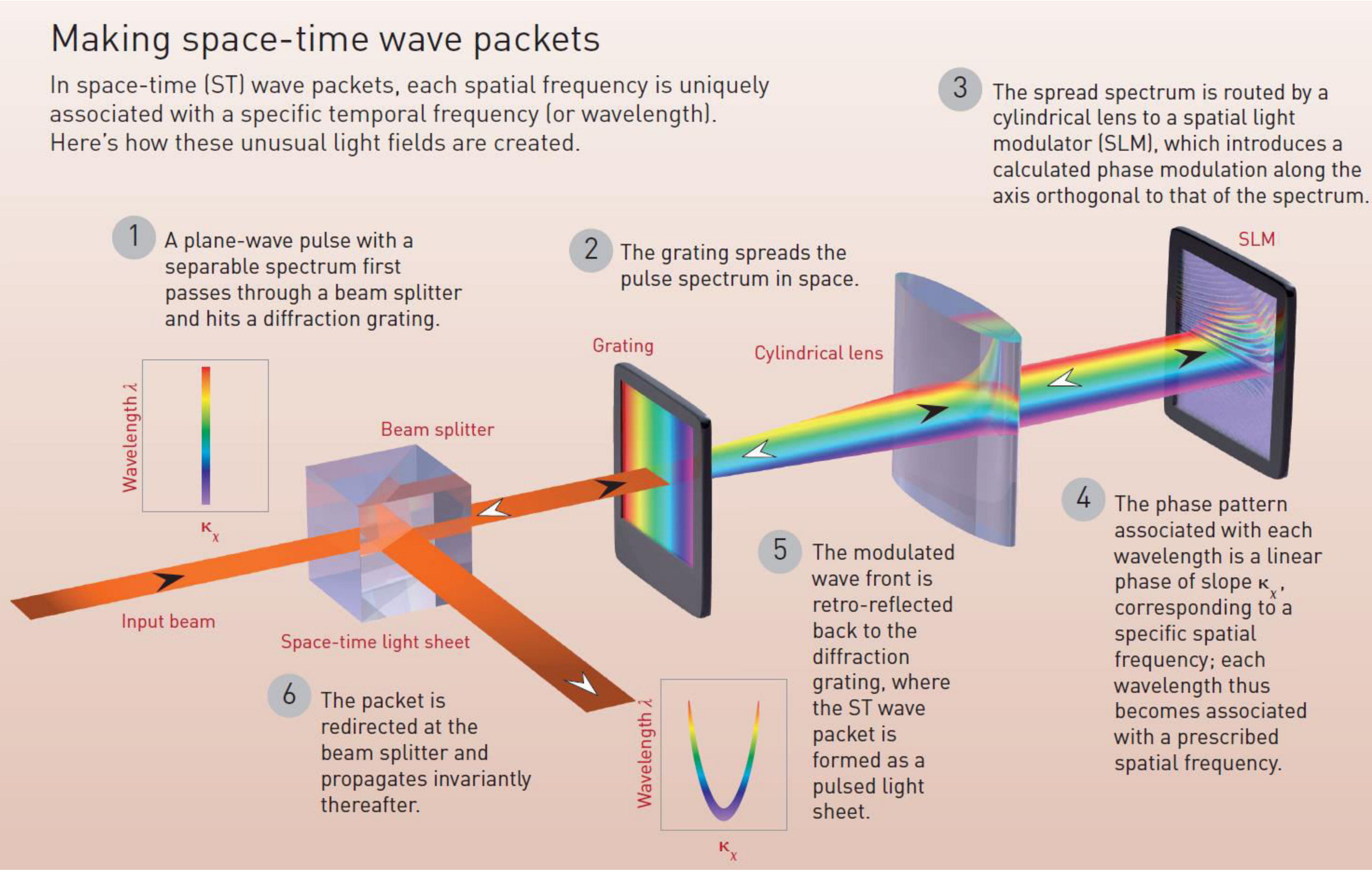
Nature Photonics **11**, 733-740 (2017)

Diffraction-free and dispersion-free beams



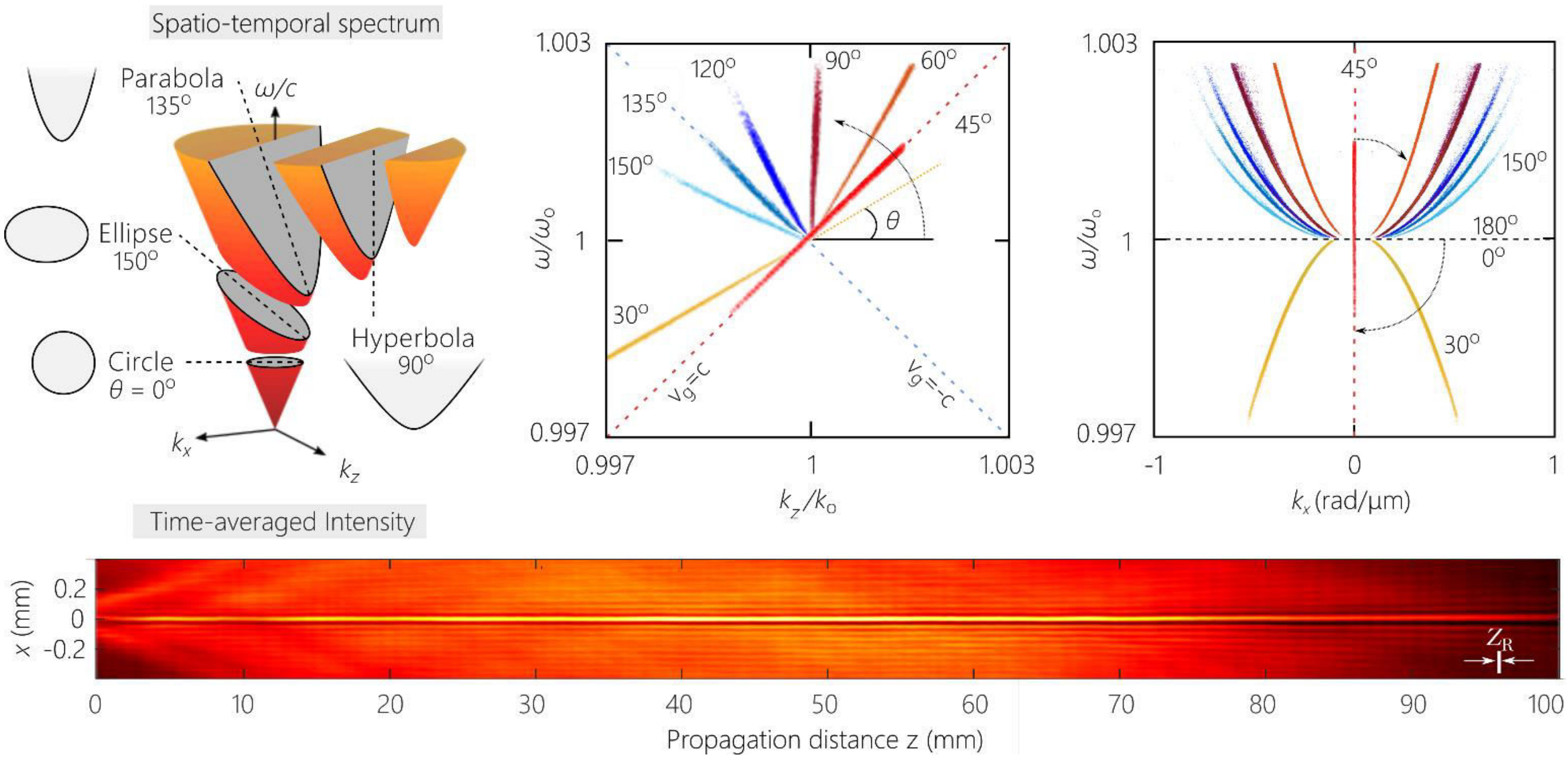


Synthesis of space-time beams



The desired correlation between ω and k_x is implemented with a computer-controlled spatial light modulator (SLM).

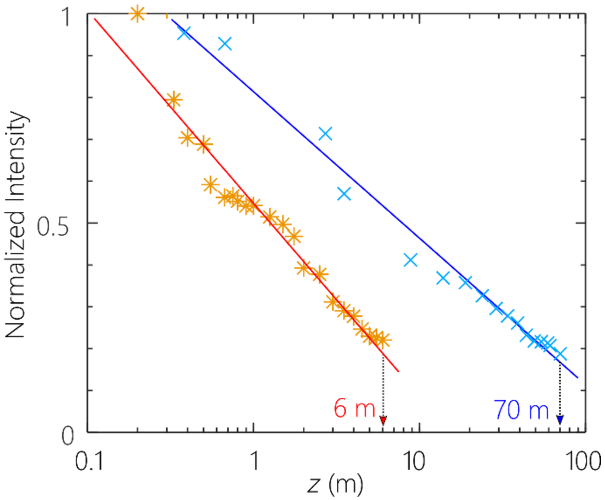
Synthesis of ST wave packets

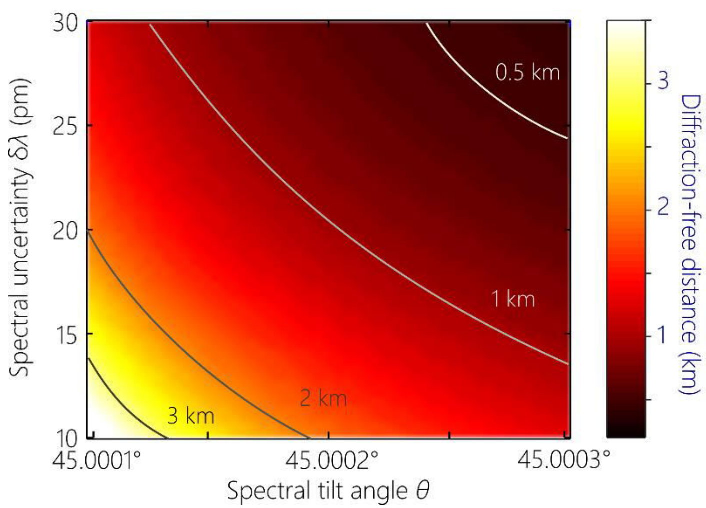


$$\omega - \omega_o = (k_z - k_o) c \tan \theta$$

Current achievements

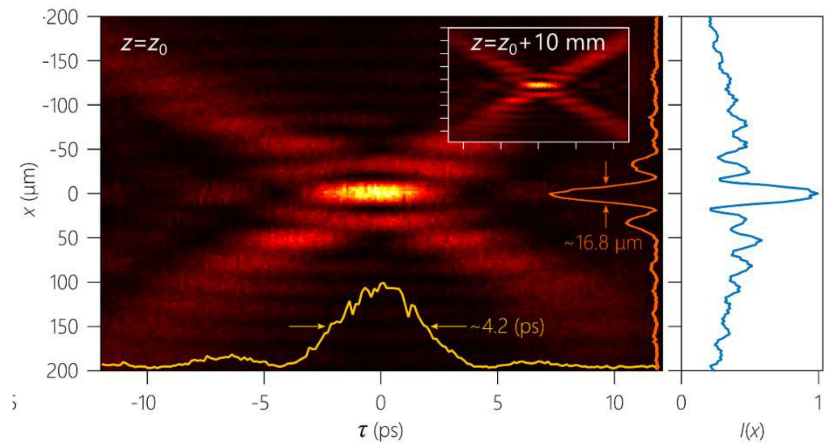
Diffraction-free propagation

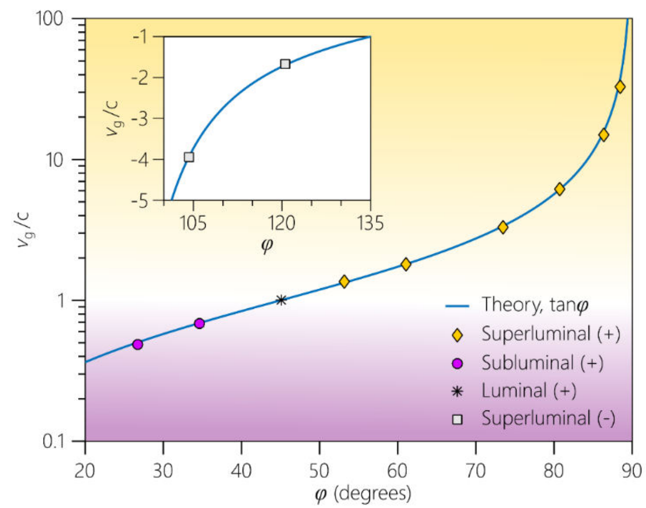




Opt. Lett. **44**, 2073 (2019)

Arbitrary group velocity in free space of space-time beams





Nat. Commun. **8**, 739 (2019)

Current achievements

1. Diffraction-free, dispersion-free pulsed beams in free space

   Nat. Photon. **11**, 733 (2017); Phys. Rev. Lett. **120**, 163901 (2018); Opt. Express **26**, 13628 (2018)

2. Self-healing after obstructive objects

   Opt. Lett. **43**, 3830 (2018)

3. Controlling the group velocity in free space and in optical materials

   Nat. Commun. **10**, 929 (2019); Optica **6**, 139 (2019); Opt. Express **27**, 12443 (2019)

4. Long-distance propagation

   Opt. Express **26**, 20111 (2018); Opt. Lett. **44**, 2073 (2019)

5. Anomalous refraction at planar interfaces

   Nat. Photon. **14**, 416 (2020); Opt. Lett. **46**, 2260 (2021)

6. Incoherent fields

   Optica **6**, 598 (2019); Opt. Lett. **44**, 5125 (2019)

7. Accelerating wave packets

   Phys. Rev. Lett. **125**, 233901 (2020)

8. Localized tunable modes in planar waveguides

   Nat. Commun. **11**, 6273 (2020)

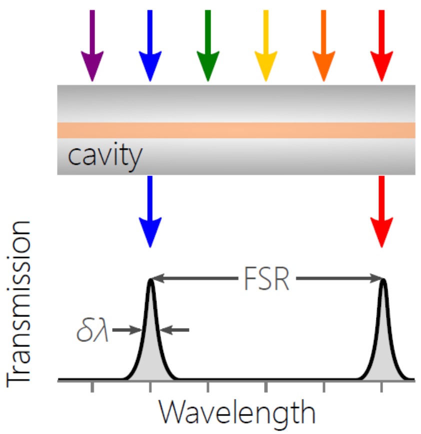
9. ST surface plasmon polaritons

   ACS Photonics **7**, 2966 (2020)

10. ***Omni-resonance in planar cavities***

    Sci. Rep. **7**, 10336 (2017); Opt. Lett. **44**, 1532 (2019); Opt. Lett. **45**, 1774 (2020); APL Photon. **5**, 106107 (2020); Adv. Opt. Mat. **9**, 2001107 (2021); arXiv:2104.08706 (2021)

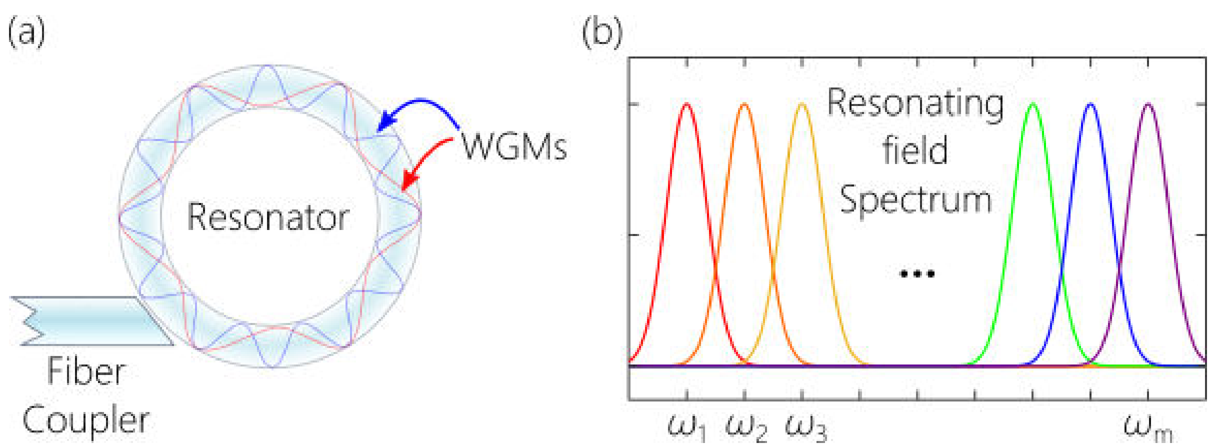
White-light cavities vs. Omni-resonance



Cavities provide resonant field buildup only at discrete resonant wavelengths, which has applications in enhanced absorption, nonlinear interactions, and sensing.

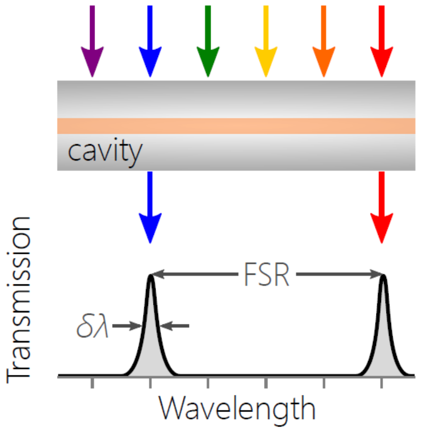
Can we instead harness the useful features of resonance over continuous broad spectra?

One can increase the cavity volume so that every wavelength can couple to a cavity mode.



Savchenkov, A. A., Matsko, A. B. & Maleki, L. White-light whispering gallery mode resonators. *Opt. Lett.* **31**, 92–94 (2006).

White-light cavities vs. Omni-resonance



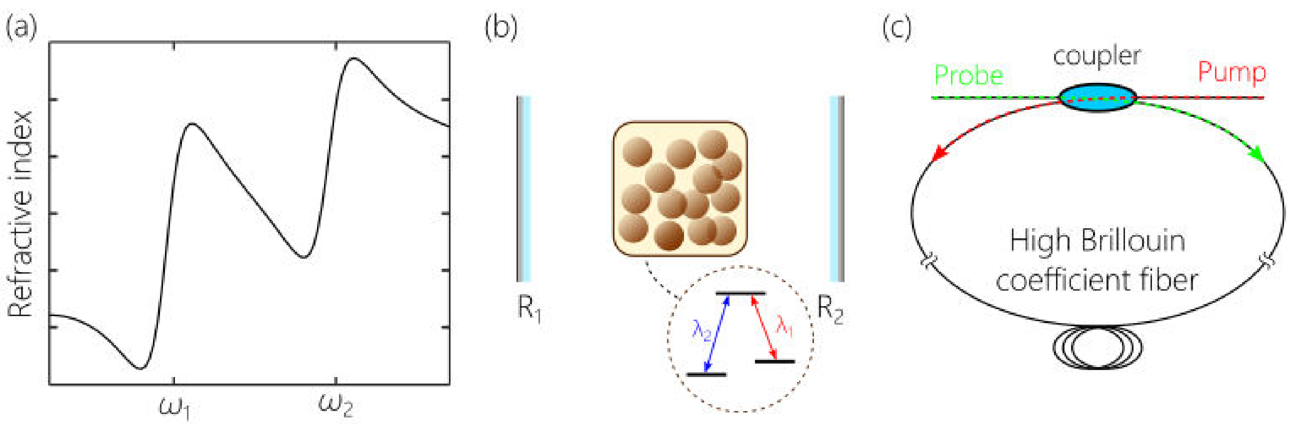
One proposal for realizing this goal is so-called 'white-light' cavities.

White-light cavities, atomic phase coherence, and gravitational wave detectors. *Opt. Commun.* **134**, 431–439 (1997).

Demonstration of a tunable-bandwidth white-light interferometer using anomalous dispersion in atomic vapor. *Phys. Rev. Lett.* **99**, 133601 (2007).

White-light cavity with competing linear and nonlinear dispersions. *Phys. Rev. A* **77**, 031801(R) (2008).

Demonstration of white light cavity effect using stimulated Brillouin scattering in a fiber loop. *J. Lightwave Technol.* **32**, 3865–3872 (2013).



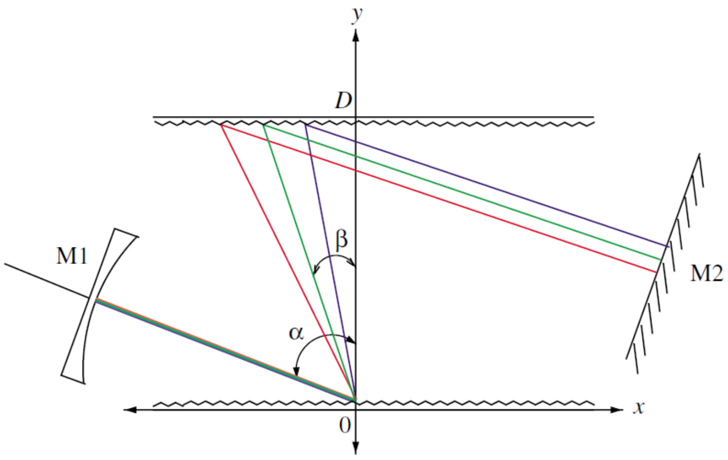
Round-trip phase: $\Phi = 2nkd = 2\frac{2\pi}{\lambda}n(\lambda)d = \text{constant} \rightarrow$ requires resonant gain

Crucially, $\frac{dn}{d\omega}$ is negative, and we have formally infinite group velocity

White-light cavities vs. Omni-resonance

Can a linear optical system produce a white-light cavity?

Example: a pair of gratings $\rightarrow$ NO



Wise, S., Mueller, G., Reitze, D., Tanner, D. B. & Whiting, B. F. Linewidth-broadened fabry-perot cavities within future gravitational wave detectors. *Class. Quantum Grav.* **21**, S1031–S1036 (2004).

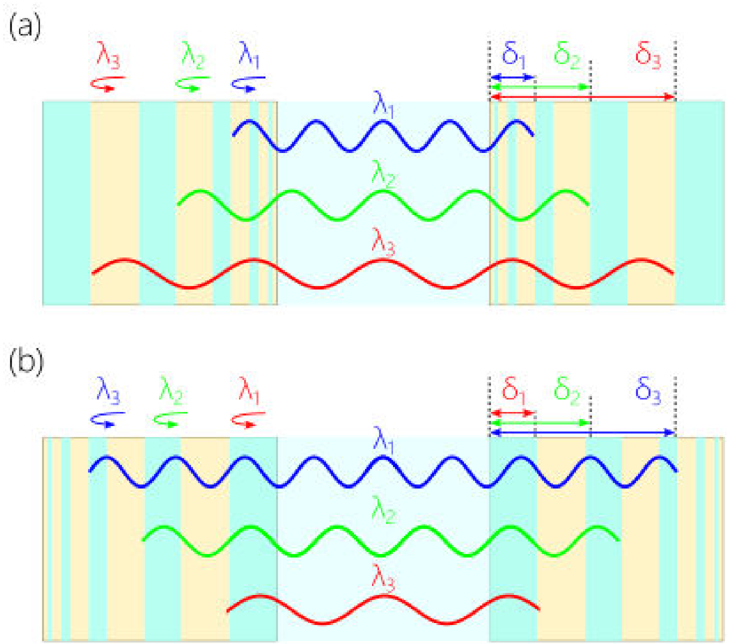
Wise, S. *et al*. Phase effects in the diffraction of light: Beyond the grating equation. *Phys. Rev. Lett.* **95**, 013901 (2005).

Despite an initial theoretical proposal, experiments (performed b the LIGO team) confirmed that a grating pair can given anomalous GVD but NOT negative group delay.

White-light cavities vs. Omni-resonance

Can a linear optical system produce a white-light cavity?

Example: a pair of chirped Bragg mirrors



Yum, H. N., Liu, X., Hemmer, P. R., Scheuer, J. & Shahriar, M. S. The fundamental limitations on the practical realizations of white light cavities. *Opt. Commun.* **305**, 260–266 (2013).

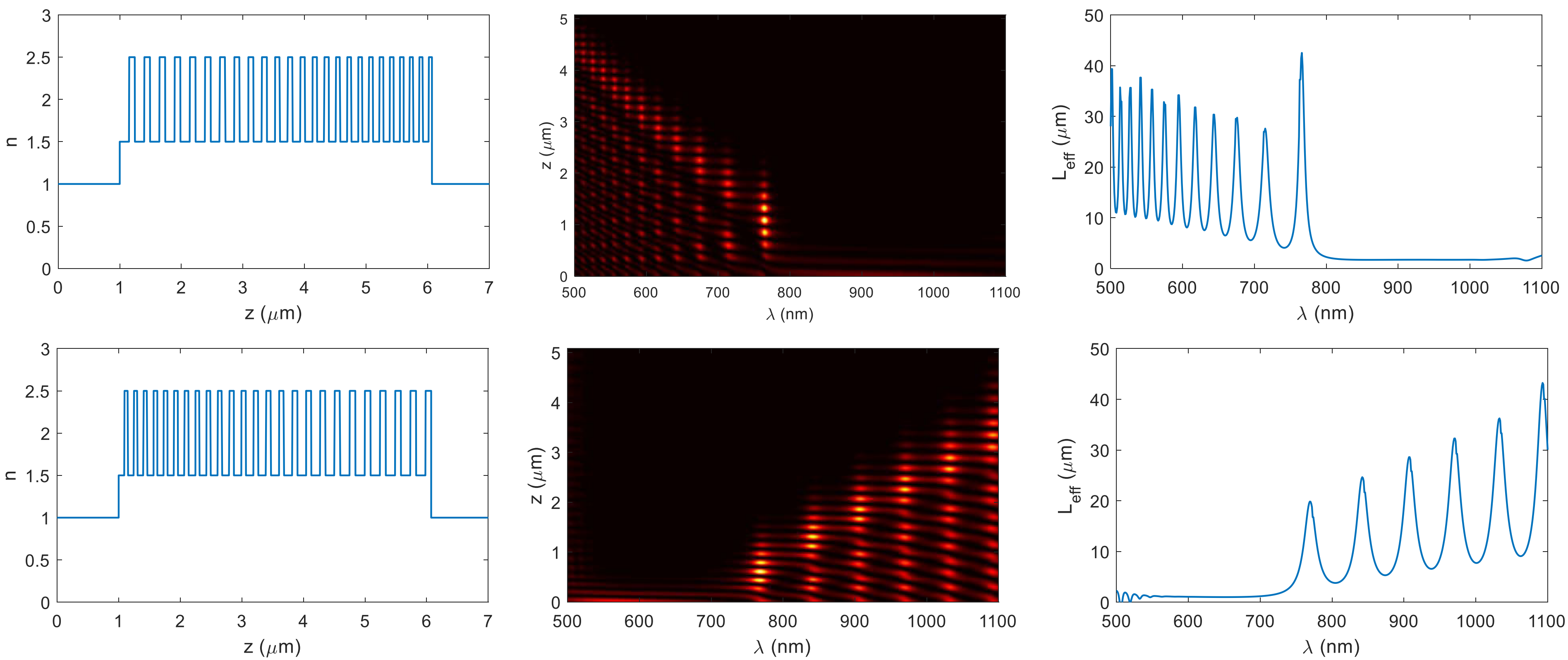
It seems initially intuitive that such chirped Bragg mirrors can be exploited to produce the white-light cavity effect.

White-light cavities vs. Omni-resonance

Can a linear optical system produce a white-light cavity?

Example: a pair of chirped Bragg mirrors

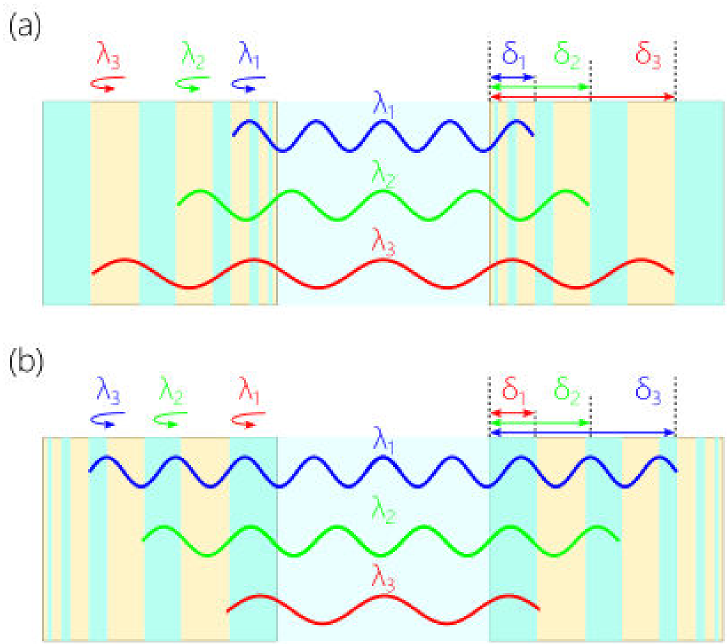
Whether positively or negatively chirped, they produce positive group delay



White-light cavities vs. Omni-resonance

Can a linear optical system produce a white-light cavity?

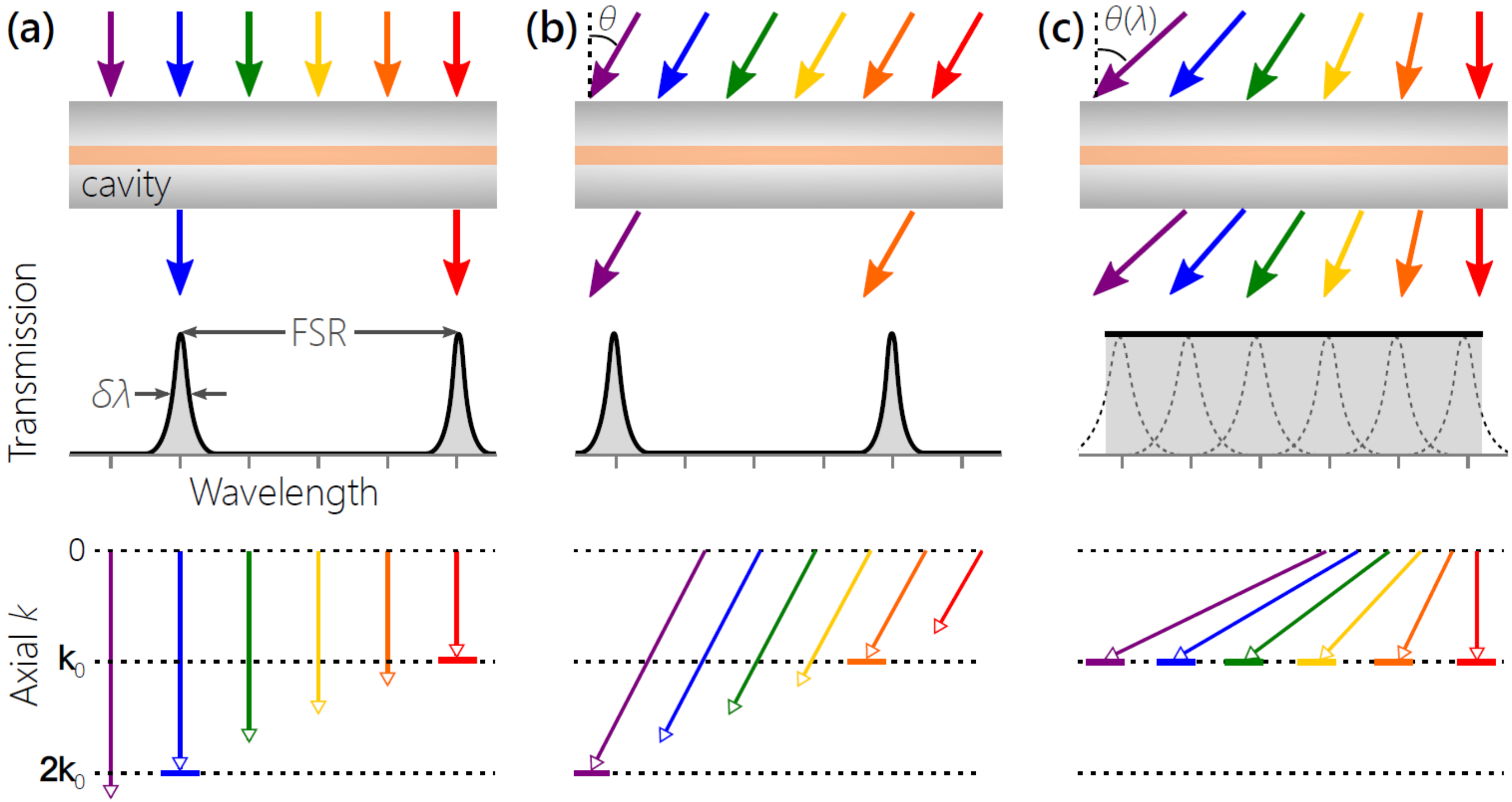
Example: a pair of chirped Bragg mirrors → NO



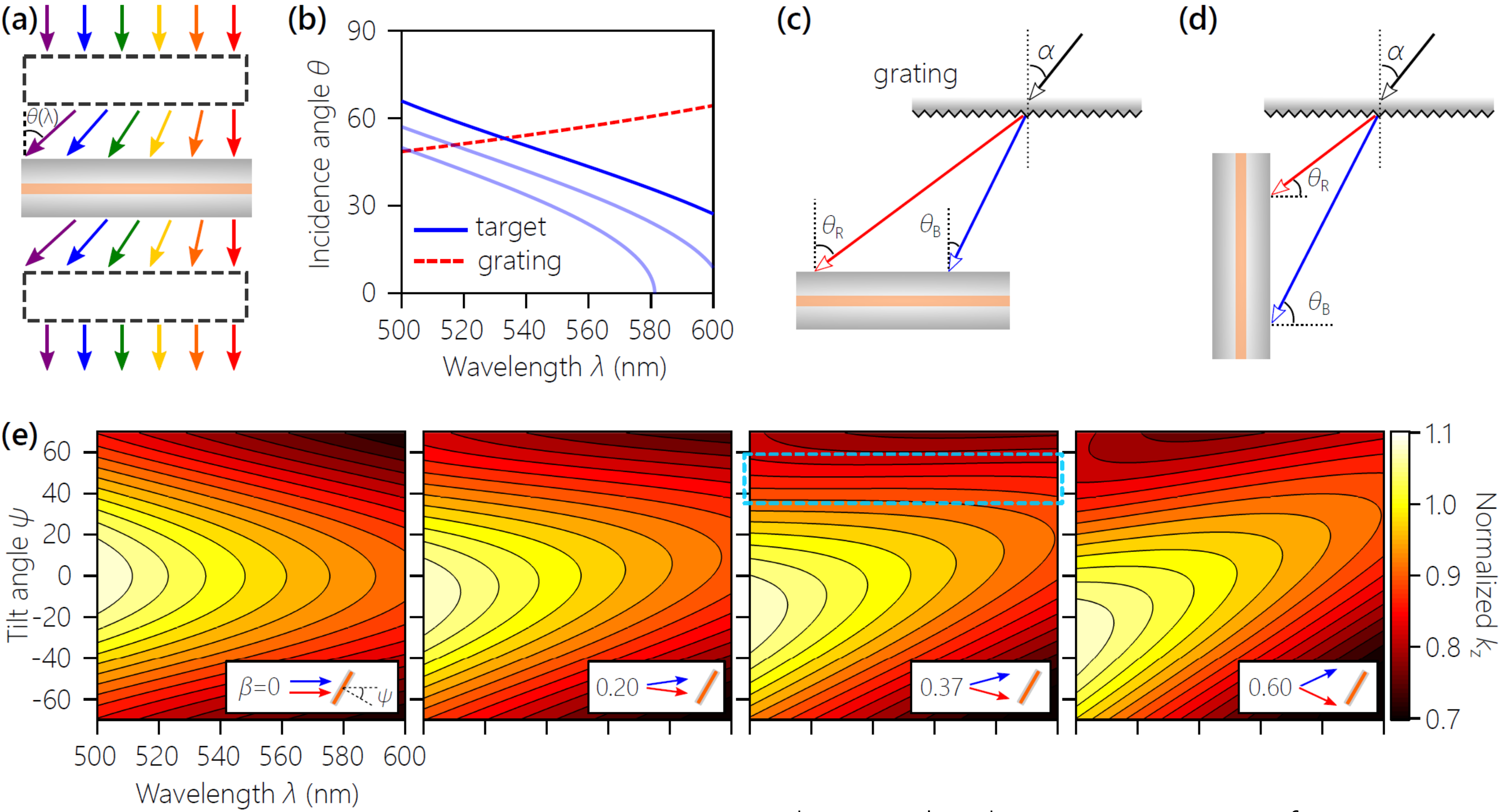
Yum, H. N., Liu, X., Hemmer, P. R., Scheuer, J. & Shahriar, M. S. The fundamental limitations on the practical realizations of white light cavities. *Opt. Commun.* **305**, 260–266 (2013).

A general statement was proven with regards to any linear system that act as arbitrary mirrors by modelling them as minimum-phase filters: no system with flat amplitude response can provide negative group delay.

Omni-resonance



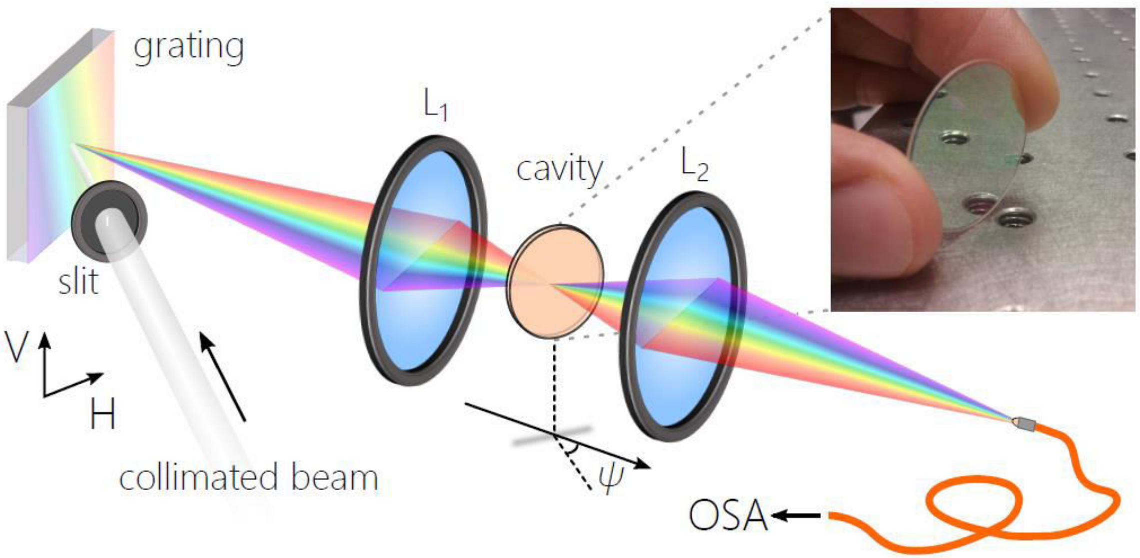
S. Shabahang, *et al.*, "Omni-resonant optical micro-cavity," Sci. Rep. **7**, 10336 (2017)

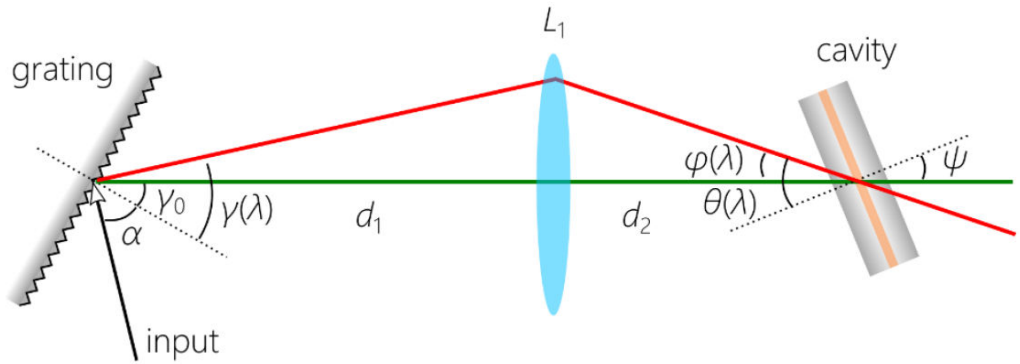


β is the angular dispersion in units of °/nm

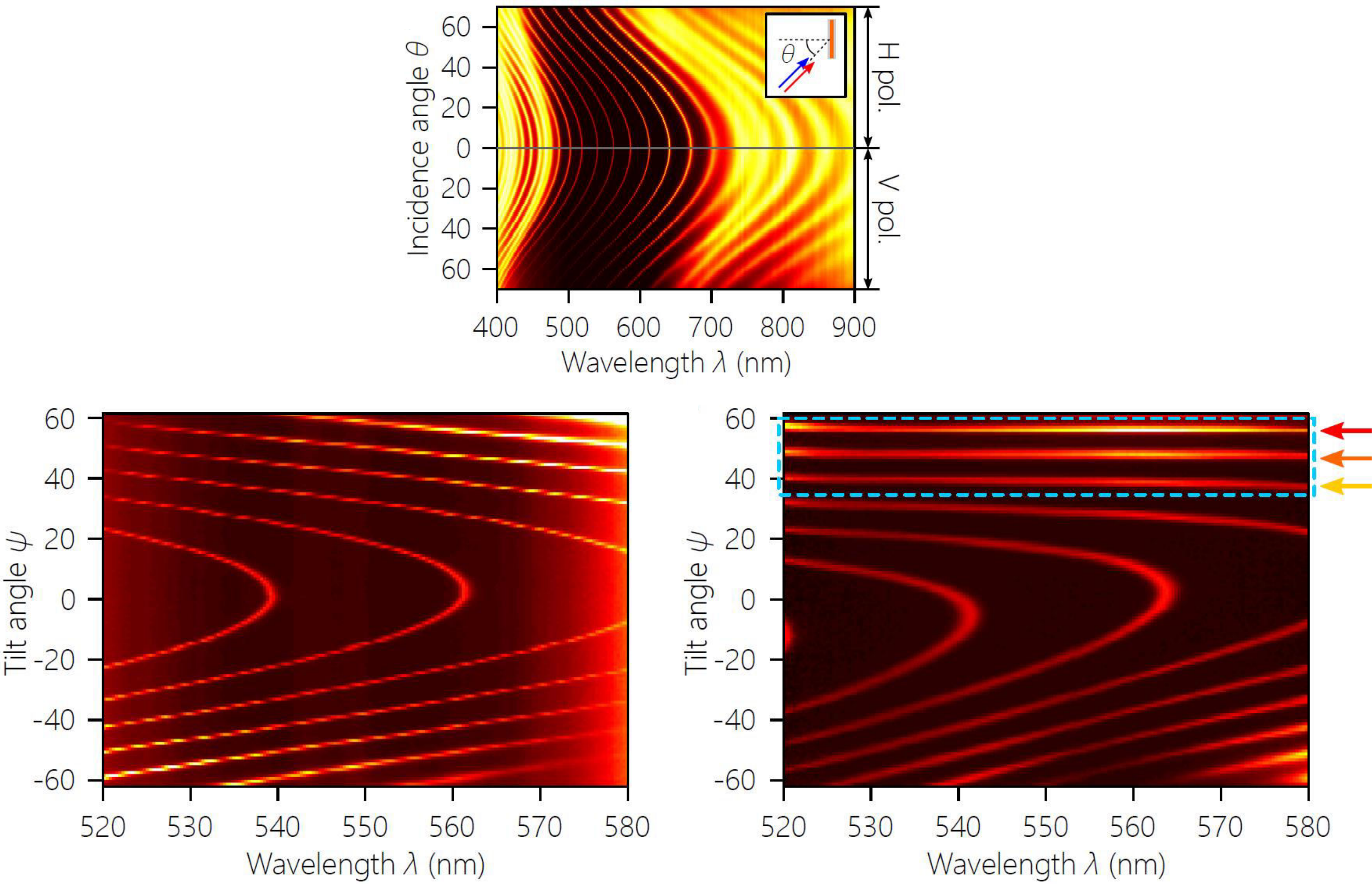
Shabahang, Sci. Rep. **7**, 10336 (2017)

Omni-resonance

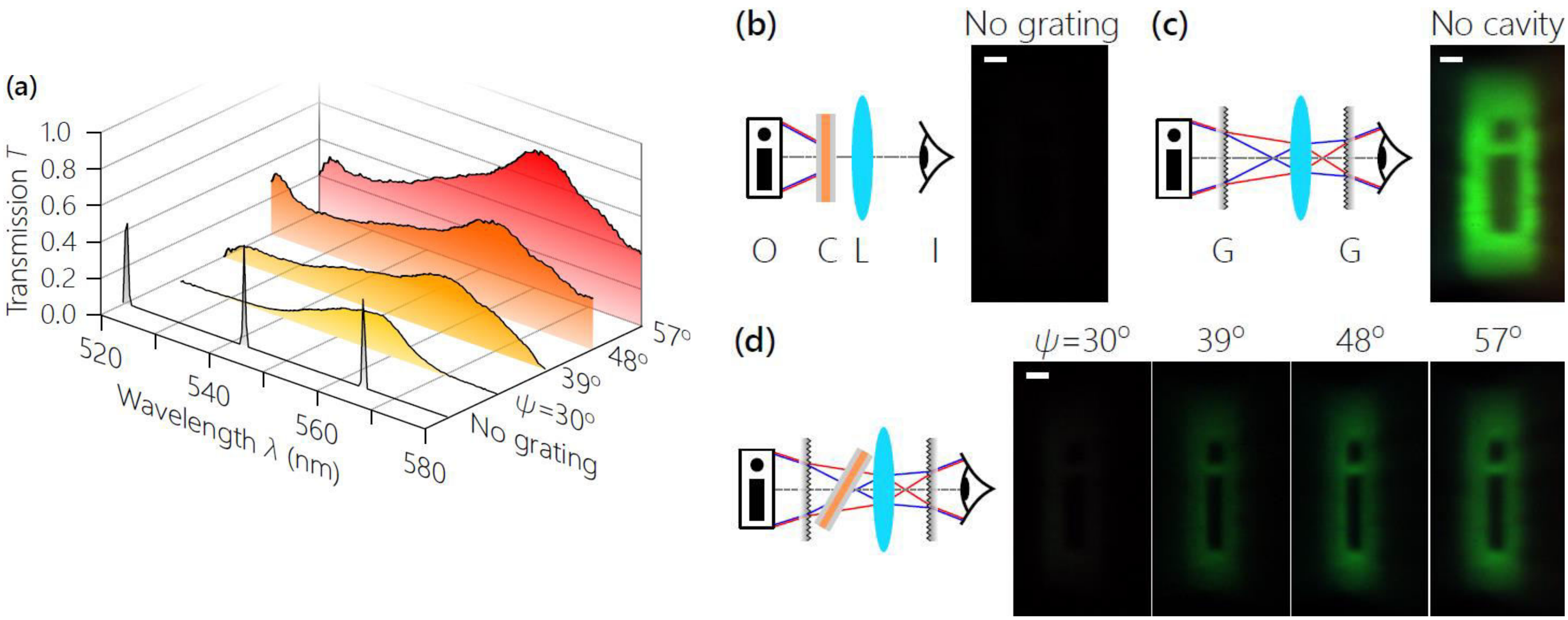




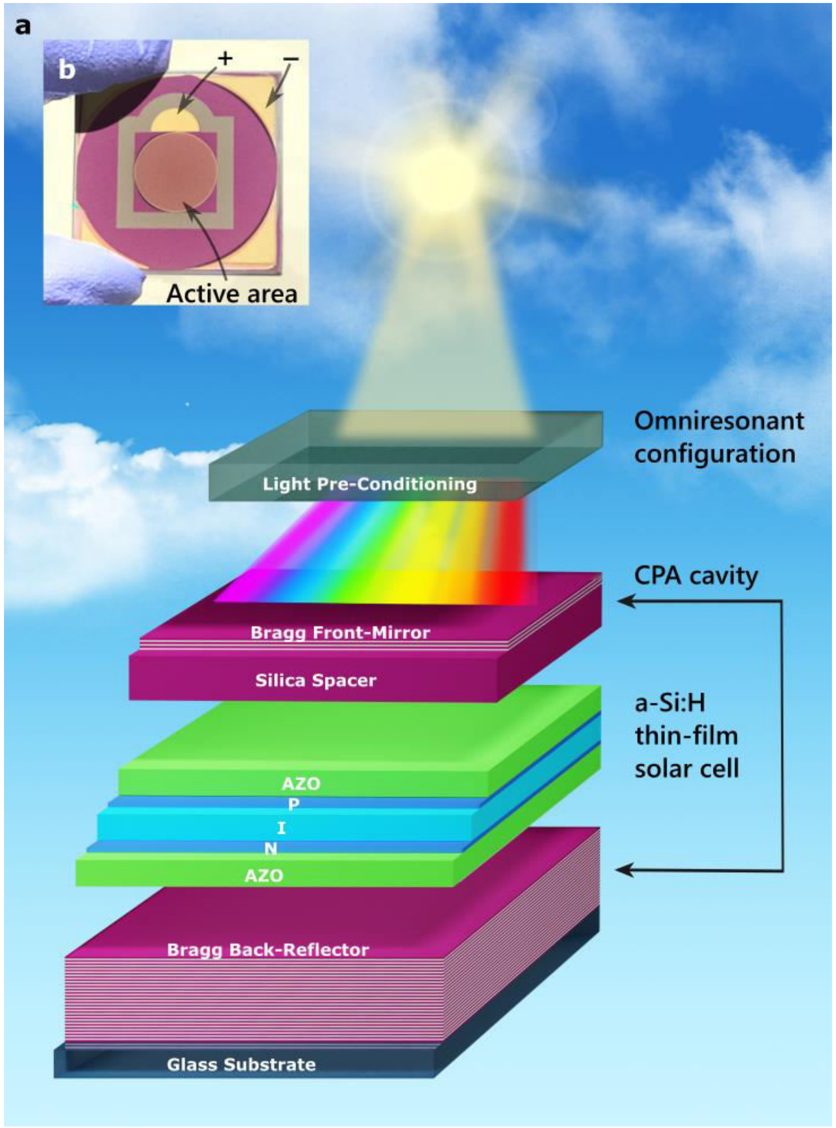
Shabahang, Sci. Rep. **7**, 10336 (2017)



Shabahang, Sci. Rep. **7**, 10336 (2017)


(a)
Transmission T
1.0
0.8
0.6
0.4
0.2
0.0
520
540
560
580
Wavelength λ (nm)
57°
48°
39°
ψ=30°
No grating
(b)
No grating
O
C
L
I
(c)
No cavity
G
G
(d)
ψ=30°
39°
48°
57°

Omni-resonance for solar energy



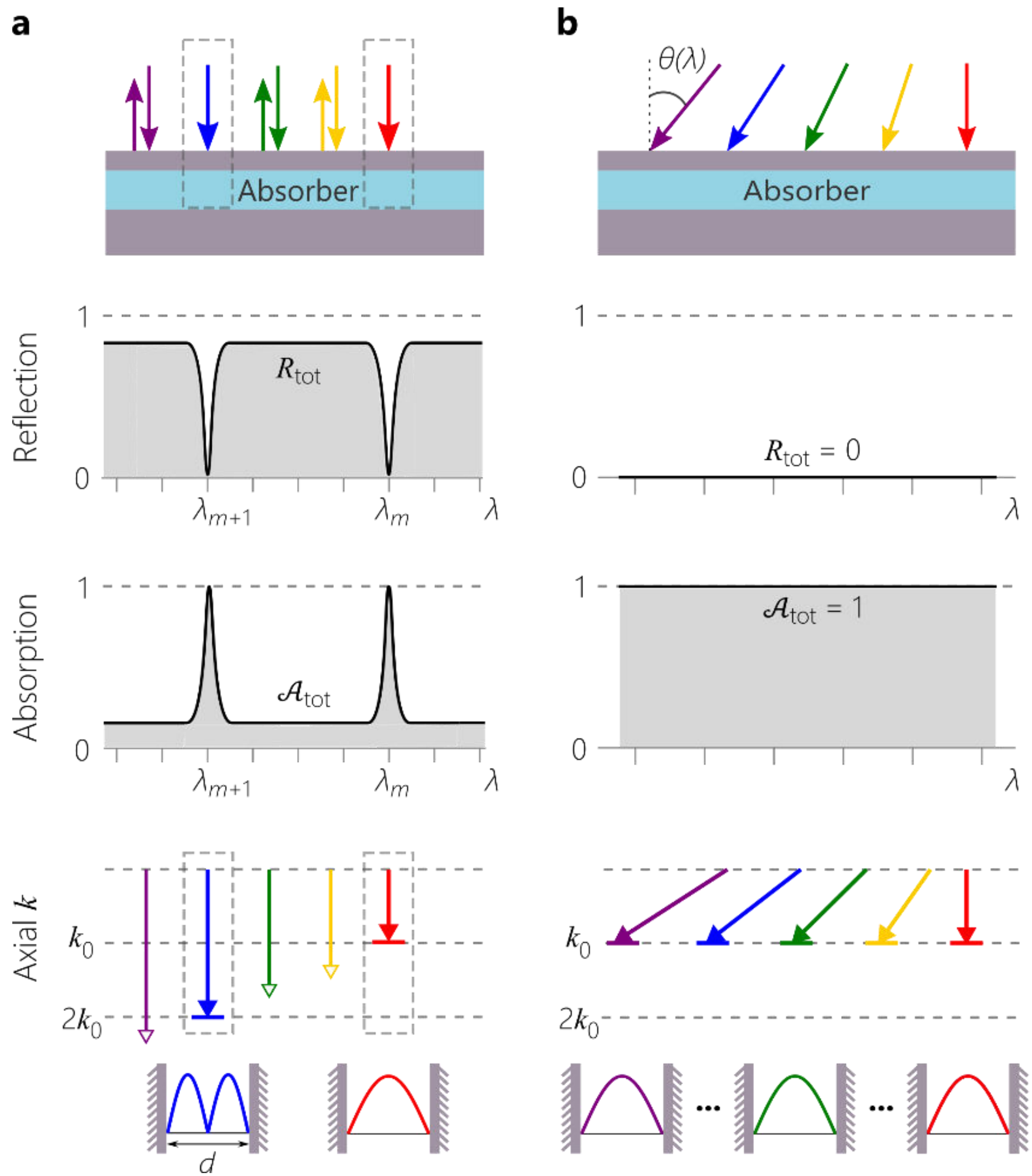
We combine two effects:

(1) Resonant enhancement of linear absorption; so-called coherent perfect absorption (CPA). Absorption is guaranteed to be 100% on resonance when the cavity is suitably designed.

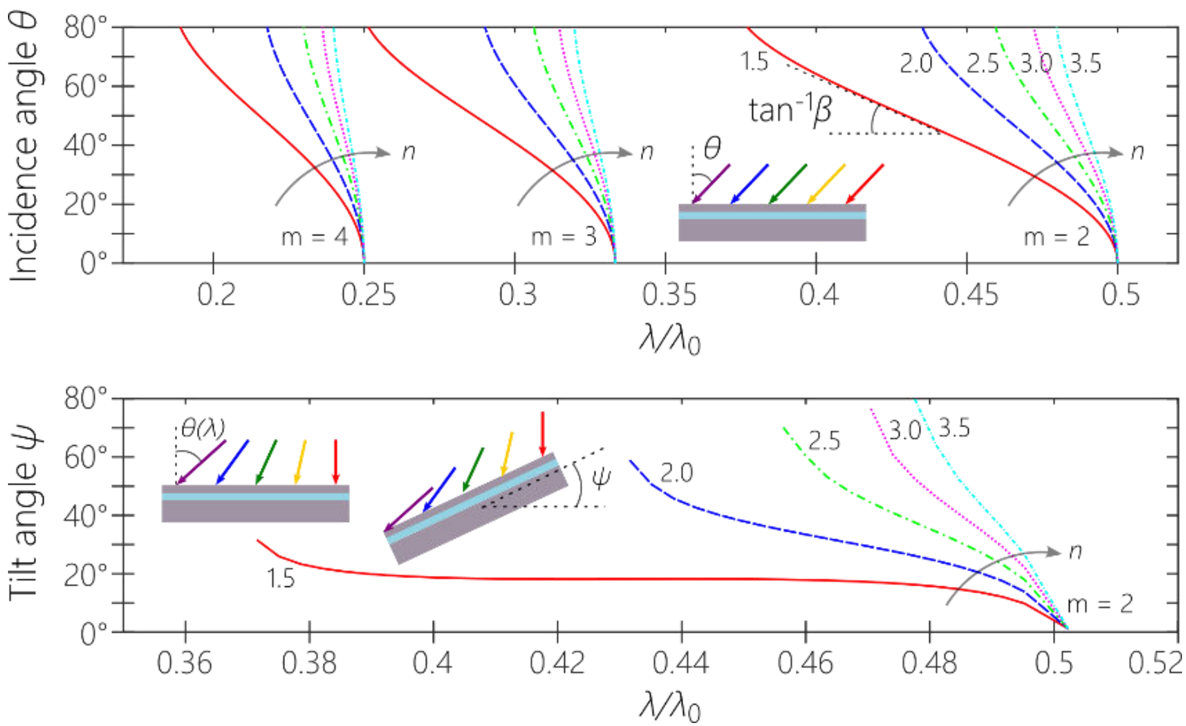
(2) Omni-resonance: providing CPA over a continuous broad spectrum rather than at discrete resonant wavelengths.

Villinger, *et al.*, "Doubling the near-infrared photocurrent in a solar cell via omni-resonant coherent perfect absorption," Adv. Opt. Mat. **9**, 2001107 (2021).

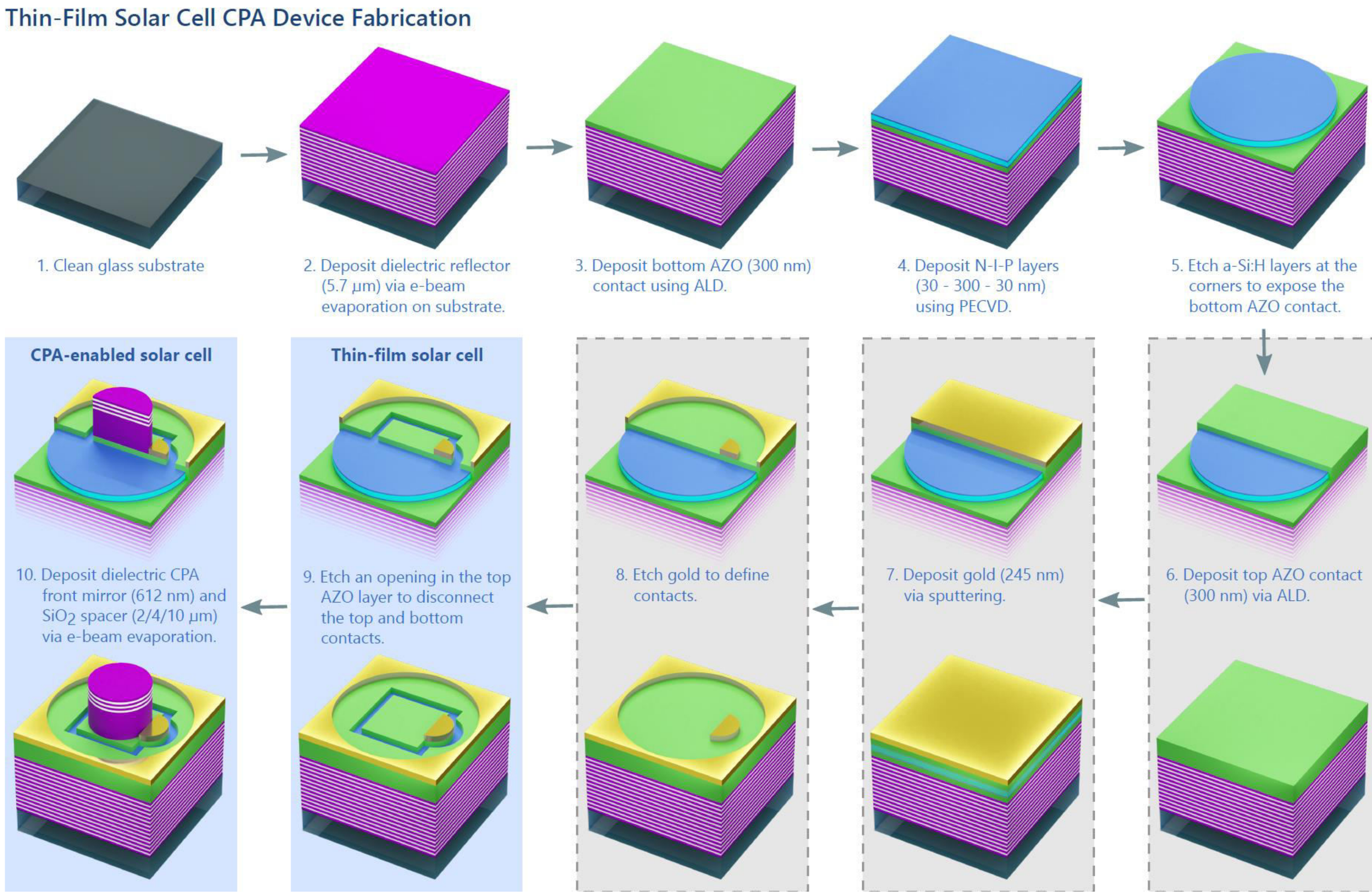
Omni-resonance for solar energy



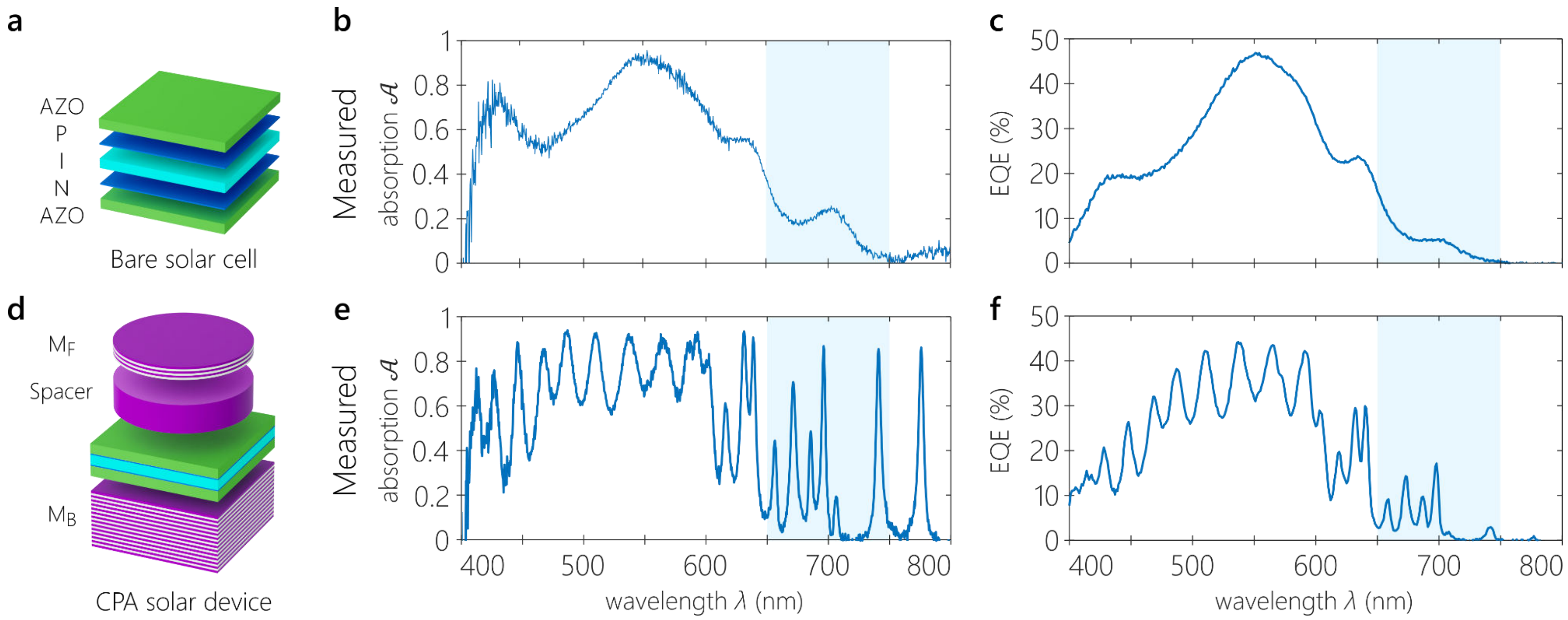
Omni-resonance for solar energy



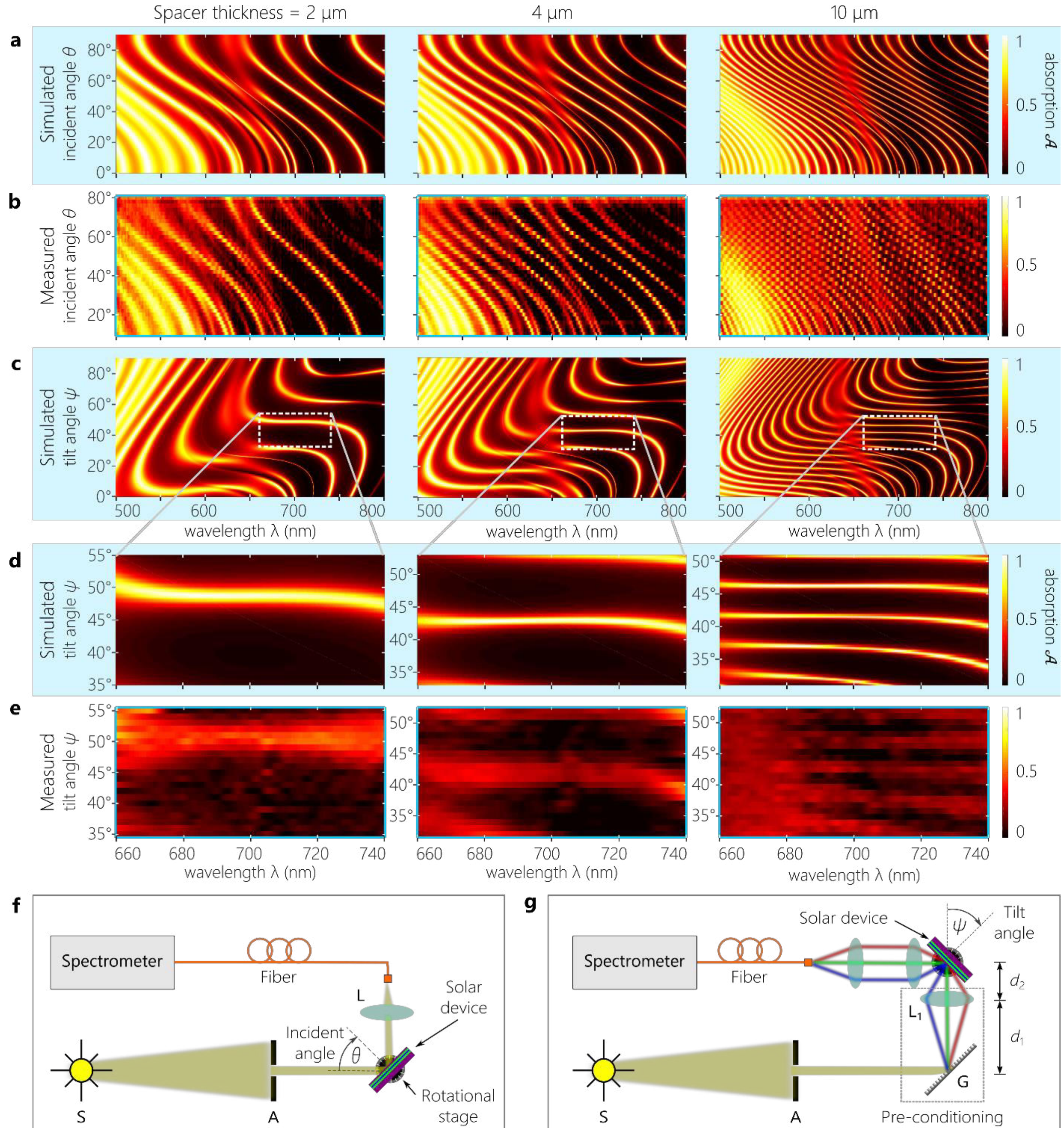
Omni-resonance for solar energy



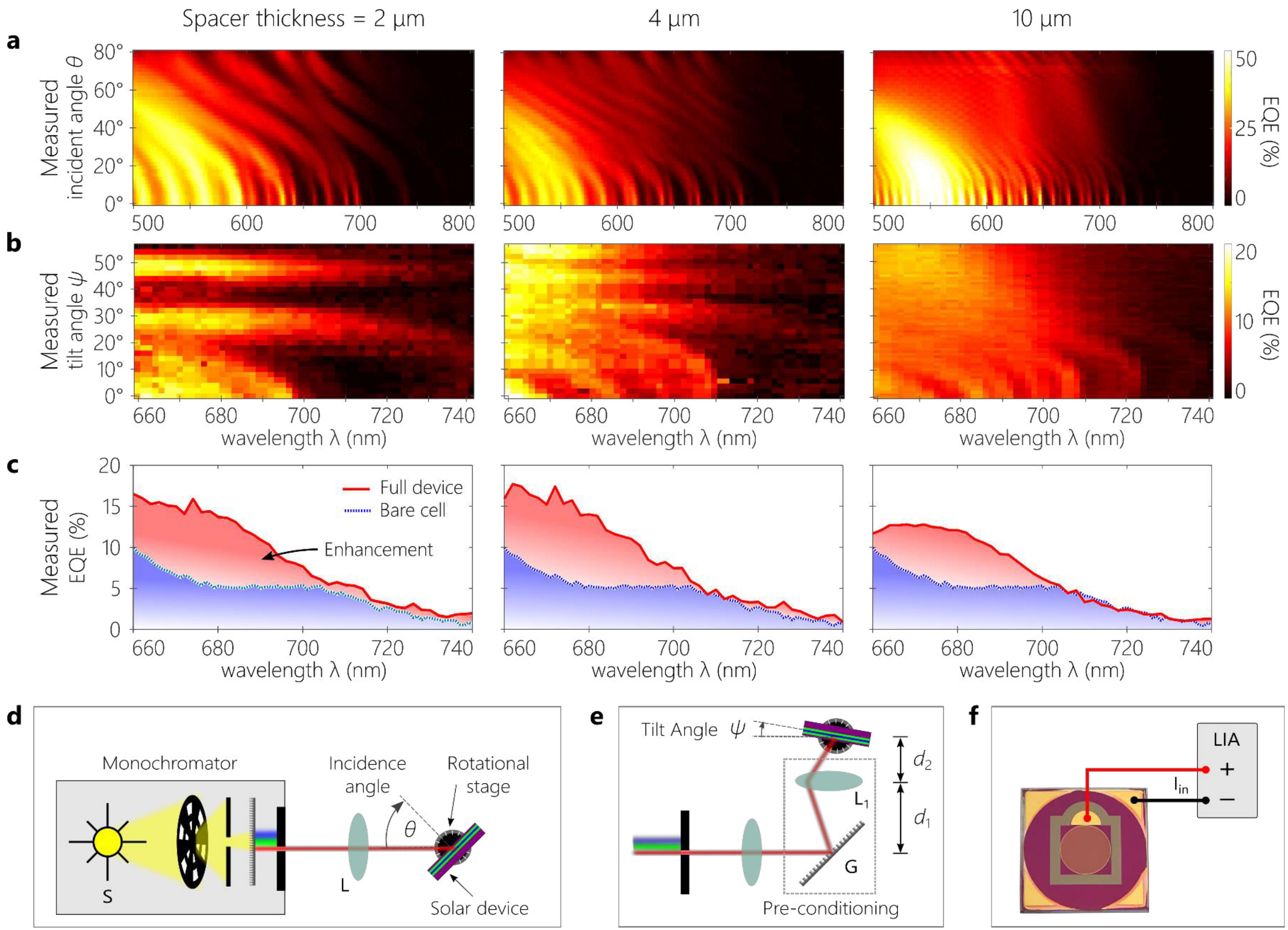
Absorption enhancement in absence of omni-resonance



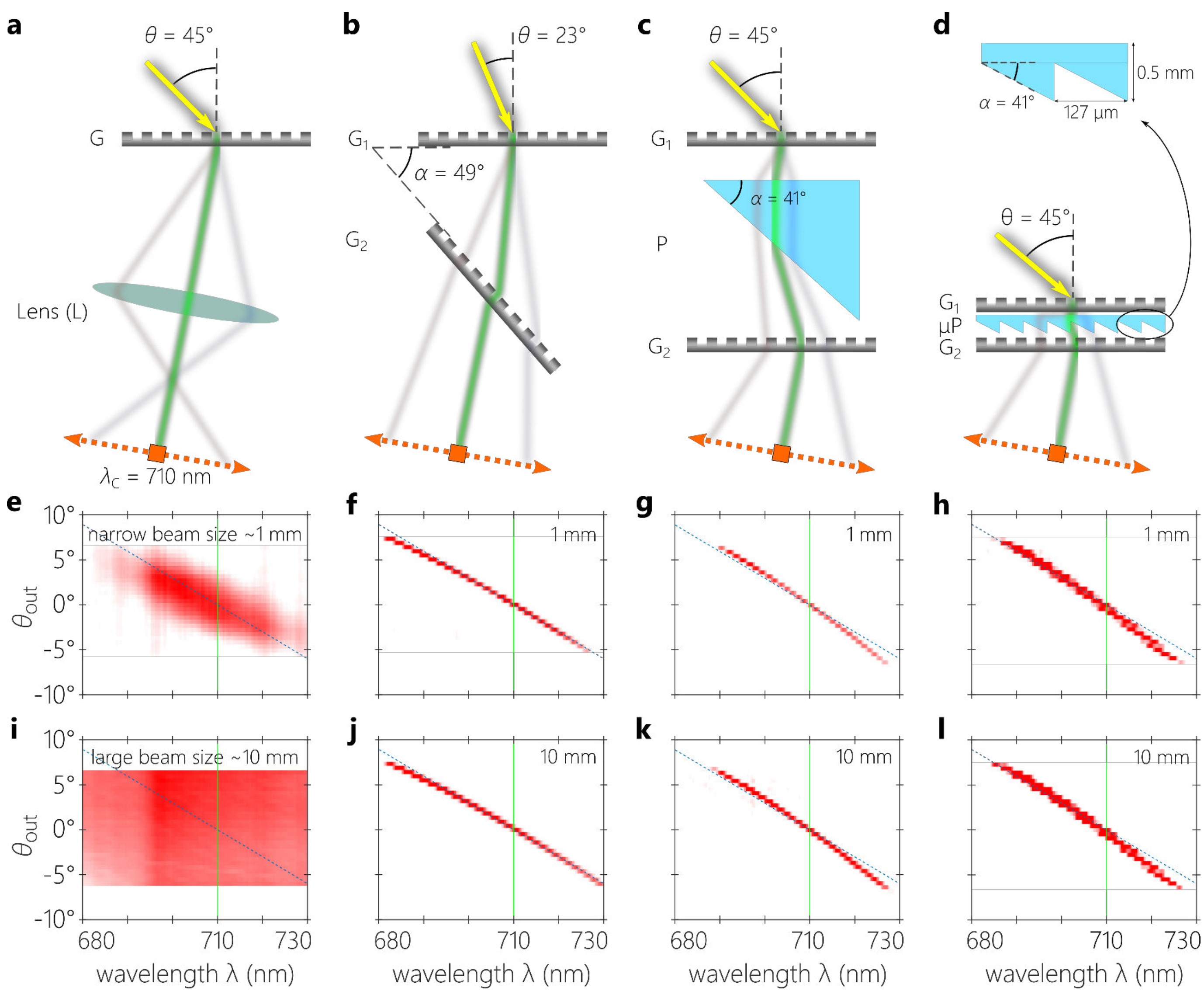
Omni-resonance for solar energy



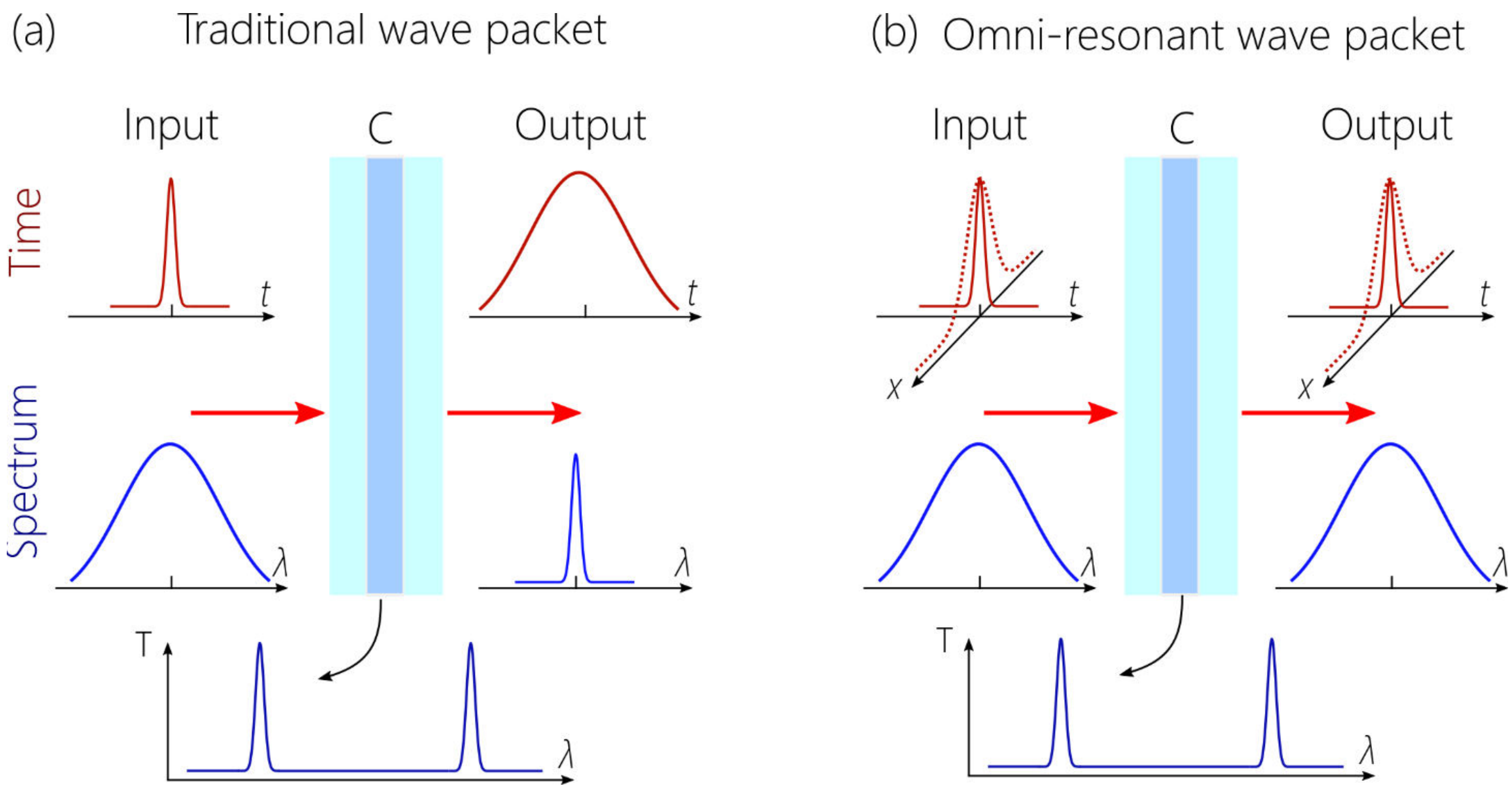
Omni-resonance for solar energy



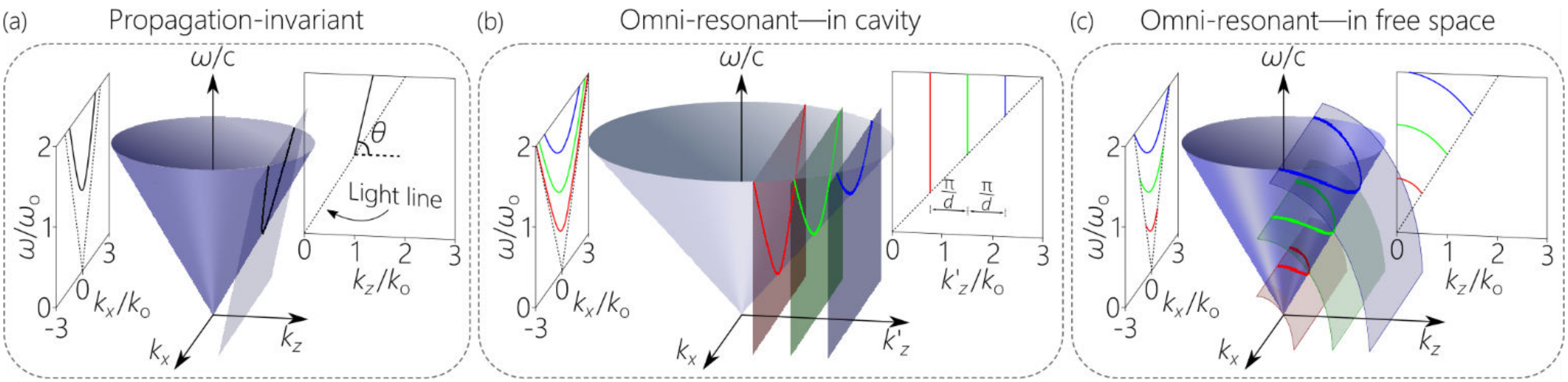
Can we achieve omni-resonance with flat optics?



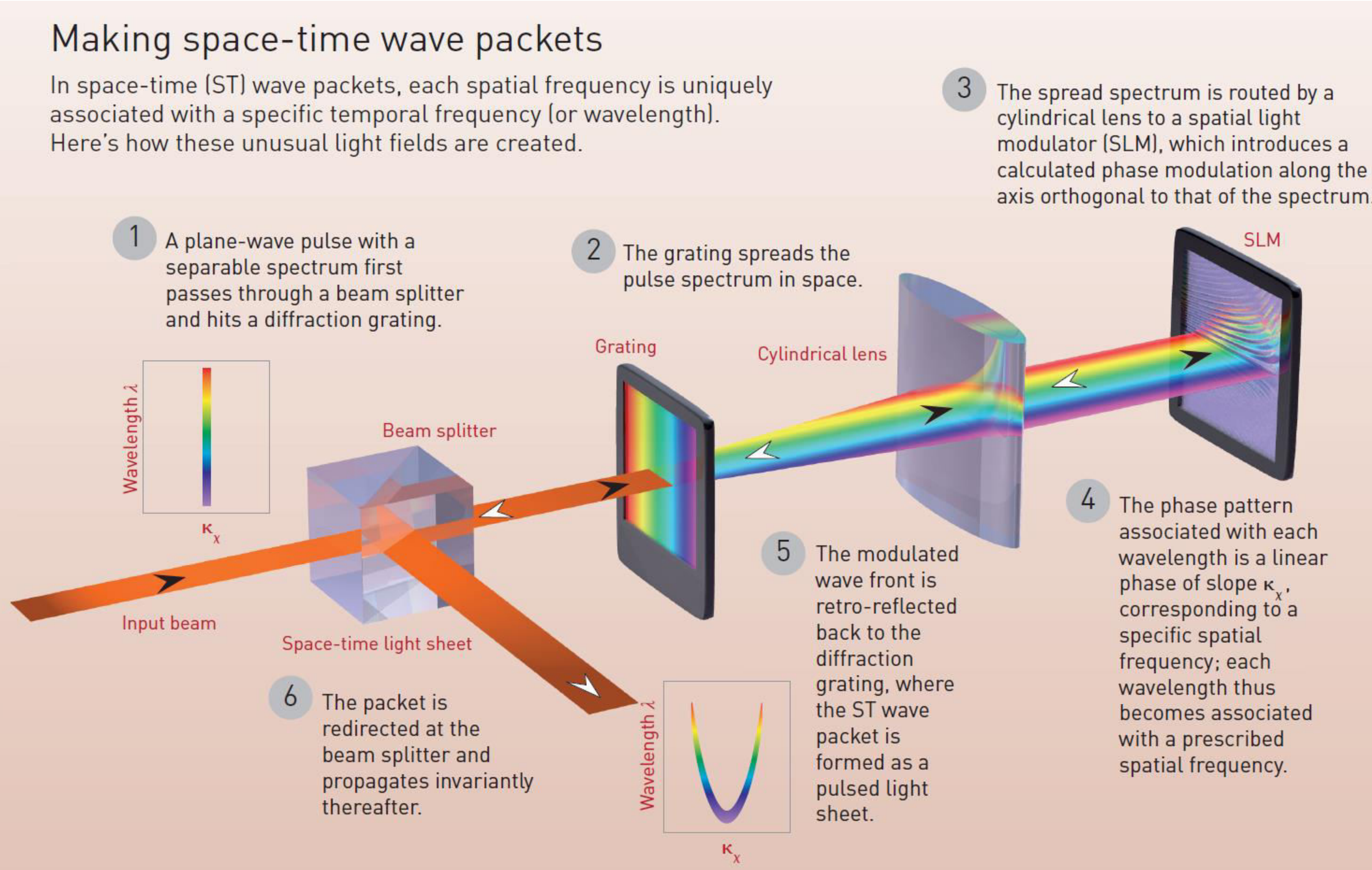
Omni-resonance with ST wave packets



Omni-resonance with ST wave packets

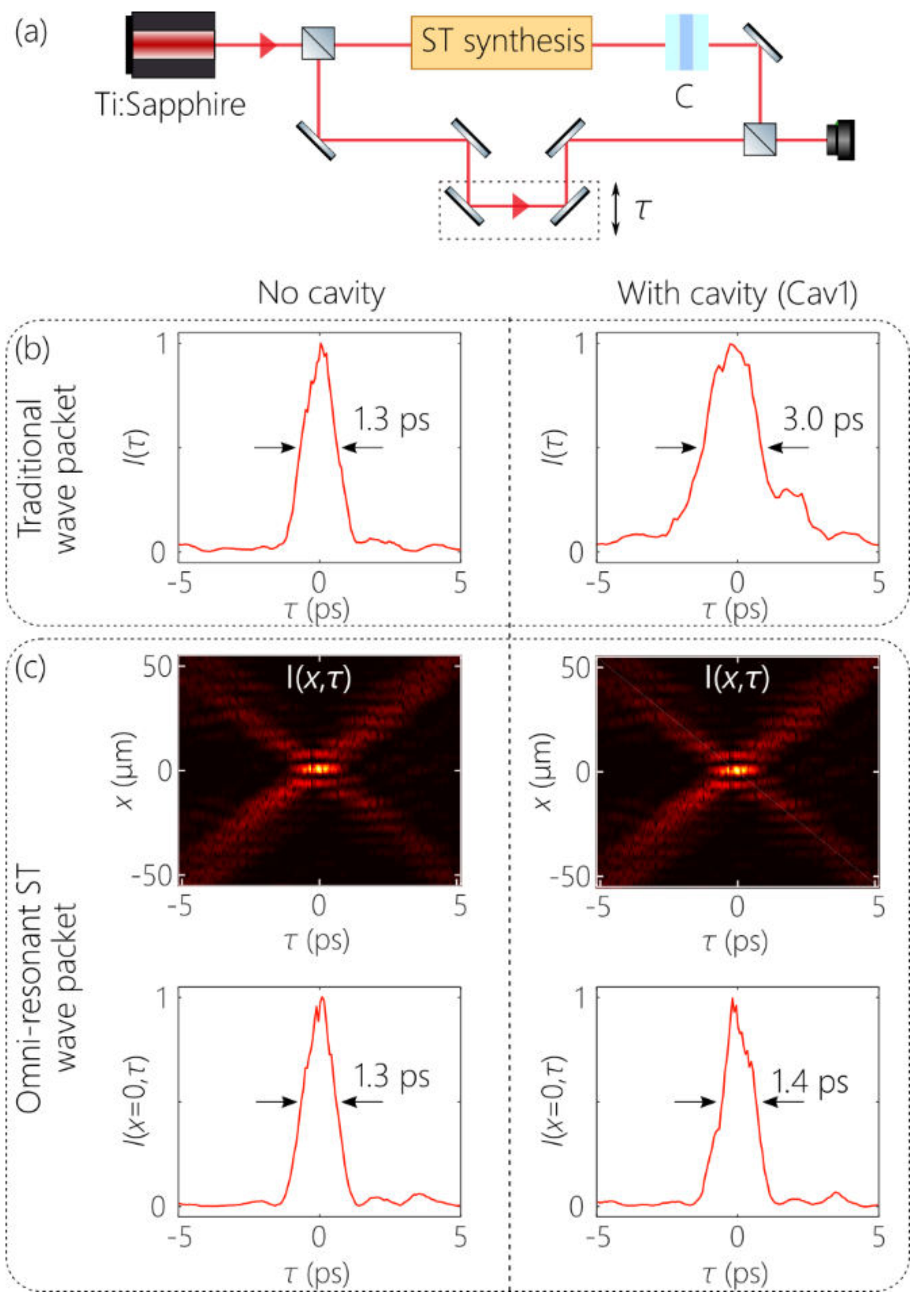


Synthesis of space-time beams

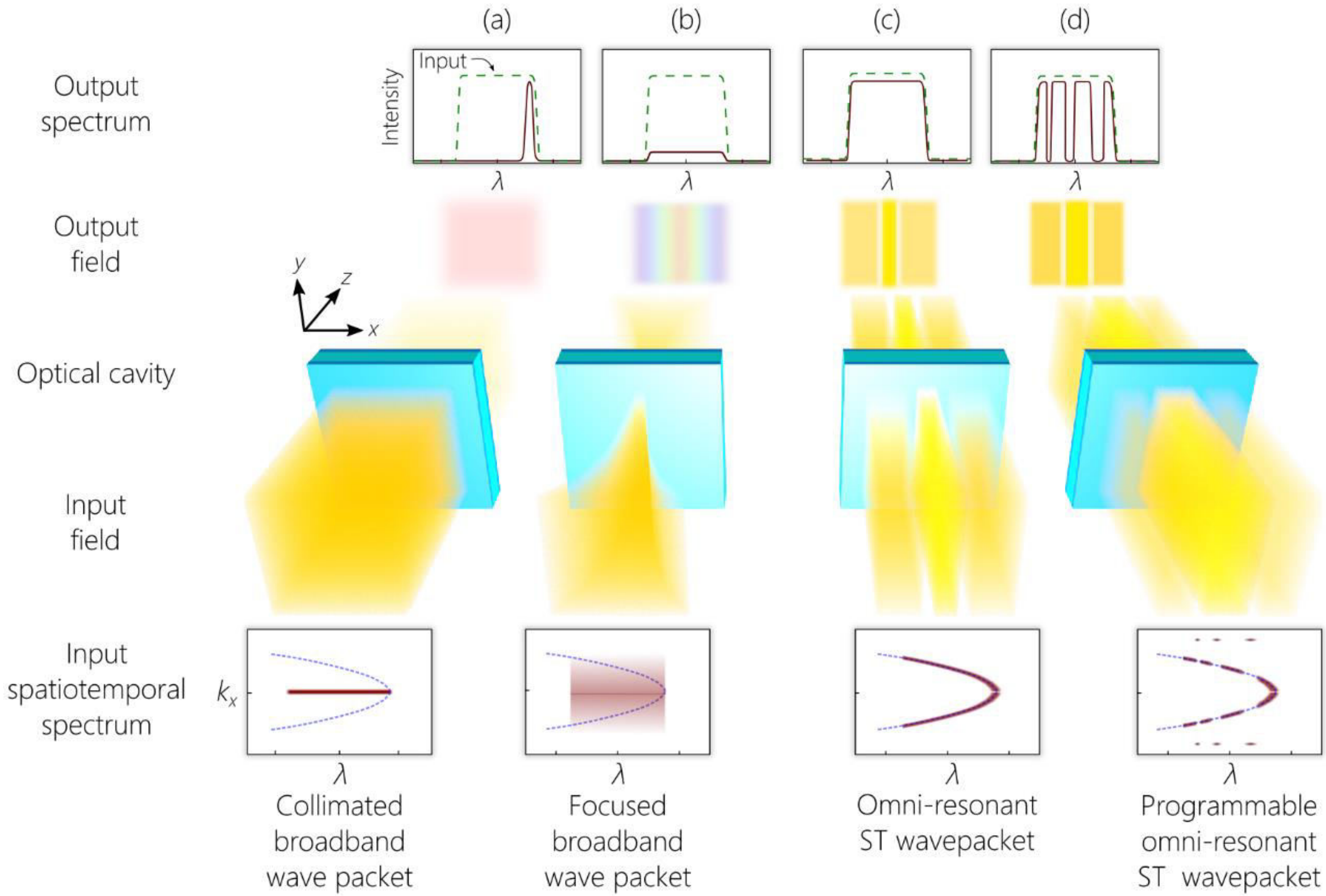


The desired correlation between ω and k_x is implemented with a computer-controlled spatial light modulator (SLM).

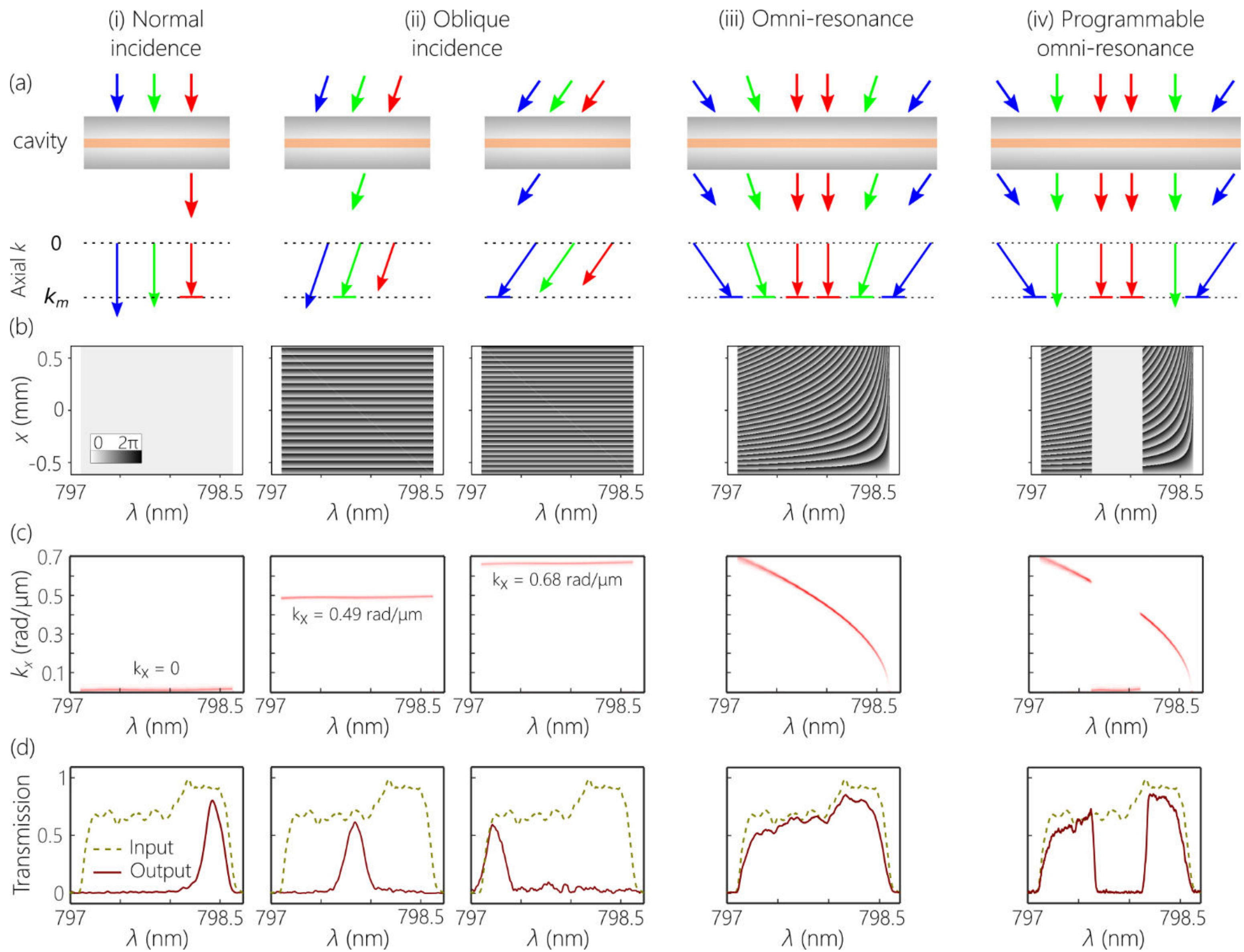
Omni-resonance with ST wave packets



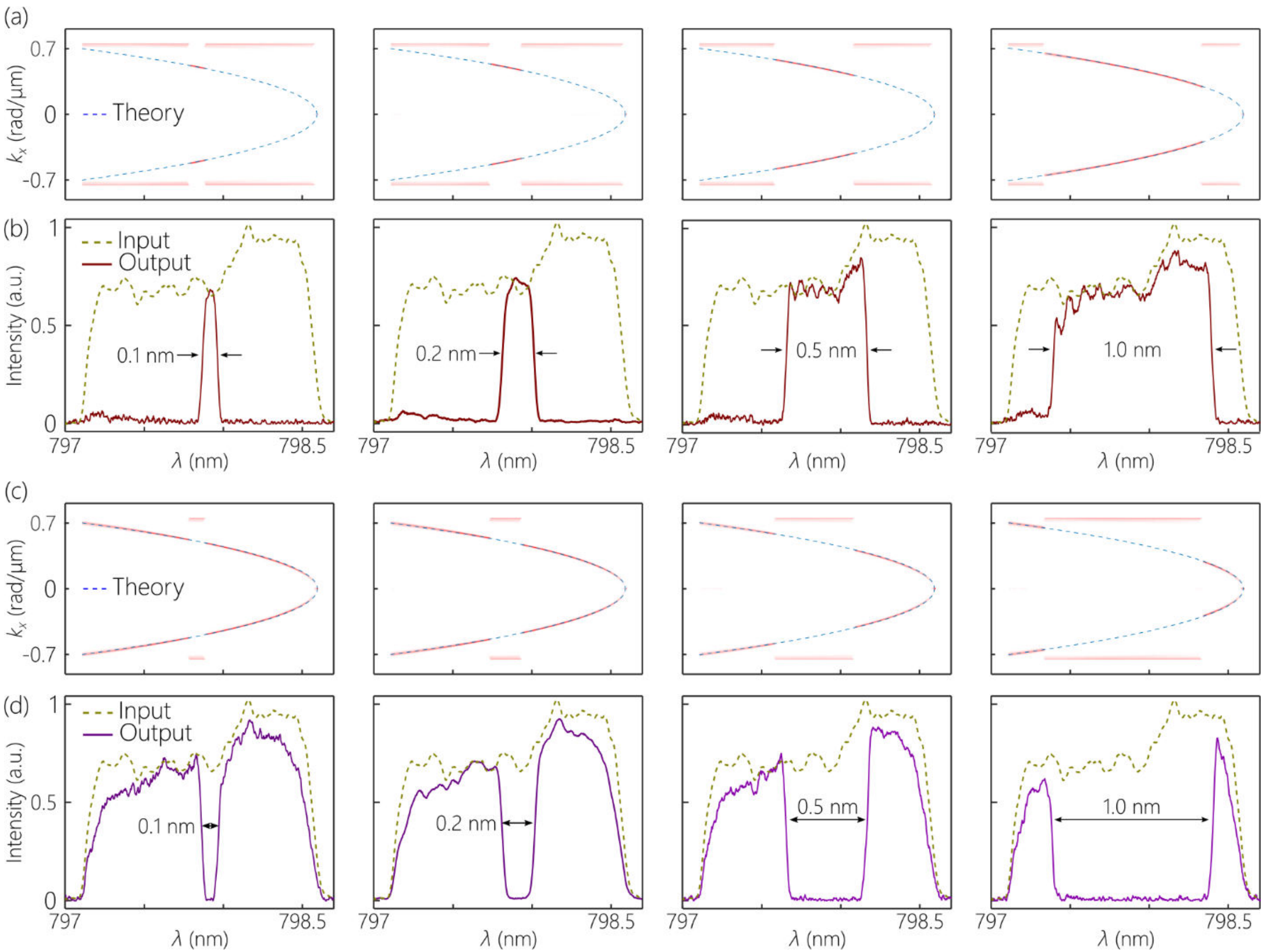
Programmable omni-resonance with ST wave packets



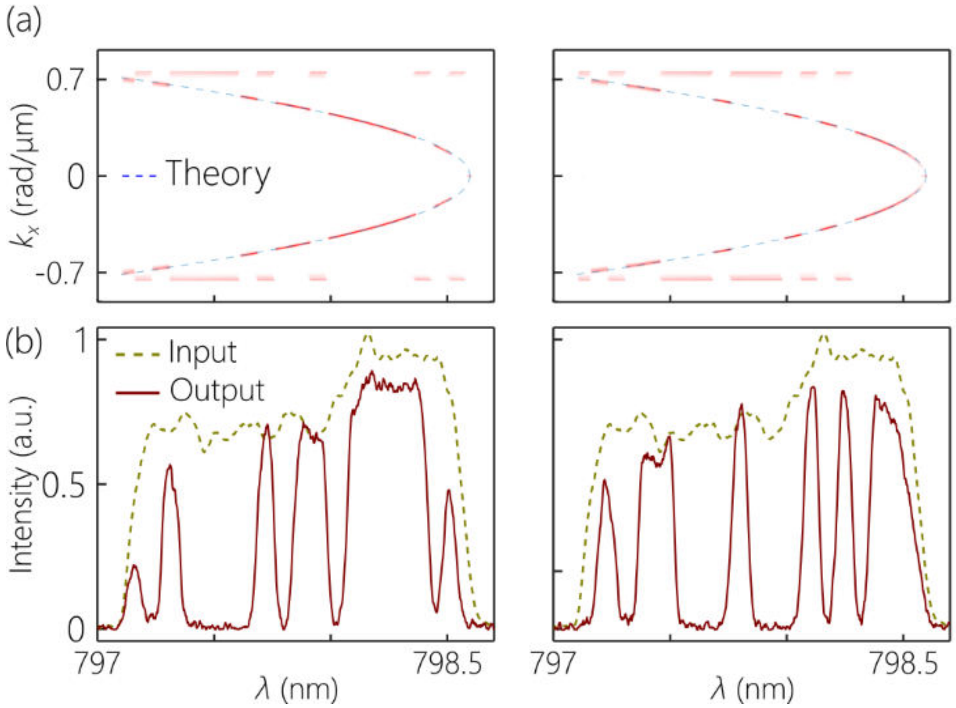
Programmable omni-resonance with ST wave packets



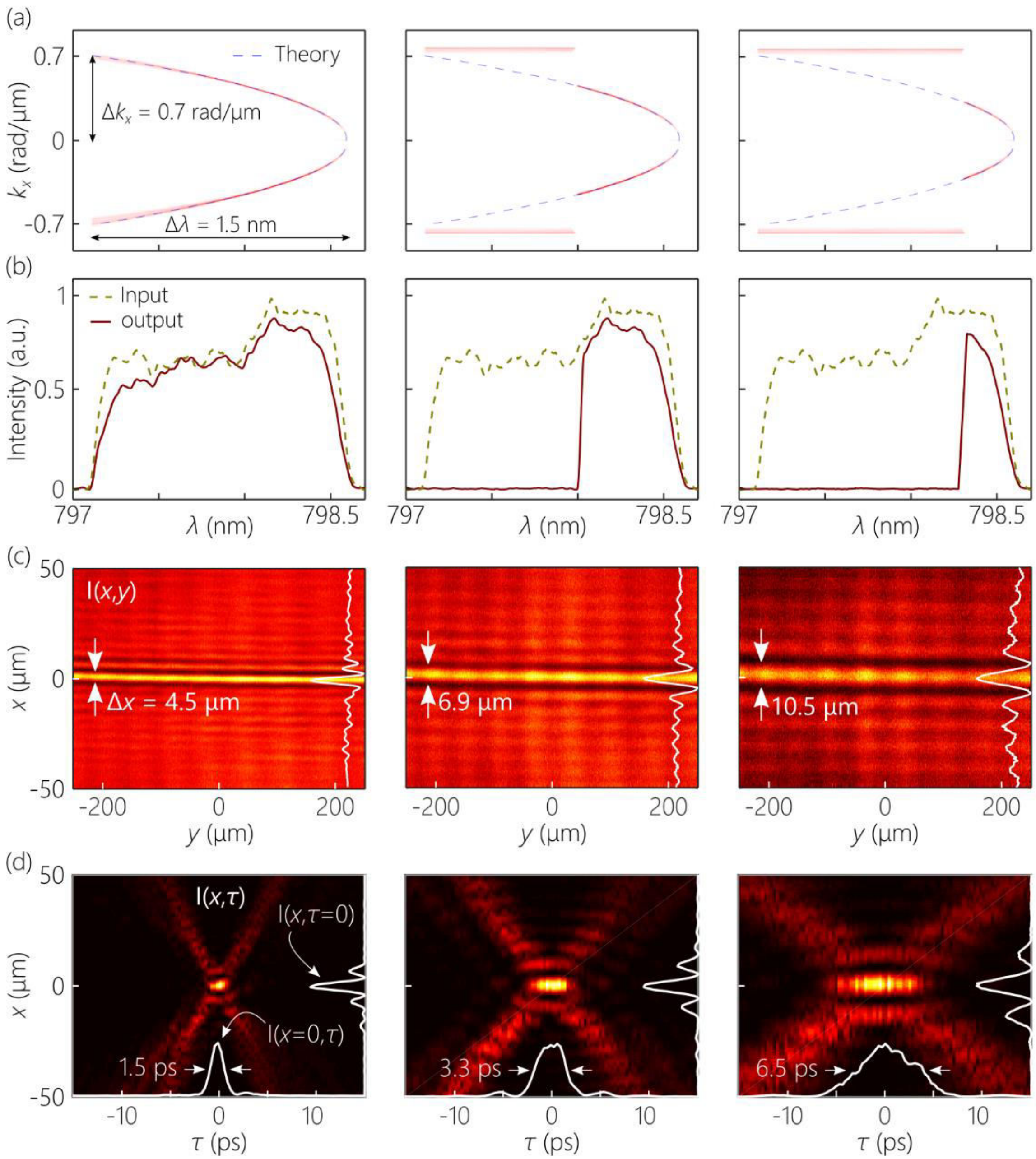
Programmable omni-resonance with ST wave packets



Programmable omni-resonance with ST wave packets



Programmable omni-resonance with ST wave packets



Conclusions

Space-time optics: Classical entanglement between the continuous spatial and temporal degrees of freedom of an optical field results in diffraction-free, dispersion-free pulsed beams. The essential feature of these 'space-time' beams is the intertwining of their spatial and temporal characteristics.
This research has impact on light-matter interactions, relativistic optical physics, astronomy, laser filamentation, biomedical imaging, in addition to laser energy deliver.

Space-time photonics: Introducing spatio-spectral correlations in the optical field lead to dramatic changes in the interaction of the field with resonant optical devices.
Novel structures and devices for nonlinear optics, enhanced optical detectors, optical imaging systems that toggle between active and passive configurations, among many other opportunities.

Space-time optics and photonics promises to deliver transformative scientific breakthroughs and introduce radically new photonic devices.