OSA Nanophotonics Technical Group

About the OSA Nanophotonics Technical Group

Mission statement

OSA Nanophotonics Technical Group focuses on the study and design of optics and optical devices that interact with light on the nanometer scale.

Group Chair

Cheng Zhang

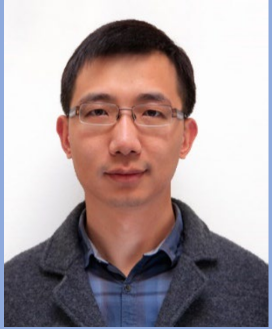
National Institute of Standards & Technology (NIST), USA
cheng.zhang@nist.gov

Social Media Officer

Sachin Kumar Srivastava

Indian Institute of Technology Roorkee, India

achinchitransh@gmail.com



Industry Officer

Sheng Liu

Apple, USA

shengliuumbc@gmail.com

Create a community for nanophotonic researchers

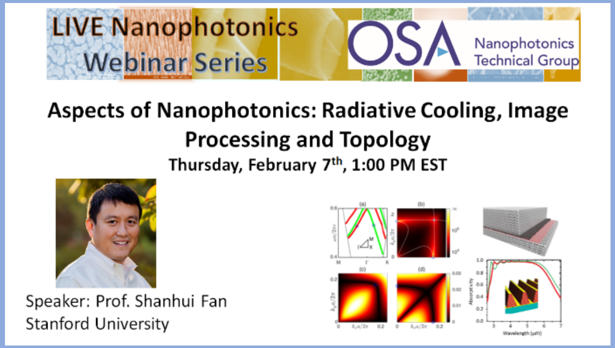
LIVE Nanophotonics WEBINAR SERIES

OSA Nanophotonics Technical Group

Enabling chip-scale trace-gas sensing systems with silicon photonics

Monday, October 30th, 11:00 AM EST

Speaker: Dr. William M.J. Green
Thomas J. Watson Research Center, IBM



LIVE Nanophotonics Webinar Series

OSA Nanophotonics Technical Group

Aspects of Nanophotonics: Radiative Cooling, Image Processing and Topology

Thursday, February 7th, 1:00 PM EST

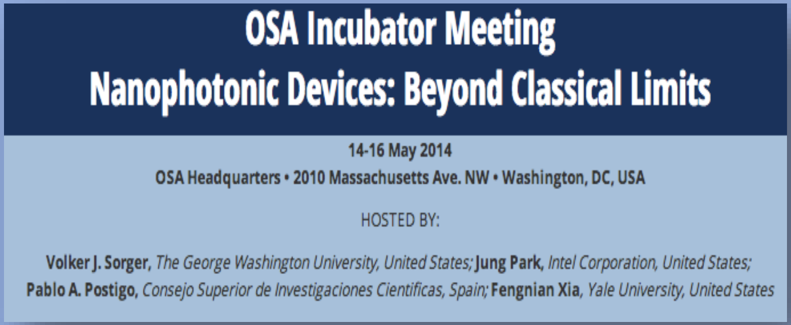
Speaker: Prof. Shanhui Fan
Stanford University

Webinars

Special events at OSA conferences

20 x 20 Talks at CLEO

Personalized mentoring at FiO



OSA Incubator Meeting
Nanophotonic Devices: Beyond Classical Limits

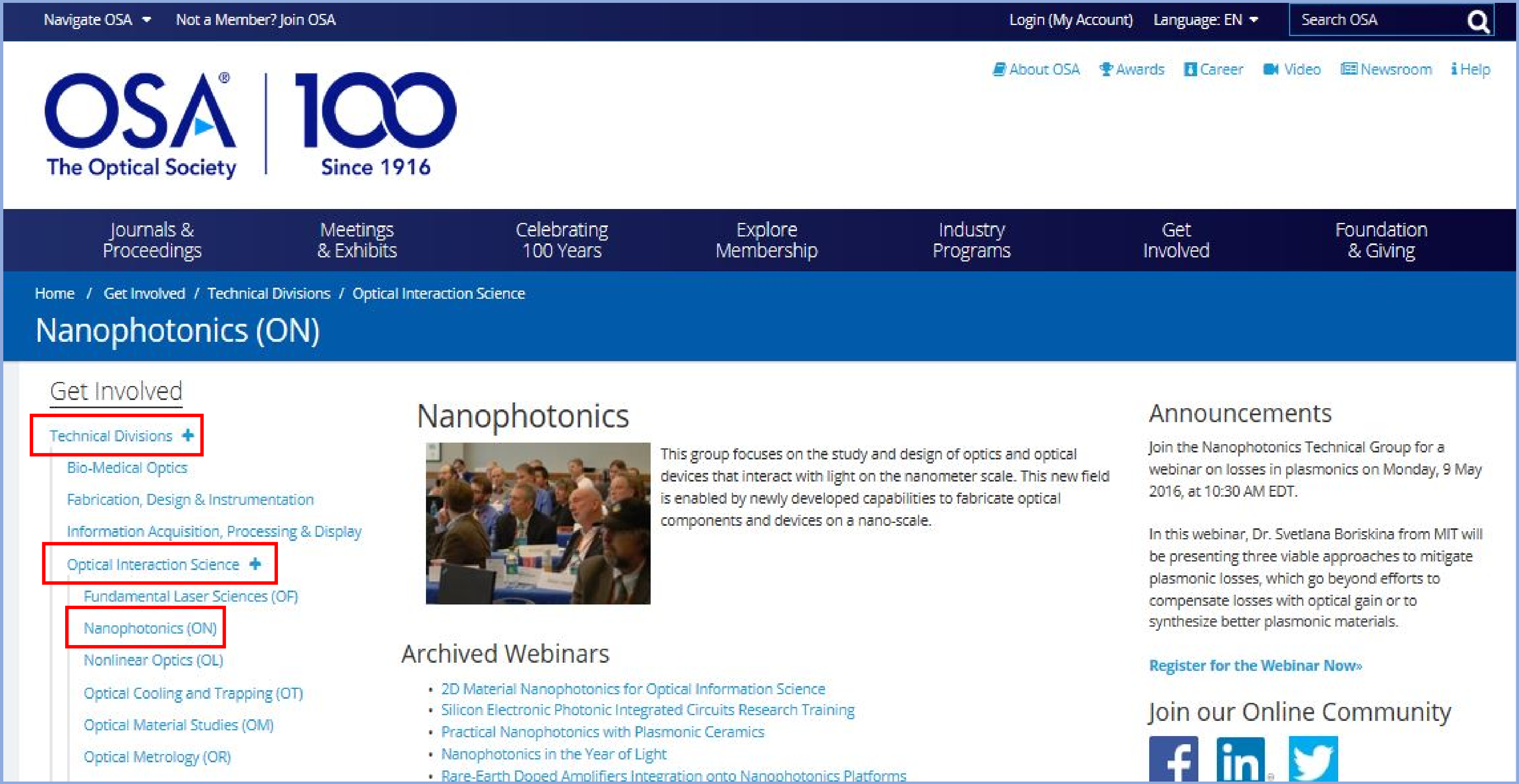
14-16 May 2014
OSA Headquarters • 2010 Massachusetts Ave. NW • Washington, DC, USA

HOSTED BY:

Volker J. Sorger, *The George Washington University, United States;* **Jung Park**, *Intel Corporation, United States;* **Pablo A. Postigo**, *Consejo Superior de Investigaciones Cientificas, Spain;* **Fengnian Xia**, *Yale University, United States*

Incubator meetings

Where to find us ?



Nanophotonics (ON)

Get Involved

- Technical Divisions +
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display
  - Optical Interaction Science +
    - Fundamental Laser Sciences (OF)
    - Nanophotonics (ON)
    - Nonlinear Optics (OL)
    - Optical Cooling and Trapping (OT)
    - Optical Material Studies (OM)
    - Optical Metrology (OR)

Nanophotonics

This group focuses on the study and design of optics and optical devices that interact with light on the nanometer scale. This new field is enabled by newly developed capabilities to fabricate optical components and devices on a nano-scale.

Archived Webinars

- 2D Material Nanophotonics for Optical Information Science
- Silicon Electronic Photonic Integrated Circuits Research Training
- Practical Nanophotonics with Plasmonic Ceramics
- Nanophotonics in the Year of Light
- Rare-Earth Doped Amplifiers Integration onto Nanophotonics Platforms

Announcements

Join the Nanophotonics Technical Group for a webinar on losses in plasmonics on Monday, 9 May 2016, at 10:30 AM EDT.

In this webinar, Dr. Svetlana Boriskina from MIT will be presenting three viable approaches to mitigate plasmonic losses, which go beyond efforts to compensate losses with optical gain or to synthesize better plasmonic materials.

Register for the Webinar Now»

Join our Online Community

Website: www.osa.org/NanophotonicsTG

Email: osananophotonics@gmail.com

Where to find us ?

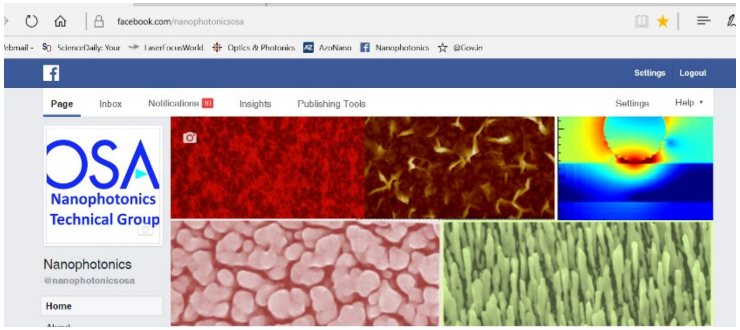
@Nano_OSA

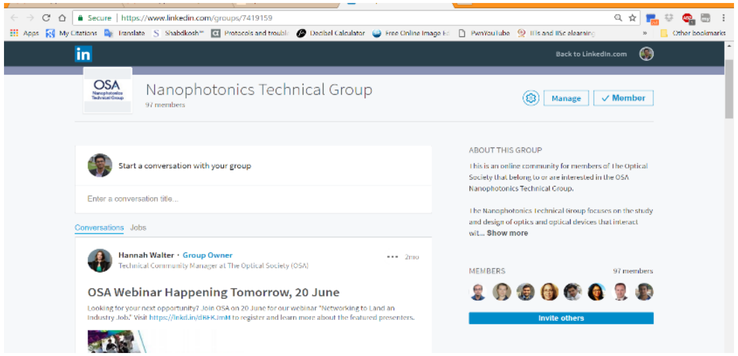
OSA Nanophotonics
@Nano_OSA
facebook.com/nanophotonicso...
Joined August 2013

OSA Nanophotonics @Nano_OSA · Aug 20
The Washington University team, led by Lan Yang, the Edwin H. & Florence G. Skinner Professor of Electrical &...

Engineers find better way to detect nanoparticles

facebook.com/nanophotonicsosa





Nanophotonics Technical Group
97 members

Start a conversation with your group

Enter a conversation title...

Hannah Walter · Group Owner · 2mo
Technical Community Manager at The Optical Society (OSA)

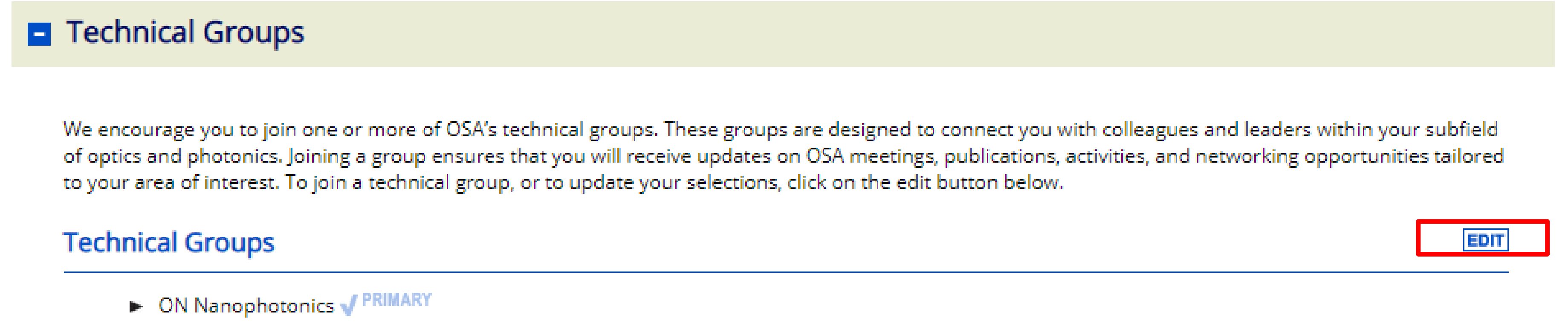
OSA Webinar Happening Tomorrow, 20 June
Looking for your next opportunity? Join OSA on 20 June for our webinar "Networking to Land an Industry Job." Visit https://lnkd.in/dBFK.ImM to register and learn more about the featured presenters.

ABOUT THIS GROUP
This is an online community for members of The Optical Society that belong to or are interested in the OSA Nanophotonics Technical Group.

The Nanophotonics Technical Group focuses on the study and design of optics and optical devices that interact wit... **Show more**

MEMBERS 97 members

How to join ON Nanophotonics group's email list?



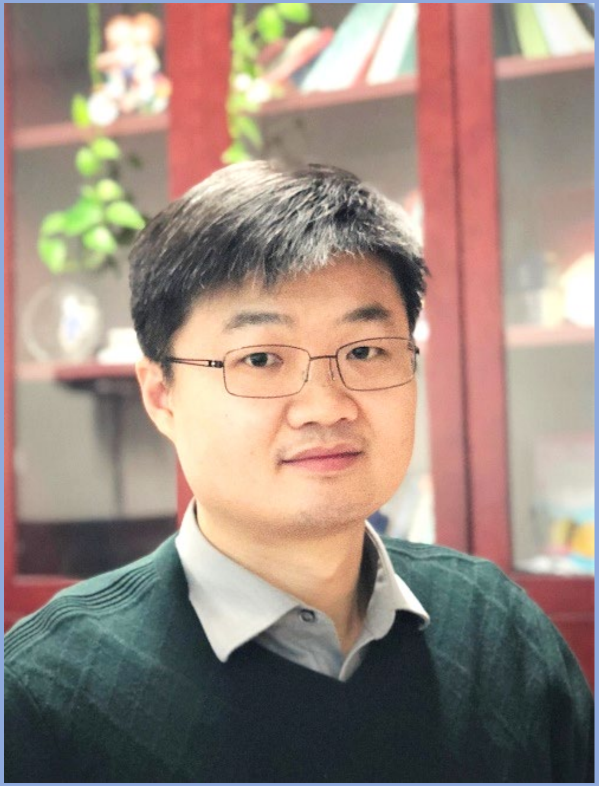
Technical Groups

We encourage you to join one or more of OSA's technical groups. These groups are designed to connect you with colleagues and leaders within your subfield of optics and photonics. Joining a group ensures that you will receive updates on OSA meetings, publications, activities, and networking opportunities tailored to your area of interest. To join a technical group, or to update your selections, click on the edit button below.

Technical Groups

► ON Nanophotonics ✓ PRIMARY

Plasmonic Nanolasers: Physics, Applications, and Challenges



Dr. Ren-Min Ma

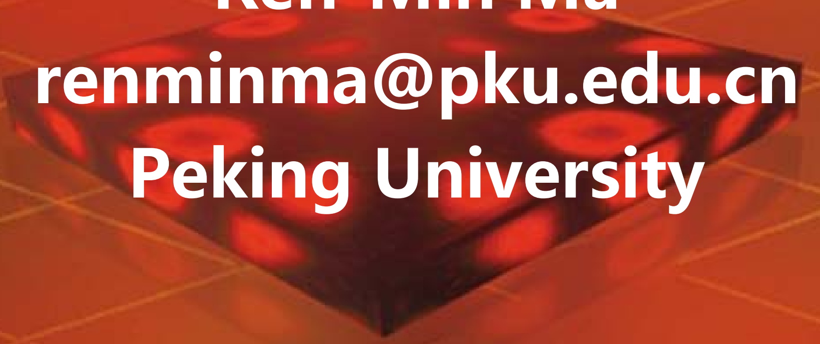
Professor, Peking University

北京大學
PEKING UNIVERSITY

OSA The Optical Society | 100 Since 1916

Plasmonic Nanolasers:

Physics, Application, and Challenges

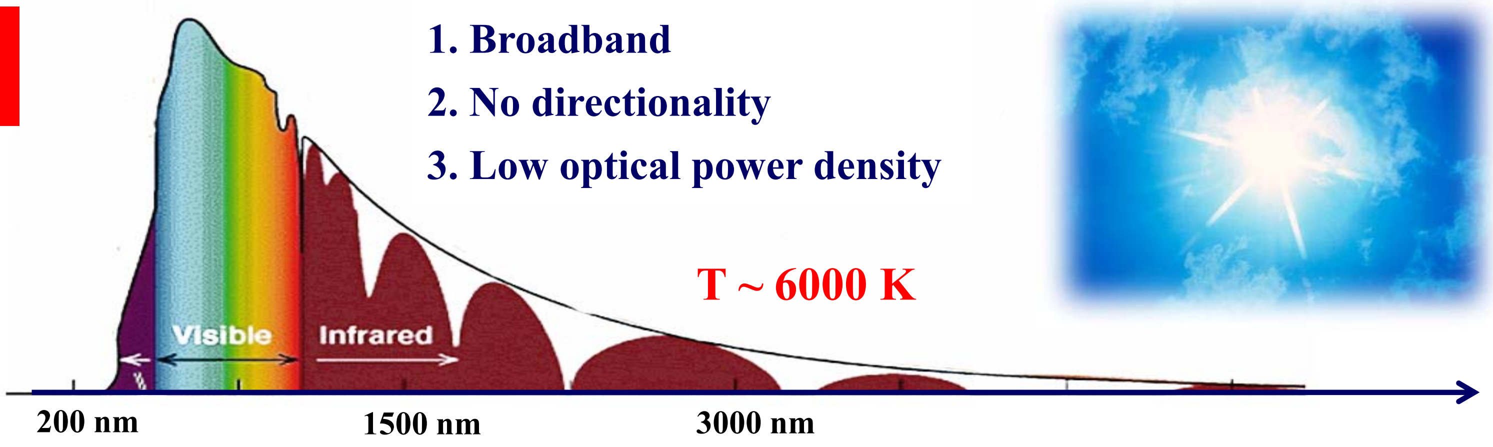


Ren-Min Ma
renminma@pku.edu.cn
Peking University

2019-09-04

The first laser: localization of light in frequency

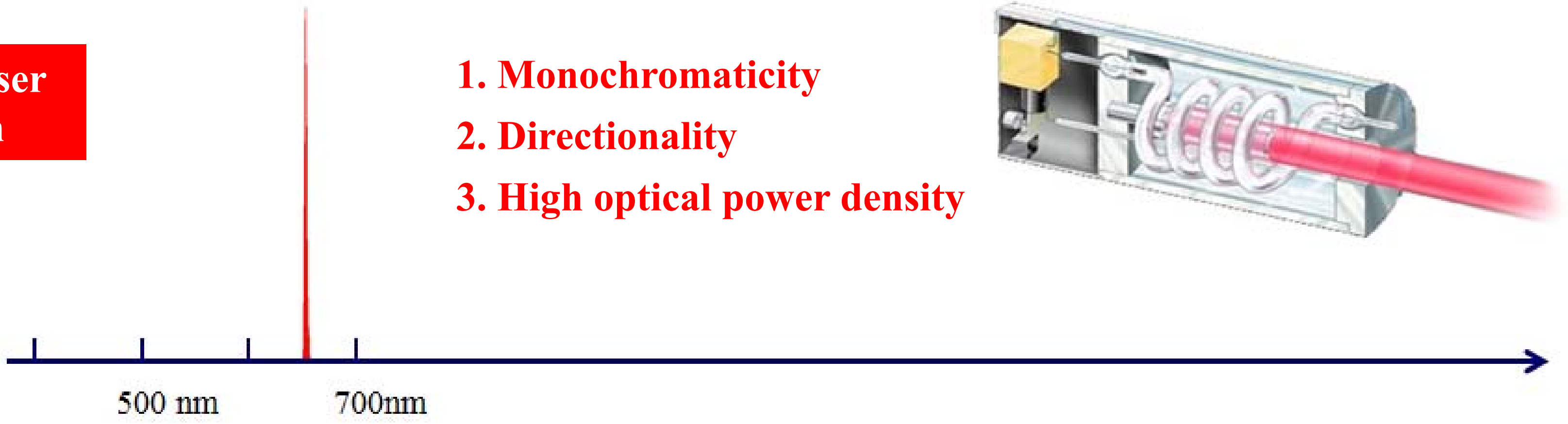
Solar Spectrum



1. Broadband
2. No directionality
3. Low optical power density

To reach the same power level of a 1mW laser with a linewidth of GHz
A thermal light need to be heated to 10^{11} K!

The 1st laser Spectrum



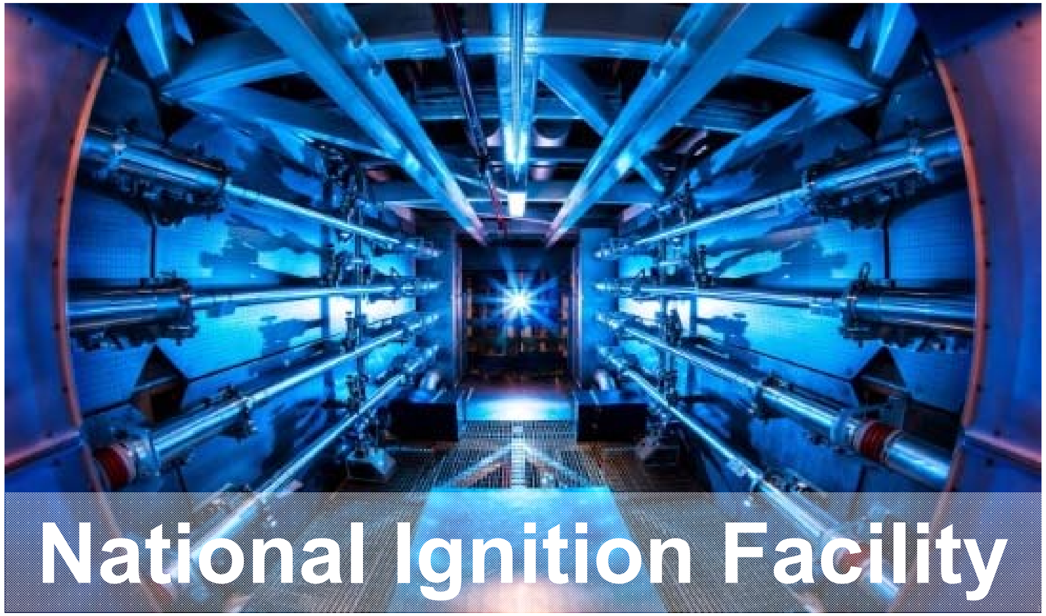
1. Monochromaticity
2. Directionality
3. High optical power density

Laser： extreme localization of EM field

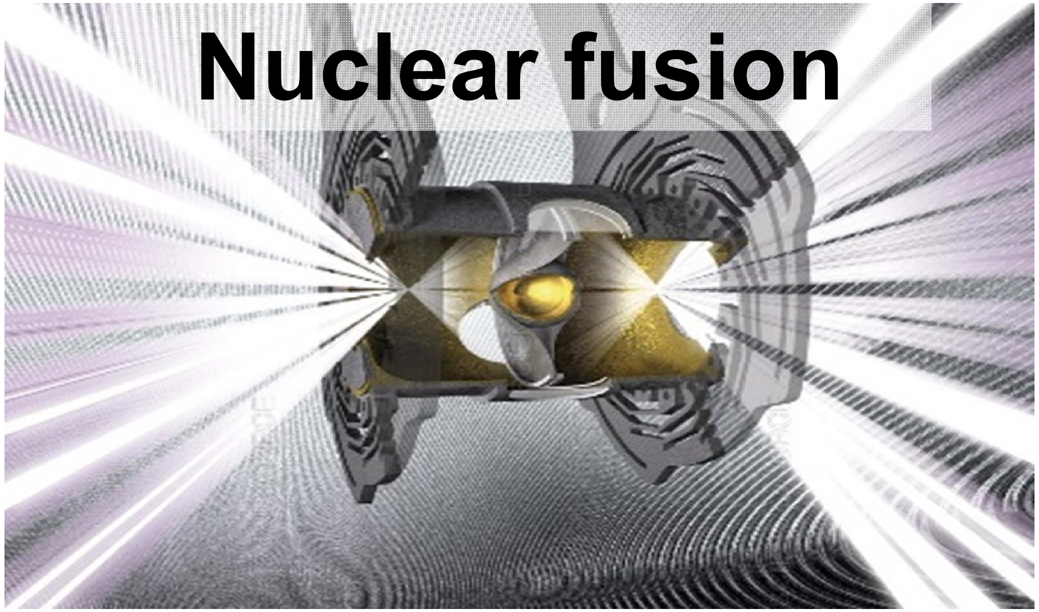
$$E=Ae^{i(kx-wt)}$$

Laser： extreme localization of EM field

$$E=\underline{A}e^{i(kx-wt)}$$



National Ignition Facility



Nuclear fusion

Laser：extreme localization of EM field

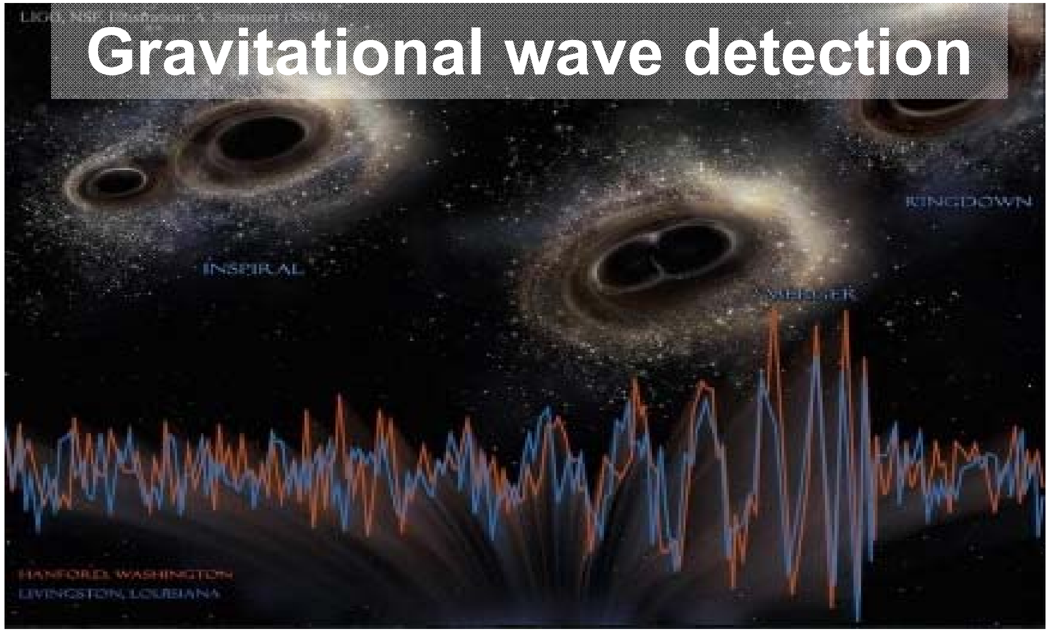
$$E=Ae^{i(\underline{k}x-wt)}$$

Laser：extreme localization of EM field

$$E=Ae^{i(kx-\underline{w}t)}$$

Ultra-narrow laser for 10^{-18} meter level detection

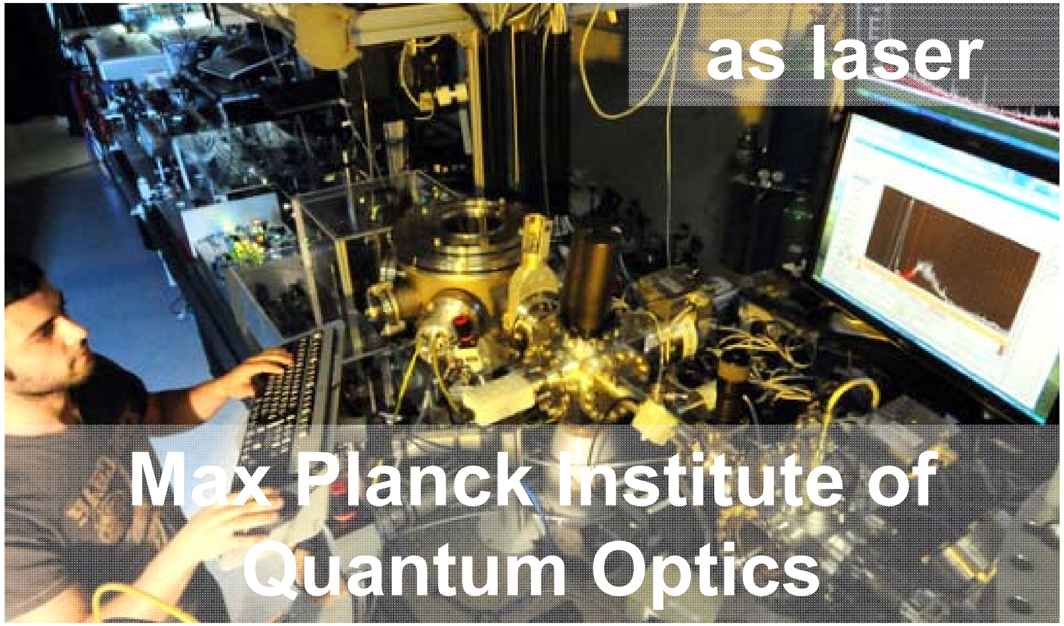
LIGO

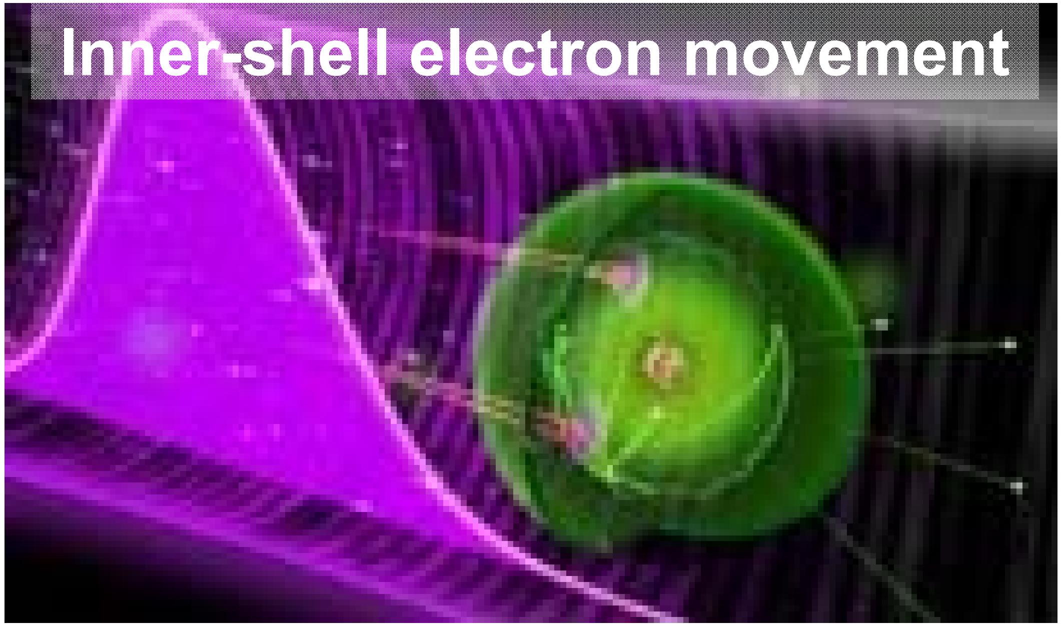


Gravitational wave detection

Laser： extreme localization of EM field

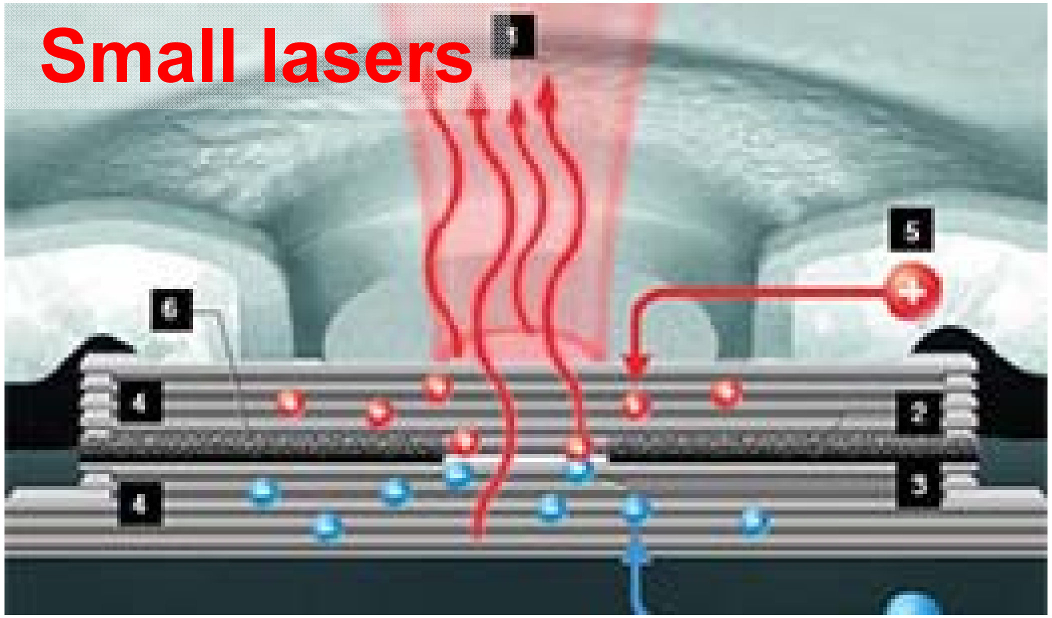
$$E=Ae^{i(kx-w\underline{t})}$$

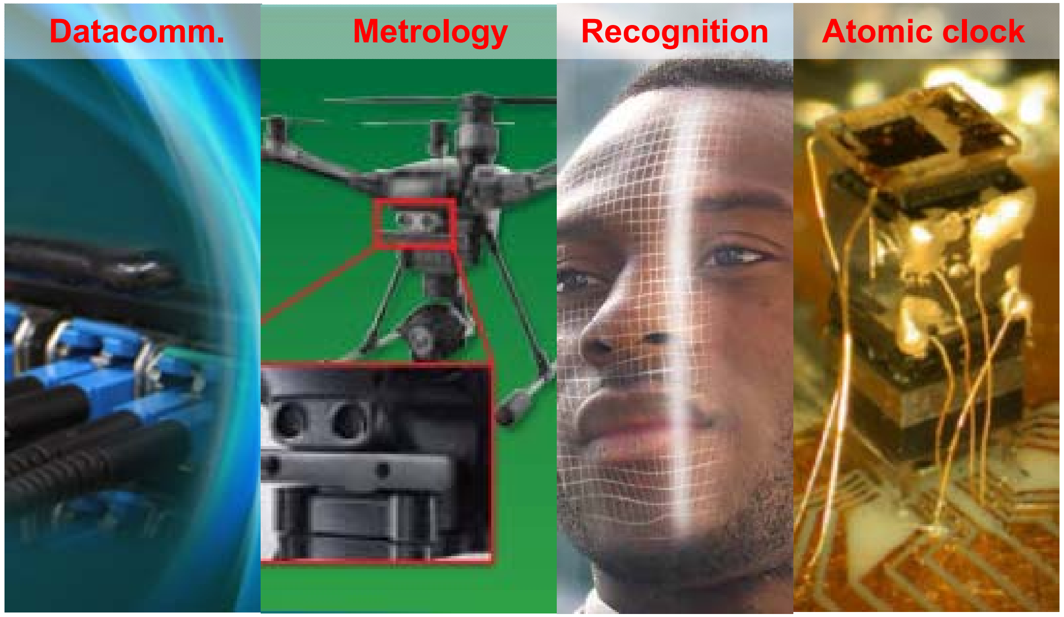




Laser： extreme localization of EM field

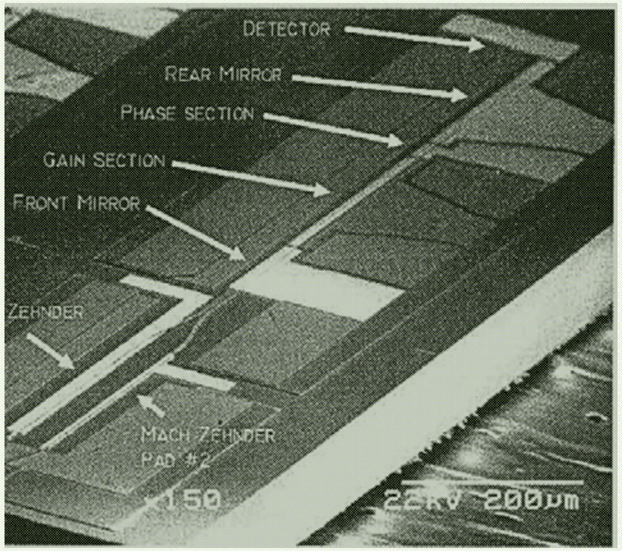
$$E=Ae^{i(k\underline{x}-wt)}$$



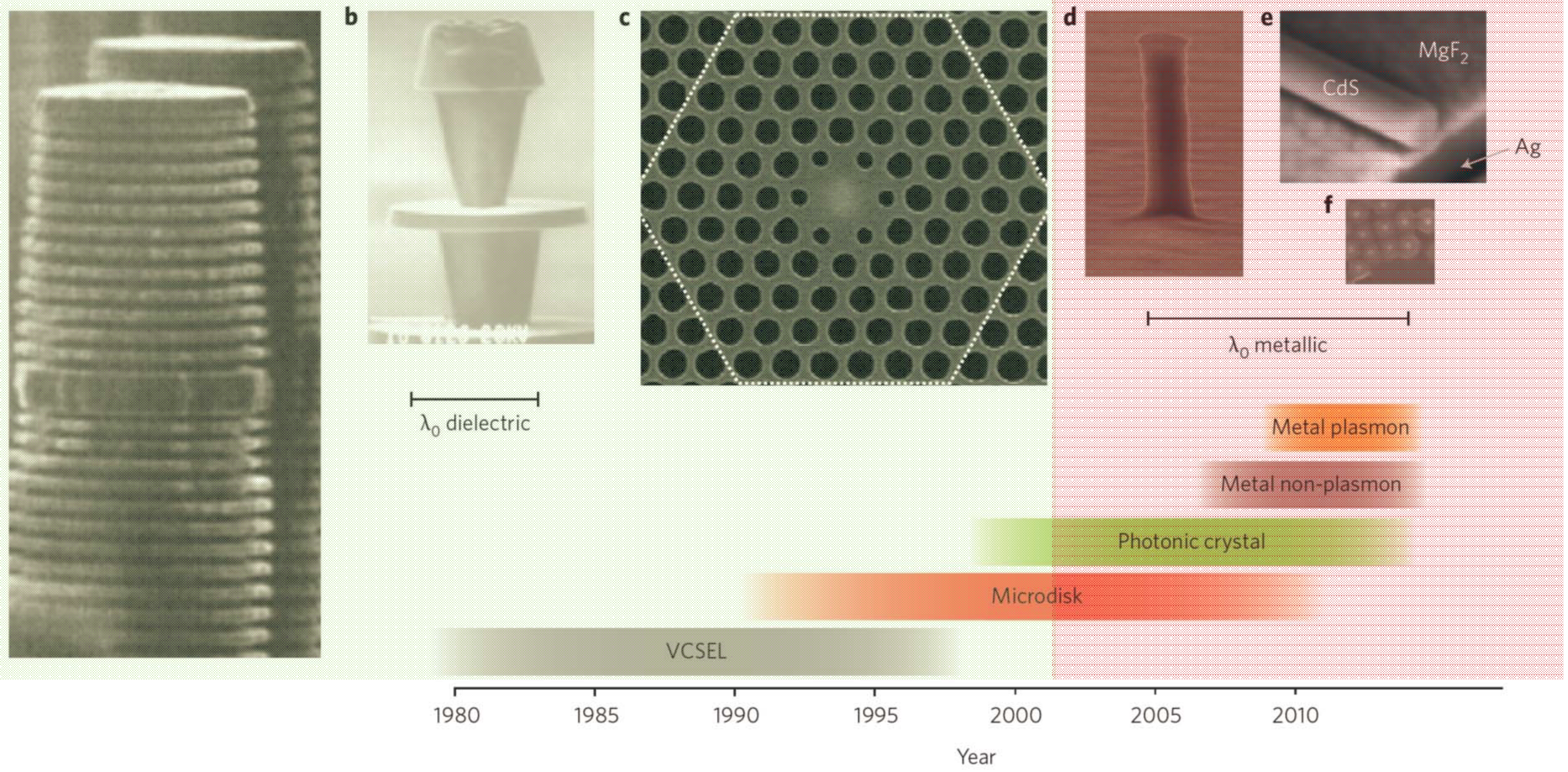


A brief history of laser miniaturization

Loss limit *e.g.* L=1μm, R=20%, $\alpha_M \sim 1.6 \times 10^4$ cm^{-1} **Diffraction limit**



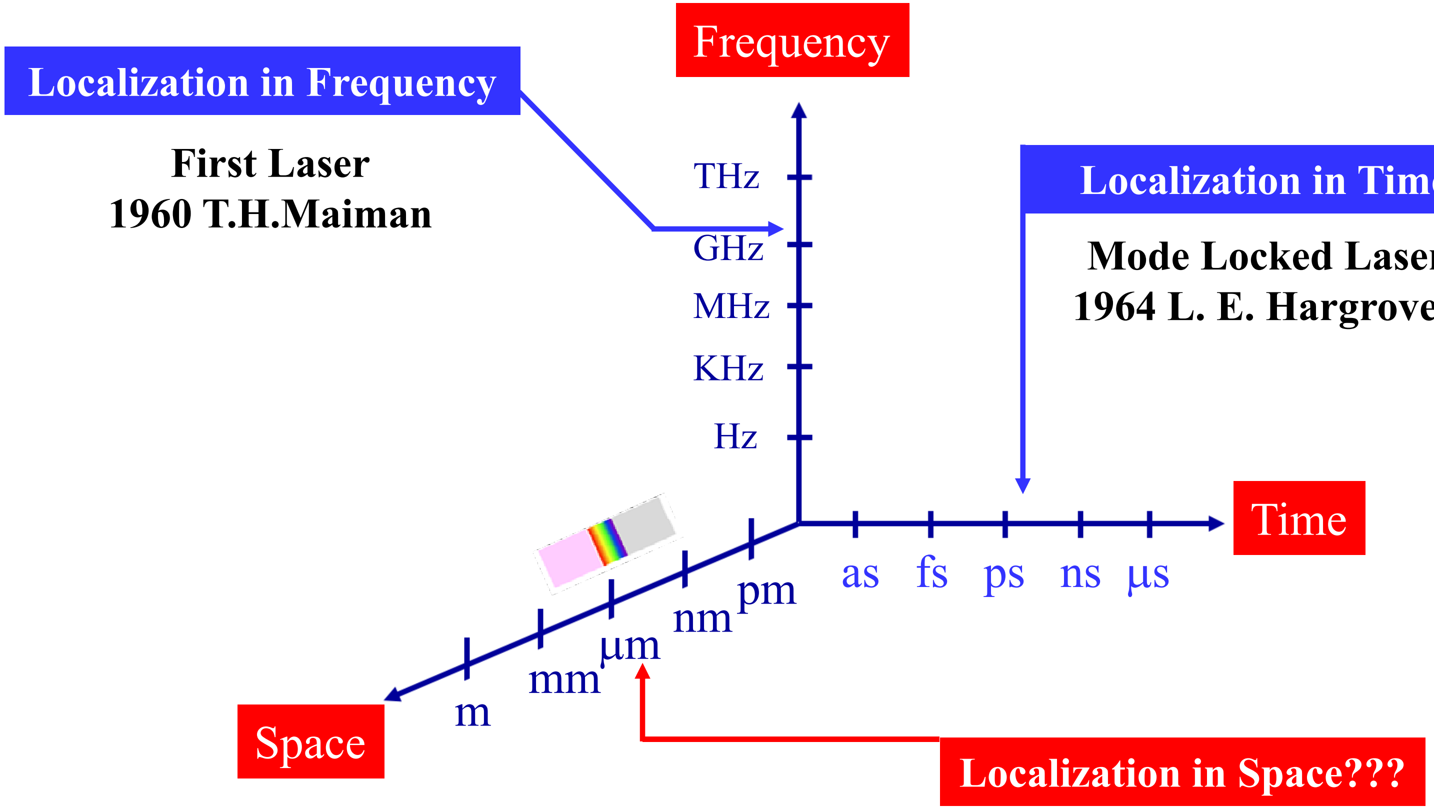
Edge emitting lasers



Optical Fiber Telecommunications
I.P. Kaminnow et al., Elsevier, Sixth edition 2013

Nature Photonics 8 (2014) 908

Extreme localization of light in space



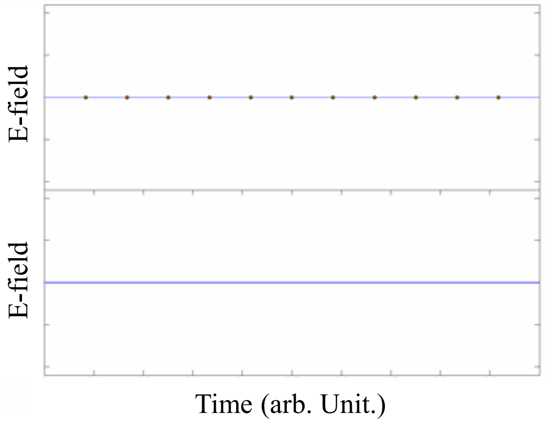
Localization in Frequency

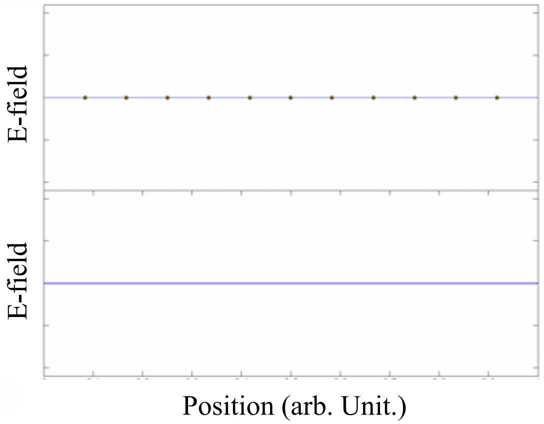
First Laser
1960 T.H.Maiman

Localization in Time

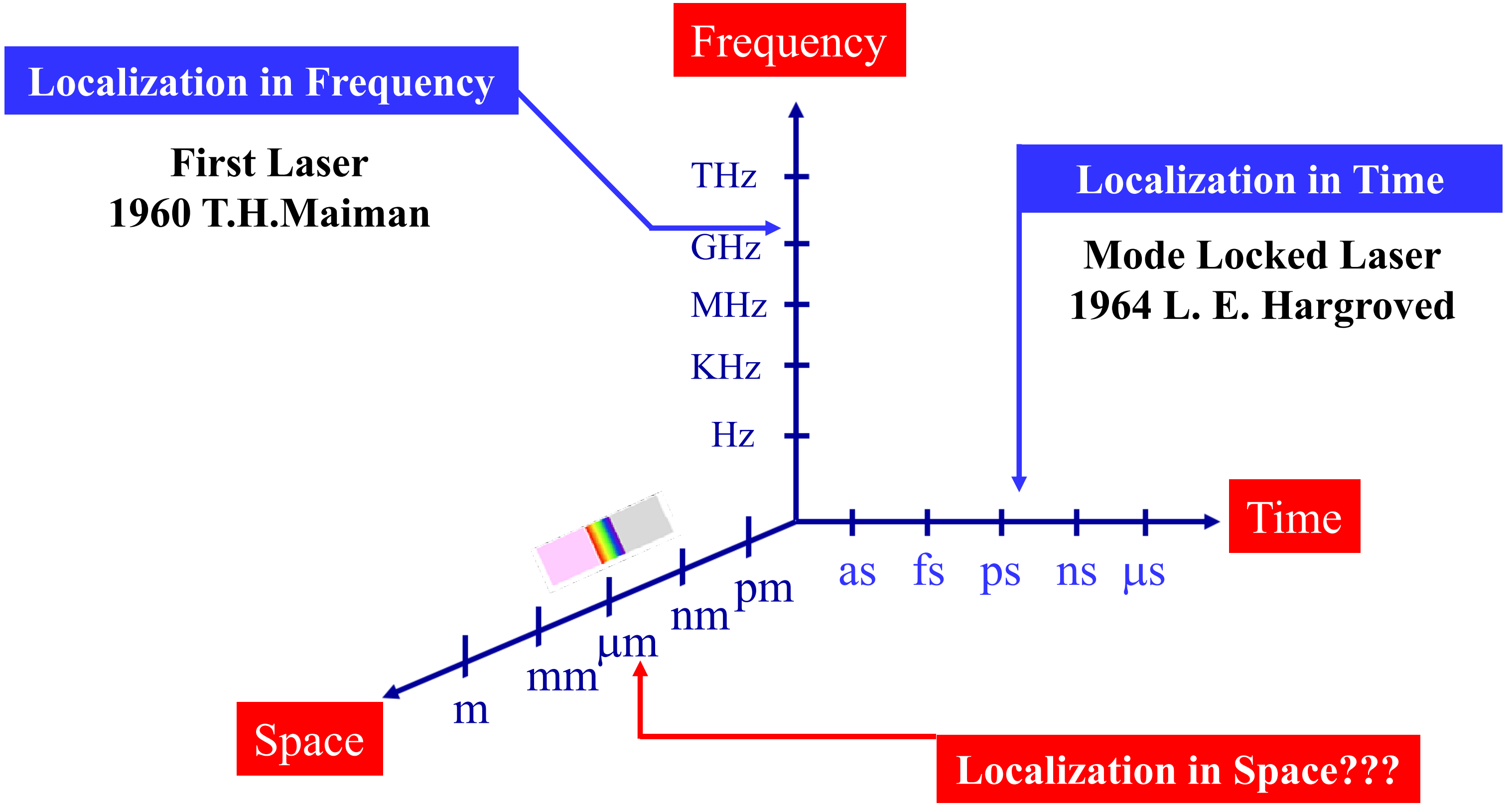
Mode Locked Laser
1964 L. E. Hargroved

Localization in Space???





Extreme localization of light in space



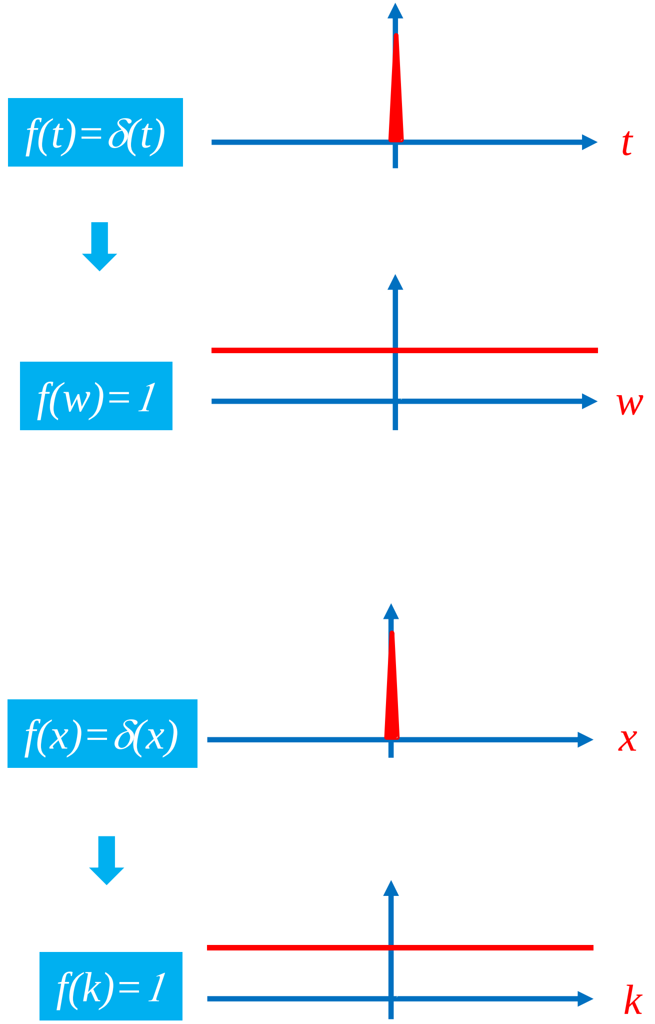
Localization in Frequency

First Laser
1960 T.H.Maiman

Localization in Time

Mode Locked Laser
1964 L. E. Hargroved

Localization in Space???



$f(t)=\delta(t)$

$f(w)=1$

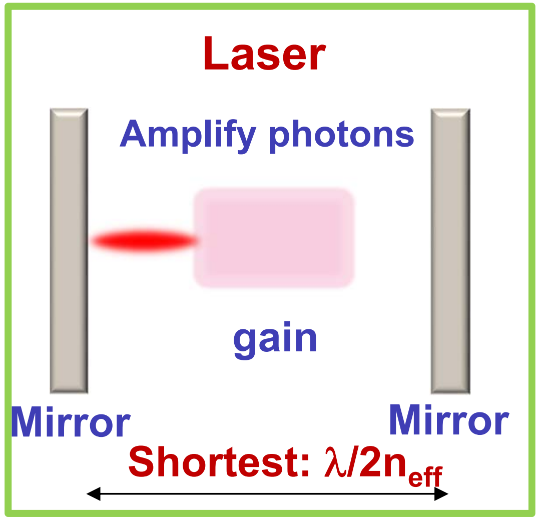
$f(x)=\delta(x)$

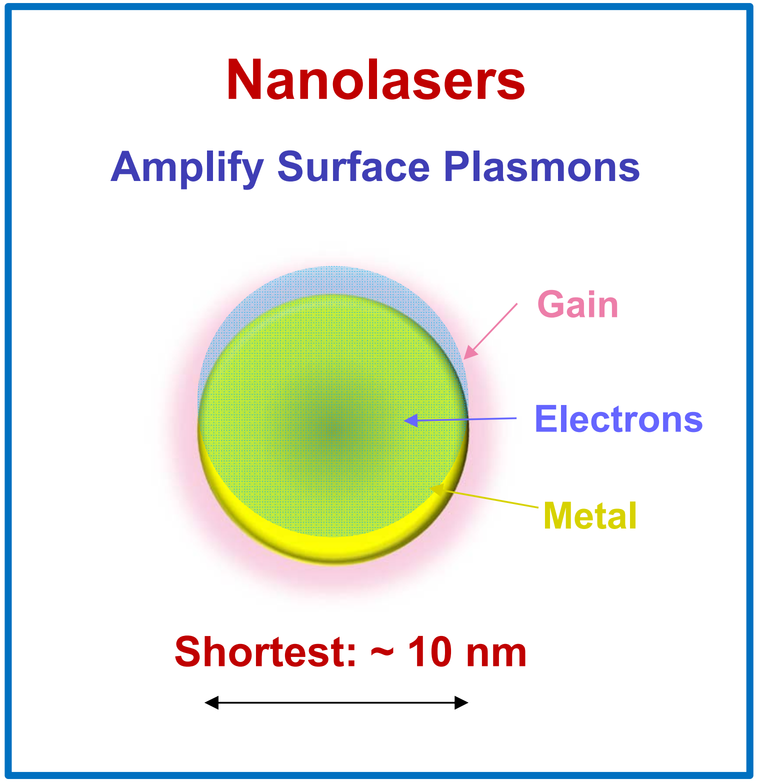
$f(k)=1$

$$k = \frac{2\pi n}{\lambda}$$

Plasmonic Nanolasers a.k.a Spasers

Laser:	**L**ightwave **A**mplification by **S**timulated **E**mission of **R**adiation
Spasers:	**S**urface **P**lasmon **A**mplification by **S**timulated **E**mission of **R**adiation

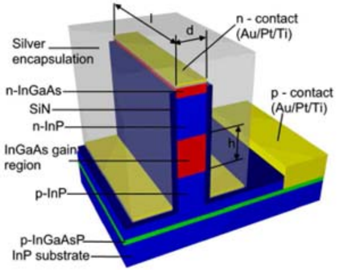




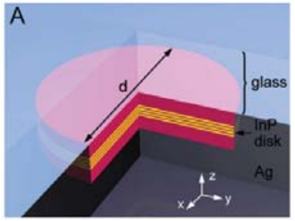
Physical Review Letters 90 027402 (2003)

Spatial localization of nanolasers in different dimensions

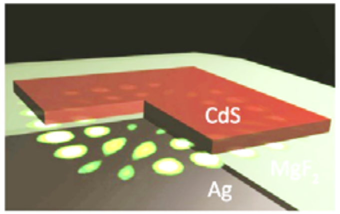
1-D



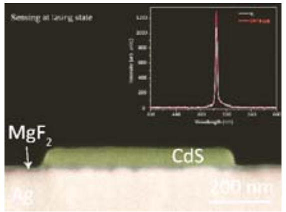
Optical Express
17 (2009) 11107



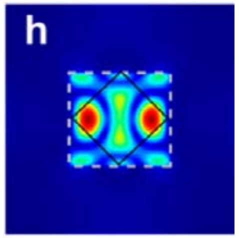
Nano Letters
10 (2010) 3679



Nature Materials
10 (2011) 110



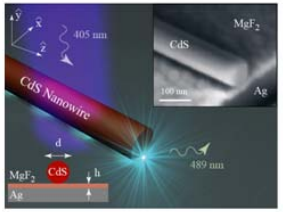
Nature Nanotech.
9 (2014) 600



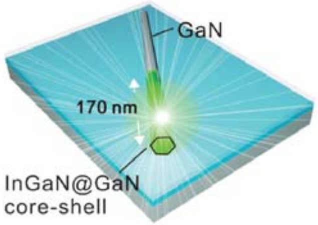
Nano Letters
16 (2016) 7822

....

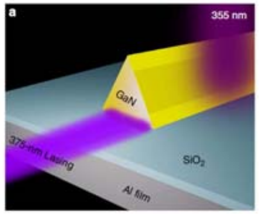
2-D



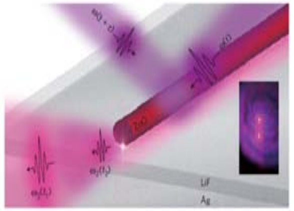
Nature
461 (2009) 629



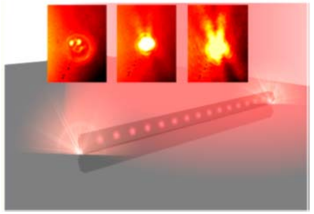
Science
337, 450-453 (2012)



Nature Commun.
5, 4953 (2014)



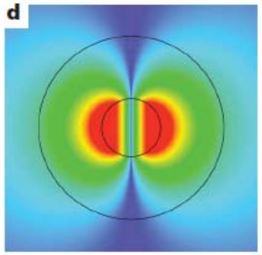
Nature Physics
10 (2014) 870



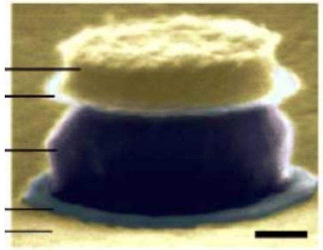
Nano Lett.
16, 2845–2850 (2016)

....

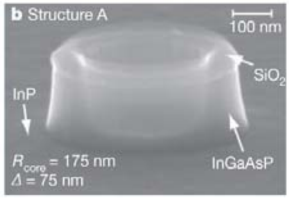
3-D



Nature
460 (2009) 1110

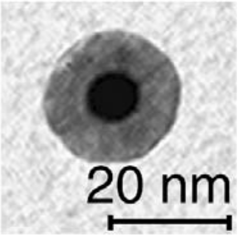


Optical Express
18 (2010) 8792



Nature
482 (2012) 204

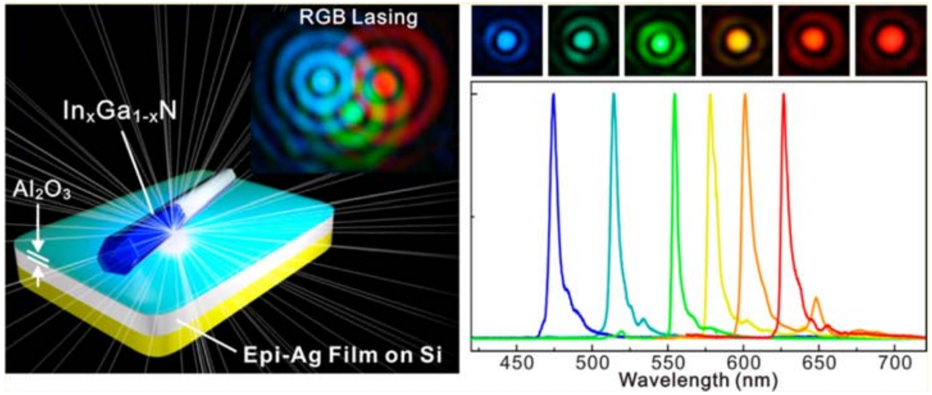
Opt. Express
21, 4728–4733 (2013)

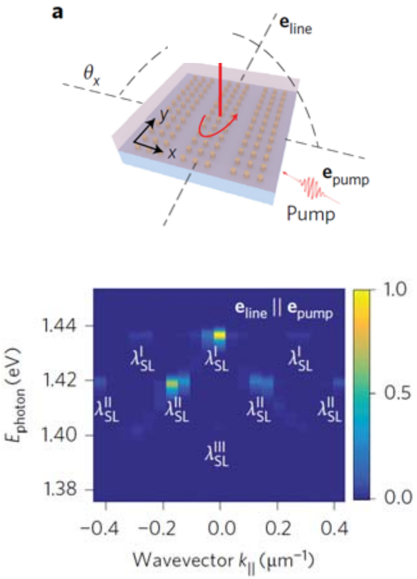


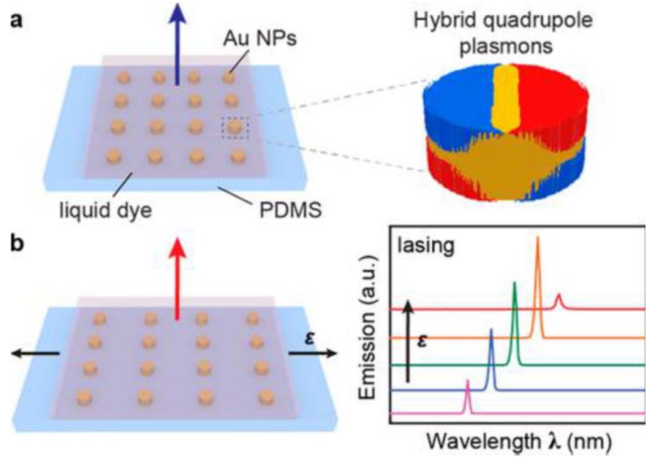
Nature Commun.
8, 15528 (2017)

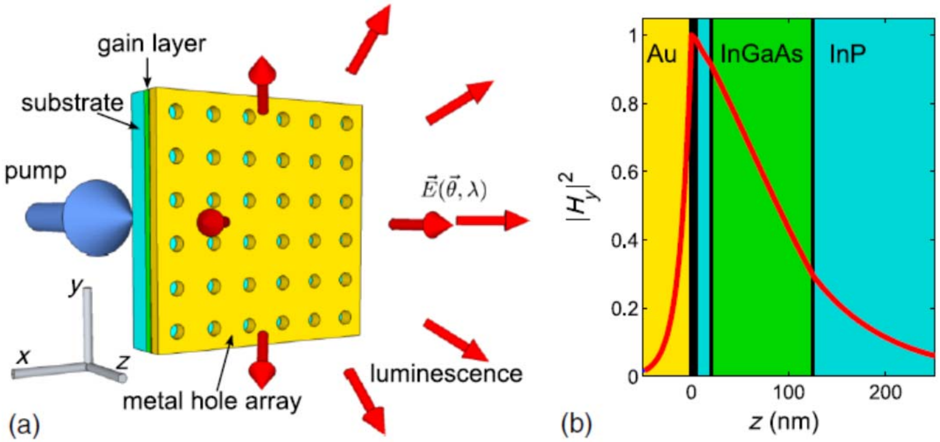
....

Plasmonic nanolasing in metal particle array

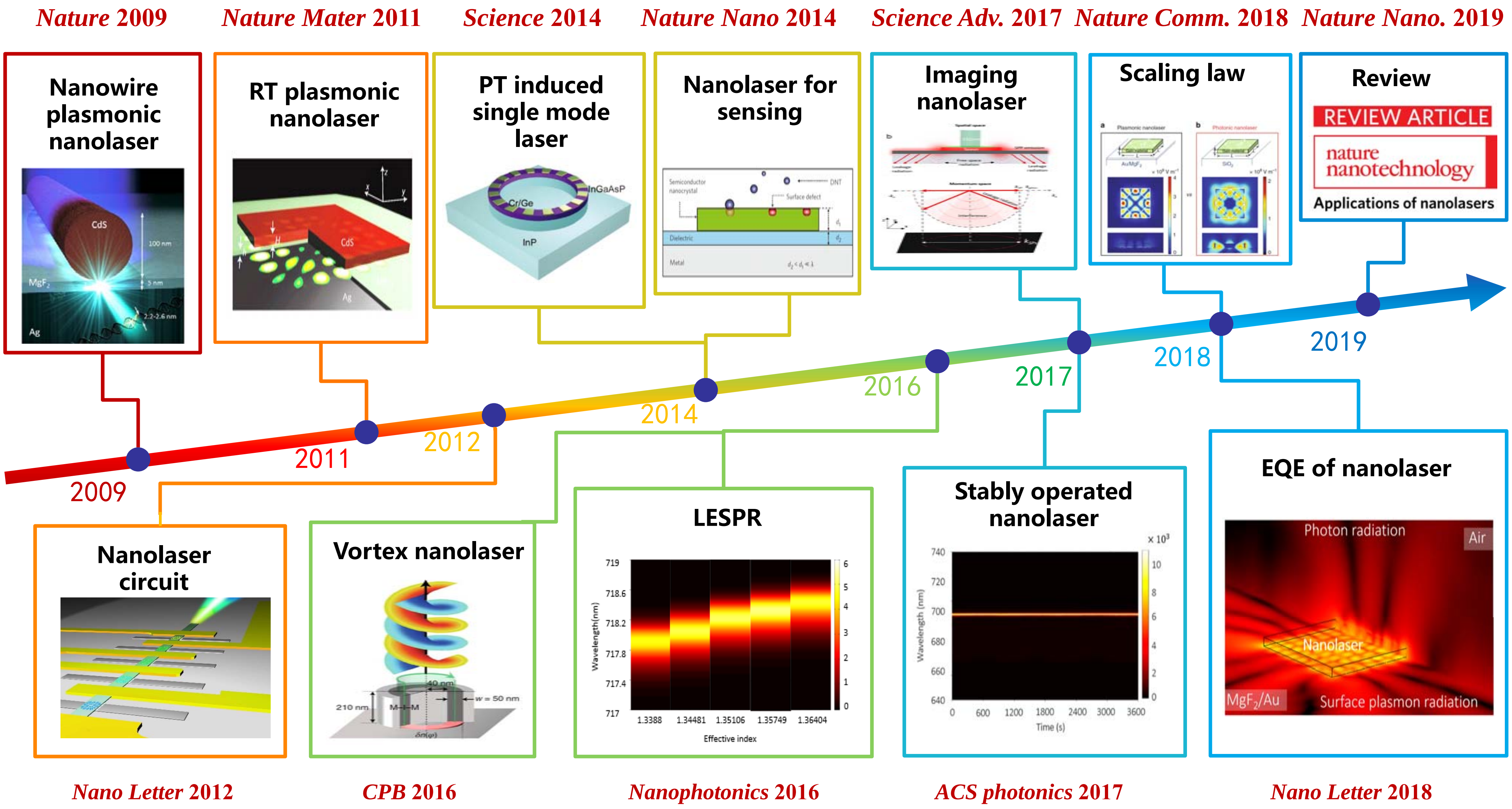








Nano Lett. **14**, 4381−4388 (2014)
Nat. Nanotech. **8,** 506-511 (2013)
Phys. Rev. Lett. **110**, 206802 (2013)
Nat. Commun. **6,** 6939 (2015)
Nat. Nanotech. **12**, 889-894 (2017)
Nano Letters DOI: 10.1021/acs.nanolett.8b01774



Nature 2009

Nanowire plasmonic nanolaser

Nature Mater 2011

RT plasmonic nanolaser

Science 2014

PT induced single mode laser

Nature Nano 2014

Nanolaser for sensing

Science Adv. 2017

Imaging nanolaser

Nature Comm. 2018

Scaling law

Nature Nano. 2019

Review

REVIEW ARTICLE

nature nanotechnology

Applications of nanolasers

Nanolaser circuit

Nano Letter 2012

Vortex nanolaser

CPB 2016

LESPR

Nanophotonics 2016

Stably operated nanolaser

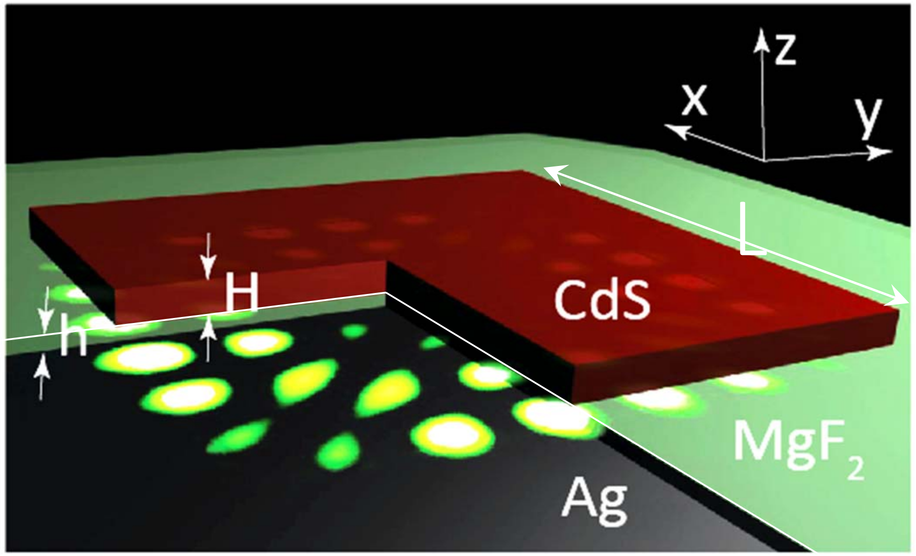
ACS photonics 2017

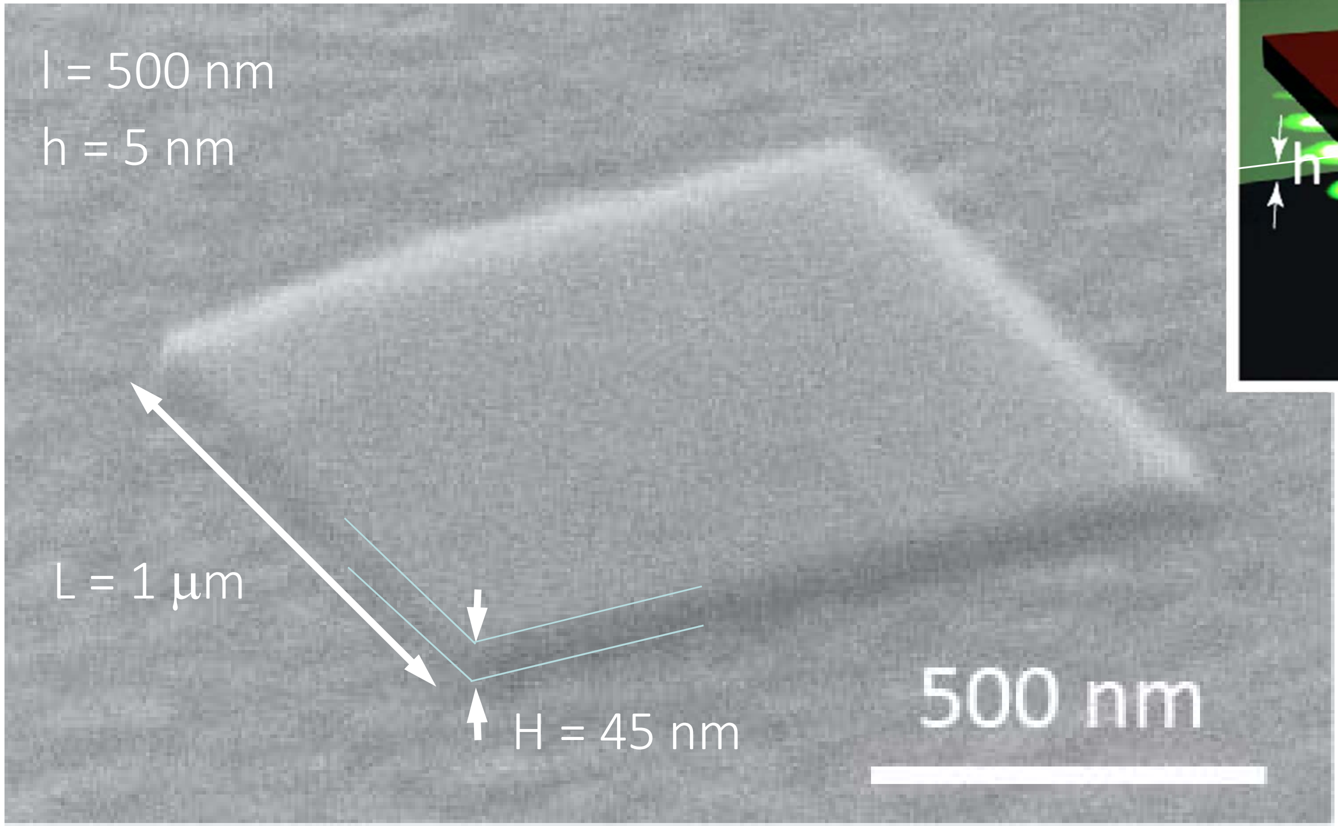
EQE of nanolaser

Nano Letter 2018

Nanosquare plasmonic nanolaser

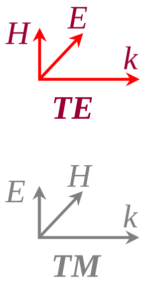
Ren-Min Ma *et al. Nature Materials* 10, 110 (2011)

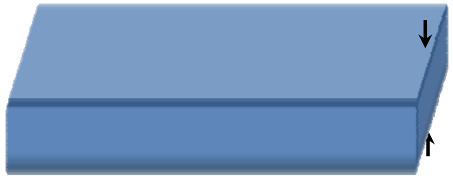




Metal-Insulator-Semiconductor Surface Plasmon Mode

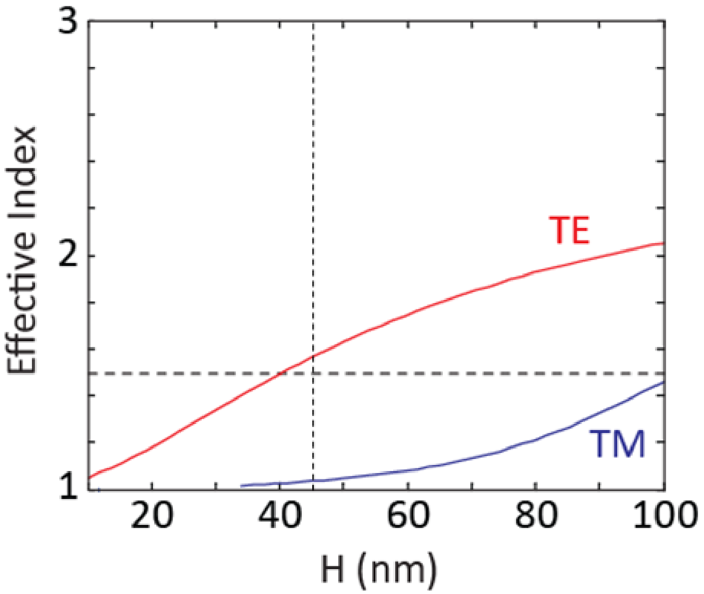
Ren-Min Ma *et al.* ***Nature Mat.*** **10**, 110 (2011)

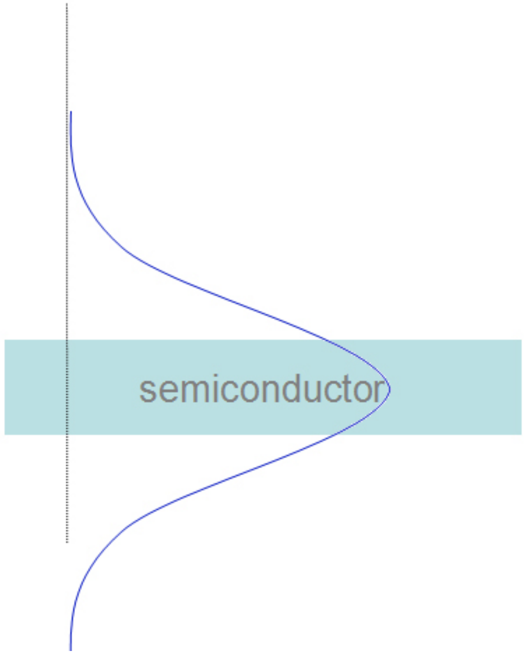




CdS

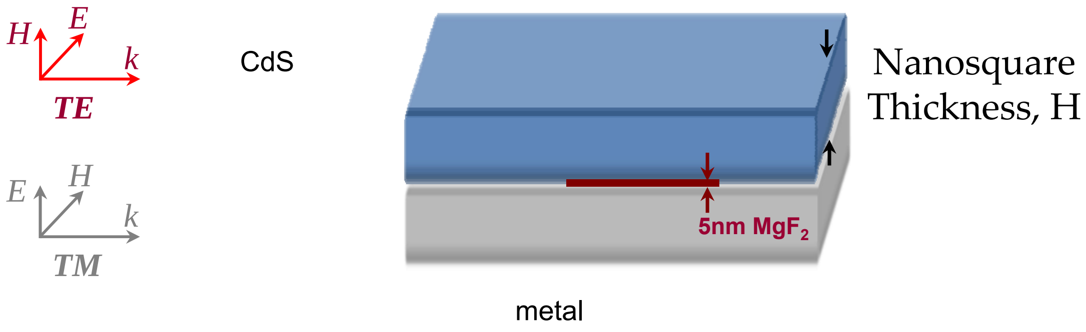
Nanosquare thickness

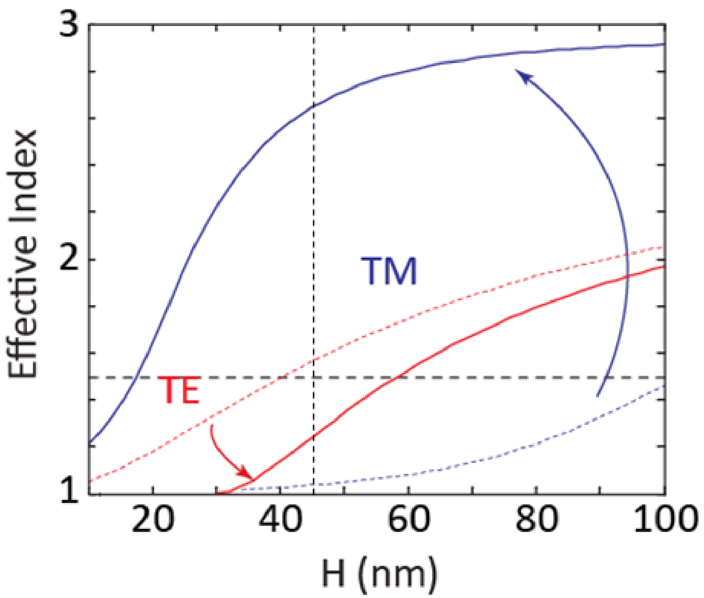


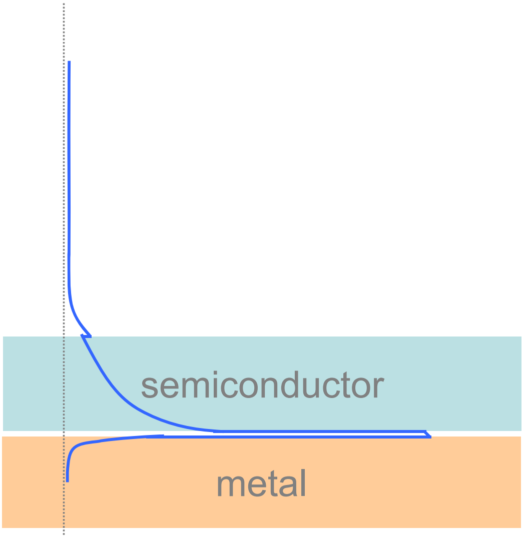


Metal-Insulator-Semiconductor Surface Plasmon Mode

Ren-Min Ma *et al.* ***Nature Mat.*** **10**, 110 (2011)



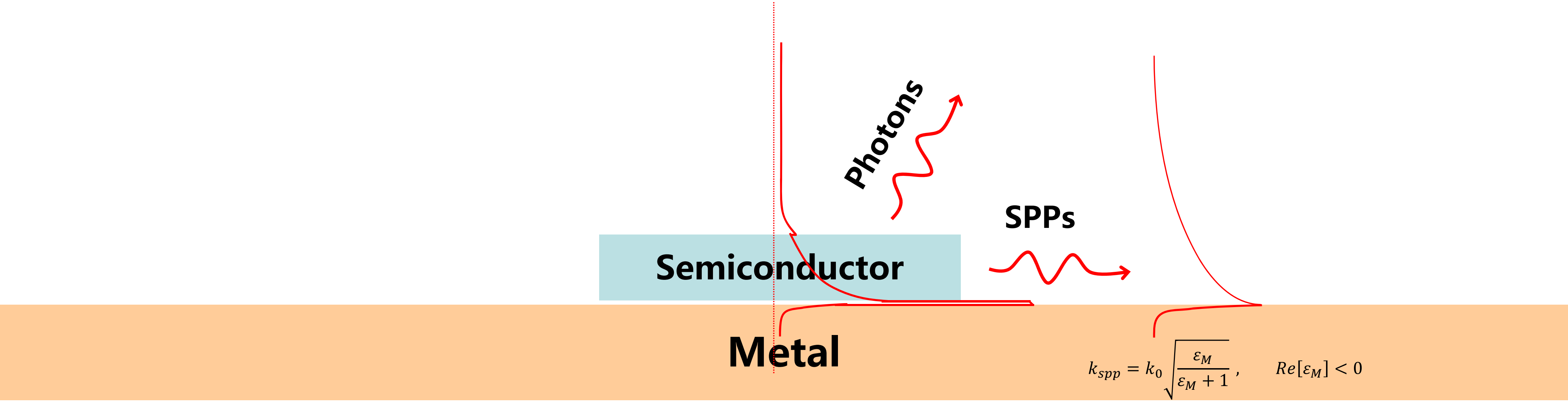




Plasmonic Nanolasers *a.k.a* Spasers

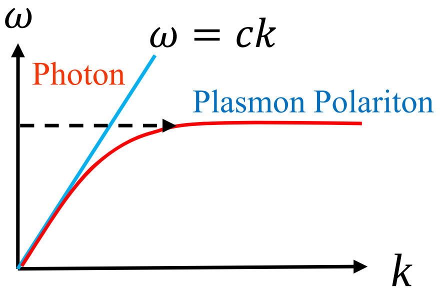
Laser: Lightwave Amplification by Stimulated Emission of Radiation

Spasers: Surface Plasmon Amplification by Stimulated Emission of Radiation



$$k_{spp} = k_0\sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}, \qquad Re[\varepsilon_M] < 0$$

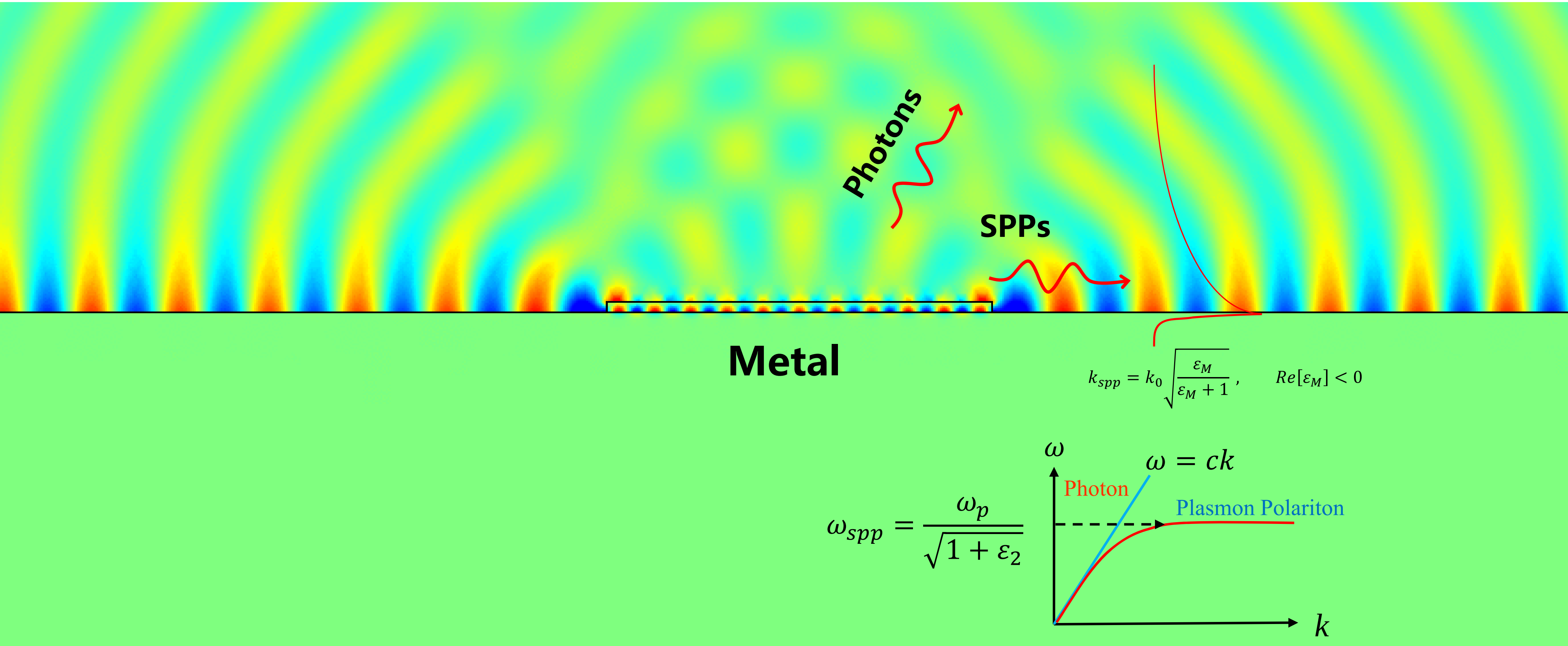
$$\omega_{spp} = \frac{\omega_p}{\sqrt{1 + \varepsilon_2}}$$



Imaging the dark emission of plasmonic nanolasers

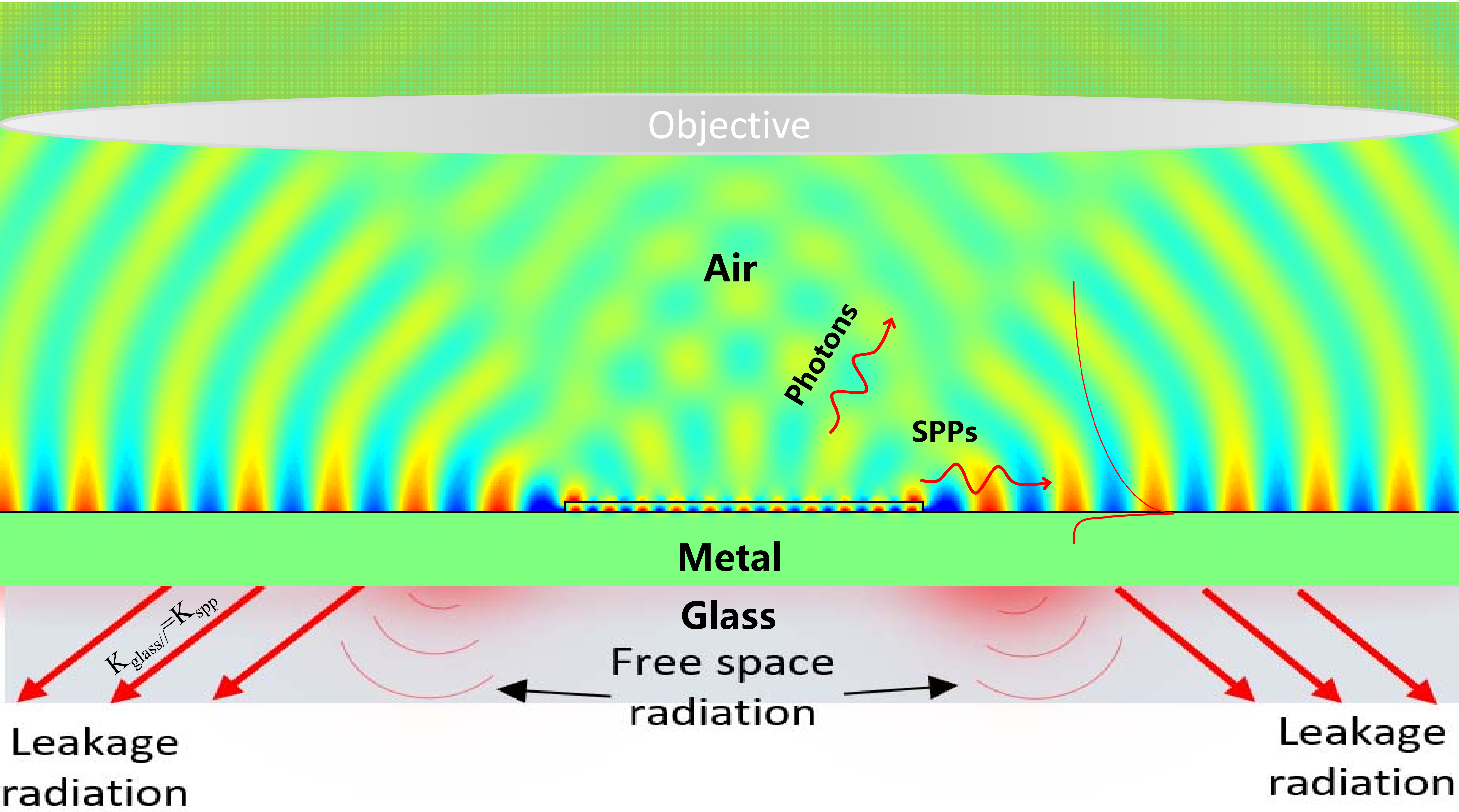
Laser: Lightwave Amplification by Stimulated Emission of Radiation

Spasers: Surface Plasmon Amplification by Stimulated Emission of Radiation

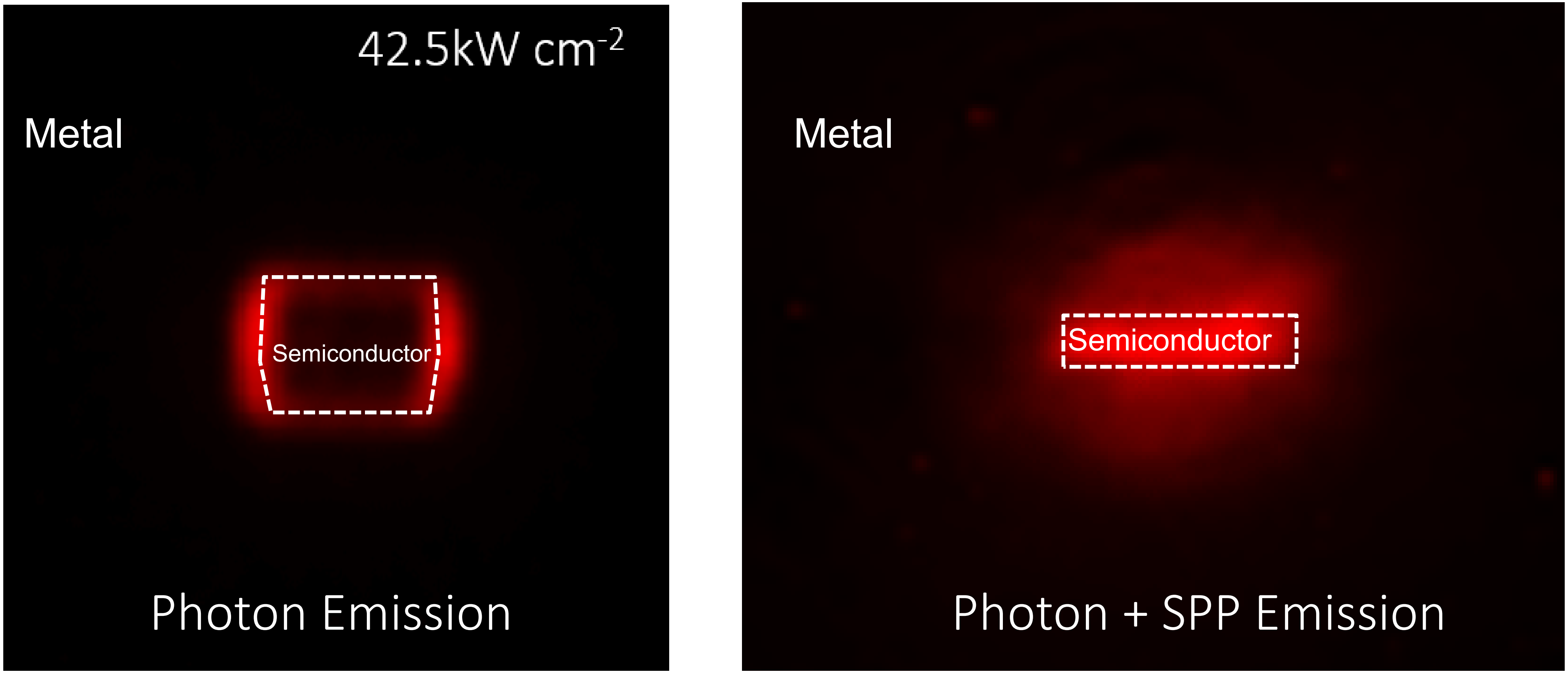


$$k_{spp} = k_0\sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}, \qquad Re[\varepsilon_M] < 0$$

$$\omega_{spp} = \frac{\omega_p}{\sqrt{1 + \varepsilon_2}}$$


Objective
Air
Photons
SPPs
Metal
Glass
$K_{glass//}=K_{spp}$
Free space radiation
Leakage radiation
Leakage radiation

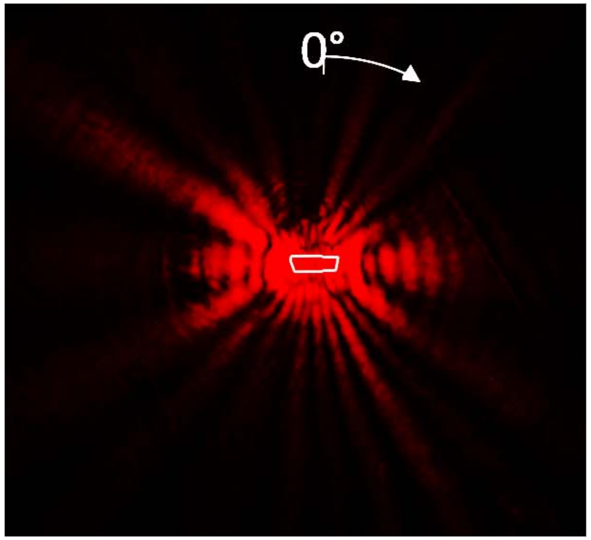
Imaging the dark emission of plasmonic nanolasers



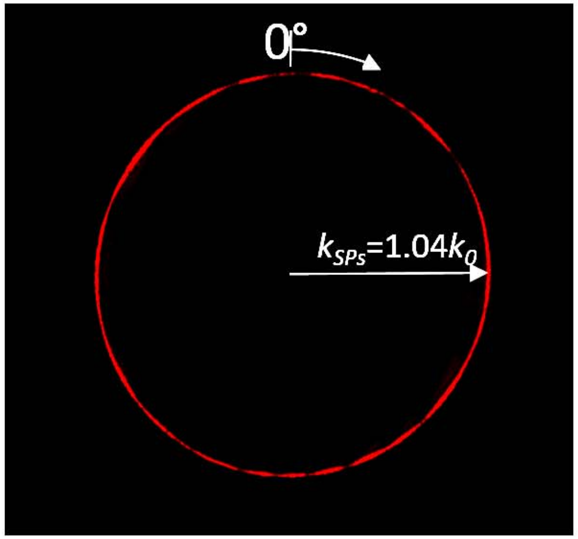
HC…RMM, Science Advances 3, e1601962 (2017)
HC…RMM, IEEE JQE, 54, 7200307 (2018)

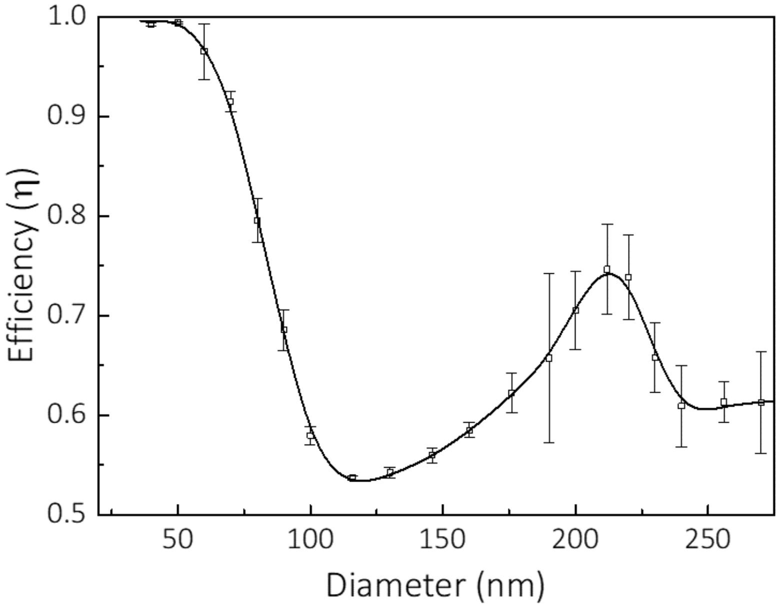
Imaging the dark emission of plasmonic nanolasers

Real space



Momentum space



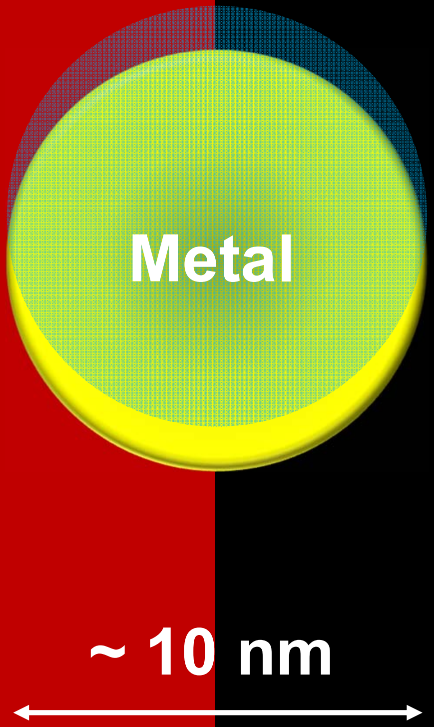


HC…RMM, Science Advances 3, e1601962 (2017)
HC…RMM, IEEE JQE, 54, 7200307 (2018)

Fascinating

for

Field Confinement



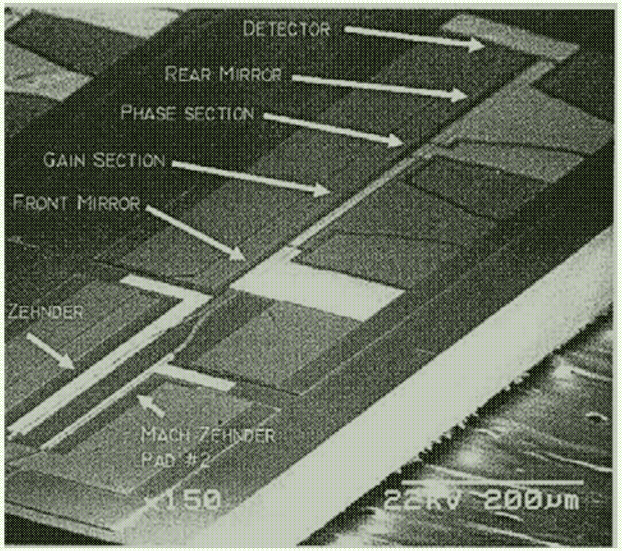
Notorious

for

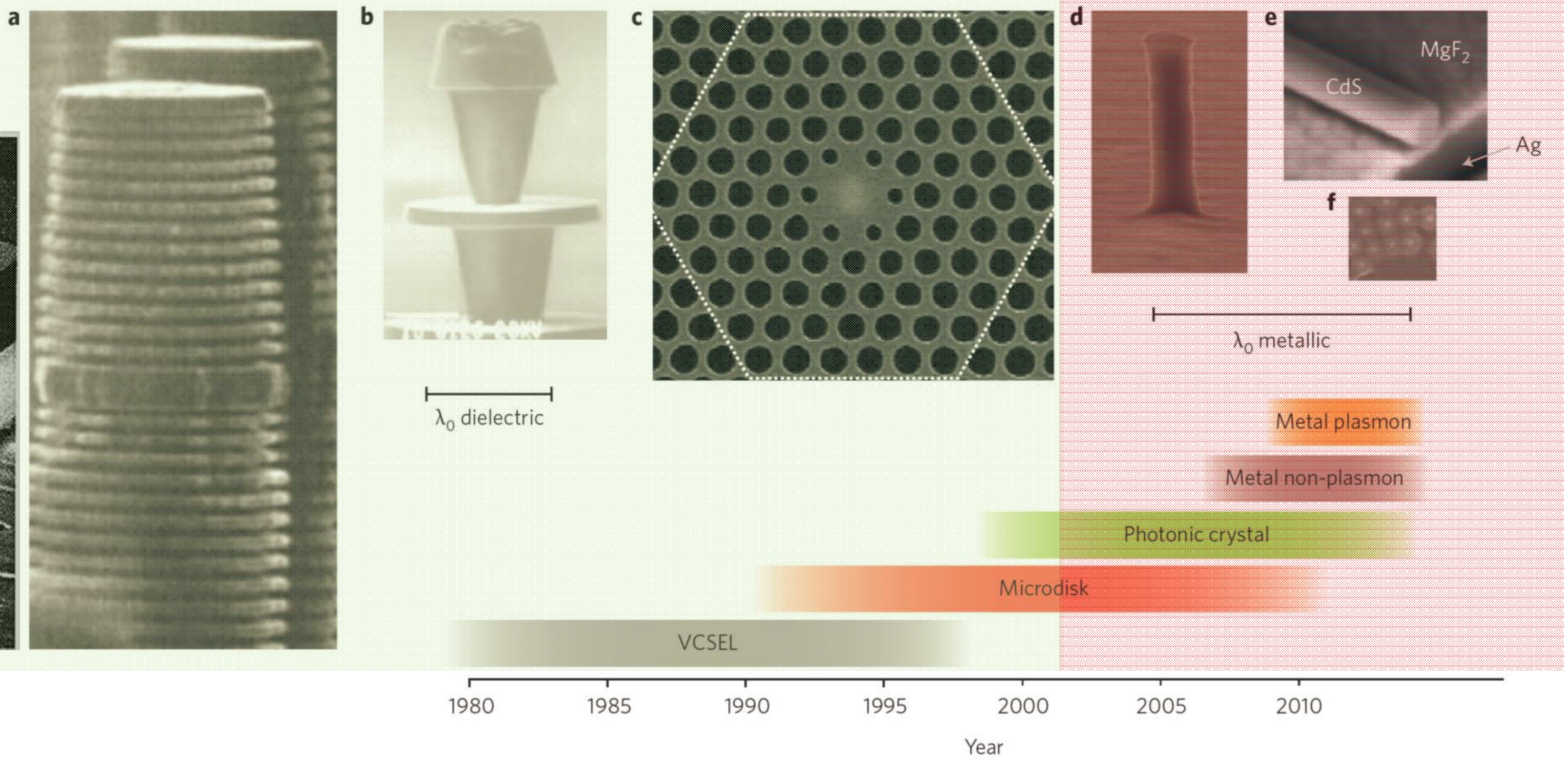
Metallic Absorption

Plasmonics for laser miniaturization, quenching thirst with poison?

Loss limit *e.g.* L=1μm, R=20%, $\alpha_M \sim 1.6 \times 10^4$ cm^{-1} **Diffraction limit**



Edge emitting lasers



Optical Fiber Telecommunications
I.P. Kaminnow et al., Elsevier, Sixth edition 2013

Nature Photonics 8 (2014) 908

Threshold of Plasmonic Nanolasers

Year	Title	Journal	Temperature	Threshold
2009	Demonstration of a spaser-based nanolaser	Nature	RT	~10 **GW** cm^{-2}
2011	Room-temperature sub-diffraction-limited plasmon laser by TIR	Nature Materials	RT	~3 **GW** cm^{-2}
2014	Ultrafast plasmonic nanowire lasers near the surface plasmon frequency	Nature Physics	RT	~1 **GW** cm^{-2}
2014	A room temperature low-threshold ultraviolet plasmonic nanolaser	Nature Communications	RT	~3 **MW** cm^{-2}
2015	Plasmonic Lasing of Nanocavity Embedding in Metallic Nanoantenna Array	Nano Letters	RT	~270 **MW** cm^{-2}
2016	High-Operation-Temperature Plasmonic Nanolasers on Single-Crystalline Al	Nano Letters	RT	~100 **MW** cm^{-2}
2009	Plasmon lasers at deep subwavelength scale	Nature	~10K	~100 **MW** cm^{-2}
2012	Thresholdless nanoscale coaxial lasers	Nature	~4.5 K	Thresholdless
2012	Plasmonic Nanolaser Using Epitaxially Grown Silver Film	Science	78 K	~3 **KW** cm^{-2}
2015	Low-Threshold near-Infrared GaAs−AlGaAs C−S NW Plasmon Laser	ACS Photonics	8 K	~1 **KW** cm^{-2}

Why threshold is high?

There is always a trade-off between field confinement and metallic loss

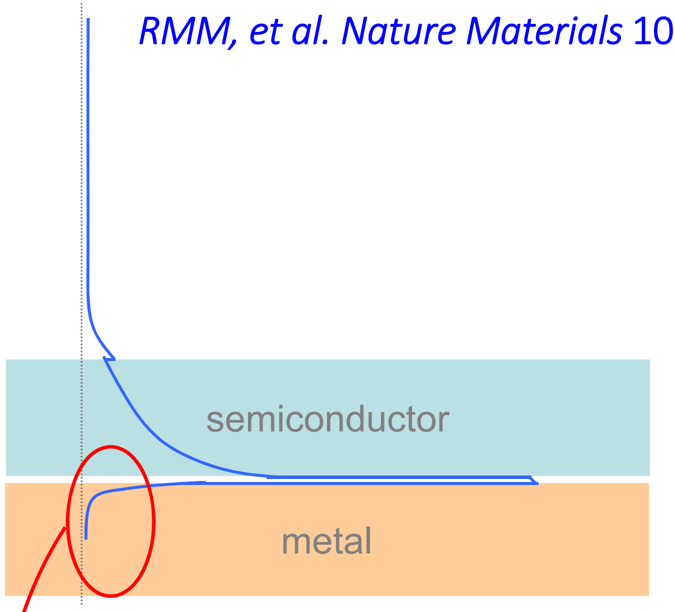
Why threshold is high?

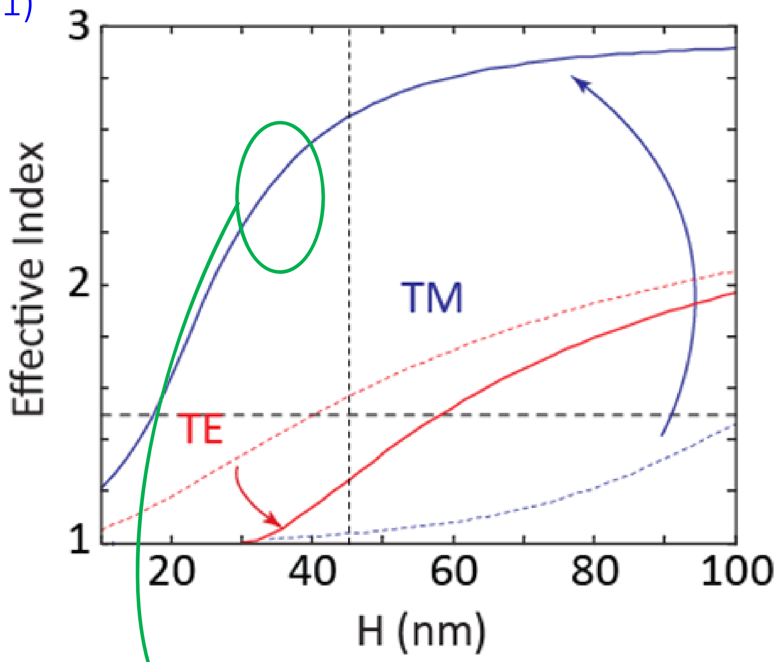
There is always a trade-off between field confinement and metallic loss

Is it intrinsically high?

Is it intrinsically high? ---Loss Perspective

RMM, et al. Nature Materials 10, 110 (2011)



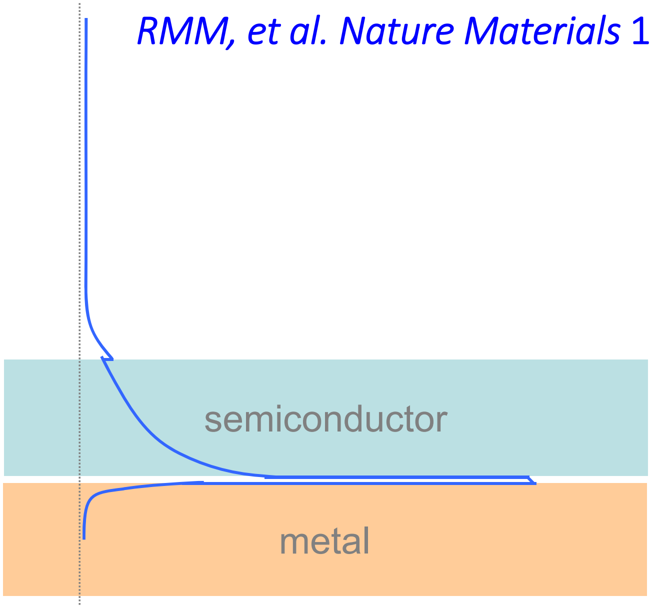


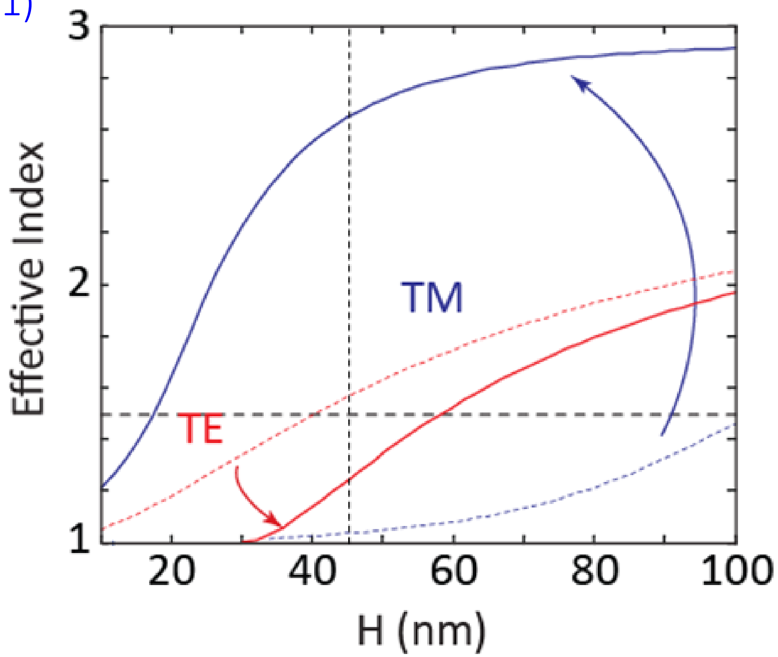
Field in metal
⇓
Optical confinement
⇓
Metal absorption loss

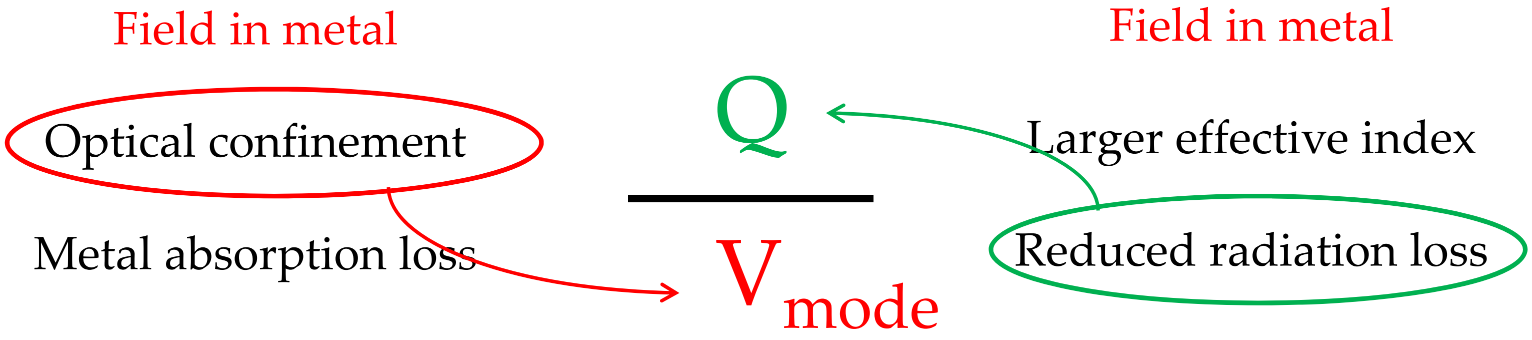
Field in metal
⇓
Larger effective index
⇓
Reduced radiation loss

Is it intrinsically high? ?---Dynamics Perspective

RMM, et al. Nature Materials 10, 110 (2011)







Field in metal

Optical confinement

Metal absorption loss

$$\frac{Q}{V_{mode}}$$

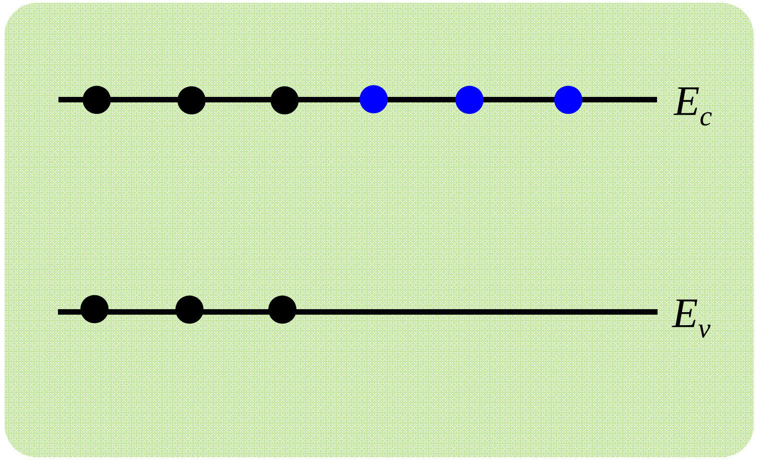
Field in metal

Larger effective index

Reduced radiation loss

Is it intrinsically high? ?---Dynamics Perspective

Purcell effect: spontaneous emission rate, $\gamma \sim Q / V_{\text{mode}}$



Accelerated γ:

Emitting faster to plasmonic mode

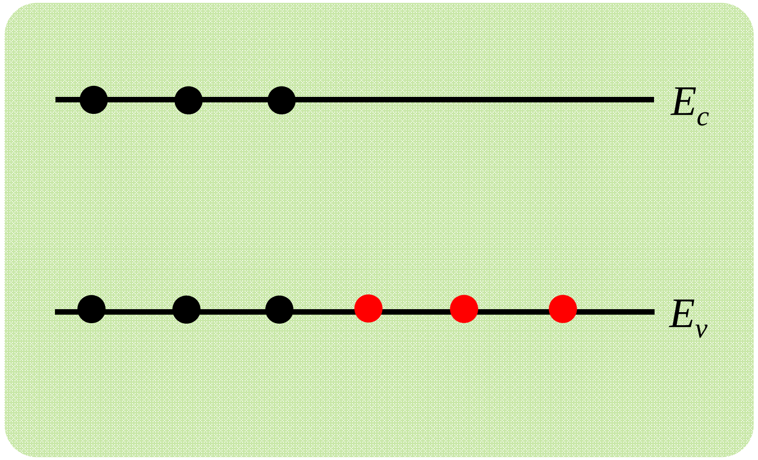
➔ lowering the threshold

Consuming carriers too faster for population inversion

➔ raising the threshold

Is it intrinsically high? ?---Dynamics Perspective

Purcell effect: spontaneous emission rate, $\gamma \sim Q / V_{mode}$



Accelerated γ:

Emitting faster to plasmonic mode

➔ lowering the threshold

Consuming carriers too faster for population inversion

➔ raising the threshold

Do we need plasmonics in a laser at all?

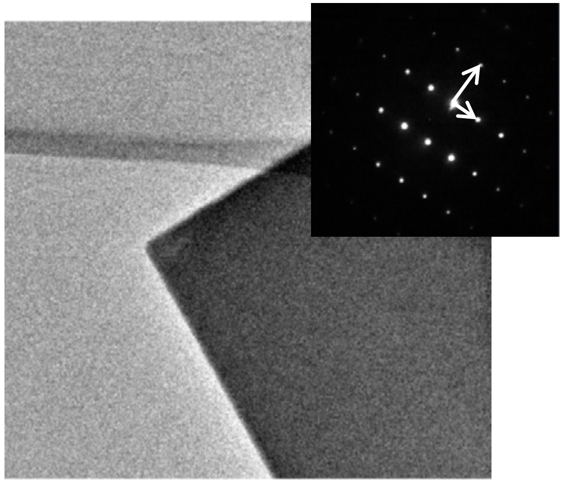
- Are plasmonic nanolasers intrinsically with high threshold due to the metallic loss?
- Are there defendable benefits of constructing plasmonic nanolasers when compared to photonic nanolasers?

Step 1. Making a low threshold plasmonic nanolaser

Better Gain Material:

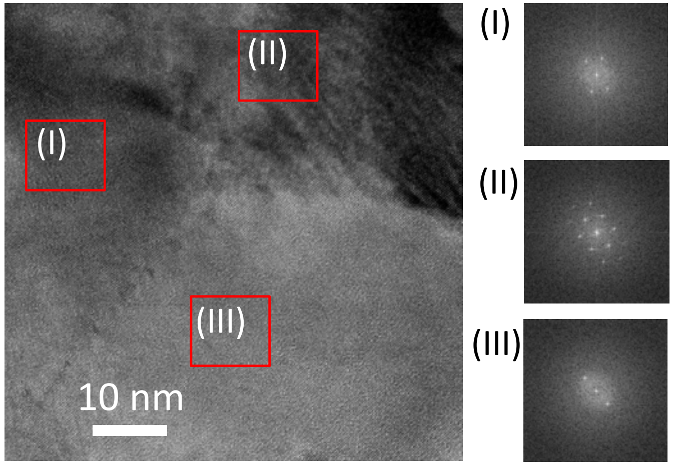
Better Metal:

Better Cavity:



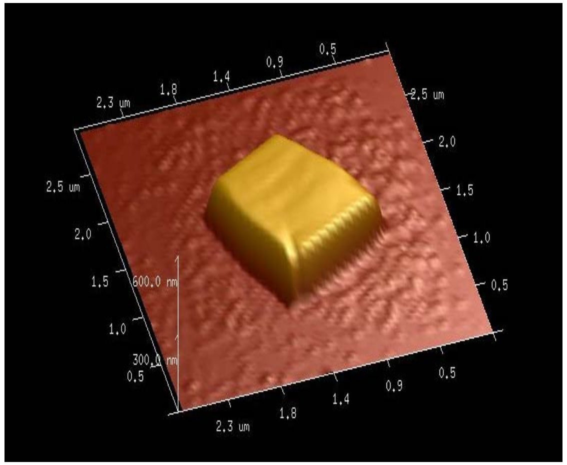
CdSe single crystal nanosquare

Internal Quantum efficiency: ~100%



Au polycrystalline film

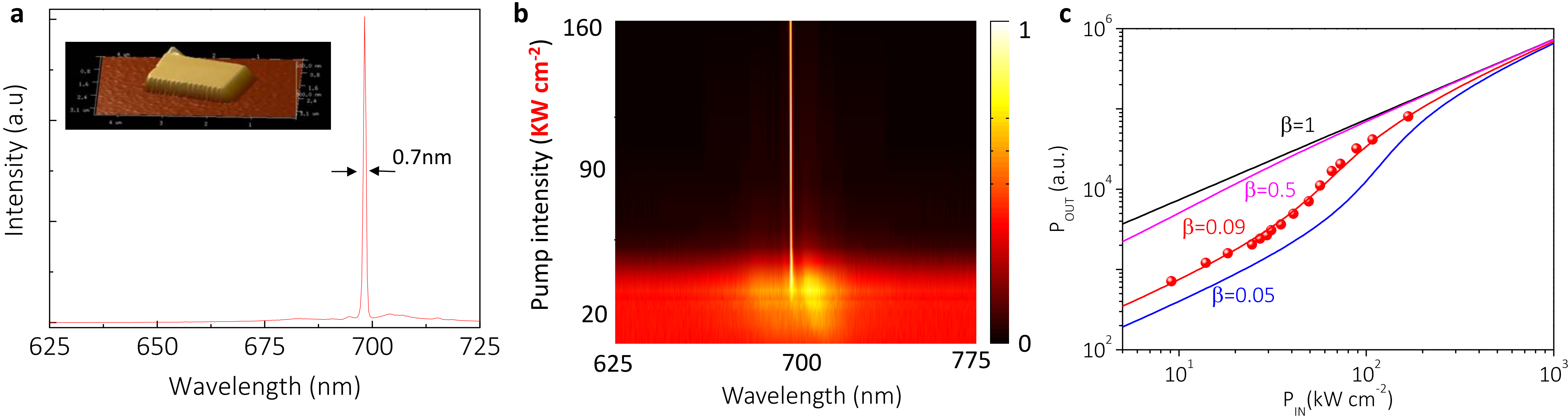
Figure of merit, $\frac{-Re[\varepsilon_m]}{Im[\varepsilon_m]}$: ~16



TIR plasmonic cavity

Quality Factor: ~100

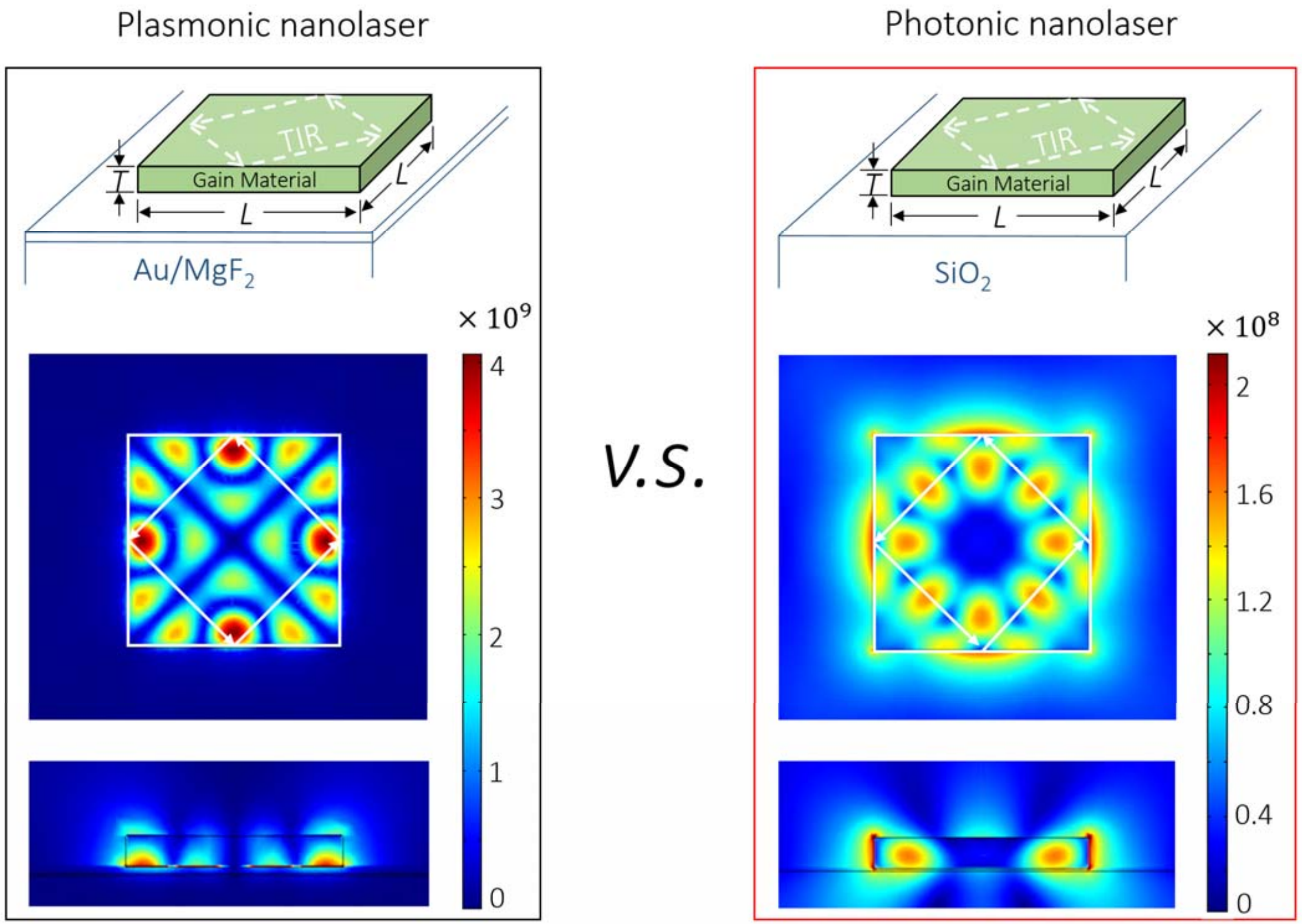
Step 1. Making a low threshold plasmonic nanolaser



Room temperature plasmonic nanolaser with threshold on the order of 10 KW cm^{-2}, corresponding to the pump density in the range of modern laser diodes

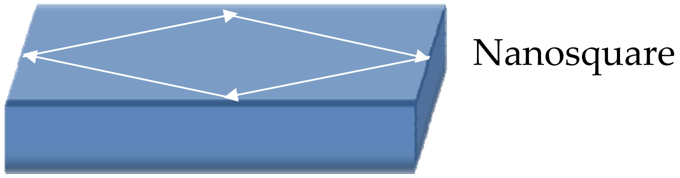
Step 2. Making a direct comparison with photonic nanolaser

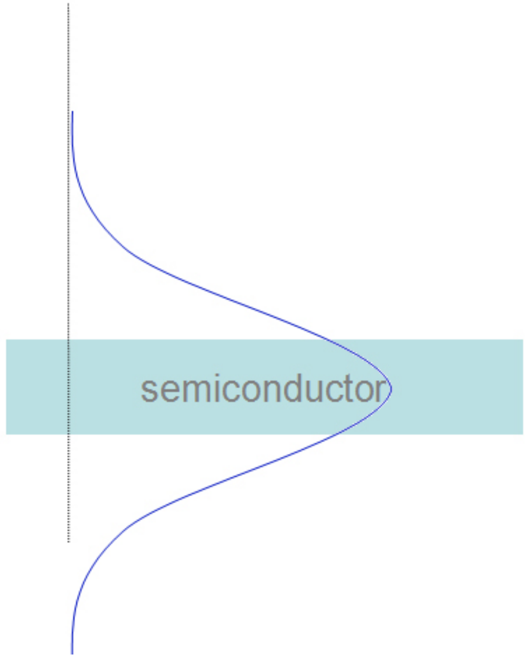
- **Over 200 devices measured**
- **Same gain material**
- **Same feedback mechanism**

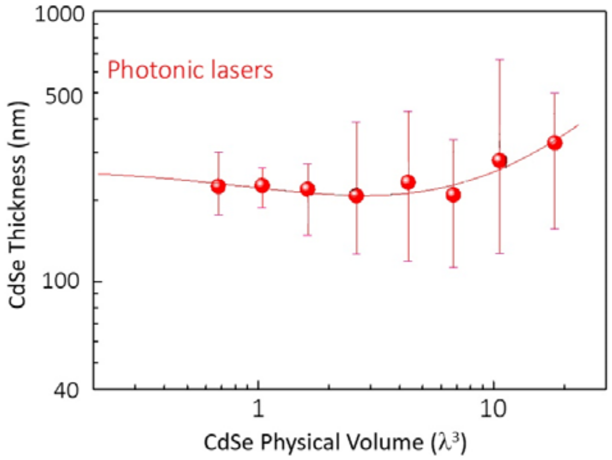


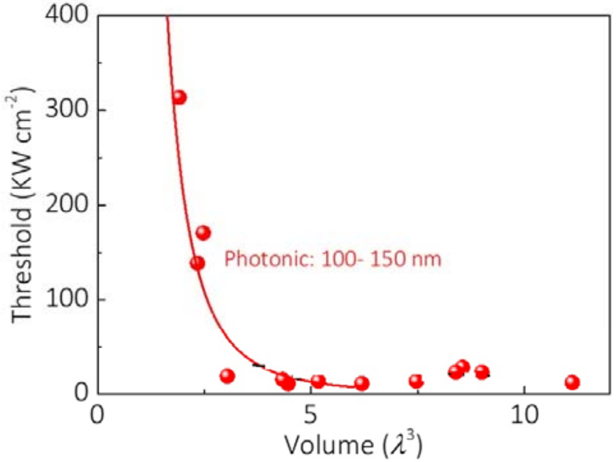
Scaling laws for photonic nanolasers

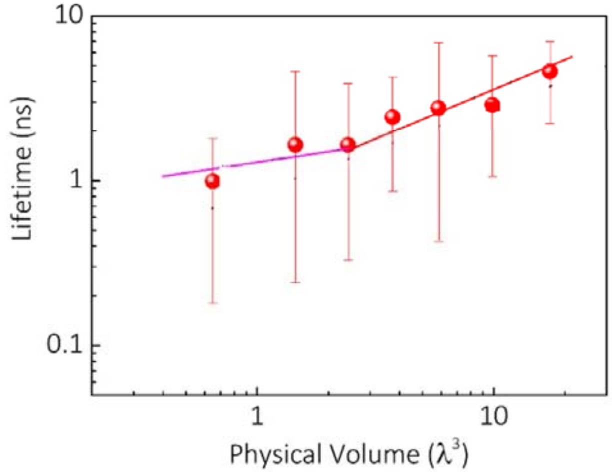
SW...RMM, Nature Communications 8, 1889 (2017) News & Views: Nature Materials 17, 116–117 (2018)

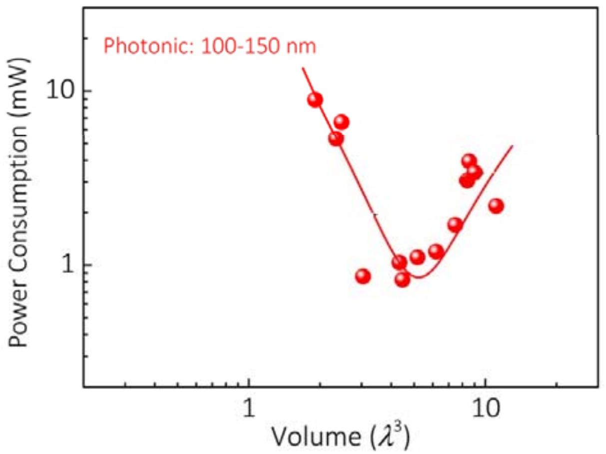








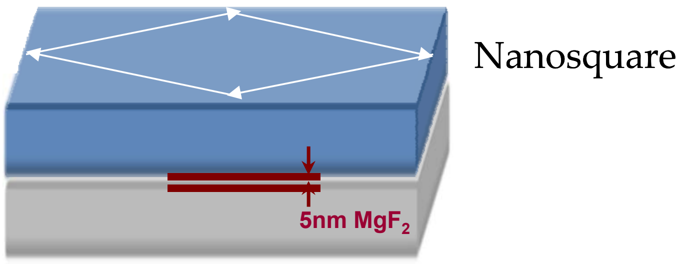


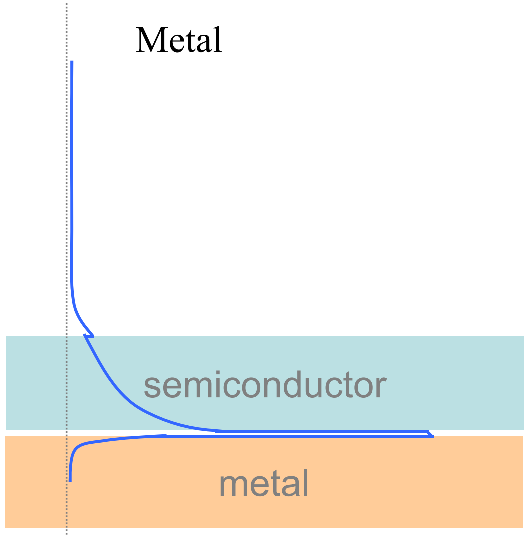


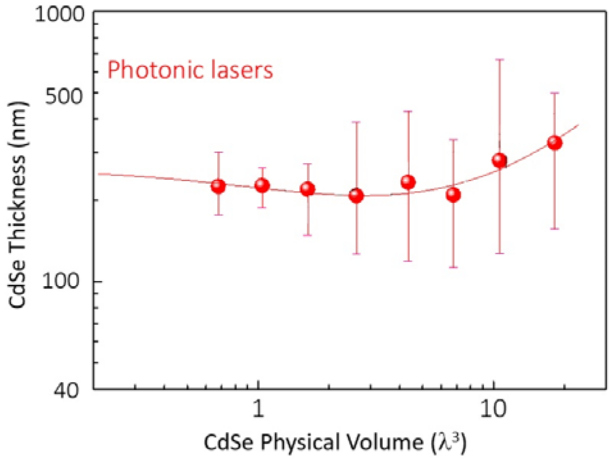
Scaling laws for photonic nanolasers

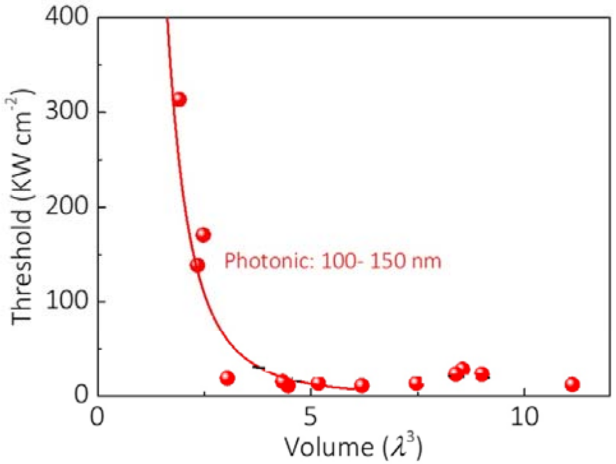
SW...RMM, Nature Communications 8, 1889 (2017)

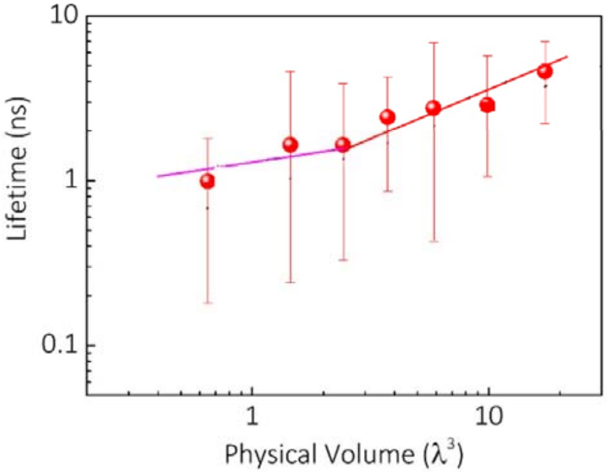
News & Views: Nature Materials 17, 116–117 (2018)

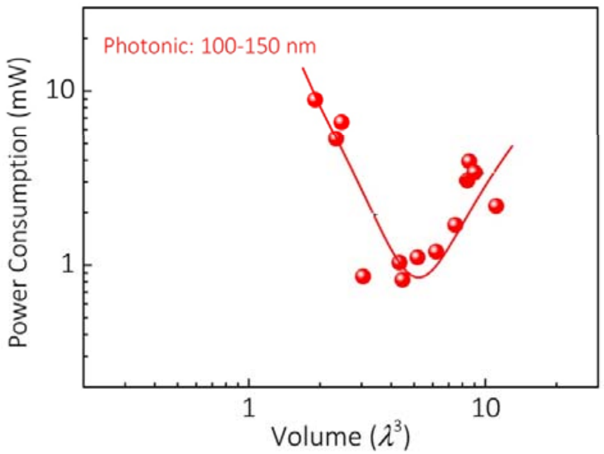






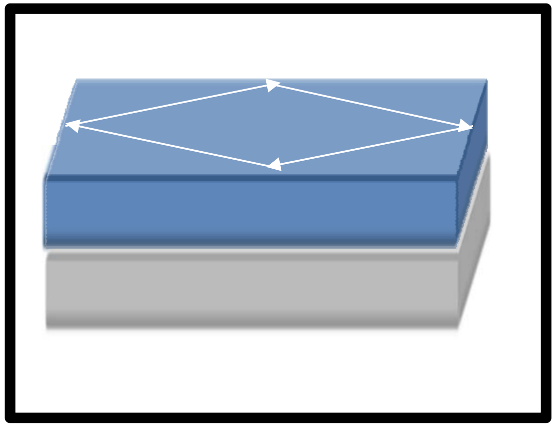




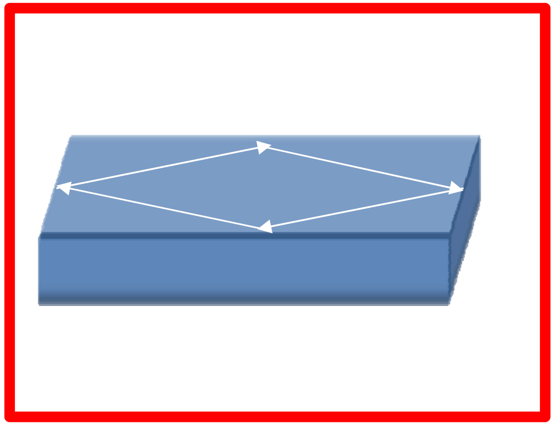


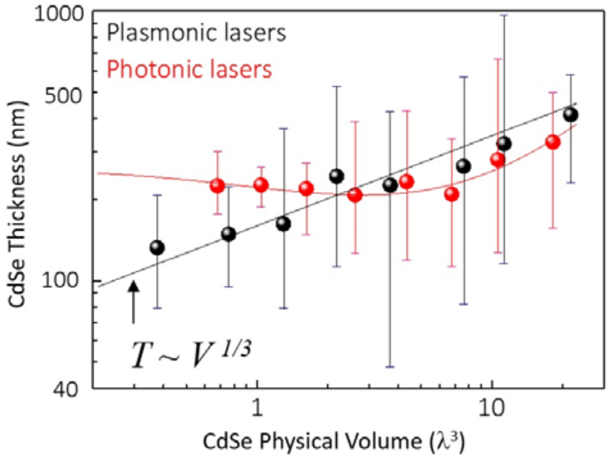
Unusual scaling laws for plasmonic nanolasers

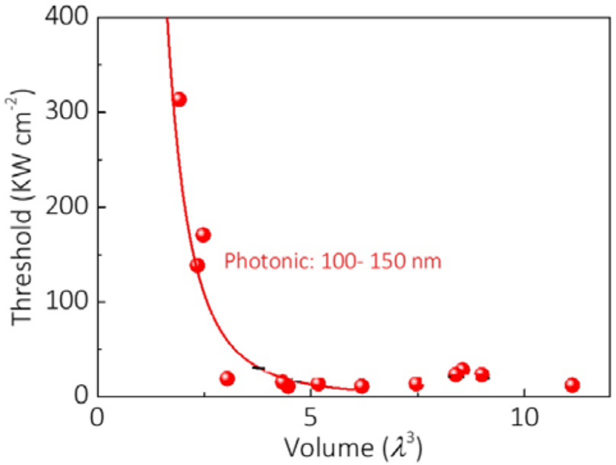
SW...RMM, Nature Communications 8, 1889 (2017)   News & Views: Nature Materials 17, 116–117 (2018)

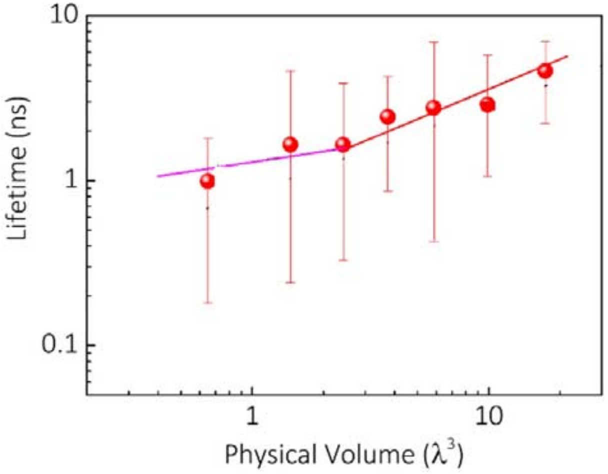


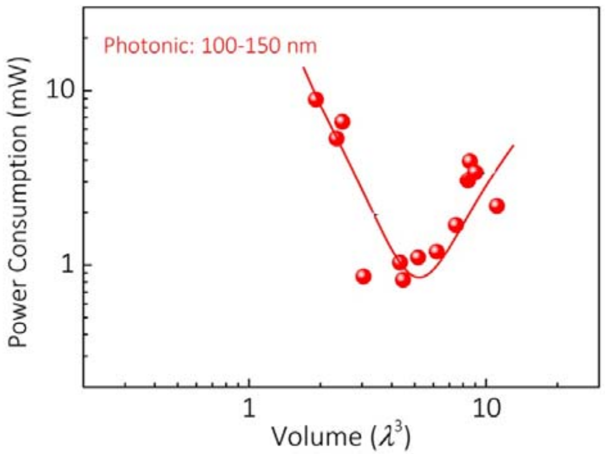
v. s.





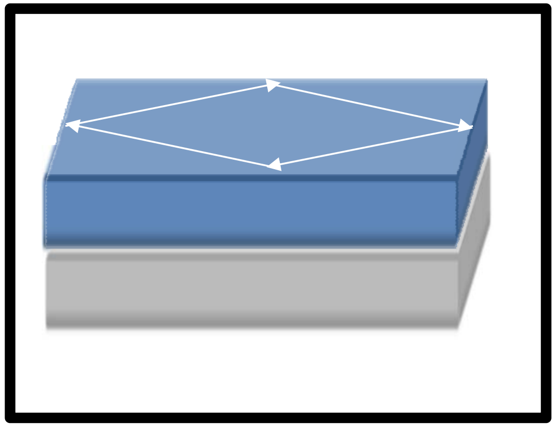




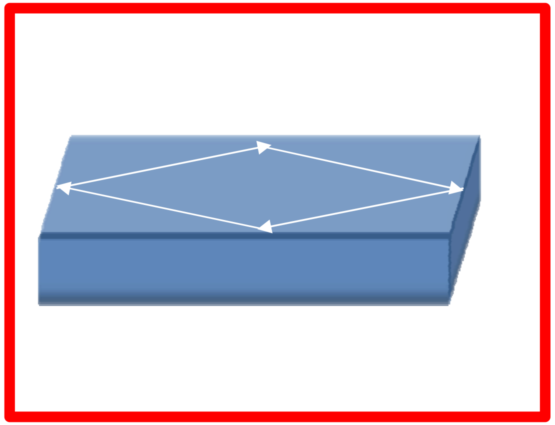


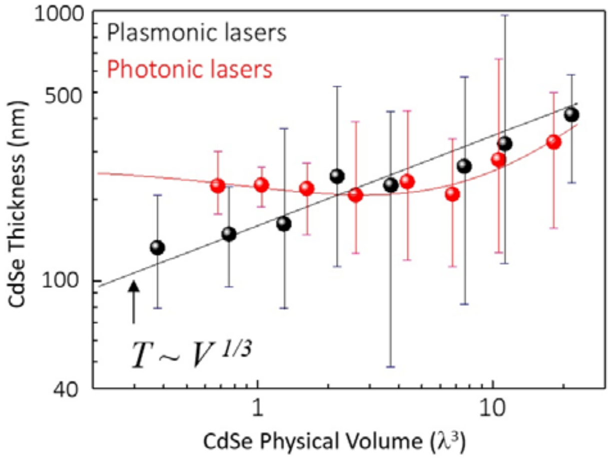
Unusual scaling laws for plasmonic nanolasers

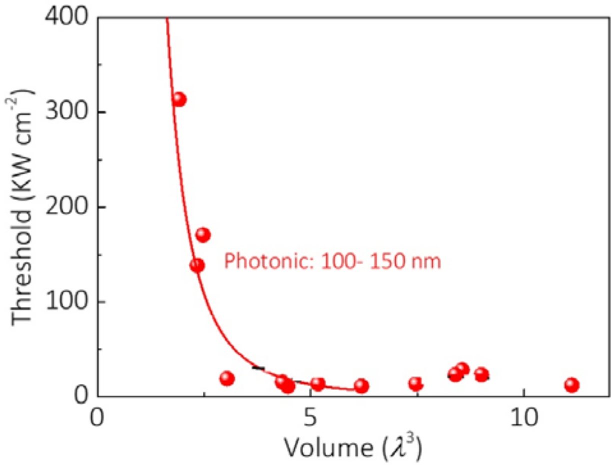
SW...RMM, Nature Communications 8, 1889 (2017)   News & Views: Nature Materials 17, 116–117 (2018)

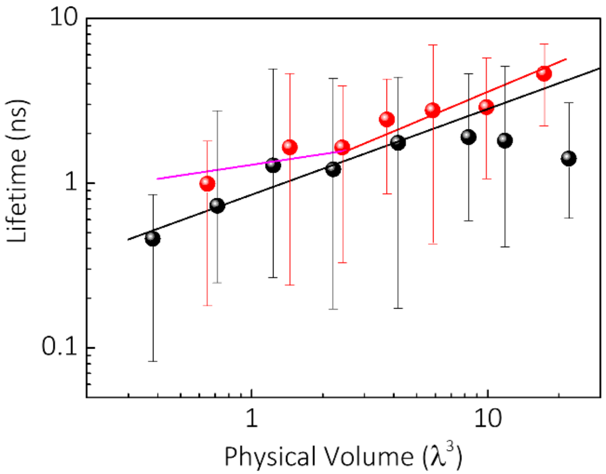


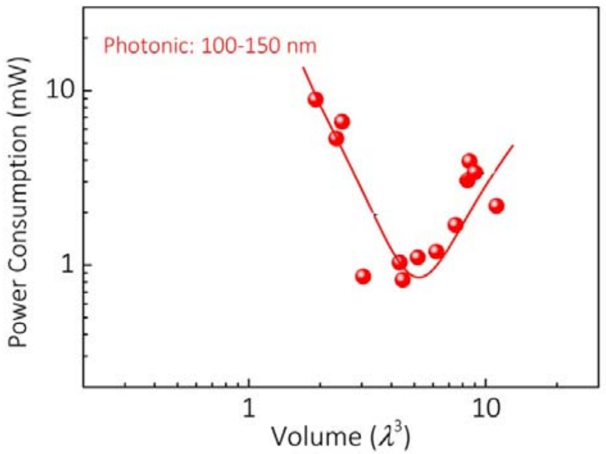
v. s.





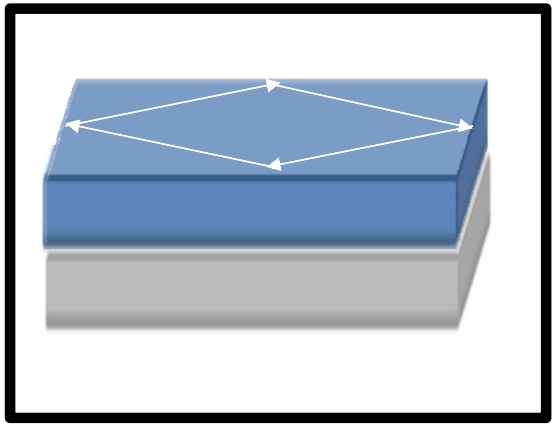




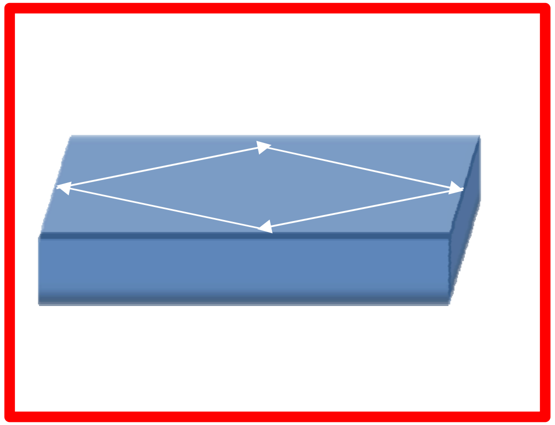


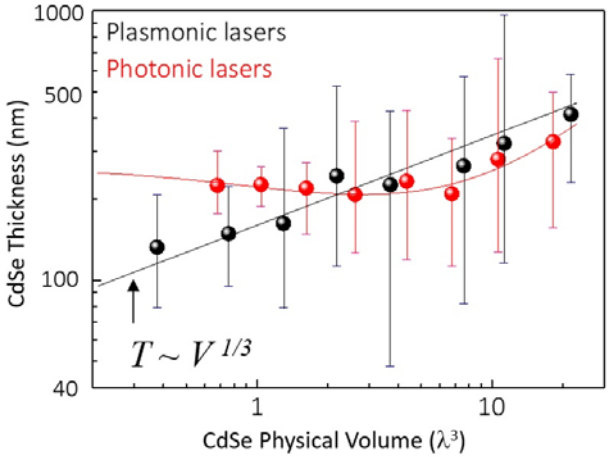
Unusual scaling laws for plasmonic nanolasers

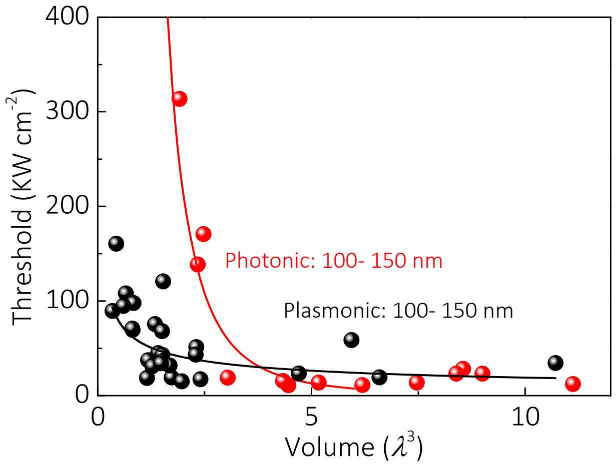
SW...RMM, Nature Communications 8, 1889 (2017) News & Views: Nature Materials 17, 116–117 (2018)

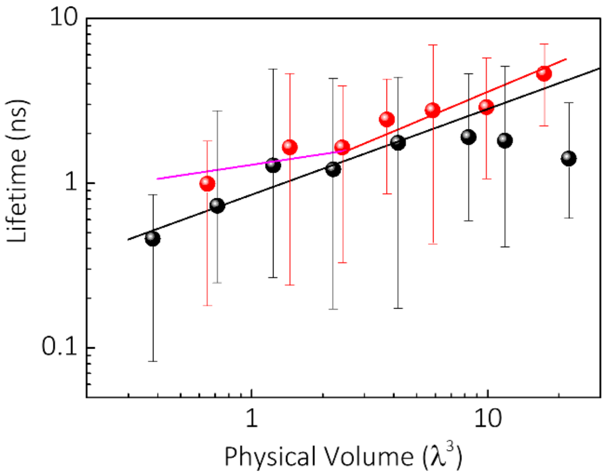


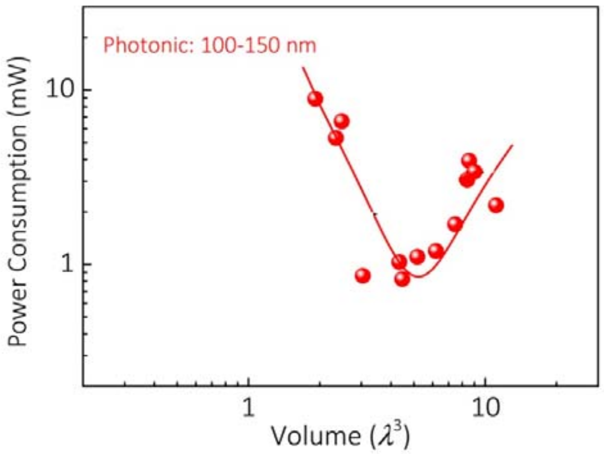
v. s.





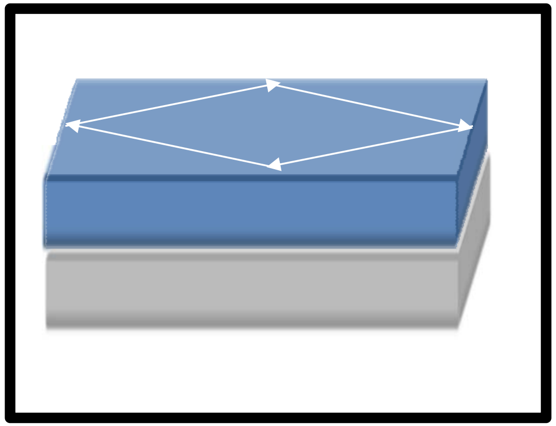




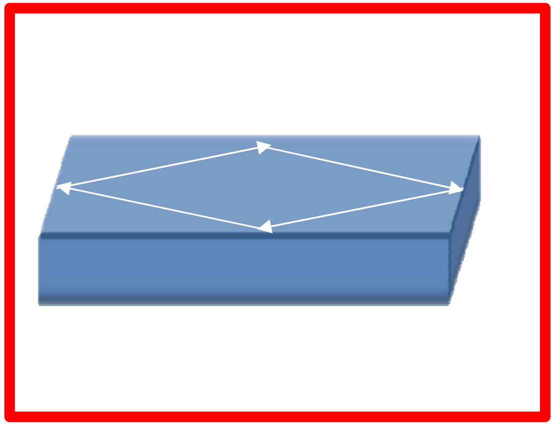


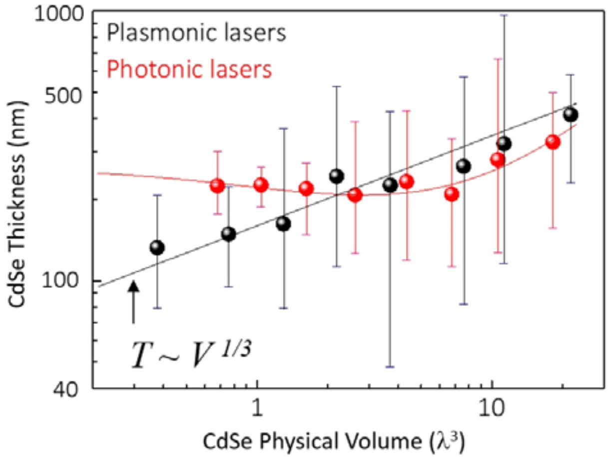
Unusual scaling laws for plasmonic nanolasers

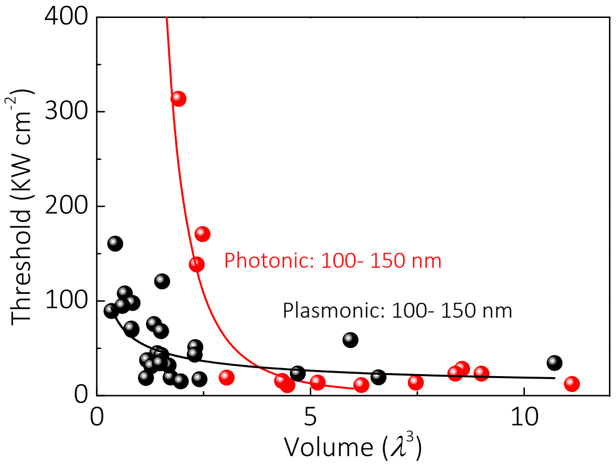
SW...RMM, Nature Communications 8, 1889 (2017)   News & Views: Nature Materials 17, 116–117 (2018)

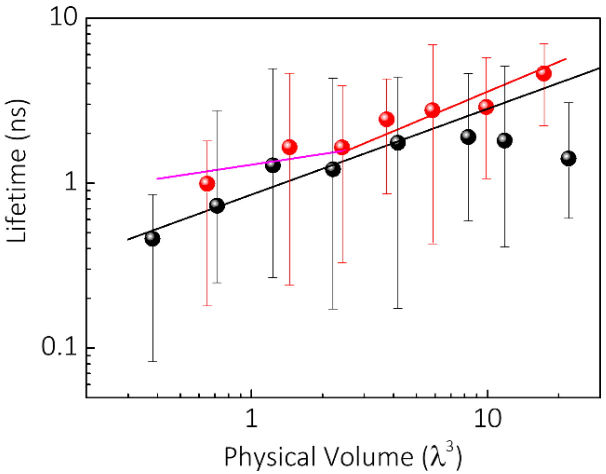


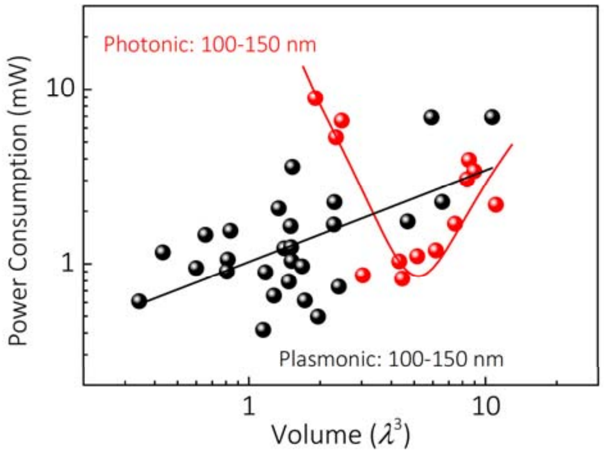
v. s.











LASER threshold minimization

$$\frac{dN}{dt} = P - AN - \Gamma A\,\beta(N - N_0)S \qquad (1)$$

$$\frac{\partial S}{\partial t} = \beta AN + \Gamma A\,\beta(N - N_0)S - \gamma S \qquad (2)$$

$$P_{\text{th}} = \frac{h\nu}{\eta A}\frac{(1+\beta)}{2}\left[\underbrace{\frac{\gamma}{\beta\Gamma}}_{\text{Cavity mode loss}} + \underbrace{F\,\frac{2n_0V}{\tau_0}}_{\text{Gain material loss}}\right]$$

Define $\zeta = \dfrac{\text{Cavity mode loss}}{\text{Gain material loss}} = \gamma\,\tau_0/\beta\,F\Gamma n_{\text{inv}}V$

$R_{\text{th}} = \eta P_{\text{th}}A/h\nu$: threshold rate of photon generation in the cavity

Normalized threshold pump rate: $\boldsymbol{\Gamma R_{\text{th}}/\gamma = (1+\beta^{-1})(1+\zeta^{-1})/2}$

LASER threshold can be minimized in two ways:

(I) $\boldsymbol{\beta \mapsto 1}$,

which demands a strong Purcell effect and small cavity.

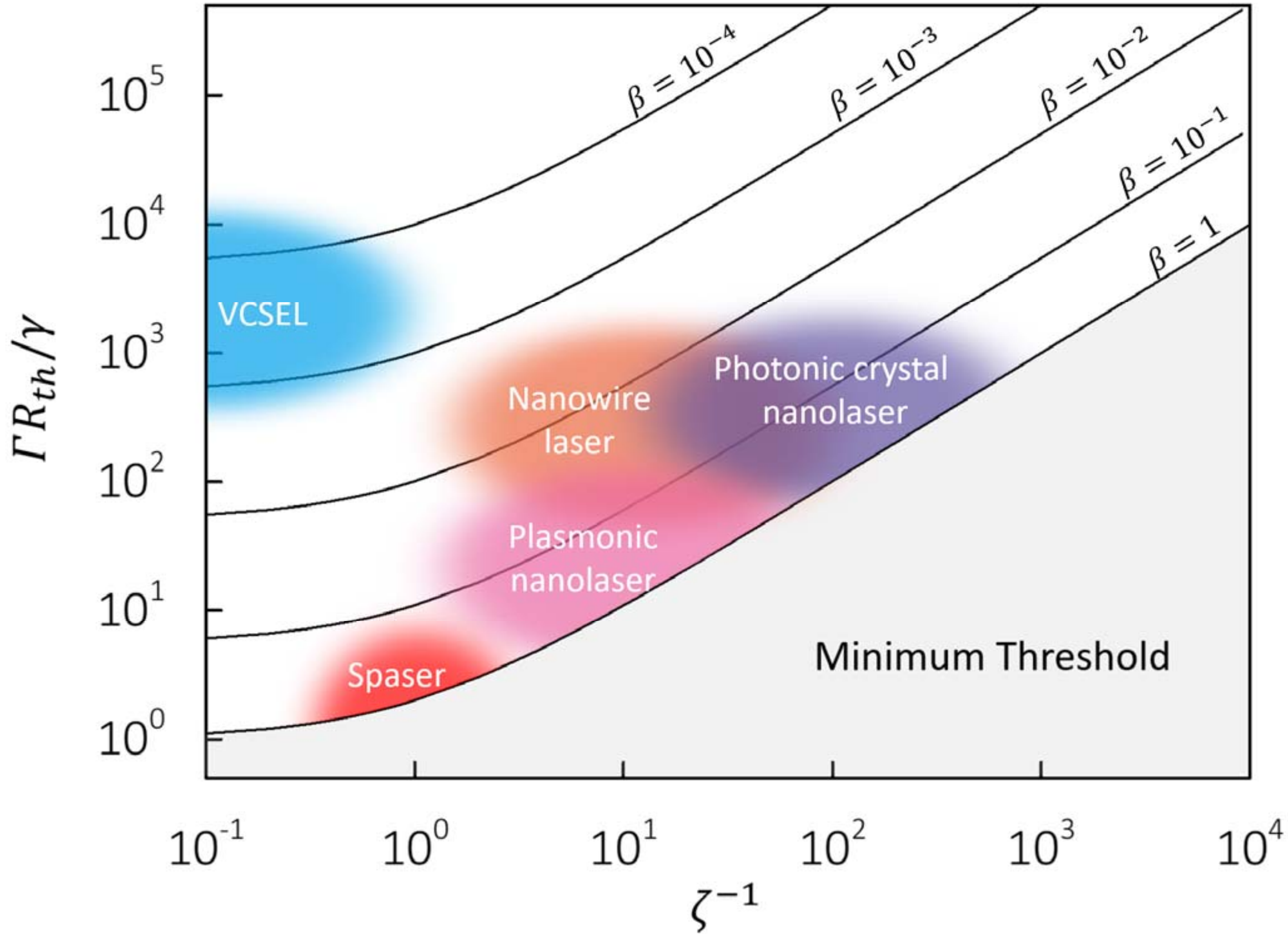
(II) $\boldsymbol{\zeta \mapsto \infty}$

which requires reduction of total loss and gain material loss at transparency

SW...RMM, Nature Communications 8, 1889, 2017

RMM & RFO, Nature Nanotechnology, *14*, 12–22, 2019

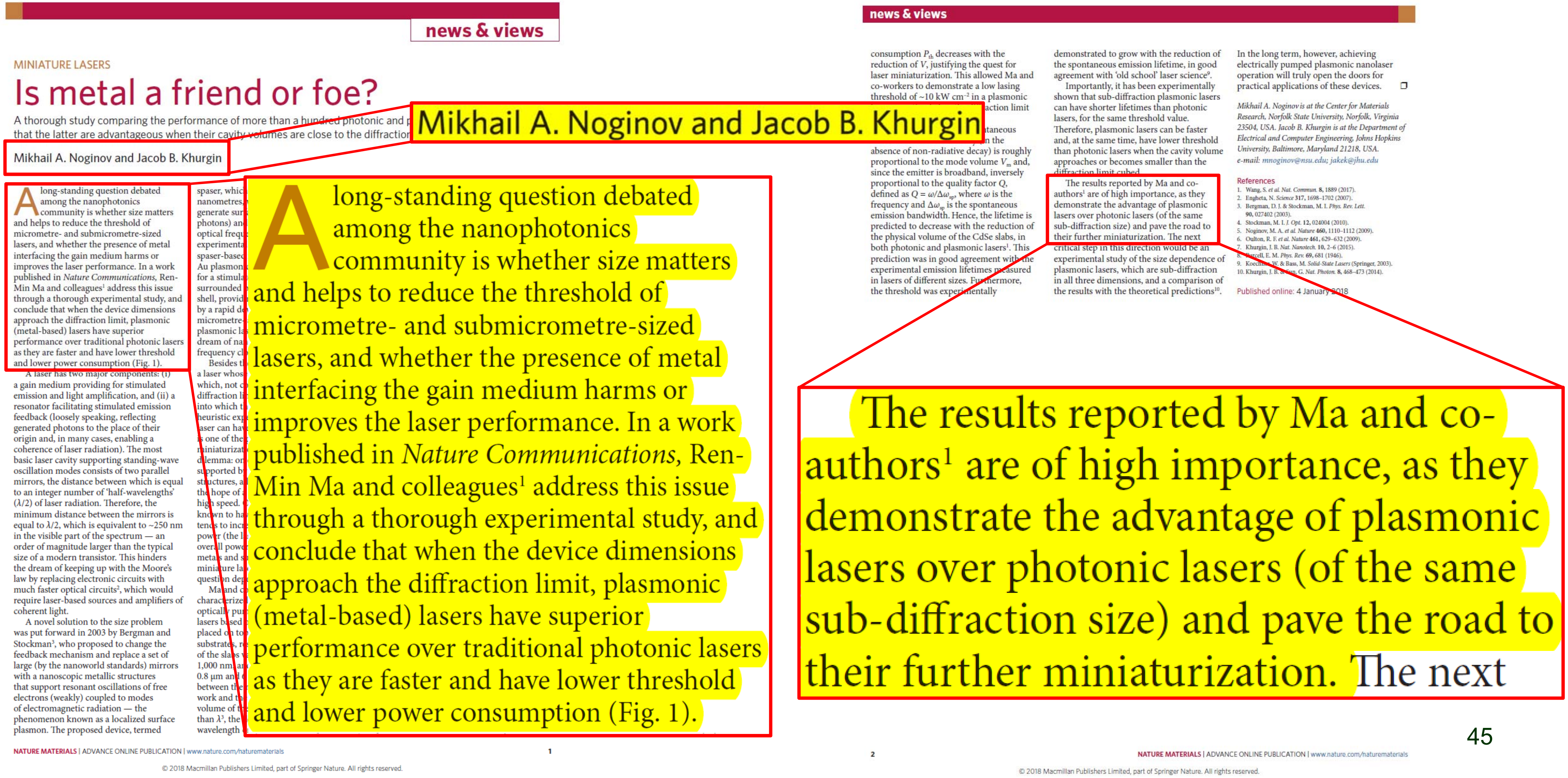
LASER threshold minimization



RMM & RFO, Nature Nanotechnology, *14, 12–22, 2019*

nature materials

Nature Materials, Doi:10.1038/nmat5065



MINIATURE LASERS

Is metal a friend or foe?

A thorough study comparing the performance of more than a hundred photonic and p… that the latter are advantageous when their cavity volumes are close to the diffraction…

Mikhail A. Noginov and Jacob B. Khurgin

Mikhail A. Noginov and Jacob B. Khurgin

A long-standing question debated among the nanophotonics community is whether size matters and helps to reduce the threshold of micrometre- and submicrometre-sized lasers, and whether the presence of metal interfacing the gain medium harms or improves the laser performance. In a work published in *Nature Communications*, Ren-Min Ma and colleagues[1] address this issue through a thorough experimental study, and conclude that when the device dimensions approach the diffraction limit, plasmonic (metal-based) lasers have superior performance over traditional photonic lasers as they are faster and have lower threshold and lower power consumption (Fig. 1).

A long-standing question debated among the nanophotonics community is whether size matters and helps to reduce the threshold of micrometre- and submicrometre-sized lasers, and whether the presence of metal interfacing the gain medium harms or improves the laser performance. In a work published in *Nature Communications*, Ren-Min Ma and colleagues[1] address this issue through a thorough experimental study, and conclude that when the device dimensions approach the diffraction limit, plasmonic (metal-based) lasers have superior performance over traditional photonic lasers as they are faster and have lower threshold and lower power consumption (Fig. 1).

A laser has two major components: (i) a gain medium providing for stimulated emission and light amplification, and (ii) a resonator facilitating stimulated emission feedback (loosely speaking, reflecting generated photons to the place of their origin and, in many cases, enabling a coherence of laser radiation). The most basic laser cavity supporting standing-wave oscillation modes consists of two parallel mirrors, the distance between which is equal to an integer number of 'half-wavelengths' ($\lambda/2$) of laser radiation. Therefore, the minimum distance between the mirrors is equal to $\lambda/2$, which is equivalent to ~250 nm in the visible part of the spectrum — an order of magnitude larger than the typical size of a modern transistor. This hinders the dream of keeping up with the Moore's law by replacing electronic circuits with much faster optical circuits[2], which would require laser-based sources and amplifiers of coherent light.

A novel solution to the size problem was put forward in 2003 by Bergman and Stockman[3], who proposed to change the feedback mechanism and replace a set of large (by the nanoworld standards) mirrors with a nanoscopic metallic structures that support resonant oscillations of free electrons (weakly) coupled to modes of electromagnetic radiation — the phenomenon known as a localized surface plasmon. The proposed device, termed

consumption P_{th} decreases with the reduction of V, justifying the quest for laser miniaturization. This allowed Ma and co-workers to demonstrate a low lasing threshold of ~10 kW cm^{-2} in a plasmonic …action limit …taneous …n the absence of non-radiative decay) is roughly proportional to the mode volume V_m and, since the emitter is broadband, inversely proportional to the quality factor Q, defined as $Q = \omega/\Delta\omega_{sp}$, where ω is the frequency and $\Delta\omega_{sp}$ is the spontaneous emission bandwidth. Hence, the lifetime is predicted to decrease with the reduction of the physical volume of the CdSe slabs, in both photonic and plasmonic lasers[1]. This prediction was in good agreement with the experimental emission lifetimes measured in lasers of different sizes. Furthermore, the threshold was experimentally demonstrated to grow with the reduction of the spontaneous emission lifetime, in good agreement with 'old school' laser science[9].

Importantly, it has been experimentally shown that sub-diffraction plasmonic lasers can have shorter lifetimes than photonic lasers, for the same threshold value. Therefore, plasmonic lasers can be faster and, at the same time, have lower threshold than photonic lasers when the cavity volume approaches or becomes smaller than the diffraction limit cubed.

The results reported by Ma and co-authors[1] are of high importance, as they demonstrate the advantage of plasmonic lasers over photonic lasers (of the same sub-diffraction size) and pave the road to their further miniaturization. The next critical step in this direction would be an experimental study of the size dependence of plasmonic lasers, which are sub-diffraction in all three dimensions, and a comparison of the results with the theoretical predictions[10]. In the long term, however, achieving electrically pumped plasmonic nanolaser operation will truly open the doors for practical applications of these devices. ❐

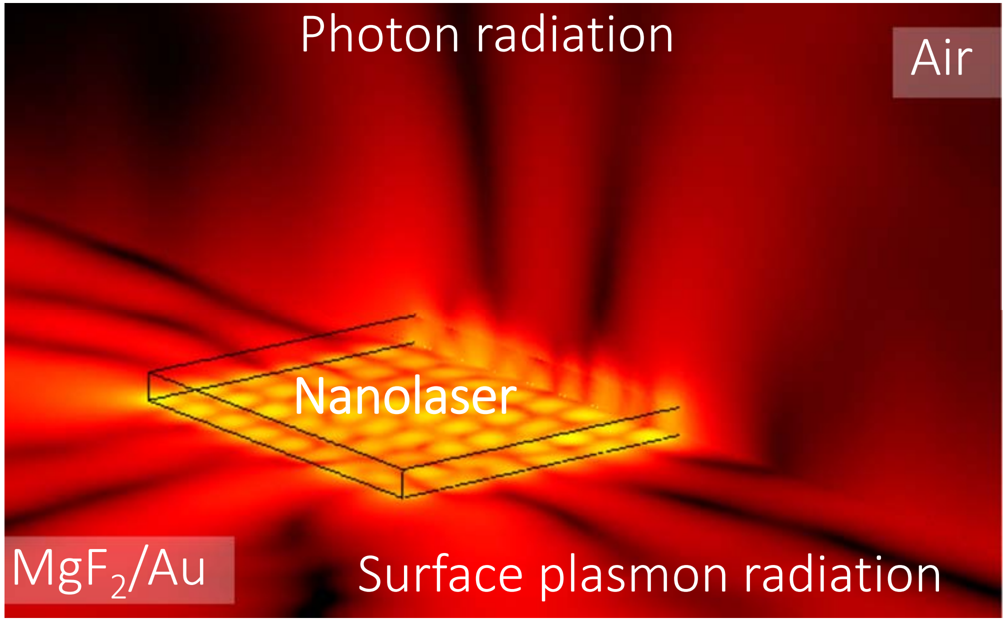
Mikhail A. Noginov is at the Center for Materials Research, Norfolk State University, Norfolk, Virginia 23504, USA. Jacob B. Khurgin is at the Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, Maryland 21218, USA.
e-mail: mnoginov@nsu.edu; jakek@jhu.edu

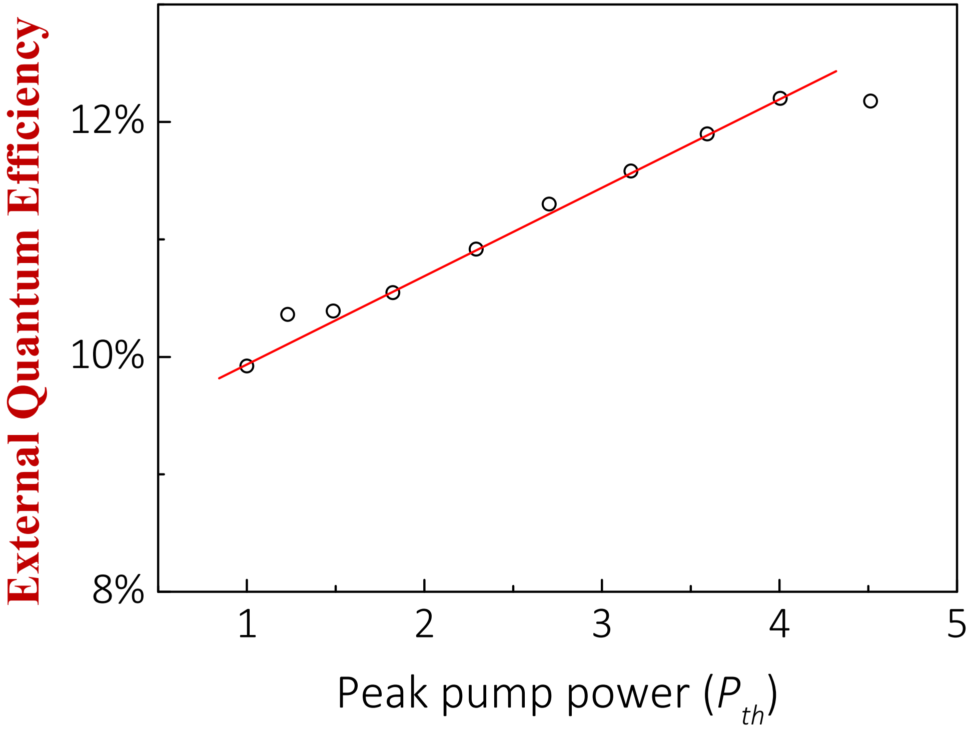
References
1. Wang, S. *et al. Nat. Commun.* **8**, 1889 (2017).
2. Engheta, N. *Science* **317**, 1698–1702 (2007).
3. Bergman, D. J. & Stockman, M. I. *Phys. Rev. Lett.* **90**, 027402 (2003).
4. Stockman, M. I. *J. Opt.* **12**, 024004 (2010).
5. Noginov, M. A. *et al. Nature* **460**, 1110–1112 (2009).
6. Oulton, R. F. *et al. Nature* **461**, 629–632 (2009).
7. Khurgin, J. B. *Nat. Nanotech.* **10**, 2–6 (2015).
8. Purcell, E. M. *Phys. Rev.* **69**, 681 (1946).
9. Koechner, W. & Bass, M. *Solid-State Lasers* (Springer, 2003).
10. Khurgin, J. B. & Sun, G. *Nat. Photon.* **8**, 468–473 (2014).

The results reported by Ma and co-authors[1] are of high importance, as they demonstrate the advantage of plasmonic lasers over photonic lasers (of the same sub-diffraction size) and pave the road to their further miniaturization. The next

Plasmonic nanolasers with external quantum efficiency exceeding 10%

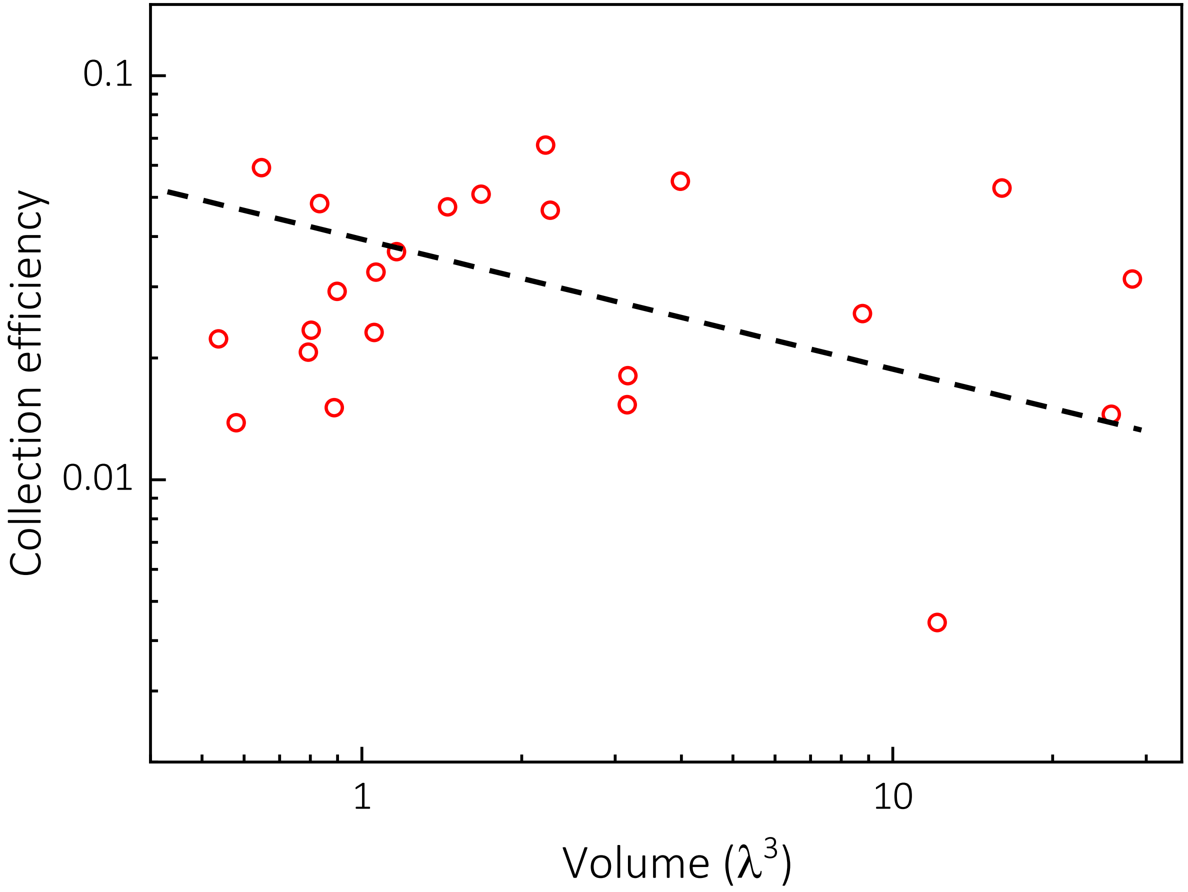
SW, HZ, RMM, Nano Letters, *18*, 7942, 2018





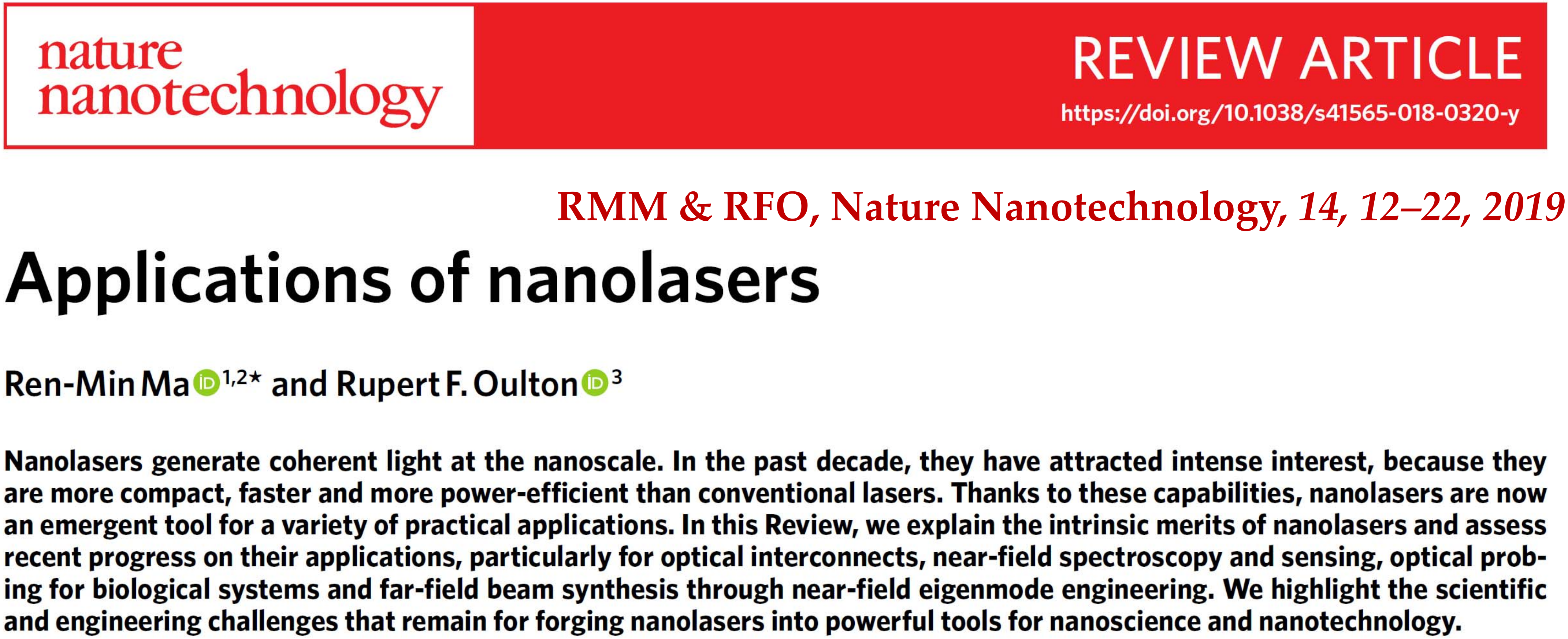
Plasmonic nanolasers with external quantum efficiency exceeding 10%

SW, HZ, RMM, Nano Letters, *18,* 7942, 2018



Extraction Efficiency:

$$\frac{Q_{\mathrm{metal}}}{Q_{\mathrm{metal}} + Q_{\mathrm{rad}}}$$



nature nanotechnology

REVIEW ARTICLE

https://doi.org/10.1038/s41565-018-0320-y

RMM & RFO, Nature Nanotechnology, *14, 12–22, 2019*

Applications of nanolasers

Ren-Min Ma[1,2]* and Rupert F. Oulton[3]

Nanolasers generate coherent light at the nanoscale. In the past decade, they have attracted intense interest, because they are more compact, faster and more power-efficient than conventional lasers. Thanks to these capabilities, nanolasers are now an emergent tool for a variety of practical applications. In this Review, we explain the intrinsic merits of nanolasers and assess recent progress on their applications, particularly for optical interconnects, near-field spectroscopy and sensing, optical probing for biological systems and far-field beam synthesis through near-field eigenmode engineering. We highlight the scientific and engineering challenges that remain for forging nanolasers into powerful tools for nanoscience and nanotechnology.

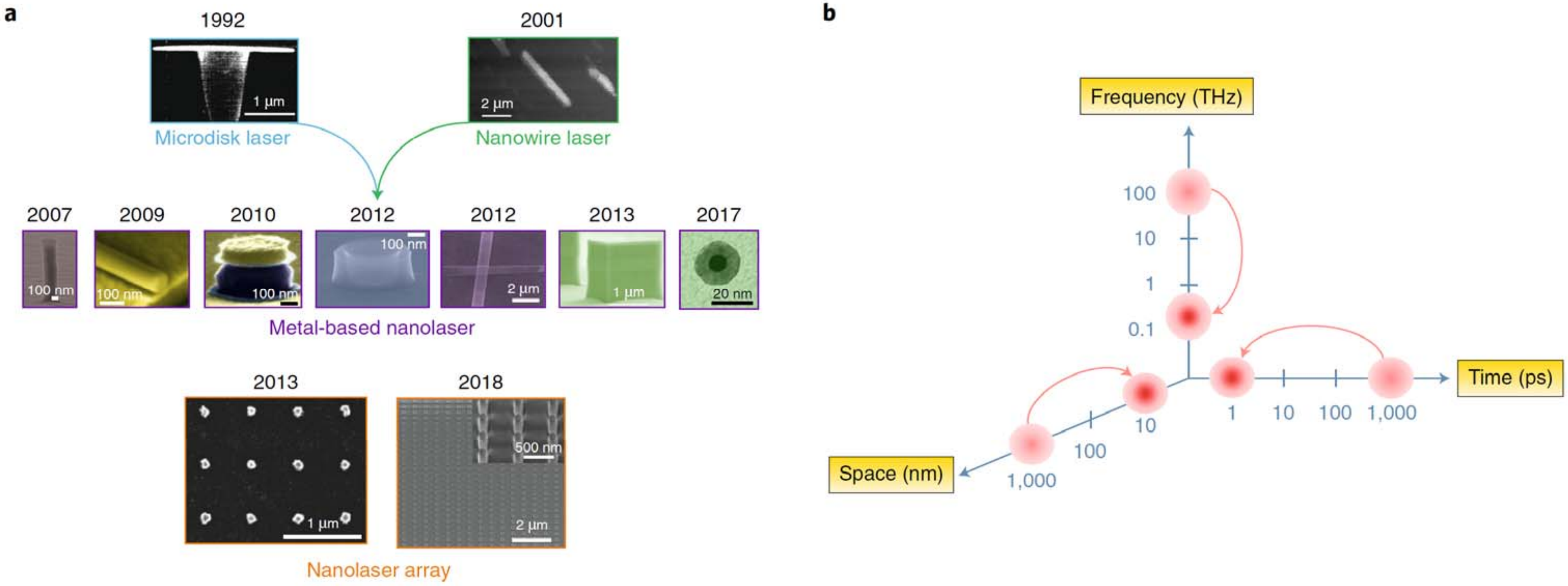
nature nanotechnology

REVIEW ARTICLE

https://doi.org/10.1038/s41565-018-0320-y

Ren-Min Ma & Rupert Oulton, Nature Nanotechnology, *14, 12–22, 2019*

Applications of nanolasers



nature
nanotechnology

REVIEW ARTICLE
https://doi.org/10.1038/s41565-018-0320-y

Ren-Min Ma & Rupert Oulton, Nature Nanotechnology, *14, 12–22, 2019*

Applications of nanolasers

Low power consumption

$\frac{1}{2} CV^2$

↓

Optical interconnects

Strong local field

$$\frac{Q}{V_m}$$

↓

Near-field spectroscopy & sensing

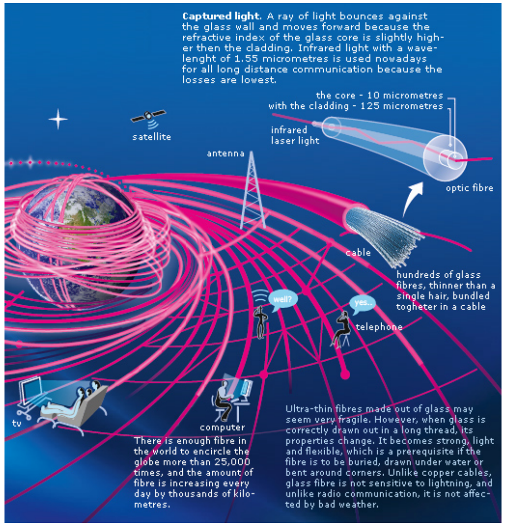
Limited cavity modes

$DOS \bullet V_{phy} \bullet \nu_{BW}$

↓

Eigenmode engineering

Optical interconnects at shorter and shorter distance



Captured light. A ray of light bounces against the glass wall and moves forward because the refractive index of the glass core is slightly higher then the cladding. Infrared light with a wavelenght of 1.55 micrometres is used nowadays for all long distance communication because the losses are lowest.

the core - 10 micrometres
with the cladding - 125 micrometres

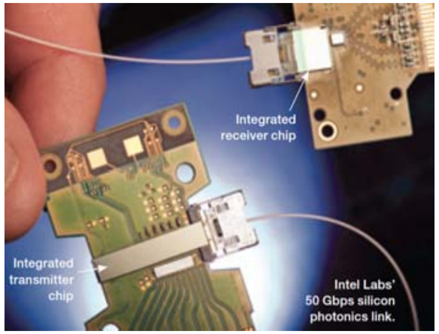
hundreds of glass fibres, thinner than a single hair, bundled togheter in a cable

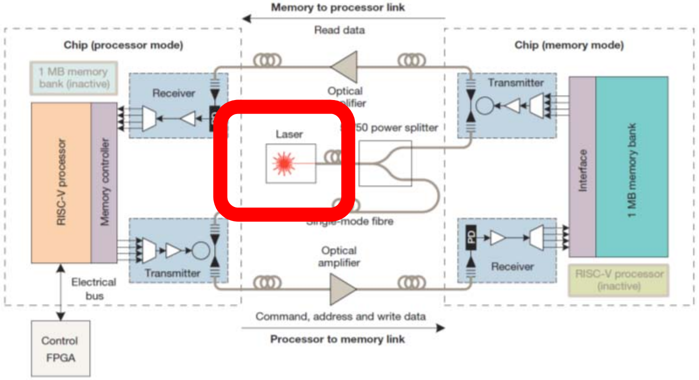
There is enough fibre in the world to encircle the globe more than 25,000 times, and the amount of fibre is increasing every day by thousands of kilometres.

Ultra-thin fibres made out of glass may seem very fragile. However, when glass is correctly drawn out in a long thread, its properties change. It becomes strong, light and flexible, which is a prerequisite if the fibre is to be buried, drawn under water or bent around corners. Unlike copper cables, glass fibre is not sensitive to lightning, and unlike radio communication, it is not affected by bad weather.

Google data center

Intel optical interconnects





70 million transistors+850 optical device

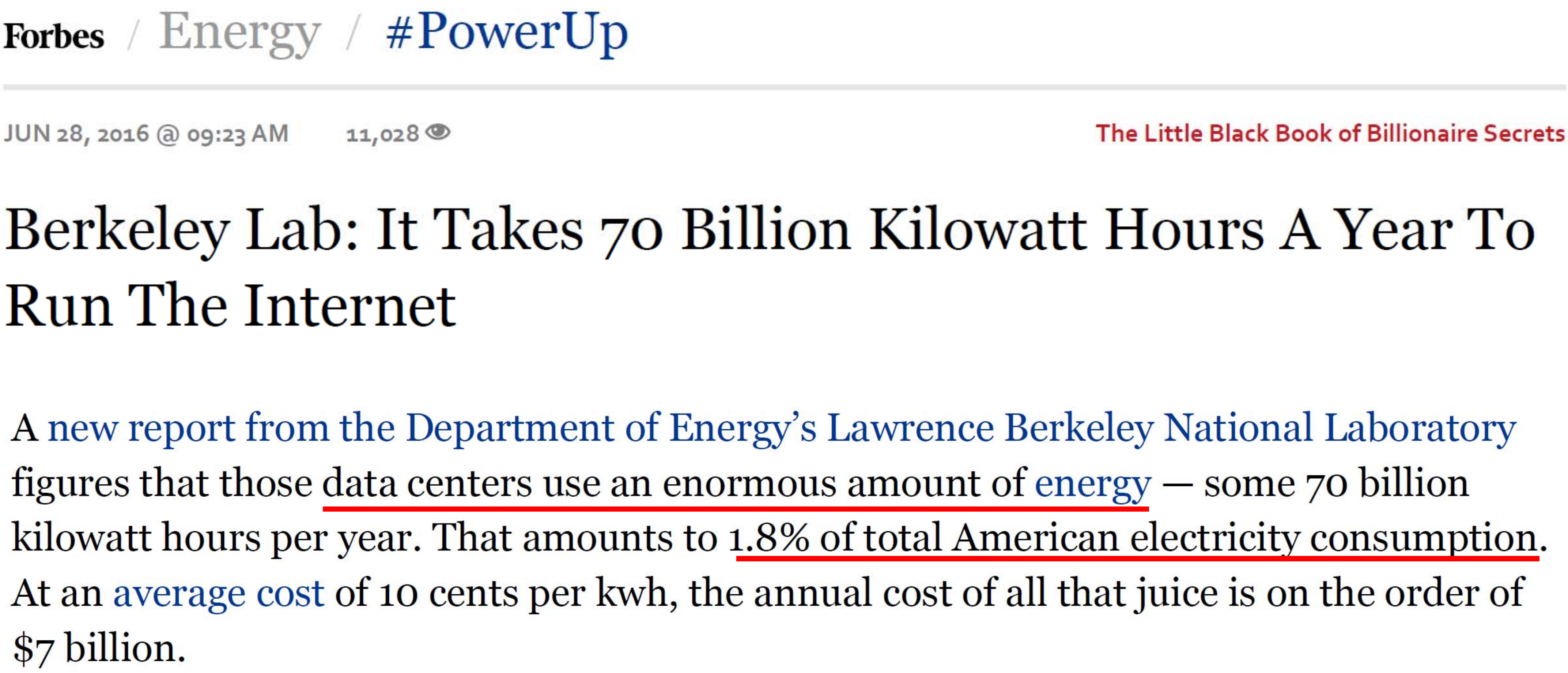
Nature 5228, 535, 2015

1 cm

1 m

1000 m

1000 km



Forbes / Energy / #PowerUp

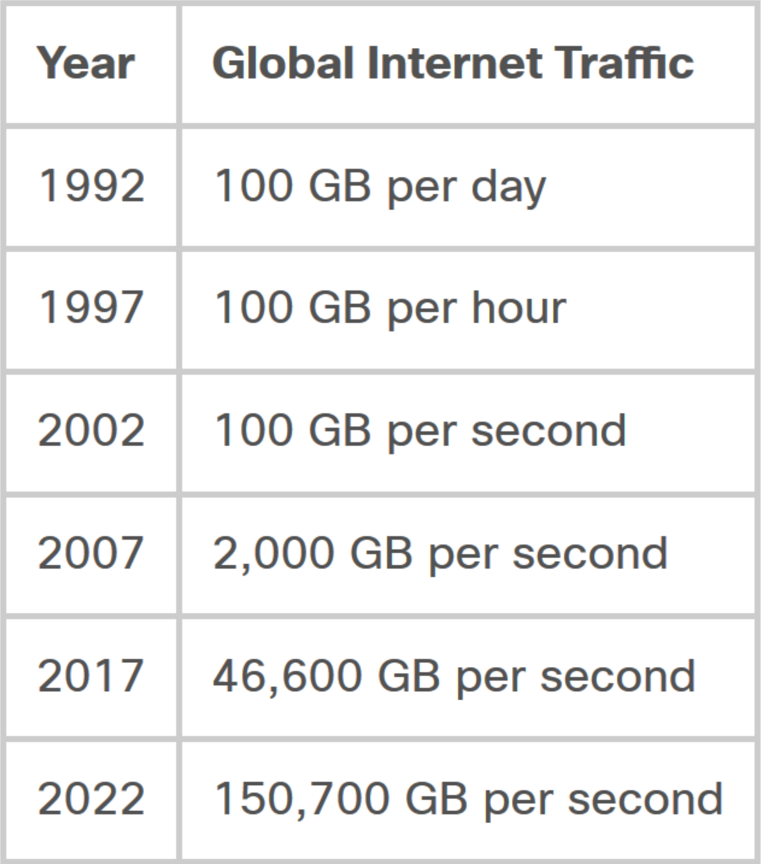
JUN 28, 2016 @ 09:23 AM 11,028

The Little Black Book of Billionaire Secrets

Berkeley Lab: It Takes 70 Billion Kilowatt Hours A Year To Run The Internet

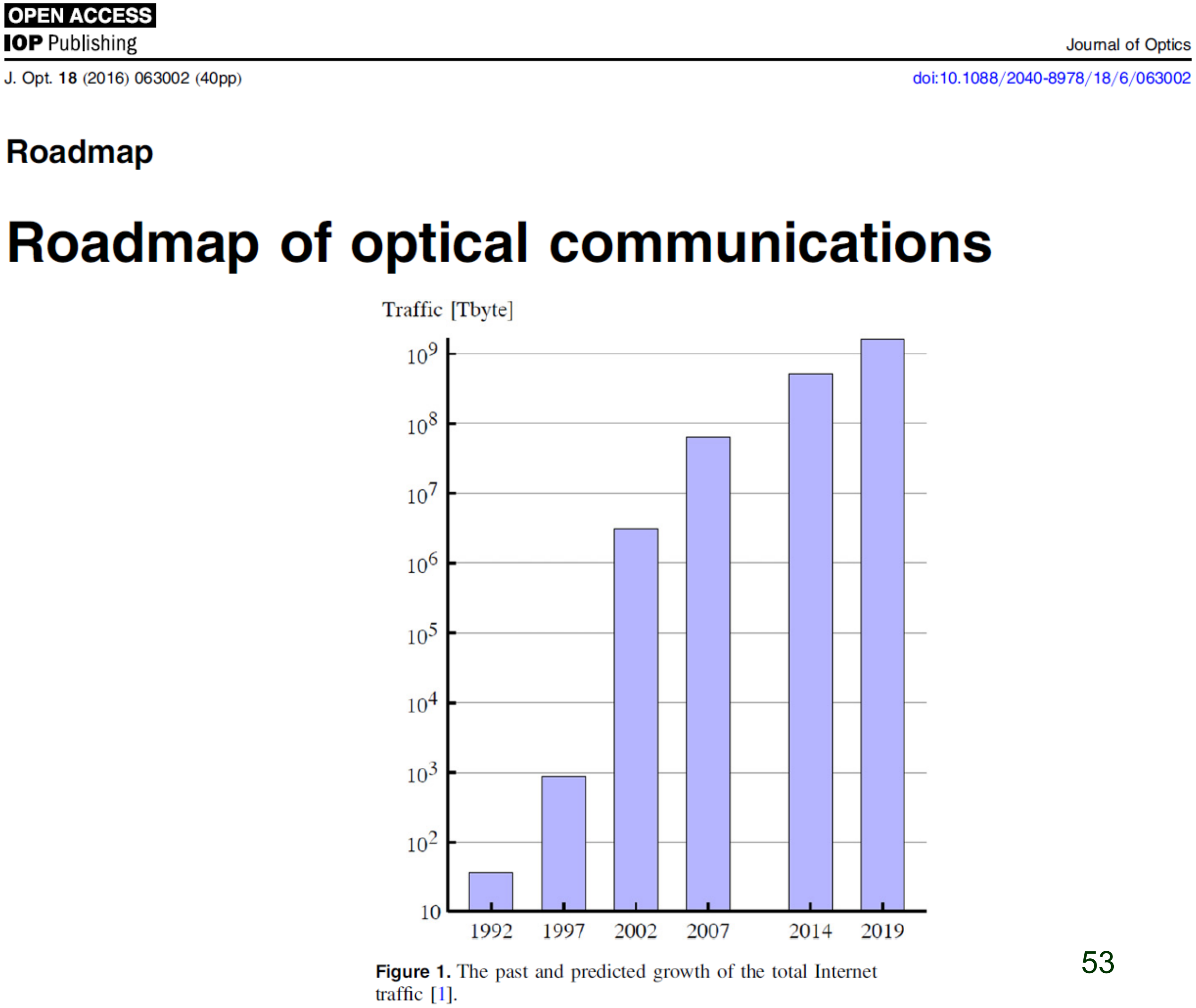
A new report from the Department of Energy's Lawrence Berkeley National Laboratory figures that those data centers use an enormous amount of energy — some 70 billion kilowatt hours per year. That amounts to 1.8% of total American electricity consumption. At an average cost of 10 cents per kwh, the annual cost of all that juice is on the order of $7 billion.

The Zettabyte Era: Trends and Analysis - Cisco



Year	Global Internet Traffic
1992	100 GB per day
1997	100 GB per hour
2002	100 GB per second
2007	2,000 GB per second
2017	46,600 GB per second
2022	150,700 GB per second

Source: Cisco VNI, 2018.



OPEN ACCESS
IOP Publishing

Journal of Optics

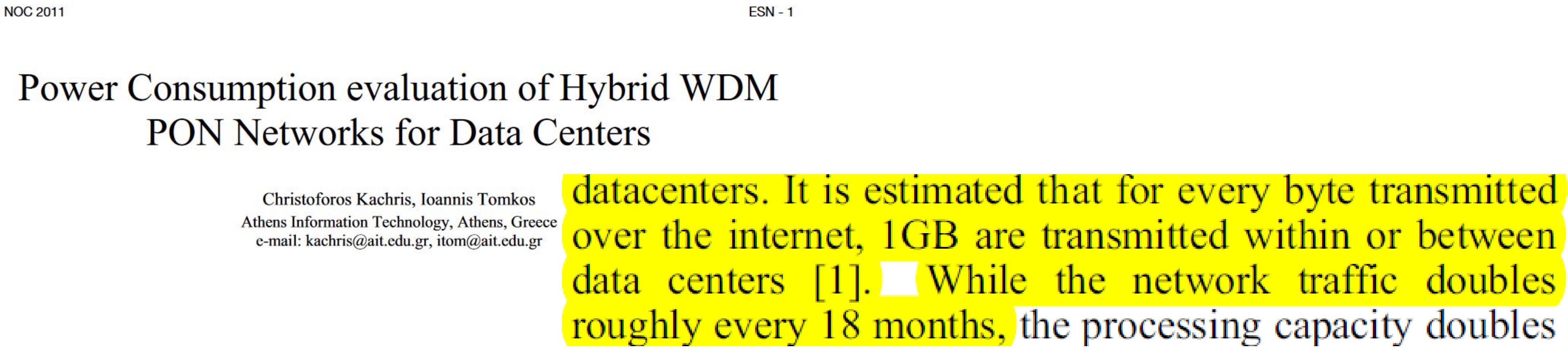
J. Opt. **18** (2016) 063002 (40pp)

doi:10.1088/2040-8978/18/6/063002

Roadmap

Roadmap of optical communications

Figure 1. The past and predicted growth of the total Internet traffic [1].

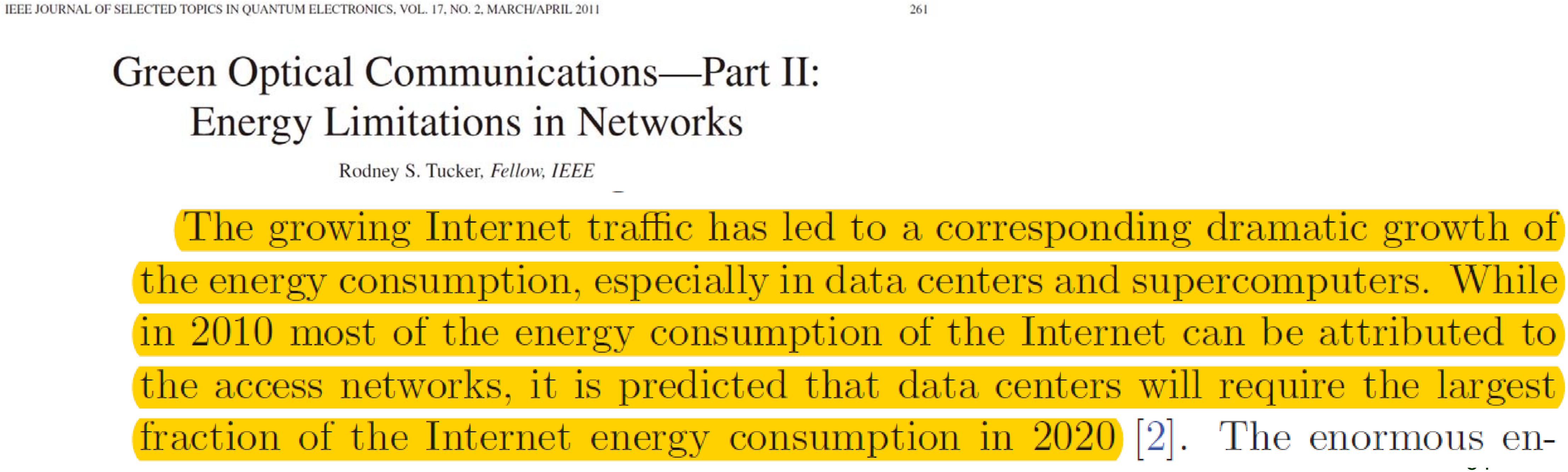


NOC 2011 ESN - 1

Power Consumption evaluation of Hybrid WDM PON Networks for Data Centers

Christoforos Kachris, Ioannis Tomkos
Athens Information Technology, Athens, Greece
e-mail: kachris@ait.edu.gr, itom@ait.edu.gr

datacenters. It is estimated that for every byte transmitted over the internet, 1GB are transmitted within or between data centers [1]. While the network traffic doubles roughly every 18 months, the processing capacity doubles



IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 17, NO. 2, MARCH/APRIL 2011 261

Green Optical Communications—Part II: Energy Limitations in Networks

Rodney S. Tucker, *Fellow, IEEE*

The growing Internet traffic has led to a corresponding dramatic growth of the energy consumption, especially in data centers and supercomputers. While in 2010 most of the energy consumption of the Internet can be attributed to the access networks, it is predicted that data centers will require the largest fraction of the Internet energy consumption in 2020 [2]. The enormous en-

Target power consumption of optical interconnects

Electronic interconnects

1 pJ bit^{-1}

↓

Optical interconnects

< 10 fJ bit^{-1}

Typical device	Device Area	Power Consumption½ CV^2
Edge emitting laser	1000 μm^2	10 pJ bit^{-1}
Surface emitting laser	100 μm^2	1 pJ bit^{-1}
Smallest Surface emitting laser	**10 μm^2**	**100 fJ bit^{-1}**
Sub-micro scale laser	**1 μm^2**	**10 fJ bit^{-1}**

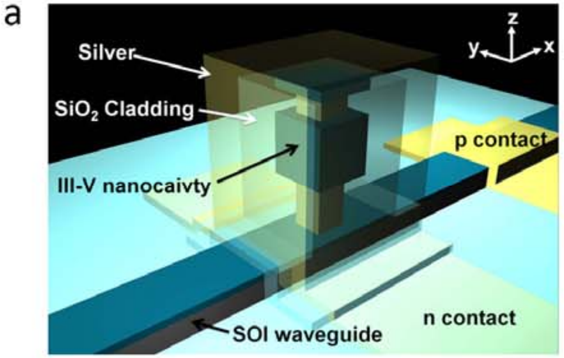
@ Anode Voltage: 1V ($h\nu$: ~1eV) ; L: 200 nm; τ: 1 ps; C_{diff}: ~ 10^{-6} F/cm^2

IEEE Transactions on Electron Devices 51, 506, 2004

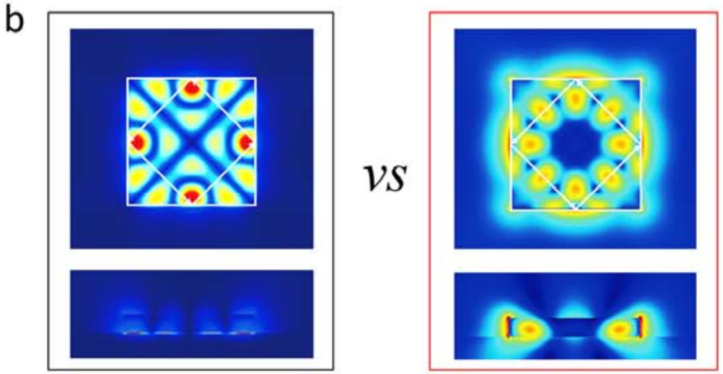
Low power consumption
½ CV^2

Nanolasers for integrated optical interconnects

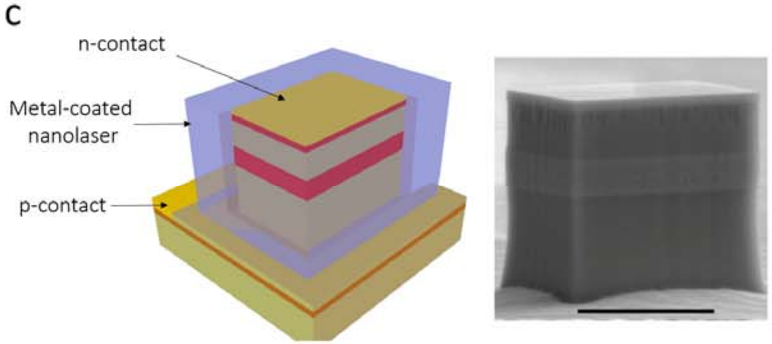
RMM & RFO, Nature Nanotechnology, *14, 12–22, 2019*



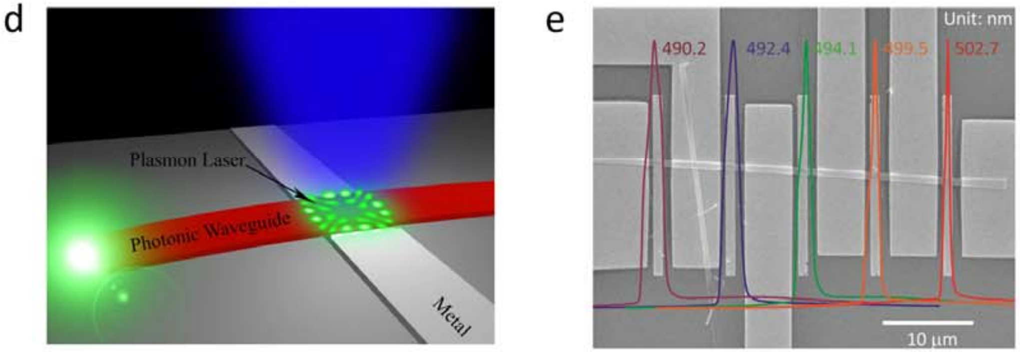
M. Wu group @ UC Berkeley



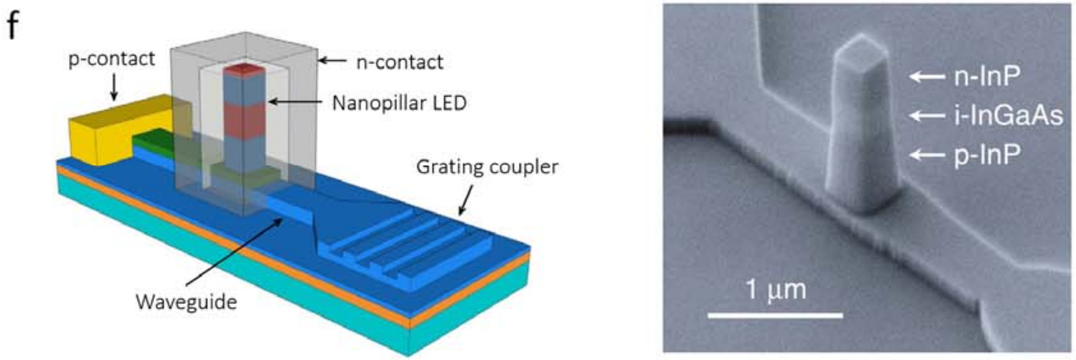
R. M. Ma group @ Peking University



C. Z. Ning group @ ASU



X. Zhang group @ UC Berkeley



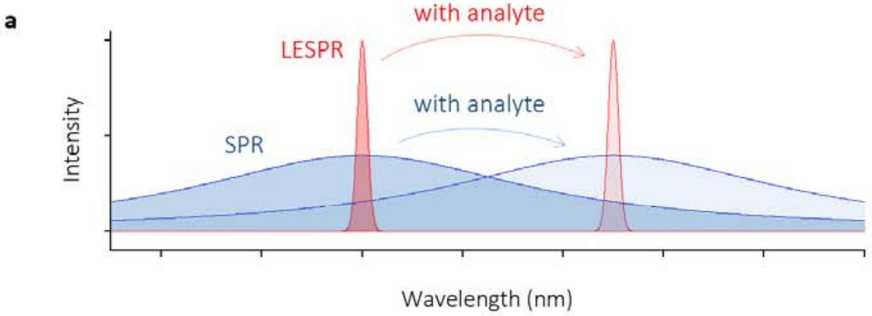
V. Dolores-Calzadilla group
@ Eindhoven University of Technology

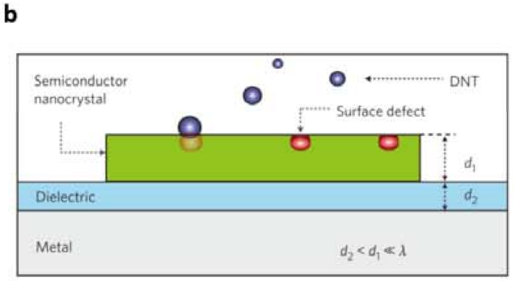
Strong local field

Q / V_m

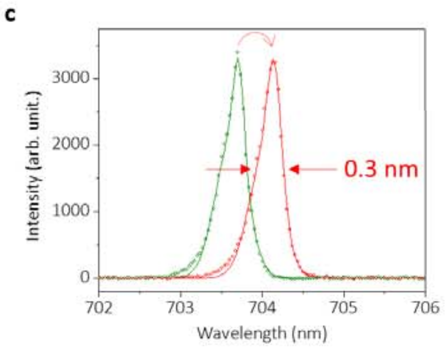
Nanolasers for near-field spectroscopy and sensing

RMM & RFO, Nature Nanotechnology, *14, 12–22, 2019*

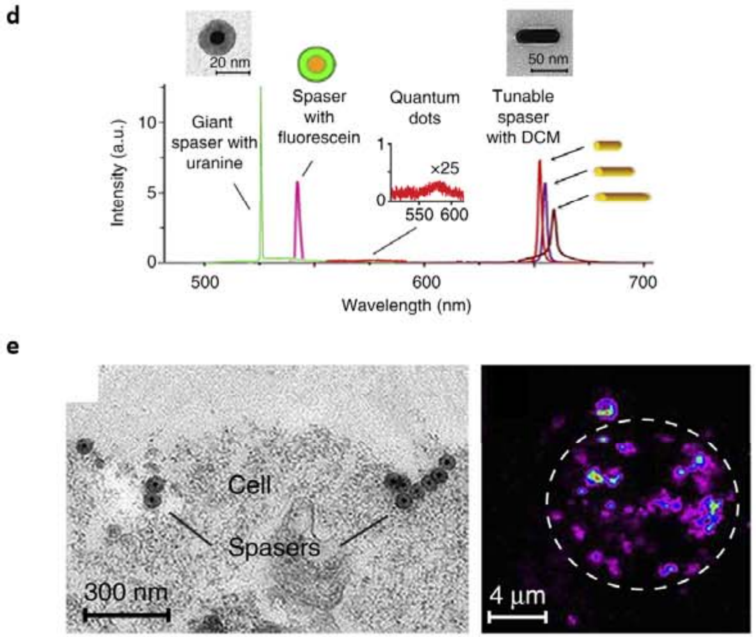




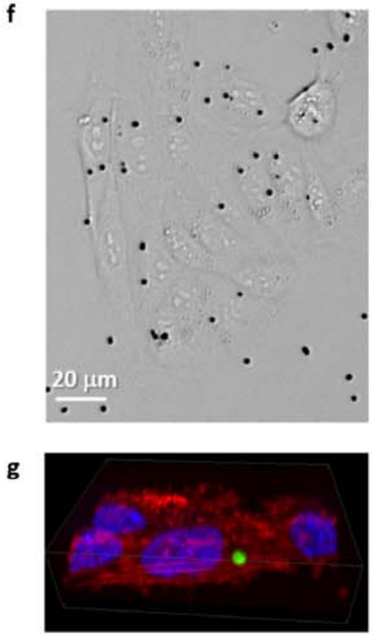
X. Zhang group
@ UC Berkeley



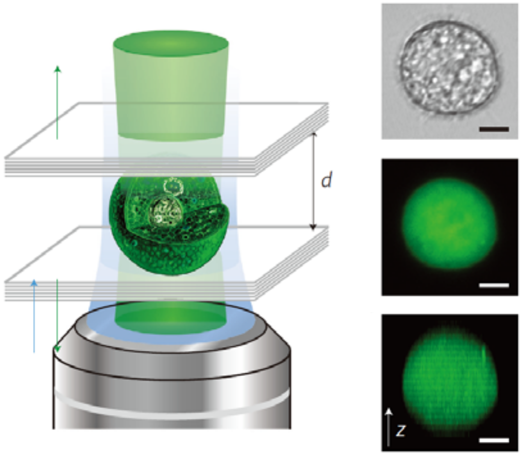
R. M. Ma group
@ Peking University



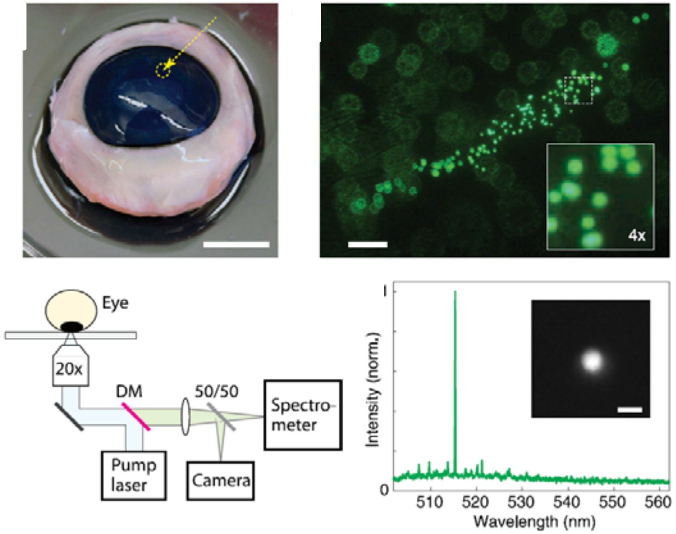
V. P. Zharov group
@ Univ. of Arkansas Medical Sci.



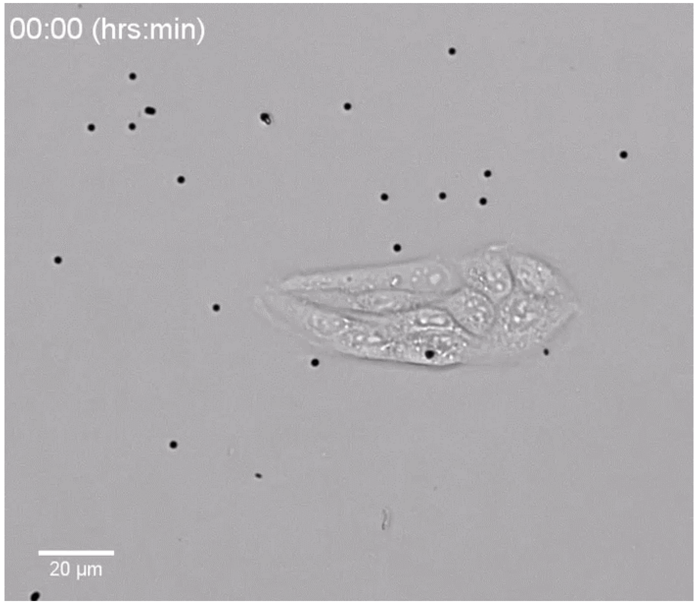
S. H. Yun Group
@ Harvard Medical School



Nature Photonics 5: 406 (2011)

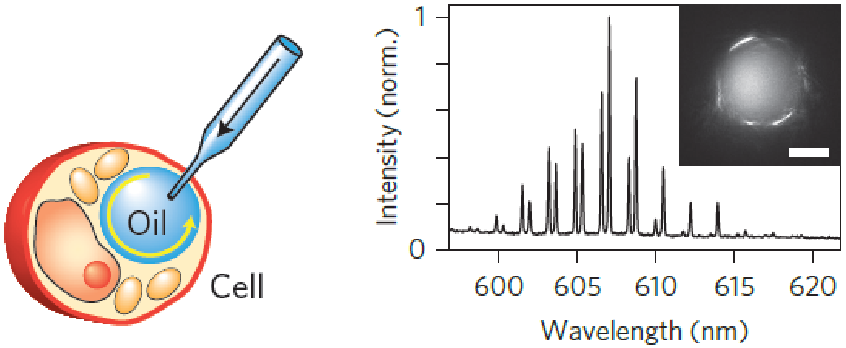


Optica 4:1080 (2017)

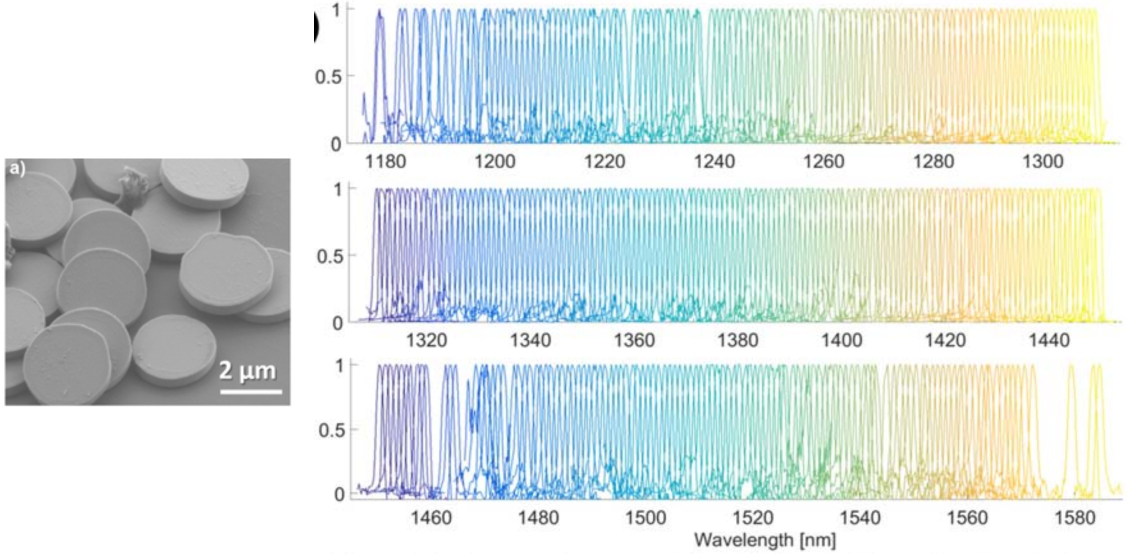


CLEO 2018, JTh5C.6

S. H. Yun Group @ Harvard Medical School



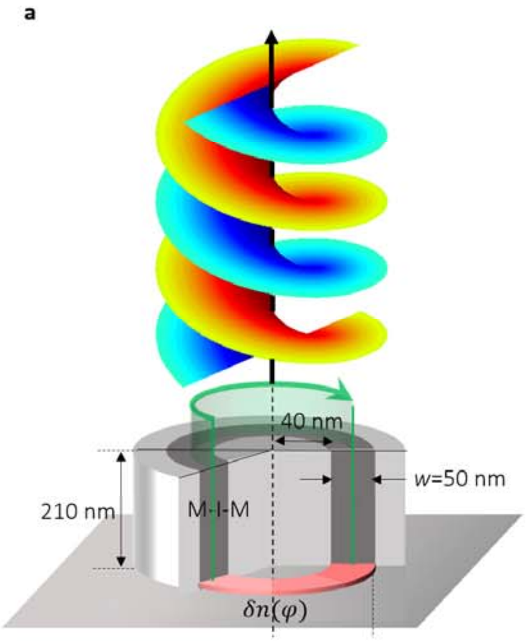
Nature Photonics 9: 572 (2015)



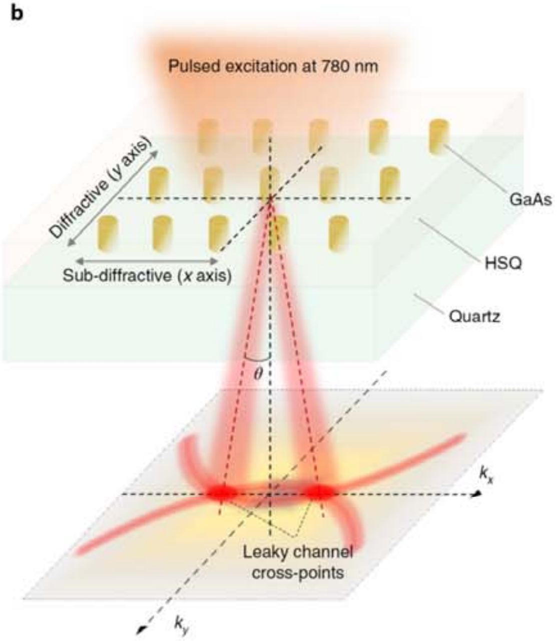
Limited cavity modes

$DOS \bullet V_{phy} \bullet \nu_{BW}$

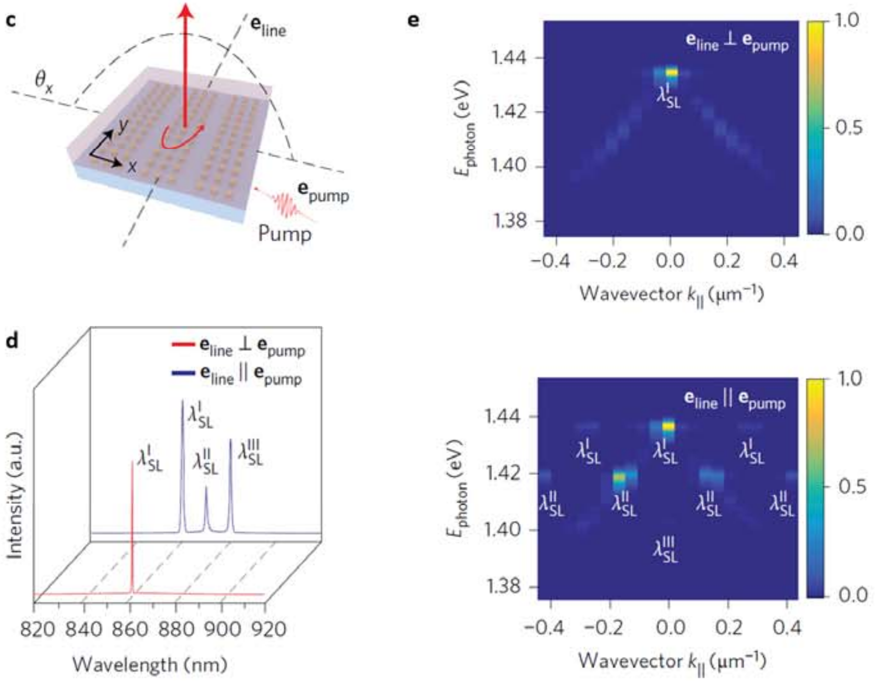
Eigenmode engineering of nanolasers for far-field applications



R. M. Ma group
@ Peking University



Arseniy I. Kuznetsov group
@ Data Storage Institute, Singapore



T. Odom group
@ Northwestern University

Revealing the missing dimension at exceptional points

---Chiral plasmonic nanocavity for lasing and single emitter vortex radiation

Manuscript submitted

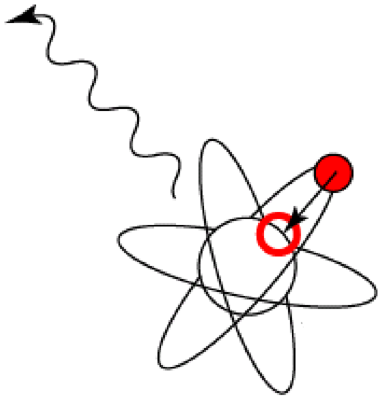
Theory: arXiv:1707.01055

Canonical paradigm to consider radiation process: eigenmode + emitter

Photon eigenstates

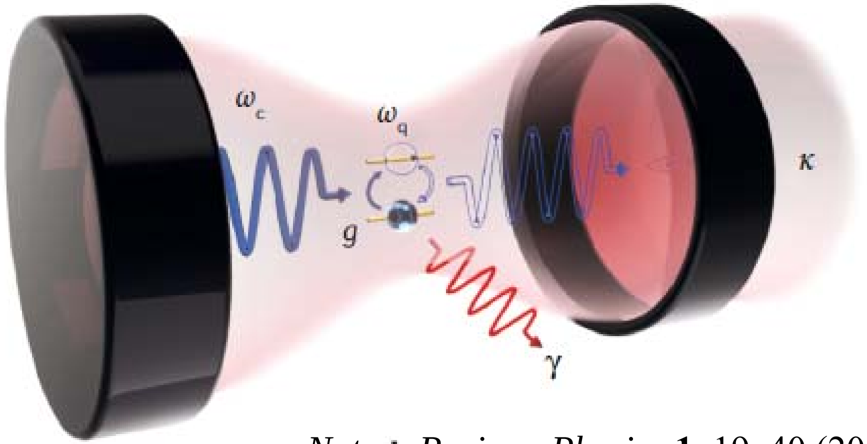
+

Emitter



Canonical paradigm to consider radiation process: eigenmode + emitter

Emitters couple with cavity eigenmode



Nature Reviews Physics **1**, 19–40 (2019)

Nature **445**, 896–899 (2007).

Phys. Rev. Lett. **95**, 067401 (2005).

Nature **535**, 127–130 (2016).

Science **363**, 42 (2019)

Nat. Photonics **1**, 449-458 (2007).

Nat. Photonics **9**, 427-435 (2015).

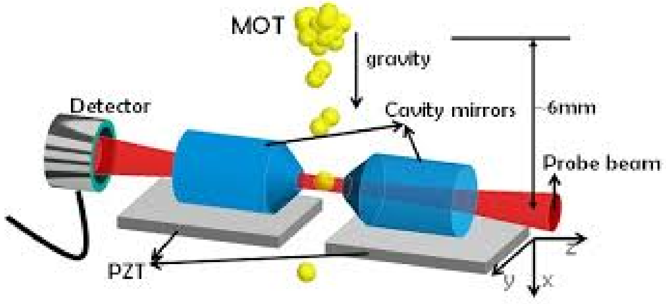
Nature **432**, 200–203 (2004).

……..

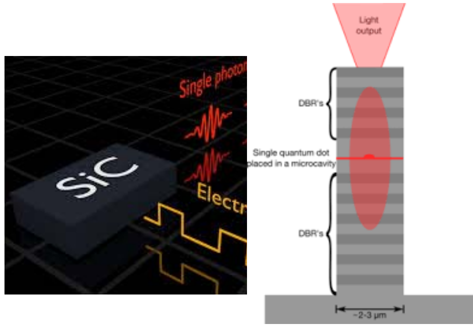
LED

Lasers

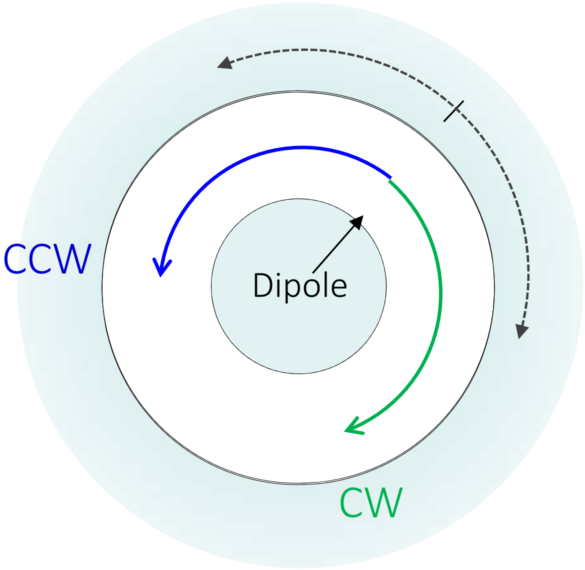
Cavity QED

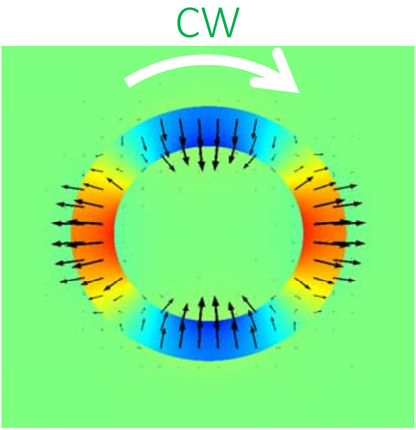


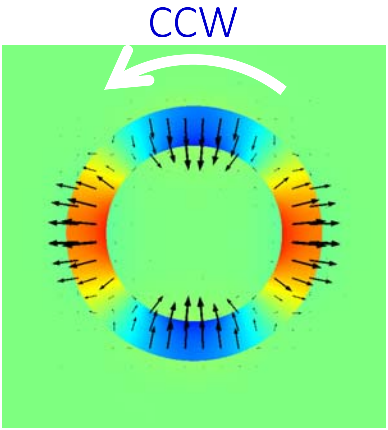
Single photon source



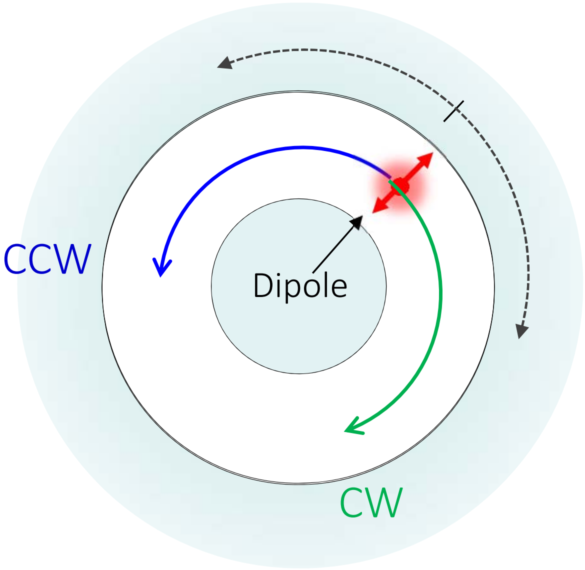
Single emitter inside a ring cavity

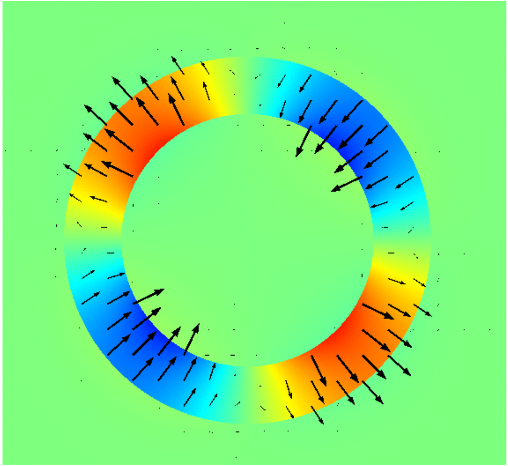


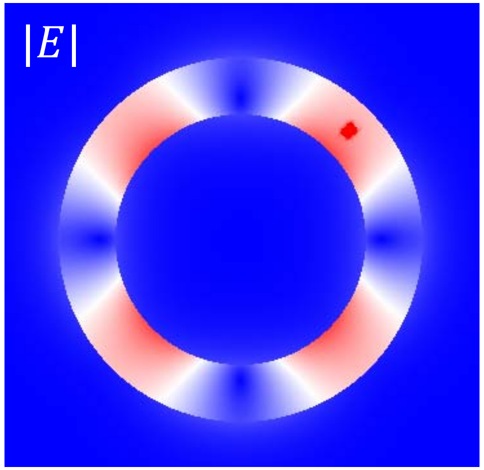


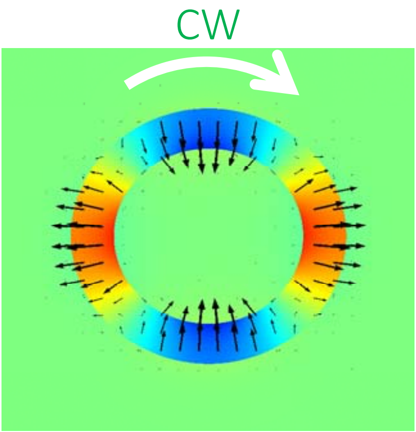


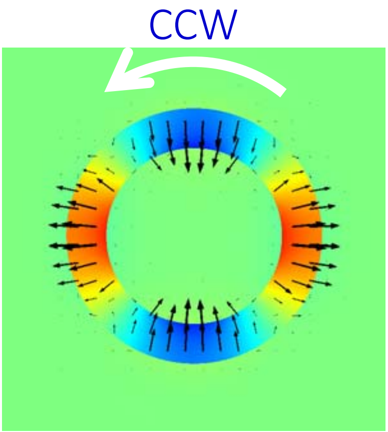
Single emitter inside a ring cavity



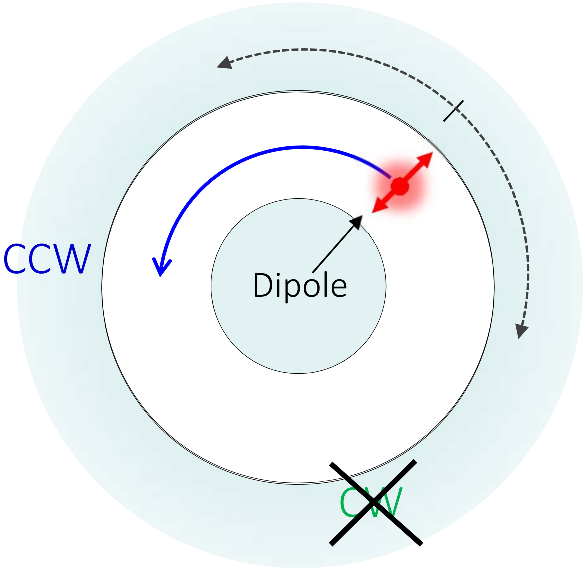


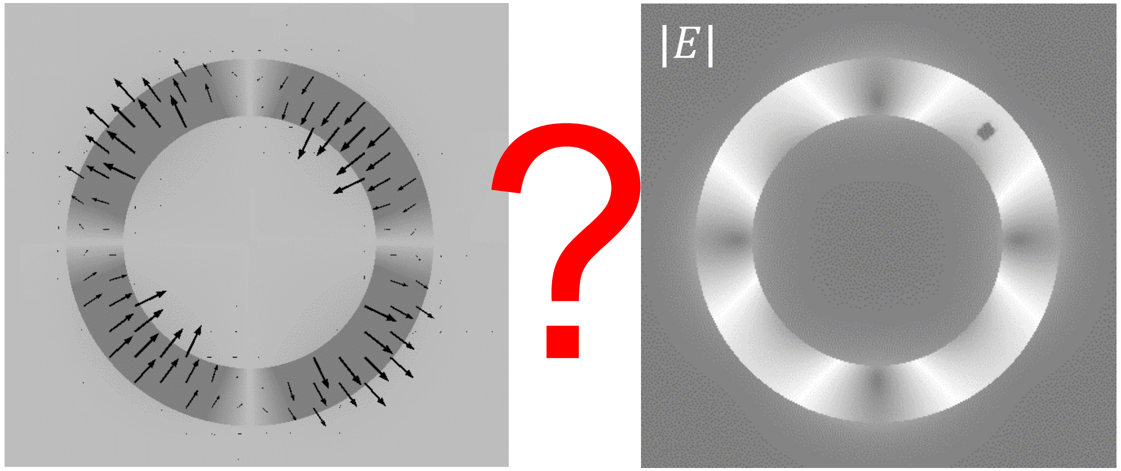


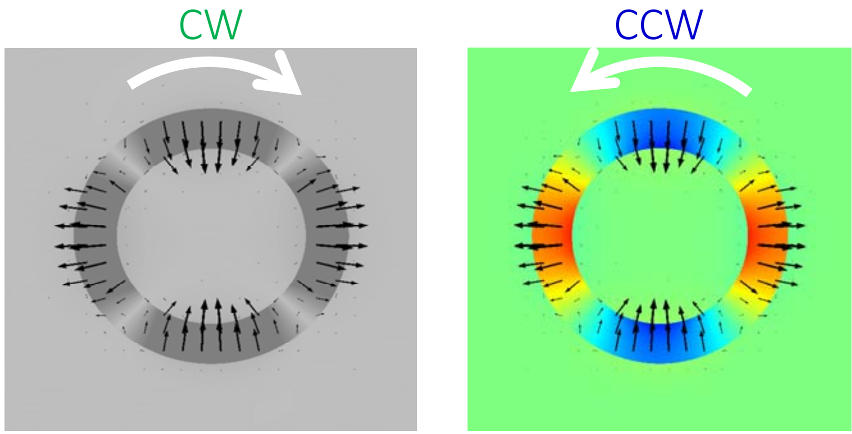




Single emitter inside a ring cavity





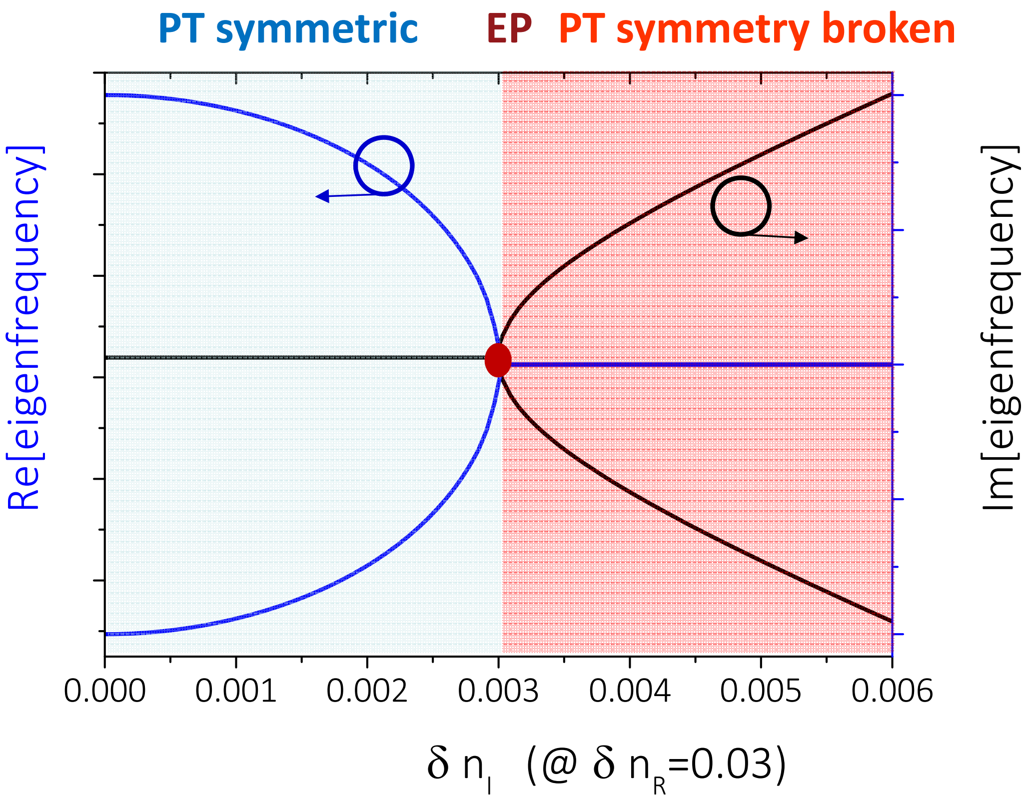


- How does an emitter interacts with an electromagnetic environment with incomplete eigenbasis?

- Will it radiate to the remianed eigenstate as it is only eigenstate of the Hamiltonian?

Parity time symmetric ring cavity at Exceptional Point

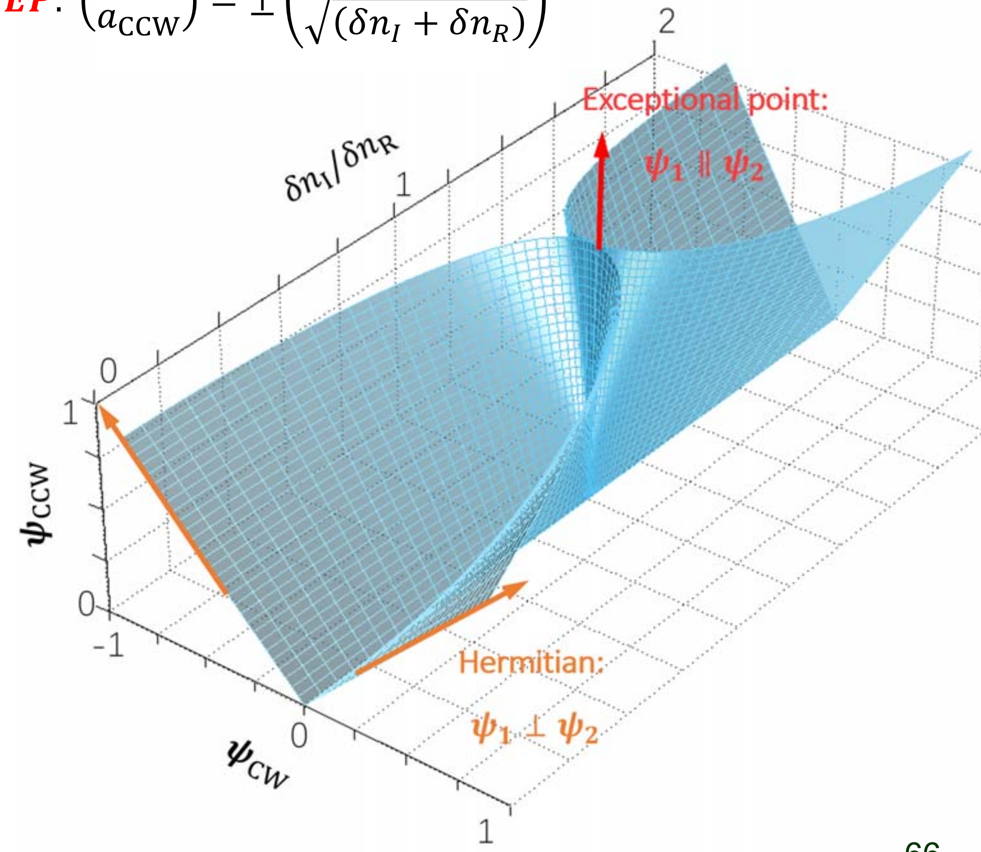
Eigenfrequencies



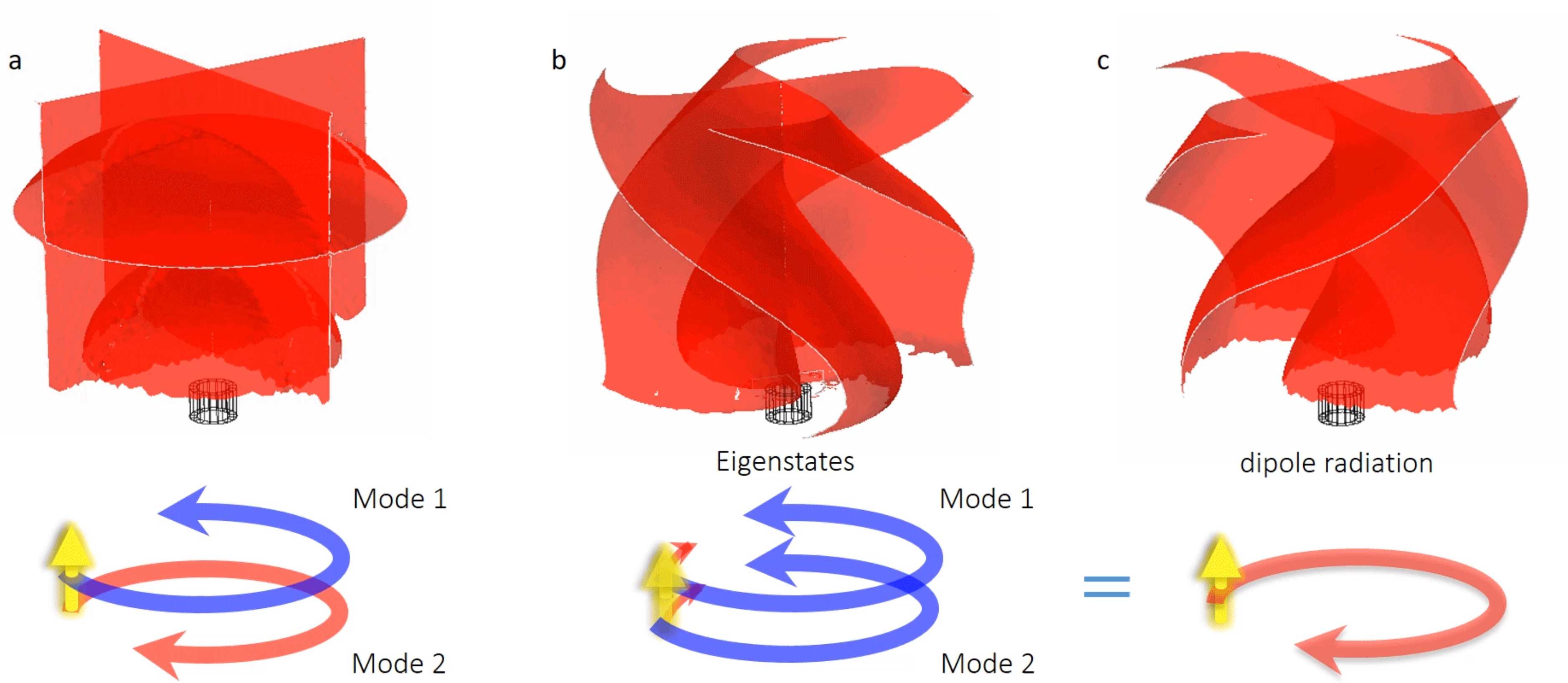
$$\Omega = \omega - i\gamma_{\text{tot}} \pm i\kappa\sqrt{\delta n_I^2 - \delta n_R^2}$$

Eigenstates

$$@\ EP:\ \begin{pmatrix} a_{\text{CW}} \\ a_{\text{CCW}} \end{pmatrix} = \pm\left(\frac{0}{\sqrt{(\delta n_I + \delta n_R)}}\right)$$

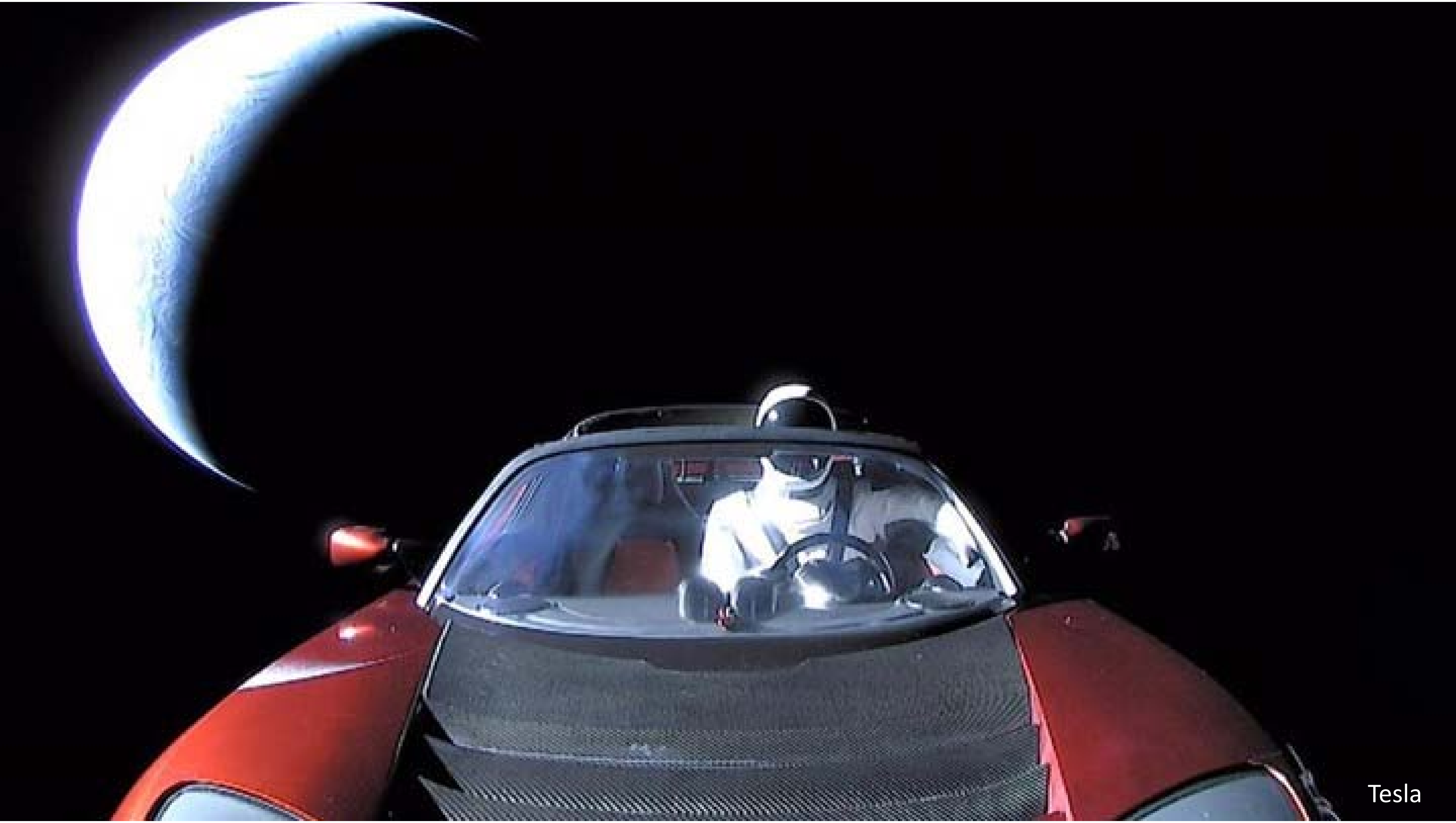


Chiral-reversing dipole radiation



Manuscript submitted

Theory: arXiv:1707.01055

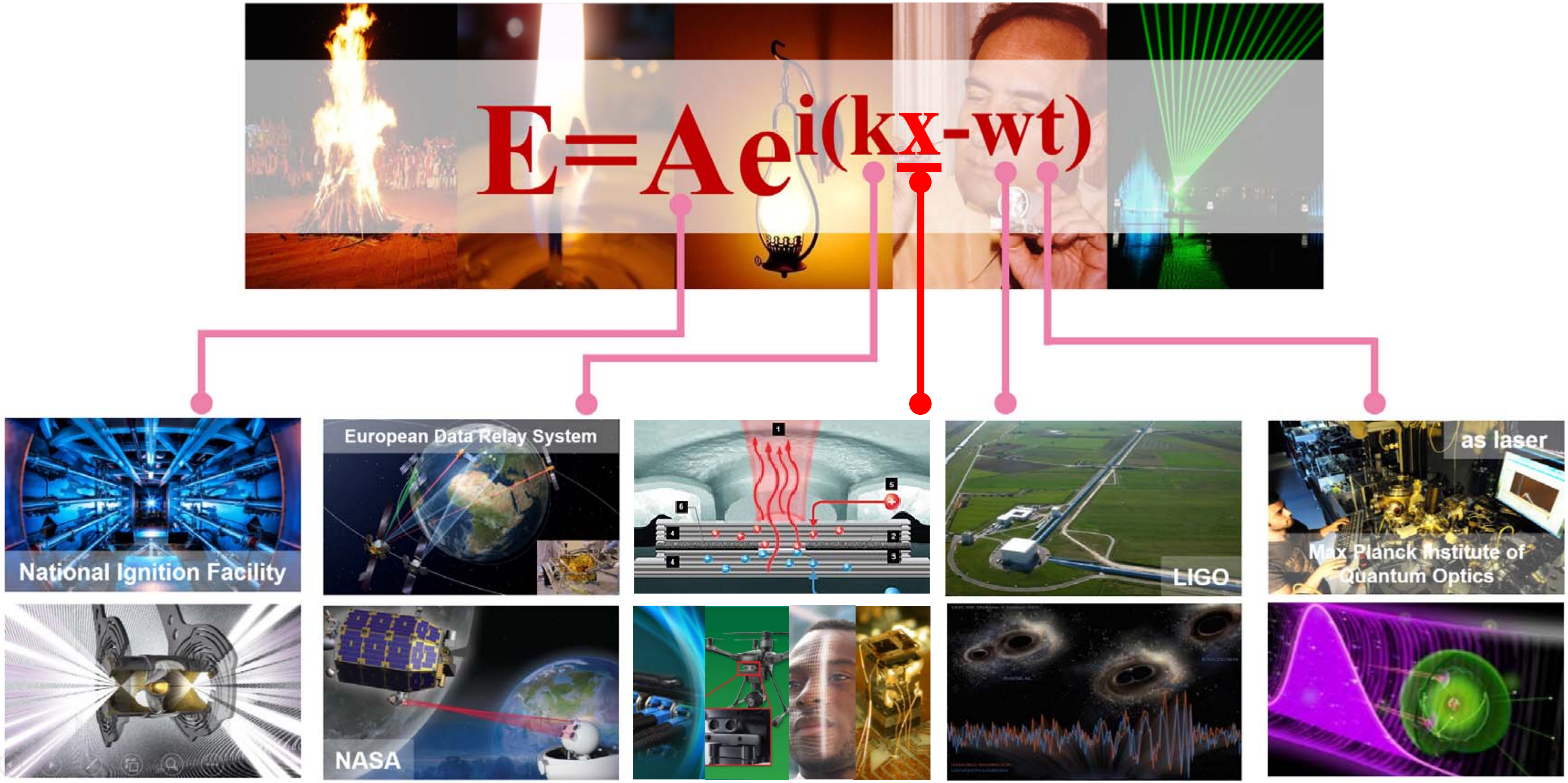


Tesla

Ant-man

Conclusion

Laser： extreme localization of EM field



$$E=Ae^{i(k\underline{x}-wt)}$$

Acknowledgement

Collaborators:

Prof. Xiang Zhang @ UC Berkeley

Prof. Rupert Oulton @ Imperial College

Prof. Lun Dai @ Peking University

Prof. Shuang Zhang @ University of Birmingham

Prof. Li Ge @ CUNY

Prof. Nicolas Fang @ MIT

Prof. Shining Zhu @ NJU

Prof. Jia Zhu @ NJU

Prof. Jie Zhu @ HKPU

….

Students & Postdoc:


Suo Wang


Hua-Zhou Chen


Jia-Qi Hu


Xing-Yuan Wang


Bo Li


Yi-Lun Wang

国家自然科学基金委员会 NSFC

千人計劃 RECRUITMENT PROGRAM OF GLOBAL EXPERTS

中华人民共和国教育部 Ministry of Education of the People's Republic of China

北京市科学技术委员会 Beijing Municipal Science & Technology Commission

Thank you for your attention!

Peking University Campus

Ren-Min Ma
renminma@pku.edu.cn

Postdoc and research professor openings