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.

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Create a community for nanophotonic researchers

- **Webinars**
  - 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
  - Aspects of Nanophotonics: Radiative Cooling, Image Processing and Topology
    - Thursday, February 7th, 1:00 PM EST
    - Speaker: Prof. Shanhui Fan
    - Stanford University

- **Special events at OSA conferences**
  - 20 x 20 Talks at CLEO
  - Personalized mentoring at FiO

- **Incubator meetings**
  - 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. Sorge, The George Washington University, United States; Jung Park, Intel Corporation, United States;
        - Pablo A. Postigo, Consejo Superior de Investigaciones Científicas, Spain; Fengxian Xia, Yale University, United States
Where to find us?

Website: www.osa.org/NanophotonicsTG
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Where to find us?

@Nano_OSA

facebook.com/nanophotonicsosa

LinkedIn logo with QR code
How to join ON Nanophotonics group’s email list?

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.
Plasmonic Nanolasers: Physics, Applications, and Challenges

Dr. Ren-Min Ma
Professor, Peking University
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

T ~ 6000 K

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

\[ E = A e^{i(kx - wt)} \]
Laser: extreme localization of EM field

\[ E = \Delta e^{i(kx-wt)} \]

Nuclear fusion

National Ignition Facility
Laser: extreme localization of EM field

\[ E = A e^{i(kx - wt)} \]
Laser: extreme localization of EM field

\[ E = A e^{i(kx - wt)} \]

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

Gravitational wave detection
Laser: extreme localization of EM field

\[ E = Ae^{i(kx-wt)} \]

Max Planck Institute of Quantum Optics

as laser

Inner-shell electron movement
Laser: extreme localization of EM field

\[ E = A e^{i(kx - wt)} \]
A brief history of laser miniaturization

Loss limit

\[ e.g. \quad L = 1 \mu m, \quad R = 20\%, \quad \alpha_M \sim 1.6 \times 10^4 \text{ cm}^{-1} \]

Diffraction limit

Edge emitting lasers

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

Nature Photonics 8 (2014) 908
Extremal localization of light in space

Localization in Frequency

First Laser
1960 T.H. Maiman

THz
GHz
MHz
KHz
Hz

Localization in Time

Mode Locked Laser
1964 L. E. Hargrove

as fs ps ns μs

Localization in Space???

Extreme localization of light in space
Localization of light with lasers

Localization in Frequency

First Laser 1960 T.H. Maiman

Mode Locked Laser 1964 L. E. Hargroved

Localization in Time

f(t) = δ(t)

f(w) = 1

f(x) = δ(x)

f(k) = 1

Extreme localization of light in space

\[ k = \frac{2\pi n}{\lambda} \]
Plasmonic Nanolasers a.k.a Spasers

Laser: Lightwave Amplification by Stimulated Emission of Radiation
Spasers: Surface Plasmon Amplification by Stimulated Emission of Radiation

Spatial localization of nanolasers in different dimensions

1-D

Optical Express
17 (2009) 1107

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

Nat. Nanotech. 8, 506-511 (2013)
Nat. Commun. 6, 6939 (2015)
Nat. Nanotech. 12, 889-894 (2017)
Nano Letters DOI: 10.1021/acs.nanolett.8b01774
Nanosquare plasmonic nanolaser

Metal-Insulator-Semiconductor Surface Plasmon Mode

Ren-Min Ma et al. *Nature Mat.* 10, 110 (2011)
Metal-Insulator-Semiconductor Surface Plasmon Mode

Plasmonic Nanolasers *a.k.a* Spasers

**Laser:** Lightwave Amplification by Stimulated Emission of Radiation

**Spasers:** Surface Plasmon Amplification by Stimulated Emission of Radiation

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

\[ \omega_{spp} = \frac{\omega_p}{\sqrt{1 + \varepsilon_2}} \]
Imaging the dark emission of plasmonic nanolasers

**Laser:** Lightwave Amplification by Stimulated Emission of Radiation

**Spasers:** Surface Plasmon Amplification by Stimulated Emission of Radiation

\[ k_{\text{SPP}} = k_0 \sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}, \quad \text{Re}[\varepsilon_M] < 0 \]

\[ \omega_{\text{SPP}} = \frac{\omega_p}{\sqrt{1 + \varepsilon_2}} \]

\[ \omega = ck \]
SPPs

Plasmon Polariton

Photon

\[ \omega_0 \approx \omega_1 + \varepsilon \frac{k}{c} \omega \]

Objective

Metal

Glass

Air

Photon

SPPs

Leakage radiation

Free space radiation

Leakage radiation

K_{glass} = K_{SPP}
Imaging the dark emission of plasmonic nanolasers

HC…RMM, IEEE JQE, 54, 7200307 (2018)
Imaging the dark emission of plasmonic nanolasers

HC...RMM, IEEE JQE, 54, 7200307 (2018)
Metal ~ 10 nm

Fascinating for Field Confinement

Notorious for Metallic Absorption

~ 10 nm
Plasmonics for laser miniaturization, quenching thirst with poison?

Edge emitting lasers

Loss limit

\[ e.g. \ L=1\mu m, \ R=20\%, \ \alpha_M \sim 1.6 \times 10^4 \text{ cm}^{-1} \]

Diffraction limit

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

Nature Photonics 8 (2014) 908
# Threshold of Plasmonic Nanolasers

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

\[ RMM, \text{ et al. Nature Materials 10, 110 (2011)} \]

- Field in metal
- Optical confinement
- Metal absorption loss

- Field in metal
- Larger effective index
- Reduced radiation loss
Is it intrinsically high? --- Dynamics Perspective


Field in metal
Optical confinement
Metal absorption loss

Q

V mode

Larger effective index
Reduced radiation loss
Purcell effect: spontaneous emission rate, $\gamma \sim \frac{Q}{V_{\text{mode}}}$

- Emitting faster to plasmonic mode $\Rightarrow$ lowering the threshold
- Consuming carriers too faster for population inversion $\Rightarrow$ raising the threshold

Is it intrinsically high? ?---Dynamics Perspective
Purcell effect: spontaneous emission rate, $\gamma \sim Q / V_{\text{mode}}$

- Emitting faster to plasmonic mode $\Rightarrow$ lowering the threshold
- Consuming carriers too faster for population inversion $\Rightarrow$ raising the threshold

Is it intrinsically high? --- Dynamics Perspective
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:
CdSe single crystal nanosquare
Internal Quantum efficiency: ~100%

Better Metal:
Au polycrystalline film
Figure of merit, $\frac{-Re[\varepsilon_m]}{Im[\varepsilon_m]}$: ~16

Better Cavity:
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)  
Scaling laws for photonic nanolasers

SW...RMM, Nature Communications 8, 1889 (2017)  
Unusual scaling laws for plasmonic nanolasers

SW...RMM, Nature Communications 8, 1889 (2017)  
Unusual scaling laws for plasmonic nanolasers

SW...RMM, Nature Communications 8, 1889 (2017)  
Unusual scaling laws for plasmonic nanolasers

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

Unusual scaling laws for plasmonic nanolasers

SW...RMM, Nature Communications 8, 1889 (2017)  
LASER threshold minimization

\[ \frac{dN}{dt} = P - AN - \Gamma A \beta (N - N_0)S \]  
(1)

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

\[ P_{th} = \frac{h\nu (1 + \beta)}{\eta A \beta} \left[ \frac{\gamma}{\beta \Gamma} + F \frac{2n_0 V}{\tau_0} \right] \]

Cavity mode loss

Gain material loss

Define \( \zeta = \frac{\text{Cavity mode loss}}{\text{Gain material loss}} = \gamma \tau_0 / \beta F \Gamma n_{\text{inv}} V \)

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

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

LASER threshold can be minimized in two ways:

(I) \( \beta \rightarrow 1 \),

which demands a strong Purcell effect and small cavity.

(II) \( \zeta \rightarrow \infty \)

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
MINIATURE LASERS

Is metal a friend or foe?

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 interfaces the gain medium harms or improves the laser performance. In a work published in *Nature Communications*, Ren-Min Ma and colleagues 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).

The results reported by Ma and co-authors 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

References

Mikhail A. Noginov and Jacob B. Khurgin

NATURE MATERIALS, DOI:10.1038/nmat5065
Plasmonic nanolasers with external quantum efficiency exceeding 10%

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

Photon radiation

Nanolaser

\( \text{MgF}_2/\text{Au} \)

Surface plasmon radiation

External Quantum Efficiency

\( \text{Peak pump power (} P_{th} \text{)} \)

8%  9%  10%  11%  12%

1  2  3  4  5
Plasmonic nanolasers with external quantum efficiency exceeding 10%

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

Extraction Efficiency:

\[
\frac{Q_{\text{metal}}}{Q_{\text{metal}} + Q_{\text{rad}}}
\]
Applications of nanolasers

Ren-Min Ma\textsuperscript{1,2,*} and Rupert F. Oulton\textsuperscript{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.
Applications of nanolasers

[Diagram showing the evolution of nanolasers from 1992 to 2018, including microdisk and nanowire lasers, metal-based nanolasers, and nanolaser arrays.]
Applications of nanolasers

- Low power consumption: \( \frac{1}{2} CV^2 \)
- Strong local field: \( \frac{Q}{V_m} \)
- Limited cavity modes: \( DOS \cdot V_{phy} \cdot V_{BW} \)

Optical interconnects
Near-field spectroscopy & sensing
Eigenmode engineering

Ren-Min Ma & Rupert Oulton, Nature Nanotechnology, 14, 12–22, 2019
Optical interconnects at shorter and shorter distance

70 million transistors + 850 optical devices

Intel optical interconnects

Google data center

Nature 5228, 535, 2015
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

<table>
<thead>
<tr>
<th>Year</th>
<th>Global Internet Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>100 GB per day</td>
</tr>
<tr>
<td>1997</td>
<td>100 GB per hour</td>
</tr>
<tr>
<td>2002</td>
<td>100 GB per second</td>
</tr>
<tr>
<td>2007</td>
<td>2,000 GB per second</td>
</tr>
<tr>
<td>2017</td>
<td>46,600 GB per second</td>
</tr>
<tr>
<td>2022</td>
<td>150,700 GB per second</td>
</tr>
</tbody>
</table>

Source: Cisco VNI, 2018.

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

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

<table>
<thead>
<tr>
<th>Typical device</th>
<th>Device Area</th>
<th>Power Consumption$^{1/2}$ CV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge emitting laser</td>
<td>1000 $\mu$m$^2$</td>
<td>10 pJ bit$^{-1}$</td>
</tr>
<tr>
<td>Surface emitting laser</td>
<td>100 $\mu$m$^2$</td>
<td>1 pJ bit$^{-1}$</td>
</tr>
<tr>
<td>Smallest Surface emitting laser</td>
<td>10 $\mu$m$^2$</td>
<td>100 fJ bit$^{-1}$</td>
</tr>
<tr>
<td>Sub-micro scale laser</td>
<td>1 $\mu$m$^2$</td>
<td>10 fJ bit$^{-1}$</td>
</tr>
</tbody>
</table>

Electronic interconnects
1 pJ bit$^{-1}$

Optical interconnects
< 10 fJ bit$^{-1}$

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

IEEE Transactions on Electron Devices 51, 506, 2004
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
Nanolasers for near-field spectroscopy and sensing

RMM & RFO, Nature Nanotechnology, 14, 12–22, 2019
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
Canonical paradigm to consider radiation process: eigenmode + emitter

Photon eigenstates + Emitter
Canonical paradigm to consider radiation process: eigenmode + emitter

Emitters couple with cavity eigenmode


LED

Lasers

Cavity QED

Single photon source

Science 363, 42 (2019)


……..
Single emitter inside a ring cavity
Single emitter inside a ring cavity
How does an emitter interact with an electromagnetic environment with incomplete eigenbasis?

Will it radiate to the remained eigenstate as it is only eigenstate of the Hamiltonian?
Parity time symmetric ring cavity at Exceptional Point

**Eigenfrequencies**

- **PT symmetric**
- **EP**
- **PT symmetry broken**

\[ \delta n_I \quad (@ \delta n_R = 0.03) \]

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

**Eigenstates**

[@ EP: \( \begin{pmatrix} a_{cw} \\ \frac{a_{ccw}}{0} \end{pmatrix} = \pm \frac{0}{\sqrt{\delta n_I + \delta n_R}} \)]
Chiral-reversing dipole radiation

Manuscript submitted  Theory: arXiv:1707.01055
Laser: extreme localization of EM field

\[ E = A e^{i(kx - wt)} \]
Acknowledgement

Collaborators:
Prof. Xiang Zhang @ UC Berkeley
Prof. Rupert Oulton @ Imperial College
Prof. Lun Dai @ Peking University
Prof. Shuang Zhang @ University of Birmingham
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Prof. Nicolas Fang @ MIT
Prof. Shining Zhu @ NJU
Prof. Jia Zhu @ NJU
Prof. Jie Zhu @ HKPU

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Hua-Zhou Chen
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Xing-Yuan Wang
Bo Li
Yi-Lun Wang
Thank you for your attention!

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