Manipulating Light with Single Nanowires

Limin Tong
State Key Laboratory of Modern Optical Instrumentation
Department of Optical Engineering, Zhejiang University

2012-12-07
1. Introduction
   - Nanowire Photonics

2. Nanowire Light Manipulation
   2.1 Light Generation
   2.2 Light Propagation
   2.3 Light Modulation
   2.4 Light Detection

3. Summary & Outlook
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3. Summary & Outlook
1. Introduction

- Nanowire

1-D structure
large aspect ratio
diameter $10^0-10^2$ nm

close to or below the
wavelength of visible light

X. Guo et al., *Nano Lett.* 9, 4515 (2009)

Semiconductor
ZnO nanowire

Metal
Ag nanowire

X. Guo et al., *Nano Lett.* 9, 4515 (2009)
1. Introduction

Manipulating light on a nanometer scale with high flexibility

- low loss
- tight optical confinement
- strong evanescent fields
- abnormal waveguide dispersion

Wrapping light around a human hair
1. Introduction

- Why it is attractive to **Photonics**?

<table>
<thead>
<tr>
<th>Favorable properties of nanowires for photonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Sub-wavelength dimension</td>
</tr>
<tr>
<td>• Tight optical confinement</td>
</tr>
<tr>
<td>• Large surface-to-volume ratio</td>
</tr>
<tr>
<td>• Engineerable surface states</td>
</tr>
<tr>
<td>• Strong evanescent fields</td>
</tr>
<tr>
<td>• Free-standing and low-mass</td>
</tr>
<tr>
<td>• High mechanical strength</td>
</tr>
<tr>
<td>• Optically visible</td>
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</table>

- 1. Introduction
1. Introduction

- Why it is attractive to **Photonics**?

**Nanowire**

Fascinating 1-D structure for manipulating

**Electrons, photons, phonons, atoms, polaritons on the subwavelength or nanometer scale**

Intrigue a variety of opportunities for

**Fundamental study and technological applications**
1. Introduction

J. Giles, Nature 441, 265 (2006)

Nanowire

stimulates growth and actually boosts overall wealth. At least, that’s the conclusion of two of the models — one developed at the University of Cambridge, UK, and the other at the Fondazione Eni Enrico Mattei, a centre for sustainable-development research in Italy. These models suggest that stabilization policies would give an added boost to global GDP of up to 1.7% over 100 years. They assume such climate policies will bring about side benefits, such as increased investment in new technologies.

Ottmar Edenhofer, an economist at the Potsdam Institute for Climate Impact Research in Germany who edited the issue along with Grubb and others, says the new estimates of lost global GDP are significantly lower than previous ones, which put the range at 3–15%. They suggest the price will be a lot lower, agrees Terry Barker, an economist who helped developed the Cambridge model, especially as costs will be spread over 100 years.

The models are likely to influence the next report from the Intergovernmental Panel on Climate Change, due for publication next year. The authors hope the results will then filter through to governments. They say the cheapest stabilization route can only be achieved if industries are given a strong signal that carbon emissions will continue to be restricted — and that means the United States must join a future version of the Kyoto Protocol. Europe also needs to do more, say the authors, particularly in terms of investment in energy technologies, where it lags behind the United States.

But some economists are wary of the results. Jae Edmonds of the Pacific Northwest National Laboratory in Richland, Washington, describes the models as a valuable “intellectual experiment”. But he questions the fact that most of the models emphasize learning-by-doing — a process by which technology becomes cheaper.

TOP FIVE IN PHYSICS

Are you working on the hottest topic in your field? Many scientists may think so, but it has been a tough assertion to prove — until now, that is. A German physicist has devised a way of answering the ‘Hot or not?’ question for his discipline. If it stands up to scrutiny, it could be used to rate topics across the sciences. In physics, the results show that hotness — measured by a parameter known as m — correlates well with the promise of future wealth... and that promise is greatest in nanotechnology.

12.85 Carbon nanotubes
Super-strong materials and blisteringly fast electronic circuits: the potential applications of these tiny carbon tubes, discovered in 1991, are so enticing that everyone is pouring money into the field.

7.78 Fullerenes
These spheres of carbon atoms are attracting significant research interest. But the latest ranking rewards newness, so the topic may have slipped down the list because it predates nanotubes by around six years. The discovery of fullerenes earned a Nobel prize and spawned studies of numerous potential uses, such as drug delivery agents.

8.75 Nanowires
Less well studied than nanotubes, but the possible uses are similar. Nanowires could eventually prove more useful than nanotubes, because their chemistry is easier to tailor and they can be used to create nano-sized lasers.

7.84 Quantum dots
Another nanotechnology with a huge range of potential applications. These tiny specks of semiconductor material, measuring as little as a few nanometres across, have already been used to create dyes for cell biologists and new kinds of laser. Physicists hope they might one day form the basis of a quantum computer.

6.82 Giant magnetoresistance
Not a new topic, but still hot because of its economic importance. Modern hard disk drives were made possible by the discovery of giant magnetoresistant materials, which show marked falls in electrical resistance — more than around 5% — when a magnetic field is applied. Researchers are now aiming to make hard disks even more powerful.
1. Introduction

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Nanowires studied in our group

Nanowires

Glass nanofibers
e.g., Silica, phosphate

Polymer nanofibers
e.g., PMMA, PS

Semiconductor nanowires
e.g., ZnO, CdSe

Metal nanowires
e.g., Silver, gold
Nanowires studied in our group

**Nanowires**
- Glass nanofibers
e.g., Silica, phosphate
- Polymer nanofibers
e.g., PMMA, PS
- Semiconductor nanowires
e.g., ZnO, CdSe
- Metal nanowires
e.g., Silver, gold

**Optics**
- Near-field optics
- Guide wave optics
- Optoelectronics
- Nonlinear optics
- Plasmonics
- Quantum optics
- Optomechanics

Plenty of opportunities for manipulating light with nanowires
**Roadmap of Our Nanowire Photonics Research**

Since 2003

### Glass
- **2003**: Low-loss optical nanofiber
- **2004**: Nanofiber optics
- **2005**: Nanofiber coupler
- **2006**: Microfiber laser
  - *APL* 89, 143513 (2006)
- **2007**: Microfiber dye laser
  - *APL* 90, 233501 (2007)
- **2008**: Nanofiber MZI
- **2009**: Nanoﬁber photonic-plasmon near-field coupling
  - *Nano. Lett.* 9, 4515 (2009)
- **2010**: Nanowire photon-plasmon near-field coupling
- **2011**: Bandgap-engineered nanowires
  - *JACS* 133, 2037 (2011)
- **2012**: Microfiber microﬂuidic optical sensors
  - *Lab Chip* 11, 3720 (2011)

### Metal
- **2009**: Quantum-dot-activated nanofibers

### Polymer
- **2008**: Polymer single-nanofiber optical sensor

### Semiconductor
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Roadmap of Our Nanowire Photonics Research
Since 2003

### Light Manipulation
- Generation, propagation, modulation and detection of light with single nanowires

### Polymer
- Single-nanowire optical fibre lasers
- Plasma near-field coupled nanowires
- Quantum-dot activated nanofibers

### Semiconductor
- Bandgap-engineered fibres
- Microfiber dye laser
- Single-nanowire single-mode lasers

### Metal
- Carbon nanowire optical fibres

### Glass
- Low-loss optical nanofibres
- Nanofiber coupler

### Roadmap Image
- Nano Lett. 8, 2757 (2008)
- Lab Chip 11, 3720 (2011)
Contributed by many colleagues and students of our Nanophotonics Research Group

Group photo 2012-06
This talk — our recent research in

Nanowire Light Manipulation

1 Light Generation
   — Nanowire lasing

2 Light Propagation
   — Nanowire waveguiding

3 Light Modulation
   — Nanowire optical modulation

4 Light Detection
   — Nanowire photodetection
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3. Summary & Outlook
2.1 Nanowire Light Generation

One of the simplest approach — optically or electrically pumping an active nanowire (e.g., a semiconductor nanowire)
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2.1 Nanowire Light Generation

One of the simplest approach — optically or electrically pumping an active nanowire (e.g., a semiconductor nanowire)

However
ー this kind of laser
multimode $\rightarrow$ single cavity
high threshold $\rightarrow$ low endface reflectivity (1%)
Endface reflectivity

3D-FDTD

\[ R << \left( \frac{n-1}{n+1} \right)^2 \]

\( R \sim 0.01 \) @633nm

Low quality of the F-P cavity
\( \Rightarrow \) High threshold for nanowire lasing

S. S. Wang et al., *Opt. Express* 17, 10881 (2009)
Recently, relying on strong near-field coupling of nanowires, we proposed to create high-reflectivity Sagnac loop mirrors in a single nanowire

— a technique learnt from fiber optics

\[ T = (1 - 2K)^2 (1 - \gamma)^2 \exp(-2\alpha l) \]
\[ R = 4K(1-K)(1 - \gamma)^2 \exp(-2\alpha l) \]

Fold a nanowire into loop mirrors at both ends → increase the reflectivity and create additional cavities


Y. Xiao et al., *Nano Lett.* 11, 1122 (2011)
2.1 Nanowire Light Generation

4-cavity coupling $\rightarrow$ Mode selection via Vernier effect
$\rightarrow$ Single-mode low-threshold nanowire laser


One cavity, R $\sim$ 1%

4 coupled cavities
R $> 30\%$
2.1 Nanowire Light Generation

CdSe Nanowire
200-nm diameter
75-um length

Pumping light:
532-nm pulses
(5 kHz repetition rate, 15 ns pulse width)

Y. Xiao et al., Nano Lett. 11, 1122 (2011)
2.1 Nanowire Light Generation

Single-mode low-threshold nanowire laser

Y. Xiao et al., *Nano Lett.* 11, 1122 (2011)
Outline

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2.2 Nanowire Light Propagation

For dielectric nanowire waveguides, optical confinement is limited by optical diffraction.

Optical micrograph of 650-nm light guiding through a silica (D=500 nm), a ZnO (D=300 nm) and a silver (D=100 nm) nanowires in cascade.

<table>
<thead>
<tr>
<th>Photonic v.s. Plasmonic</th>
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<tbody>
<tr>
<td>Confinement</td>
</tr>
<tr>
<td>Less than $\lambda/5$</td>
</tr>
<tr>
<td>Better than $\lambda/10$</td>
</tr>
<tr>
<td>Loss</td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>Very high</td>
</tr>
</tbody>
</table>

X. Guo et al., Laser Photon. Rev. (In press)
Chemically grown metal nanowire is one of the most attractive candidates owing to its unparalleled uniformities and sidewall smoothness → low scattering loss.
However, there are great challenges for using tightly confined plasmonic nanowires, e.g., efficient coupling light into plasmons in single nanowires conventionally using bulk components with low efficiency.

A. W. Sanders et al., Nano Lett. 6, 1822 (2006)
Relying on tight confinement & strong near-field interaction of nanowire waveguides, we proposed directly coupling a dielectric and a metal nanowire by highly localized near-field interaction.
2.2 Nanowire Light Propagation

Which was confirmed by both numerical simulation and experimental result

Simulation

Experimental

Coupling a 633-nm light from a 500-nm-diameter silica nanofiber to a 200-nm-diameter silver nanowire

300-nm silica nanofiber
80-nm silver nanowire
@633-nm wavelength

Silica nanofiber
Silver nanowire

20μm
After optimization of the geometric parameters, coupling efficiency can go typically higher than 50%.

Fractional output from the Ag nanowire: 49%

Deducting the guiding loss:
- Ag about 0.43 dB/µm
- ZnO lower than 0.001dB/µm

Coupling efficiency ~75%

Silica nanofiber: D=500 nm
Ag nanowire: D=240 nm L=12µm

X. Guo et al., *Nano Lett.* 9, 4515 (2009)
Nanowire Coupling

Branch coupling of photonic and plasmonic nanowires

Coupling length ~220 nm

270-nm-diameter ZnO nanowire

240-nm-diameter Ag nanowire

X. Guo et al., Nano Lett. 9, 4515 (2009)
Nanowire Coupling

Branch coupling of photonic and plasmonic nanowires

X. Guo et al., *Nano Lett.* 9, 4515 (2009)
Fractional output from the Ag nanowire:

488nm —— 4%
532nm —— 8%
650nm —— 64%

Deducting the guiding loss:

Ag about 0.43 dB/µm
ZnO lower than 0.001 dB/µm

Coupling efficiency ~82%

X. Guo et al., *Nano Lett.* 9, 4515 (2009)
Applications

Hybrid “Photon-Plasmon” circuits and devices

Mach-Zehnder Interferometer

X. Guo et al., *Nano Lett.* 9, 4515 (2009)
As-assembled MZI

ZnO Nanowire: D 330 nm, L 89 µm
Ag Nanowire: D 120 nm, L 6.5 µm

X. Guo et al., *Nano Lett.* 9, 4515 (2009)
Hybrid “Photon-Plasmon” circuits and devices

Mach-Zehnder Interferometer

ZnO Nanowire: D 330 nm, L 89 µm
Ag Nanowire: D 120 nm, L 6.5 µm

FSR = 2.75 nm @710 nm

Potential applications: sensors, modulators etc.

X. Guo et al., Nano Lett. 9, 4515 (2009)
2.2 Nanowire Light Propagation

For tighter confinement with higher localization →

Au nanorods doped polymer nanowires

Au nanorods:
20 nm diameter, 100 nm length

P. Wang et al., Nano Lett. 12, 3145 (2012)
Au-Nanorod-doped nanofibers

Au nanorods doped PS nanofibers

SPP resonance spectra of Au nanorods doped in PAM polymer nanowires

P. Wang et al., *Nano Lett.* 12, 3145 (2012)
For guided light with wavelength of 785 nm (coincided with the L-SPR peak), the photon-LSPR-conversion efficiency goes up to **70% for a single nanorod**.

**Potentials**: optical sensing, nonlinear optics ...

P. Wang et al., *Nano Lett.* 12, 3145 (2012)
Au-Nanorod-doped nanofiber plasmonics

Humidity sensing

Fast response, high sensitivity, no photo-bleaching

P. Wang et al., *Nano Lett.* 12, 3145 (2012)
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2.4 Nanowire Light Detection

In conventional photodetection scheme, light was irradiated on the nanowire.

Relying on the tight confinement of a nanowire waveguide, we tried a waveguiding detection of light in single nanowires.

using NW length (~100 um) rather than the thickness (~ 0.5 um) for light capture
greatly enhance the light-matter interaction

2.4 Nanowire Light Detection

Make it possible for light detection with sub-bandgap effects

Enhanced Sub-bandgap effects

• Sub-bandgap photoconductivity, infrared optical quenching

F. X. Gu et al., Nanotechnology 22, 425201 (2011)
2.4 Nanowire Light Detection

Make it possible for light detection with sub-bandgap effects

Extrinsic photoconductivity

CdS nanowire photodetection @ 593 nm

Extend the spectral response to longer wavelength with high sensitivity

Compared with irradiation scheme, waveguiding detection offer an enhancement factor of \( \sim 10^5 \)

F. X. Gu et al., Nanotechnology 22, 425201 (2011)
To further extend the spectral range, we developed a source-moving VLS growth technique, and obtained bandgap-engineered nanowires.

CdSSe nanowire with gradient lattices and compositions along the length of the nanowire

To further extend the spectral range, we developed a source-moving VLS growth technique, and obtained bandgap-engineered nanowires with bandgap continuously engineered from 500 to 700 nm.

CdSSe nanowire with gradient lattices and compositions along the length of the nanowire.

2.4 Nanowire Light Detection

Using a bandgap-engineered CdSSe nanowire for light detection, and incorporated with infrared quenching effect


Infrared quenching of photoconductivity in a 350 nm diameter CdSSe NW. $I_b$ is established by 532 nm light at constant $P_{in}$ of 10 nW is quenched upon the addition of 1550 nm signal light

we have successfully covered the spectral range from 400 to 1600 nm using a single nanowire

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3. Summary & Outlook
Summary

- Waveguiding photonic nanowires offer favorable properties for manipulating light on the nanoscale.

- Manipulating light with single nanowires have brought new opportunities for light generation, propagation, modulation and detection.
Outlook

For light manipulation

How far can we go?
— depends on —
How well can we confine and guide the light

What's the next?
Nanowire + New Physics

Optical confinement

Quantum confinement

Atomic wire | Nanowire | Microwire

Glass NW | Semiconductor NW | Metal NW

Nanotube/Nanowire

Metal AW

0.1 nm 1 nm 10 nm 100 nm 1000 nm 10 um

Nonlinear optics | Quantum optics

Guide wave optics | Near-field optics

Guide wave optics

Guide wave optics

Guide wave optics
Optics in an optical nanofiber has been envisioned in glass optical nanofibers in recent years.

Acknowledgement

Collaborators

**Peking University** (China)
Qihuang Gong, Ying Gu, Lun Dai

**University of Houston** (USA)
Jiming Bao

**Fudan University** (China)
Weitao Liu

**Hunan University** (China)
Anlian Pan

**Harvard University** (USA)
Eric Mazur

**Zhejiang University** (China)
Min Qiu

**Gatech** (USA)
Younan Xia
Acknowledgement

National Science Foundation of China (NSFC)

National Basic Research Program (973) of China

Ministry of Education, China

National Science Foundation of USA (NSF)

etc.
Thank you