Less is more: Extreme optics with zero refractive index

3rd International Conference on Nano- and Microjoining
Niagara Falls, ON, Canada, 26 September 2016

@eric_mazur
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Extreme optics with zero refractive index

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Enabling nanophotonics
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Enabling nanophotonics

1 zero index
2 fabrication
Enabling nanophotonics

1. zero index
2. fabrication
3. results
wave equation

\[ \nabla^2 \vec{E} - \frac{\mu \varepsilon}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \]

solution

\[ \vec{E} = \vec{E}_0 e^{i(kx - \omega t)} \]

where

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} c = \frac{1}{n} c \]
wave equation

\[ \nabla^2 \vec{E} - \frac{\mu}{\epsilon} \vec{E} = 0 \]

solution

\[ \vec{E} = \vec{E}_0 e^{i(kx - \omega t)} \]

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1 zero index
wave equation

\[ \nabla^2 \vec{E} - \frac{\mu}{\epsilon} \frac{\vec{E}}{c^2} = 0 \]

solution

\[ \vec{E} = \vec{E}_o e^{i(kx - \omega t)} \quad \rightarrow \quad \vec{E} = \vec{E}_o e^{-i\omega t} \]

where

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\epsilon \mu}} \quad c = \frac{1}{n} \quad c \]

1 zero index
wave equation

\[ \nabla^2 \vec{E} - \frac{\mu}{\varepsilon_0^2} \vec{E} = 0 \]

solution

\[ \vec{E} = \vec{E}_0 e^{i(kx - \omega t)} \quad \rightarrow \quad \vec{E} = \vec{E}_0 e^{-i\omega t} \]

where

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} \quad c = \frac{1}{n} c \quad \rightarrow \quad \infty \]

zero index
$n > 1$
$0 < n < 1$
$n = 0$
n < 0
zero index
What about causality?
What about causality?
What about causality?
What about causality?

speed of light $c$

zero index
What about causality?

speed of light $c$

constant phase

What about causality?

zero index

distance (µm)

time (fs)

250
200
150
100
50
0

0 5 10 15

distance (µm)
What about causality?

- group velocity $v_g > c$
- speed of light $c$
- constant phase

[Diagram showing a plot with axes for distance (µm) and time (fs), illustrating the relationship between group velocity and speed of light.]
What about causality?

- group velocity: $v_g > c$
- speed of light: $c$
- constant phase

Diagram: Graph showing time (fs) on the y-axis and distance (µm) on the x-axis. The graph demonstrates the relationship between time and distance, highlighting the concept of causality in the context of light propagation.
What about causality?

- **group velocity**: $v_g > c$
- **speed of light**: $c$
- **constant phase**
- **high-frequency precursors**

**1 zero index**
What about causality?

signal *always* travels at speed $c$!
What about causality?
What can we do with uniform phase?
$n = 0$
$n = 0$
$n = 0$
“tunneling with infinite decay length”

\[ n = 0 \]
how?

\[ n = \sqrt{\varepsilon \mu} \]
how?

\[ n = \sqrt{\varepsilon \mu} \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \]
how?

\[ n = \sqrt{\varepsilon \mu} \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \]
how?

\[ \varepsilon \to 0 \quad \text{and} \quad n = \sqrt{\varepsilon \mu} \to 0 \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \]
how?

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but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \to \infty \]
how?

\[ \varepsilon \rightarrow 0 \quad n = \sqrt{\varepsilon \mu} \rightarrow 0 \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \rightarrow 1 \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \rightarrow \infty \]
how?

\[ \mu \to 0 \quad \quad n = \sqrt{\varepsilon \mu} \to 0 \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \]

\( \text{zero index} \)
how?

\[ \mu \to 0 \quad \quad n = \sqrt{\varepsilon \mu} \to 0 \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \to 0 \]

\[ \text{zero index} \]
how?

\[ \mu \to 0 \]

\[ n = \sqrt{\varepsilon \mu} \to 0 \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z - 1}{Z + 1} \to -1 \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \to 0 \]
how?

\[ \varepsilon, \mu \rightarrow 0 \quad \quad n = \sqrt{\varepsilon \mu} \rightarrow 0 \]

but \( \varepsilon \) and \( \mu \) also determine reflectivity

\[ R = \frac{Z-1}{Z+1} \]

where

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \quad \text{finite!} \]
but $\mu \neq 1$ requires a magnetic response!
Engineering a magnetic response
Engineering a magnetic response

bulk material

properties derive from constituent atoms
Engineering a magnetic response

bulk material

properties derive from constituent atoms
Engineering a magnetic response

bulk material

properties derive from constituent atoms

composite material

properties derive from constituent units

$E$
Engineering a magnetic response

bulk material

properties derive from
constituent atoms

composite material

properties derive from
constituent units

zero index
Engineering a magnetic response

use array of dielectric rods
Engineering a magnetic response

incident electromagnetic wave ($\lambda_{\text{eff}} \approx a$)
Engineering a magnetic response

produces an electric response…
Engineering a magnetic response

... but different electric fields front and back...
Engineering a magnetic response

...induce different polarizations on opposite sides...
Engineering a magnetic response

...causing a current loop...
Engineering a magnetic response

...which, in turn, produces an induced magnetic field
Engineering a magnetic response

adjust design so electrical and magnetic resonances coincide
Engineering a magnetic response

adjustable parameters
Engineering a magnetic response

adjustable parameters

$d$
Engineering a magnetic response

adjustable parameters

$d$

1 zero index
Engineering a magnetic response

adjustable parameters

$\alpha$

$\delta$

$\sim$
Engineering a magnetic response

adjustable parameters

1 zero index
Engineering a magnetic response

adjustable parameters

\[ d = 422 \text{ nm}, \quad a = 690 \text{ nm}, \quad n = 1.57 \quad (\text{SU8}) \]
relative permittivity/permeability

$\text{Re}(\varepsilon_r^{\text{eff}})$

$\text{Re}(\mu_r^{\text{eff}})$

wavelength (nm)

1520 1560 1600 1640 1680

1 zero index
The graph shows the real part of the refractive index ($\text{Re}(n_{\text{eff}})$) and the real part of the impedance ($\text{Re}(Z_{\text{eff}})$) as functions of wavelength (nm). The wavelength range is from 1520 nm to 1680 nm. The refractive index values are negative, indicating a negative index of refraction, which is characteristic of zero-index materials. The impedance values are positive and increase with wavelength.
at design wavelength (1590 nm)
below design wavelength (1530 nm)
above design wavelength (1650 nm)
How to fabricate?

1 zero index
2 fabrication
On-chip zero-index fabrication

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. zero index
2. fabrication
On-chip zero-index fabrication

1. zero index
2. fabrication
On-chip zero-index fabrication

1. zero index
2. fabrication
On-chip zero-index fabrication

1 zero index

2 fabrication
On-chip zero-index fabrication

1. zero index
2. fabrication
1 zero index
2 fabrication
1 zero index  2 fabrication
1 zero index                             2 fabrication
1 zero index  
2 fabrication
1  zero index

2  fabrication

500 nm

1  zero index

2  fabrication

500 nm
Can make this in any shape!
On-chip zero-index prism

1. zero index
2. fabrication
3. results
On-chip zero-index prism

1. zero index
2. fabrication
3. results
On-chip zero-index prism

1. zero index
2. fabrication
3. results
On-chip zero-index prism

1 zero index
2 fabrication
3 results
On-chip zero-index prism

1. zero index
2. fabrication
3. results
On-chip zero-index prism

1. zero index
2. fabrication
3. results
On-chip zero-index prism

1 zero index
2 fabrication
3 results
On-chip zero-index prism
On-chip zero-index prism

1. zero index
2. fabrication
3. results
Su8 slab waveguide

prism

Si waveguide

1. zero index
2. fabrication
3. results
SU8 slab waveguide

prism

Si waveguide

SU8 calibration waveguide

1. zero index
2. fabrication
3. results
1 zero index  2 fabrication  3 results
On-chip zero-index prism

1 zero index  2 fabrication  3 results
50 µm

λ = 1570 nm
50 µm

λ = 1570 nm

1 zero index
2 fabrication
3 results
50 µm

\[ \lambda = 1570 \text{ nm} \]

1. zero index
2. fabrication
3. results
50 µm

\[ \lambda = 1570 \text{ nm} \]

1. zero index
2. fabrication
3. results
Wavelength dependence of refraction angle
Wavelength dependence of refraction angle

Diagram showing the wavelength dependence of the refractive angle. The x-axis represents the wavelength in nanometers (nm), ranging from 1480 to 1680 nm. The y-axis represents the refractive angle, with values ranging from $-45^\circ$ to $45^\circ$. The graph illustrates how the refractive angle changes with different wavelengths.
Wavelength dependence of refraction angle
Wavelength dependence of refraction angle

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>1480</th>
<th>1520</th>
<th>1560</th>
<th>1600</th>
<th>1640</th>
<th>1680</th>
</tr>
</thead>
<tbody>
<tr>
<td>refractive angle α</td>
<td>45°</td>
<td>30°</td>
<td>15°</td>
<td>0°</td>
<td>-15°</td>
<td>-30°</td>
</tr>
</tbody>
</table>

1. zero index
2. fabrication
3. results
Wavelength dependence of index

\[ n_{\text{prism}} = n_{\text{slab}} \frac{\sin \alpha}{\sin 45^\circ} \]
Wavelength dependence of index

![Graph showing the wavelength dependence of the refractive index.](image)

**1. Zero index**

**2. Fabrication**

**3. Results**
Wavelength dependence of index

![Graph showing wavelength dependence of index](image)

- **Simulation**
- **Experiment**

1. Zero index
2. Fabrication
3. Results
Wavelength dependence of index

\[ n = 0 \]

Simulation

Experiment
Zero-index metamaterials

More info: download paper!

1. zero index
2. fabrication
3. results
Where do we go from here?

1. zero index
2. fabrication
3. results
Where do we go from here?

Need to eliminate losses in metal mirrors

1 zero index  2 fabrication  3 results
Where do we go from here?

Removing mirrors causes radiative losses

1 zero index  2 fabrication  3 results
Where do we go from here?

Eliminate losses using “bound in continuum” state

1 zero index     2 fabrication     3 results
Exciting applications ahead

supercoupling

1 zero index  2 fabrication  3 results
Exciting applications ahead

1. zero index
2. fabrication
3. results
Exciting applications ahead

1. zero index
2. fabrication
3. results

supercoupling

NLO

quantum optics

SHG $\omega' = 2\omega$
Exciting applications ahead

- **SHG**
  - \( \omega' = 2\omega \)
  - Phase matching

**Supercoupling**

**NLO**

**Quantum optics**

1. Zero index
2. Fabrication
3. Results
Exciting applications ahead

- **SHG**
  - $\omega' = 2\omega$
  - phase matching

**Supercoupling**

**NLO**

**Quantum optics**

1. Zero index
2. Fabrication
3. Results
Exciting applications ahead

SHG

\[ \omega' = 2\omega \]

phase matching

supercoupling

NLO

quantum optics

1 zero index  2 fabrication  3 results
Exciting applications ahead

SHG $\omega' = 2\omega$

at zero index

$k = 0$

supercoupling

NLO

quantum optics

1 zero index

2 fabrication

3 results
Exciting applications ahead

SHG \[ \omega' = 2\omega \]

at zero index \[ \vec{k}' = 0 \]

supercoupling

NLO

quantum optics

1. zero index
2. fabrication
3. results