Less is more:
Extreme optics with zero refractive index

Sichuan University
Chengdu, China, 21 December 2015
Less is more: Extreme optics with zero refractive index

Sichuan University
Chengdu, China, 21 December 2015
n
index
zero index
experiments
Propagation of EM wave
Propagation of EM wave

governed by wave equation

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

governed by wave equation

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

Solution:

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

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} \frac{c}{n} = \frac{1}{n} c \]
Propagation of EM wave
governed by wave equation

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

Solution:

\[ \vec{E} = \vec{E}_0 e^{i(\mathbf{k} \cdot \mathbf{x} - \omega t)} \]

where

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

and

\[ n = \sqrt{\varepsilon \mu} \].
Propagation of EM wave

governed by wave equation

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where

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

and

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

In dispersive media \( n = n(\omega) .\)
Dielectric constant

Lorentz oscillator

![Diagram of dielectric constant and Lorentz oscillator](image)
Dielectric constant

- Frequency (rad/s)
- Dielectric constant
- Index

Graph showing the dielectric constant as a function of frequency (rad/s) with markers for MW, IR, VIS, UV, and X regions.
Dielectric constant

![Graph showing the dielectric constant against frequency in radians per second (rad/s), with frequency ranging from $10^6$ to $10^{18}$ and dielectric constant ranging from 1 to 10, with vacuum represented at 1. The graph indicates distinct regions for microwave (MW), infrared (IR), visible (VIS), ultraviolet (UV), and X-ray.]
Dielectric constant

![Graph showing dielectric constant vs. frequency (rad/s)]

- **Frequency (rad/s):** 10^6, 10^8, 10^10, 10^12, 10^14, 10^16, 10^18
- **Dielectric constant:** 1 (vacuum), 10^6, 10^8, 10^10, 10^12, 10^14, 10^16, 10^18
- **Labels:**
  - Electronic
  - Vacuum
Dielectric constant
Dielectric constant
Dielectric constant

- Dipolar
- Ionic
- Electronic
- Vacuum
Lorentz and Drude models

dielectric

metal
for a strong (dielectric) resonance $\varepsilon$ can become negative
Lorentz and Drude models

valence electrons in dielectric then behave like a plasma
Lorentz and Drude models

with plasma frequency above the resonance
Lorentz and Drude models

(and far below the UV region)
Index also determined by magnetic response

\[ n = \sqrt{\frac{\mu}{\epsilon}} \]
Index also determined by magnetic response

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

and magnetic response shows similar resonances
Magnetic response

![Graph showing magnetic susceptibility versus frequency (rad/s). The graph indicates the magnetic response across various domains: domains, nuclear, electronic, and vacuum. The x-axis represents frequency (rad/s) ranging from $10^2$ to $10^{14}$, while the y-axis represents magnetic susceptibility. The graph notes that the response is divided into microwave (MW) and infrared (IR) regions.]
Magnetic response

but magnetic resonances occur below optical frequencies
Magnetic response

so, in optical regime, $\mu \approx 1$
Index of refraction

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

Both \( \epsilon \) and \( \mu \) are complex and their real parts can be negative.
Index of refraction

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

Both \( \varepsilon \) and \( \mu \) are complex and their real parts can be negative.

What happens when \( \text{Re} \varepsilon \) and/or \( \text{Re} \mu \) is negative?
Write complex quantities as

\[ \epsilon = |\epsilon| e^{i\theta} \quad \mu = |\mu| e^{i\phi} \]
Write complex quantities as

\[ \varepsilon = |\varepsilon| e^{i\theta} \quad \mu = |\mu| e^{i\phi} \]
Write complex quantities as

\[ \varepsilon = |\varepsilon| e^{i\theta} \quad \mu = |\mu| e^{i\phi} \]

Index

\[ n = \sqrt{\varepsilon \mu} e^{i\theta + \phi} \]
Write complex quantities as

\[ \varepsilon = |\varepsilon| e^{i\theta} \quad \mu = |\mu| e^{i\phi} \]

Index

\[ n = \sqrt{|\varepsilon||\mu|} e^{i\frac{\theta+\phi}{2}} \]
Q: Is this the only possible solution?

1. yes
2. no, there’s one more
3. there are many more
4. it depends
There is another root...
There is another root...

Can add $2\pi$ to exponent

$$e^{i(\theta+\phi)} = e^{i[\theta+\phi+2\pi]}$$
There is another root...

Can add \(2\pi\) to exponent

\[ e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]} \]

and so

\[ n = \sqrt{\varepsilon \mu} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]} \]
There is another root...

Can add $2\pi$ to exponent

$$e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]}$$

and so

$$n = \sqrt{\varepsilon \mu} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$
There *is* another root...

Can add $2\pi$ to exponent

$$e^{i(\theta+\phi)} = e^{i[\theta+\phi+2\pi]}$$

and so

$$n = \sqrt{\varepsilon \mu} e^{i\left(\frac{\theta+\phi + \pi}{2}\right)}$$

but...

$$k = \frac{2\pi n}{\lambda_o} = \frac{2\pi (n' + in'')}{\lambda_o} = k' + ik''$$
There is another root...

Can add $2\pi$ to exponent

$$e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]}$$

and so

$$n = \sqrt{\varepsilon|\mu}e^{i\frac{\theta+\phi+\pi}{2}}$$

but...

$$k = \frac{2\pi n}{\lambda_o} = \frac{2\pi(n'+in'')}{\lambda_o} = k' + ik''$$

and

$$E = E_oe^{i(kx-\omega t)} = E_oe^{-k''x}e^{i(k'x-\omega t)}$$
There is another root...

Can add $2\pi$ to exponent

$$e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]}$$

and so

$$n = \sqrt{\varepsilon \| \mu \} e^{i \left[ \frac{\theta+\phi+\pi}{2} \right]}$$

but...

$$k = \frac{2\pi n}{\lambda_o} = \frac{2\pi (n' + in'')}{\lambda_o} = k' + ik''$$

and

$$E = E_o e^{i(kx - \omega t)} = E_o e^{-k''x} e^{i(k'x - \omega t)}$$
There is another root...

Can add $2\pi$ to exponent

\[ e^{i(\theta+\phi)} = e^{i[\theta+\phi+2\pi]} \]

and so

\[ n = \sqrt{\varepsilon \mu} e^{i\left[\frac{\theta+\phi+\pi}{2}\right]} \]

but...

\[ k = \frac{2\pi n}{\lambda_o} = \frac{2\pi(n' + in'')}{\lambda_o} = k' + ik'' \]

and

\[ E = E_o e^{i(kx-\omega t)} = E_o e^{-k''x} e^{i(k'x-\omega t)} \]
There *is* another root...

Can add $2\pi$ to exponent

$$e^{+i(\theta+\phi)} = e^{+i[\theta+\phi+2\pi]}$$

and so

$$n = \sqrt{\varepsilon \mu} e^{i\left[\frac{\theta+\phi}{2} + \pi\right]}$$

but...

$$k = \frac{2\pi n}{\lambda_o} = \frac{2\pi (n' + i n'')}{\lambda_o} = k' + ik''$$

and

$$E = E_o e^{i(kx - \omega t)} = E_o e^{-k'' x} e^{i(k' x - \omega t)}$$

must lie here for passive material
Q: Is this the only possible solution?

1. yes ✓
2. no, there’s one more
3. there are many more
4. it depends
To find $n$ (passive materials):

1. Draw line that bisects $\epsilon$ and $\mu$
2. Choose upper branch
For certain values of $\epsilon$ and $\mu$, we can get a negative $\text{Re}(n)$!
Q: Must both $\text{Re}\epsilon < 0$ and $\text{Re}\mu < 0$ to get a negative index?

1. yes
2. no
Q: Must both $\text{Re}\,\epsilon < 0$ and $\text{Re}\,\mu < 0$ to get a negative index?

1. yes

2. no ✓
Note: need magnetic response to achieve $n \leq 0!$
Now remember

\[ k = \frac{2\pi n}{\lambda_o} = \frac{2\pi (n' + in'')}{\lambda_o} = k' + ik'' \]
Now remember

\[ k = \frac{2\pi n}{\lambda_o} = \frac{2\pi(n' + in'')}{\lambda_o} = k' + ik'' \]

Spatial and temporal dependence of wave component

\[ E = E_0 e^{i(kx - \omega t)} = E_0 e^{-k''x} e^{i(k'x - \omega t)} \]
Now remember

\[ k = \frac{2\pi n}{\lambda_o} = \frac{2\pi(n' + in'')}{\lambda_o} = k' + ik'' \]

Spatial and temporal dependence of wave component

\[ E = E_0 e^{i(kx - \omega t)} = E_0 e^{-k''x} e^{i(k'x - \omega t)} \]

When \( \text{Re}(n) < 0, \ k' < 0 \), and so phase velocity reversed!
When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
classification of (non-lossy) materials
classification of (non-lossy) materials

\[ \text{Re } \varepsilon > 0 \quad \text{Re } \mu > 0 \]

dielectrics

\[ \text{Re } \varepsilon > 0 \quad \text{Re } \mu > 0 \]
classification of (non-lossy) materials

\[ \text{Re } \varepsilon < 0 \quad \text{Re } \mu > 0 \]

\[ \text{Re } \varepsilon > 0 \quad \text{Re } \mu > 0 \]

 metals  \hspace{2cm} \text{dielectrics}
classification of (non-lossy) materials

Re $\varepsilon$ $<$ 0 $\Re \mu > 0$

Re $\varepsilon$ $>$ 0 $\Re \mu > 0$

metals
dielectrics

Re $\varepsilon$

Re $\mu$
classification of (non-lossy) materials

- **Re $\varepsilon < 0$  Re$\mu > 0$**
  - metals
  - electric plasma
  - evanescent wave

- **Re $\varepsilon > 0$  Re$\mu > 0$**
  - dielectrics
  - propagating wave
classification of (non-lossy) materials

- **Re $\varepsilon > 0$ Re $\mu > 0$**
  - dielectrics
  - electric plasma
  - evanescent wave

- **Re $\varepsilon < 0$ Re $\mu > 0$**
  - metals
  - evanescent wave

- **Re $\varepsilon > 0$ Re $\mu < 0$**
  - negative index

- **Re $\varepsilon < 0$ Re $\mu < 0$**
  - propagating wave
classification of (non-lossy) materials

- **Re(ε) < 0, Re(μ) > 0**: electric plasma, evanescent wave
- **Re(ε) > 0, Re(μ) > 0**: propagating wave
- **Re(ε) < 0, Re(μ) < 0**: negative index, reverse propagating wave

**Metals**:
- **Re(ε) < 0, Re(μ) > 0**: electric plasma
- **Re(ε) < 0, Re(μ) < 0**: negative index

**Dielectrics**:
- **Re(ε) > 0, Re(μ) > 0**: propagating wave
classification of (non-lossy) materials

Re\(\mu\) vs Re\(\varepsilon\):
- **Metals** (Re\(\varepsilon < 0\), Re\(\mu > 0\))
  - Electric plasma
  - Evanescent wave

- **Dielectrics** (Re\(\varepsilon > 0\), Re\(\mu > 0\))
  - Propagating wave

- **Negative index** (Re\(\varepsilon < 0\), Re\(\mu < 0\))
  - Magnetic plasma
  - Reverse propagating wave

- **Evanescent wave** (Re\(\varepsilon > 0\), Re\(\mu < 0\))
  - (Not in optical regime)
common materials very limited

- Metals: Re $\varepsilon < 0$, Re $\mu > 0$
  - Electric plasma
  - Evanescent wave

- Dielectrics: Re $\varepsilon > 0$, Re $\mu > 0$
  - Propagating wave

- Negative index: Re $\varepsilon < 0$, Re $\mu < 0$
  - Magnetic plasma
  - Reverse propagating wave

- Not in optical regime: Re $\varepsilon > 0$, Re $\mu < 0$
common materials very limited

limited by diffraction

Re ε < 0  Reμ > 0
electric plasma
 evanescent wave

Re ε > 0  Reμ > 0
dielectrics
 propagating wave

Re ε < 0  Reμ < 0
magnetic plasma
 reverse propagating wave

Re ε > 0  Reμ < 0
negative index
(1st optical regime)

Re ε < 0  Reμ < 0
magnetic plasma
 evanescent wave
(1st optical regime)
common materials very limited

lossy & no propagation

\[ \text{lossy & no propagation} \]

\[ \text{index} \]
common materials very limited

- metals: \( \text{Re} \varepsilon < 0 \) \( \text{Re} \mu > 0 \)
  - electric plasma
  - evanescent wave

- dielectrics: \( \text{Re} \varepsilon > 0 \) \( \text{Re} \mu > 0 \)
  - propagating wave

- magnetic plasma: \( \text{Re} \varepsilon < 0 \) \( \text{Re} \mu < 0 \)
  - reverse propagating wave
  - evanescent wave

- negative index
  - (not in optical regime)

superlensing but...
common materials very limited

we’re stuck here!
What happens on the axes?

- **Re \( \varepsilon > 0 \) Re \( \mu > 0 \)**: Dielectrics
  - Electric plasma
  - Evanescent wave
  - Magnetic plasma
  - Evanescent wave

- **Re \( \varepsilon < 0 \) Re \( \mu > 0 \)**: Metals
  - Electric plasma
  - Evanescent wave

- **Re \( \varepsilon > 0 \) Re \( \mu < 0 \)**: Negative index
  - Reverse propagating wave

- **Re \( \varepsilon < 0 \) Re \( \mu < 0 \)**: (Not in optical regime)
what if we let $\varepsilon = 0$?

<table>
<thead>
<tr>
<th>Re $\varepsilon$</th>
<th>Re $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;$ 0</td>
<td>$&gt;$ 0</td>
</tr>
<tr>
<td>electric plasma</td>
<td>propagating wave</td>
</tr>
<tr>
<td>$&lt;$ 0</td>
<td>$&lt;$ 0</td>
</tr>
<tr>
<td>magnetic plasma</td>
<td>evanescent wave</td>
</tr>
<tr>
<td>$&gt;$ 0</td>
<td>$&gt;$ 0</td>
</tr>
<tr>
<td>dielectrics</td>
<td>reverse propagating wave</td>
</tr>
</tbody>
</table>

negative index

(not in optical regime)

1 index

2 zero index
what if we let $\varepsilon = 0$?

if $\varepsilon = 0$, then $n = 0$!

1 index

2 zero index
Q: If \( n = 0 \), which of the following is true?

1. the frequency goes to zero.
2. the phase velocity becomes infinite.
3. both of the above.
4. neither of the above.
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

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

solution

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

where

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

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

solution

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

where

$$\frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} c = \frac{1}{n} c$$

1 index 2 zero index
wave equation

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

solution

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

where

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\epsilon\mu}} c = \frac{1}{n} c \quad \rightarrow \quad \infty \]
Q: If \( n = 0 \), which of the following is true?

1. the frequency goes to zero.
2. the phase velocity becomes infinite. ✓
3. both of the above.
4. neither of the above.
$n > 1$
$0 < n < 1$
$n = 0$

1. index
2. zero index
\( n < 0 \)
$n = 0$
\[ n = 0 \]
$n = 0$
“tunneling with infinite decay length”

\[ n = 0 \]
how?

\[ n = \sqrt{\varepsilon \mu} \]
but $\varepsilon$ and $\mu$ also determine reflectivity

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$
how?

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

where

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

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

where

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

1 index  2 zero index
how?

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

where

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

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \to 1 \]

where

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

1 index 2 zero index
how?

μ → 0 \quad \quad n = \sqrt{\varepsilon \mu} \quad \rightarrow 0

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

where

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

1. index
2. zero index
how?

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

where

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

1. index
2. zero index
how?

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \to -1 \]

where

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

1 index 2 zero index
how?

\[ \varepsilon, \mu \to 0 \]

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

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

\[ r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

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

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…

$\vec{E}$
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

1 index                             2 zero index                 3 experiments
Engineering a magnetic response

adjustable parameters

d

1 index

2 zero index

3 experiments
Engineering a magnetic response

adjustable parameters

\[ d \quad a \quad d \quad d \quad d \quad d \quad d \]
Engineering a magnetic response

adjustable parameters

index 1  zero index 2  experiments 3
The graph shows the relationship between frequency and the real part of the relative permittivity and permeability, $\Re(\varepsilon_{r,\text{eff}})$ and $\Re(\mu_{r,\text{eff}})$, respectively. The x-axis represents the frequency $\omega a / 2 \pi c$, and the y-axis represents the relative permittivity/permeability. The graph includes two lines: one for $\Re(\varepsilon_{r,\text{eff}})$ and another for $\Re(\mu_{r,\text{eff}})$. The lines are labeled accordingly in the graph. The caption includes three main points:

1. **Index**: This refers to the specific index of the material being studied.
2. **Zero Index**: This indicates a comparison or reference to a zero-index material.
3. **Experiments**: This denotes the nature of the study or the data collected through experiments.
frequency ($\omega a/2\pi c$)

refractive index

Re($n_{\text{eff}}$)

Re($Z_{\text{eff}}$)

0.40 0.42 0.44 0.46 0.48 0.50

/endash\-cap0.6

/endash\-cap0.4

/endash\-cap0.2

0.2 0.4 0.6

4

2

0

0

impedance

refractive index

Re($Z_{\text{eff}}$)

Re($n_{\text{eff}}$)

1  index

2  zero index

3  experiments

frequency ($\omega a/2\pi c$)
How to fabricate?
On-chip zero-index fabrication

1 index

2 zero index

3 experiments
On-chip zero-index fabrication

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

1. index
2. zero index
3. experiments

SiO₂
On-chip zero-index fabrication

Si

SiO₂

Au

1 index

2 zero index

3 experiments
On-chip zero-index fabrication

1. Index
2. Zero index
3. Experiments
On-chip zero-index fabrication

1. index
2. zero index
3. experiments
1 index                             2 zero index                 3 experiments
On-chip zero-index prism
On-chip zero-index prism
On-chip zero-index prism
On-chip zero-index prism
On-chip zero-index prism
On-chip zero-index prism
On-chip zero-index prism

1 index  2 zero index  3 experiments
On-chip zero-index prism
On-chip zero-index prism
1 index                             2 zero index                 3 experiments
1 index                             2 zero index                 3 experiments
SU8 slab waveguide

prism

Si waveguide

1 index
2 zero index
3 experiments
SU8 slab waveguide

prism

SU8 calibration waveguide

Si waveguide

1 index                             2 zero index                 3 experiments
at design wavelength (1590 nm)
below design wavelength (1530 nm)
above design wavelength (1650 nm)
On-chip zero-index prism

1 index
2 zero index
3 experiments
$50 \, \mu\text{m}$

$\lambda = 1570 \, \text{nm}$
1 index  2 zero index  3 experiments

$50 \, \mu m$

$\lambda = 1570 \, \text{nm}$
50 µm

$\lambda = 1570 \text{ nm}$

1. index
2. zero index
3. experiments
index  zero index  experiments
Wavelength dependence of refraction angle

1. Index
2. Zero index
3. Experiments
Wavelength dependence of refraction angle

index                             zero index                 experiments
Wavelength dependence of refraction angle

- Index
- Zero index
- Experiments
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 $\alpha$</td>
<td>45°</td>
<td>30°</td>
<td>15°</td>
<td>0°</td>
<td>$-15^\circ$</td>
<td>$-30^\circ$</td>
</tr>
</tbody>
</table>

Wavelength dependence of refraction angle

1. index
2. zero index
3. experiments
Wavelength dependence of index

1. index
2. zero index
3. experiments
Wavelength dependence of index

![Graph showing wavelength dependence of index with experiment and simulation data.](image)

- **1** index
- **2** zero index
- **3** experiments
More extreme optics

- suppressing losses
- beam steering & supercoupling
- nonlinear optics
- quantum optics

1 index
2 zero index
3 experiments
• on-chip zero-index material
• uniform field inside material (infinite wavelength)
• many exciting applications ahead!
Zero-index metamaterials

PHASE-CHANGE MATERIALS
Multi-level memory

MID-INFRARED SOURCES
Powerful pulse train

OPTICAL COMPUTING
Analog approach

More info: download paper!
The Team: Yang Li, Shota Kita, Orad Reshef, Philip Muñoz, Daryl Vulis, Marko Lončar

Funding: National Science Foundation

for a copy of this presentation:

http://ericmazur.com

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