Less is more: Extreme optics with zero index

Brown University
Providence, RI, 28 September 2015
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@eric__mazur
1 index  2 zero index  3 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:

$$\vec{E} = \vec{E}_o e^{i(kx - \omega t)}$$
Propagation of EM wave
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\[ \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} \frac{c}{n} = \frac{1}{n} c \]
Propagation of EM wave

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where

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

and

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

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

where

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

and

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

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

Lorentz oscillator

![Graph showing dielectric constant and its components, ε', ε'', and ω.](image)
Dielectric constant
Dielectric constant

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

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

- MW
- IR
- VIS
- UV
- X
Dielectric constant

![Graph showing the change in dielectric constant with frequency.](Image)

- **Frequency (rad/s)**: 10^6 to 10^18
- **Dielectric Constant**: 1 to 10^12
- **Regions**: Vacuum, Electronic, Microwave (MW)

**Legend**: MW - Microwave
Dielectric constant
Dielectric constant

- Dipolar
- Ionic
- Electronic
- Vacuum

Frequency (rad/s):
- $10^6$
- $10^8$
- $10^{10}$
- $10^{12}$
- $10^{14}$
- $10^{16}$
- $10^{18}$
Dielectric constant

![Graph showing dielectric constant variation with frequency](image)

- **Frequency (rad/s)**
- **Dielectric constant**
  - Vacuum: 1
  - Electronic: 1
  - Ionic: 1
  - Dipolar: 1

Frequency ranges:
- **MW**
- **IR**
- **VIS**
- **UV**
- **X**
Lorentz and Drude models

The diagrams illustrate the behavior of dielectric and metal materials with respect to frequency ($\omega$) and permittivity ($\varepsilon$). The permittivity is divided into real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts.

- **Dielectric**: The diagram shows a peak at $\omega_j$ and a dip at $\omega''$.
- **Metal**: The diagram shows a sharp increase at $\omega_p$.
for a strong (dielectric) resonance $\varepsilon$ can become negative

Lorentz and Drude models
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

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

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

and magnetic response shows similar resonances
Magnetic response

![Graph showing magnetic susceptibility vs. frequency (rad/s) with domains, nuclear, electronic, and vacuum levels.](image)
Magnetic response

but magnetic resonances occur below optical frequencies

![Graph showing magnetic response](chart.png)
Magnetic response

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

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

Both \( \varepsilon \) 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

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

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Write complex quantities as

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

Index

\[ n = \sqrt{|\varepsilon| |\mu| e^{i(\theta+\phi)/2}} \]
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

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

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

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

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...

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and so

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

but...

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

1 index
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 $\Re \epsilon < 0$ and $\Re \mu < 0$ 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

\[ k = \frac{2\pi n}{\lambda_o} = \frac{2\pi (n' + in'')}{\lambda_o} = k' + ik'' \]
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Spatial and temporal dependence of wave component

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

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

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

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

dielectrics

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

\[
\begin{align*}
\text{Re} \varepsilon &< 0 \quad \text{Re} \mu > 0 \\
\text{Re} \varepsilon &> 0 \quad \text{Re} \mu > 0 \\
\end{align*}
\]
classification of (non-lossy) materials

\[
\begin{align*}
\text{metals} & : \Re \varepsilon < 0 \quad \Re \mu > 0 \\
\text{dielectrics} & : \Re \varepsilon > 0 \quad \Re \mu > 0
\end{align*}
\]
classification of (non-lossy) materials

- **Dielectrics**
  - \(\text{Re} \, \varepsilon > 0\)
  - \(\text{Re} \, \mu > 0\)
  - Evanescent wave
  - Propagating wave

- **Metals**
  - \(\text{Re} \, \varepsilon < 0\)
  - \(\text{Re} \, \mu > 0\)
  - Electric plasma

Index
classification of (non-lossy) materials

- **Re \(\varepsilon\) > 0, Re \(\mu\) > 0**: Dielectrics
- **Re \(\varepsilon\) < 0, Re \(\mu\) > 0**: Electric plasma, evanescent wave
- **Re \(\varepsilon\) < 0, Re \(\mu\) < 0**: Negative index
- **Re \(\varepsilon\) > 0, Re \(\mu\) > 0**: Propagating wave
classification of (non-lossy) materials

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

dielectrics

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

electric plasma

evanescent wave

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

metal

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

negative index

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

reverse propagating wave

propagating wave
classification of (non-lossy) materials

- **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)
  - $\Re \varepsilon > 0$, $\Re \mu < 0$
  - Evanescent wave
common materials very limited

- Re $\varepsilon < 0$ Re$\mu > 0$
  - electric plasma
  - evanescent wave
- Re $\epsilon > 0$ Re$\mu > 0$
  - propagating wave
- Re $\epsilon < 0$ Re$\mu < 0$
  - magnetic plasma
  - reverse propagating wave
- Re $\epsilon > 0$ Re$\mu < 0$
  - evanescent wave

(not in optical regime)
common materials very limited

limited by diffraction

 metals
 Re ε < 0  Reμ > 0
 electric plasma
 evanescent wave

 Re ε > 0  Reμ > 0
 dielectrics
 propagating wave

 magnetic plasma
 reverse propagating wave
 evanescent wave
 Re ε < 0  Reμ < 0
 negative index

 Re ε > 0  Reμ < 0
 (not in optical regime)
common materials very limited

lossy & no propagation

1 index
common materials very limited

\[ \Re \varepsilon < 0 \quad \Re \mu > 0 \]
- electric plasma
- evanescent wave

\[ \Re \varepsilon > 0 \quad \Re \mu > 0 \]
- propagating wave

\[ \Re \varepsilon < 0 \quad \Re \mu < 0 \]
- reverse propagating wave
- negative index

\[ \Re \varepsilon > 0 \quad \Re \mu < 0 \]
- magnetic plasma
- evanescent wave

(metals)

(magnetic plasma)

(superlensing but...)

(2 index)

(not in optical regime)
common materials very limited

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

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

- **Re $\varepsilon > 0$  Re$\mu > 0$**
  - Propagating wave
  - Dielectrics

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

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

- **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**
  - $\Re \varepsilon > 0$, $\Re \mu < 0$
  - reverse propagating wave
  - evanescent wave

(not in optical regime)
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

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

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

1 index 2 zero index
wave equation

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

solution

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

where

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

1 \hspace{1cm} \text{index} \hspace{1cm} 2 \hspace{1cm} \text{zero index}
wave equation

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

solution

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

where

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon \mu}} c = \frac{1}{n} c \quad \rightarrow \quad \infty \]
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.
$0 < n < 1$
$n = 0$
$n < 0$
$n = 0$
$n = 0$
\[ n = 0 \]
“tunneling with infinite decay length”

\[ n = 0 \]
how?

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

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

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

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

\text{1 index} \quad \text{2 zero index}
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?

but $\varepsilon$ and $\mu$ also determine reflectivity

$$n = \sqrt{\varepsilon \mu} \to 0$$

$$\varepsilon \to 0$$

where

$$Z = \sqrt{\frac{\mu}{\varepsilon}}$$

1 index

2 zero index
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

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

1 index

2 zero index
but $\varepsilon$ and $\mu$ also determine reflectivity

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \rightarrow 1$$

where

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

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

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

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

where

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

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

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

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

where

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

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

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

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

where

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

index \#1 \quad zero index \#2
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

\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \quad \text{finite!} \]

\( 1 \) index \hspace{1cm} \( 2 \) zero index
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 ($\lambda_{\text{eff}} \approx d$)
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

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

\[ d \]
Engineering a magnetic response

adjustable parameters

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

adjustable parameters

\[ d \quad a \quad n \]

1 index  2 zero index  3 experiments
The diagram shows the relationship between the frequency \( \omega a / 2\pi c \) and the real parts of the effective relative permittivity \( \text{Re}(\varepsilon_r^{\text{eff}}) \) and effective relative permeability \( \text{Re}(\mu_r^{\text{eff}}) \). The graph plots these values against a frequency range of 0.40 to 0.50.

1. **Index**
2. **Zero Index**
3. **Experiments**
Frequency ($\omega a/2\pi c$)

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

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

0.40 0.42 0.44 0.46 0.48 0.50

/-cap0.6/-cap0.4/-cap0.2

0 0.2 0.4

/-cap2/-cap4

0 0

/-cap2/-cap4

1 index

2 zero index

3 experiments
How to fabricate?
On-chip zero-index fabrication
On-chip zero-index fabrication

Si

SiO₂

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
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
index                             zero index                 experiments
1 index                             2 zero index                 3 experiments

500 nm
index                             zero index                 experiments
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
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
On-chip zero-index prism

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

1. index
2. zero index
3. experiments
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
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 µm

λ = 1570 nm

1 index

2 zero index

3 experiments
50 µm = 1570 nm

1. index
2. zero index
3. experiments
50 µm

$\lambda = 1570 \text{ nm}$

1. index
2. zero index
3. experiments
$50 \, \mu m$ = 1570 nm

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

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

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

![Graph showing wavelength dependence of refraction angle.]
Wavelength dependence of refraction angle

Index 2 Zero Index 3 Experiments
Wavelength dependence of refraction angle

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

Refractive index

Wavelength (nm)

1 index
2 zero index
3 experiments
Wavelength dependence of index

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<tr>
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<td>1640</td>
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<td>1680</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

1. Index
2. Zero index
3. Experiments

Experiment vs Simulation

Refractive index vs Wavelength (nm)
More extreme optics

• suppressing losses
• beam steering & supercoupling
• nonlinear optics
• quantum optics
• on-chip zero-index material

• uniform field inside material (infinite wavelength)

• many exciting applications ahead!
Appearing in November!

1 index
2 zero index
3 experiments
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