Less is more:
Extreme optics with zero refractive index

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NUS
Singapore, 24 August 2016
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Extreme optics with zero refractive index

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n
1 index 2 zero index
1 index
2 zero index
3 experiments
Propagation of EM wave
Propagation of EM wave

governed by wave equation

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

\[ \vec{E} = \vec{E}_o e^{i(kx - \omega t)} \]
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\[ n = \sqrt{\varepsilon \mu} . \]
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where

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

and

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

In dispersive media \( n = n(\omega) \).
Index of refraction

\[ n = \sqrt{\varepsilon \mu} \]
Index of refraction

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

So \( n(\omega) \) determined by response of material to external fields
Index of refraction

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

So \( n(\omega) \) determined by response of material to external fields
Index of refraction

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

So \( n(\omega) \) determined by response of material to external fields
Index of refraction

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

So \( n(\omega) \) determined by response of material to external fields

\( \varepsilon(\omega) \) measure of attenuation of electric field
Index of refraction

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

So \( n(\omega) \) determined by response of material to external fields

[Diagram showing valence electrons, ionic cores, and free electrons]
Dielectric constant

Lorentz oscillator
Dielectric constant

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

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

The graph illustrates the dielectric constant across different frequency ranges, from $10^6$ to $10^{18}$ rad/s, highlighting the transition between microwave (MW), infrared (IR), visible (VIS), ultraviolet (UV), and X-ray (X) regions. The dielectric constant shows significant variations at these transitions, with a notable drop in the vacuum region.
Dielectric constant

The diagram shows the variation of the dielectric constant with frequency (in radians per second). The graph plots the dielectric constant against frequency on a logarithmic scale. The labels on the x-axis represent different frequency ranges:

- $10^6$ rad/s
- $10^8$ rad/s
- $10^{10}$ rad/s
- $10^{12}$ rad/s
- $10^{14}$ rad/s
- $10^{16}$ rad/s
- $10^{18}$ rad/s

At lower frequencies, the dielectric constant is 1, corresponding to vacuum. As the frequency increases past $10^{12}$ rad/s, there is a significant drop in the dielectric constant, indicating the transition from vacuum to electronic behavior.

The term "MW" likely refers to the microwave region of the electromagnetic spectrum, highlighting a specific area of interest for this graph.
Dielectric constant

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

- MW
- Ionic
- Electronic
- Vacuum

- Frequency (rad/s): $10^6$ to $10^{18}$
Dielectric constant

- **MW**: Micro Wave
- **frequency (rad/s)**
- **dielectric constant**
  - dipolar
  - ionic
  - electronic
  - vacuum

Graph shows the variation of dielectric constant with frequency (in rad/s) from $10^6$ to $10^{18}$. The diagram illustrates the behavior of different types of dielectric materials at various frequencies.
Dielectric constant
Lorentz and Drude models

dielectric

metal

\[ \varepsilon' \quad \varepsilon'' \quad \omega_j \]

\[ \varepsilon' \quad \varepsilon'' \quad \omega_p \]
for a strong (dielectric) resonance $\varepsilon$ can become negative

Lorentz and Drude models

Dielectric and metal behavior.
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

\[ n = \sqrt{\frac{\omega}{\mu}} \]

and magnetic response shows similar resonances
Magnetic response

- domains
- nuclear
- electronic
- vacuum

Frequency (rad/s) x Magnetic susceptibility
Magnetic response

but magnetic resonances occur below optical frequencies
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

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

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

What happens when \( \text{Re} \epsilon \) 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

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

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

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

Index

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

Q: Is this only possible value?

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

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

but...

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

Can add $2\pi$ to exponent

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

and so

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

but...

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

and

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

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There is another root...

Can add $2\pi$ to exponent

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

and so

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must lie here for passive material
There is another root...

Can add $2\pi$ to exponent

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

and so

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

but...

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

and

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

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

1. yes ✓
2. no, there’s one more
3. there are many more
4. it depends

\[ n \]
\[ \text{Re}(n) \]
Q: Is this the only possible value?

1. yes ✔
2. no, there’s one more ✔
3. there are many more
4. it depends
Q: Is this the only possible value?

1. yes ✓
2. no, there’s one more ✓
3. there are many more
4. it depends ✓
Q: Is this the only possible value?

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
What happens when $\text{Re}\epsilon$ and/or $\text{Re}\mu$ is negative?
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 $\text{Re}(n)$?

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

1. yes  
2. no ✔️
However, need magnetic response to achieve $\text{Re}(n) \leq 0$!
What happens when $\text{Re}(n) < 0$?
What happens when \( \text{Re}(n) < 0 \)?

Remember

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

\[
E = E_0 e^{i(kx - \omega t)} = E_0 e^{-k''x} e^{i(k'x - \omega t)}
\]
What happens when $\text{Re}(n) < 0$?

Remember

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

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

When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
What happens when $\text{Re}(n) < 0$?

When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
What happens when $\text{Re}(n) < 0$?

When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
What happens when $\text{Re}(n) < 0$?

When $\text{Re}(n) < 0$, $k' < 0$, and so phase velocity reversed!
What about causality?
What about causality?
What about causality?
What about causality?

speed of light $c$
What about causality?

(speed of light c)

(reverse phase propagation)
What about causality?

- Group velocity: $v_g < c$
- Speed of light: $c$
- Reverse phase propagation
What about causality?

- Group velocity: $v_g < c$
- Speed of light: $c$
- Reverse phase propagation
What about causality?

Group velocity: \( v_g < c \)

Speed of light: \( c \)

Reverse phase propagation

High-frequency precursors
What about causality?

signal always travels at speed $c$!
What about causality?
classification of (non-lossy) materials

\[ \text{Re} \mu \]

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

dielectrics

\[ \text{Re} \mu \]

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

![Diagram showing classification of materials based on real parts of permittivity and permeability. The diagram divides materials into two regions: metals in the left region and dielectrics in the right region.]
classification of (non-lossy) materials

\[ \Re \mu, \Re \varepsilon \]

- Metals
- Dielectrics
- Electric plasma

\[ \vec{E}, \vec{B}, \vec{S} \]
classification of (non-lossy) materials
classification of (non-lossy) materials

- metals
- dielectrics
- electric plasma
- magnetic plasma
- negative index
- (not in optical regime)
classification of (non-lossy) materials

- metals
- dielectrics
- electric plasma
- magnetic plasma
- negative index

limited by diffraction

(not in optical regime)
classification of (non-lossy) materials

- metals
- electric plasma
- magnetic plasma
- negative index

no propagation

index
classification of (non-lossy) materials

![Diagram showing classification of materials]

- **Metals**
  - Electric plasma

- **Dielectrics**
  - Magnetic plasma

- **Negative Index**
  - Electric plasma
  - Magnetic plasma

**Superlensing**

**But...**
common materials very limited

- metals
- electric plasma
- air
- glass
- silicon
- magnetic plasma
- negative index
- (not in optical regime)
common materials very limited

- metals
  - electric plasma
  - silver
  - gold

- dielectrics
  - air
  - glass
  - silicon

- negative index (not in optical regime)

- magnetic plasma
common materials very limited

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

- **Reμ**:
  - **Metals**: Electric plasma
  - **Dielectrics**: Magnetic plasma

- **Reε**:
  - Negative index
  - (Not in optical regime)
what if we let $\varepsilon = 0$?
what if we let $\varepsilon = 0$?

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

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

solution

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

where

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

\[ \nabla^2 \vec{E} - \frac{\mu_0}{\epsilon_0 c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \]

solution

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

where

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

1. index
2. zero index
wave equation

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

solution

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

where

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

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

solution

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

where

\[ \frac{\omega}{k} = \frac{1}{\sqrt{\epsilon \mu}} \quad c = \frac{1}{n} \quad c \rightarrow \infty \]
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.
$n > 1$
$0 < n < 1$
$n = 0$
$n < 0$
What can we do with uniform phase?
$n = 0$

1 index
2 zero index
$n = 0$

1. index
2. zero index
$n = 0$
“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?

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

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

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

where

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

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

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

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

where

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

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

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

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

where

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

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

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

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

where

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

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

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

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

where

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

\( 1 \) index \quad \( 2 \) zero index
how?

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

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

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

where

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

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

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

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

where

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

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

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

where

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

1 index

2 zero index

3 experiments
Engineering a magnetic response

bulk material

properties derive from constituent atoms

composite material

properties derive from constituent units
Engineering a magnetic response

bulk material

properties derive from constituent atoms

composite material

properties derive from constituent units
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

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

adjustable parameters
Engineering a magnetic response

adjustable parameters

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

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

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

wavelength (nm)

1 index                             2 zero index                 3 experiments
1 index  2 zero index  3 experiments
at design wavelength (1590 nm)
below design wavelength (1530 nm)
above design wavelength (1650 nm)
How to fabricate?
On-chip zero-index fabrication

<table>
<thead>
<tr>
<th>index</th>
<th>zero index</th>
<th>experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
On-chip zero-index fabrication

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

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
On-chip zero-index fabrication
index | zero index | experiments
1 index                             2 zero index                 3 experiments
1 index  
2 zero index  
3 experiments
1 index  
2 zero index  
3 experiments
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
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
On-chip zero-index prism
1. index
2. zero index
3. experiments
1. **index**
2. **zero index**
3. **experiments**

**prism**
1 index                             2 zero index                 3 experiments
SU8 slab waveguide

prism

Si waveguide

1 index                             2 zero index                 3 experiments
SU8 slab waveguide

prism

Si waveguide

SU8 calibration waveguide

1 index                             2 zero index                 3 experiments
index | zero index | experiments
On-chip zero-index prism
50 µm

\( \lambda = 1570 \text{ nm} \)

1 index  2 zero index  3 experiments
50 µm

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

1 index  2 zero index  3 experiments
50 µm

λ = 1570 nm

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

![Graph showing the relationship between wavelength (nm) and refractive angle (α). The graph indicates the index of refraction at various wavelengths and angles.]
Wavelength dependence of refraction angle

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

1 index  2 zero index  3 experiments
Wavelength dependence of index

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

index                             zero index                 experiments
Wavelength dependence of index

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

Index: $n$

Zero index: $n = 0$

Simulation vs. Experiment

Wavelength (nm): 1480, 1520, 1560, 1600, 1640, 1680

Refractive index: $0.4, 0.2, 0$
Where do we go from here?

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

Need to eliminate losses in metal mirrors

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

Removing mirrors causes radiative losses

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

Radiative losses can be steered...

1 index

2 zero index

3 experiments
Where do we go from here?

Radiative losses can be steered...

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

...or arranged to cause focusing...

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

...or eliminated causing “bound in continuum” state

\begin{itemize}
  \item index
  \item zero index
  \item experiments
\end{itemize}
Where do we go from here?

...or eliminated causing “bound in continuum” state

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

...or eliminated causing “bound in continuum” state

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

...or eliminated causing “bound in continuum” state

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

...or eliminated causing “bound in continuum” state

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

...or eliminated causing “bound in continuum” state
Exciting applications ahead

supercoupling

1 index
2 zero index
3 experiments
Exciting applications ahead

supercoupling  NLO
Exciting applications ahead

\[ \text{SHG} \quad \omega' = 2\omega \]

supercoupling  NLO

1 index  2 zero index  3 experiments
Exciting applications ahead

\[ \text{SHG} \quad \omega' = 2\omega \]

phase matching

supercoupling  NLO

1 index  2 zero index  3 experiments
Exciting applications ahead

supercoupling

NLO

SHG \( \omega' = 2 \omega \)

phase matching
Exciting applications ahead

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

phase matching

supercoupling

NLO

index

zero index

experiments
Exciting applications ahead

SHG $\omega' = 2\omega$

at zero index

$k = 0$

supercoupling  NLO  

1 index  2 zero index  3 experiments
Exciting applications ahead

SHG $\omega' = 2\omega$

at zero index

$\vec{k} = 0$

super coupling

NLO
Exciting applications ahead

**Supercoupling**

**NLO**

**Quantum optics**

SHG \( \omega' = 2\omega \)

at zero index

\( \vec{k} = 0 \)