Single-Photon Spin-Orbit Coupling for Cluster State Quantum Computation

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Outline

- What is it?

  Overview of photon spin-orbit coupling (SOC)

- How does it work?

  Physics of SOC

- What is it good for?

  Applications of SOC for cluster state quantum computing

- Conclusions

  Progress toward observing and controlling the effect

What is it?

Overview of photon SOC

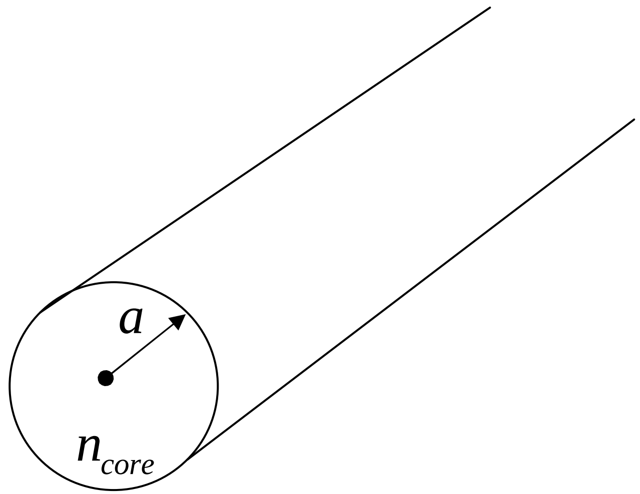
Overview of photon SOC

- Ingredients:
  - Inhomogeneous medium
  - Cylindrical symmetry
  - Quasi-paraxial photon:

    $\kappa \ll |\mathbf{k}|$, where $\kappa \equiv \sqrt{k_x^2 + k_y^2}$
  - Quasi-monochromatic

- Simplest example:

  step-index optical fiber
  - $n_{core} > n_{cladding}$
  - Infinite cladding radius



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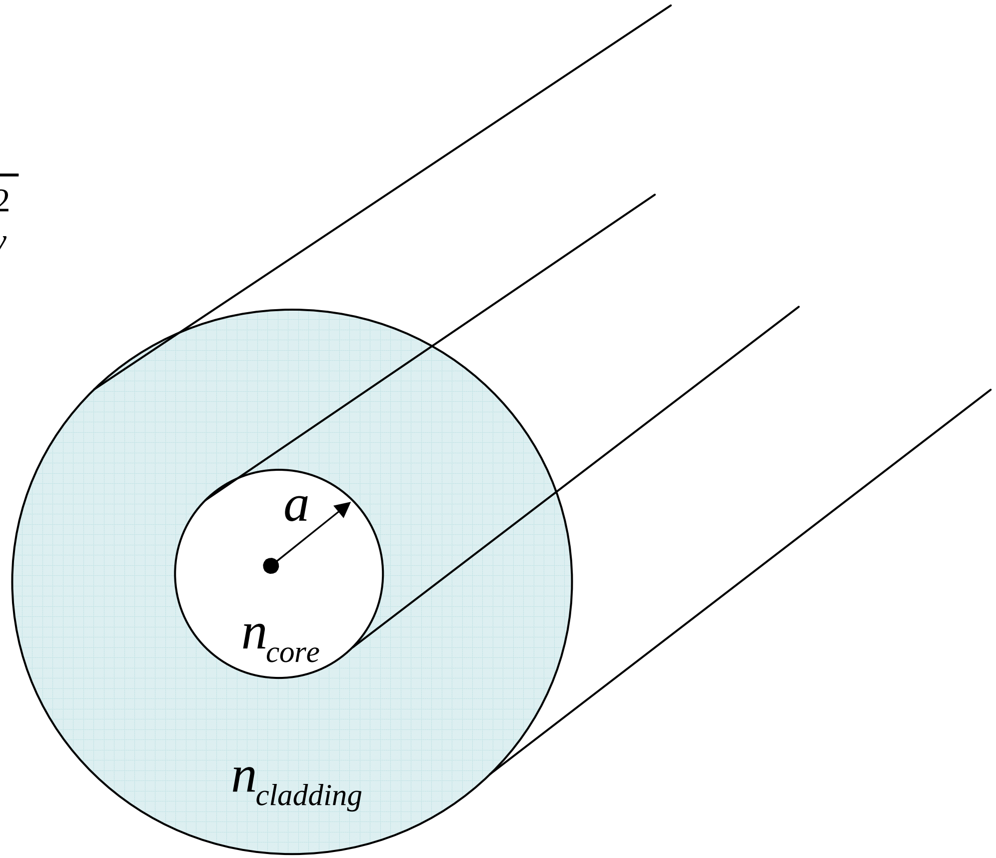
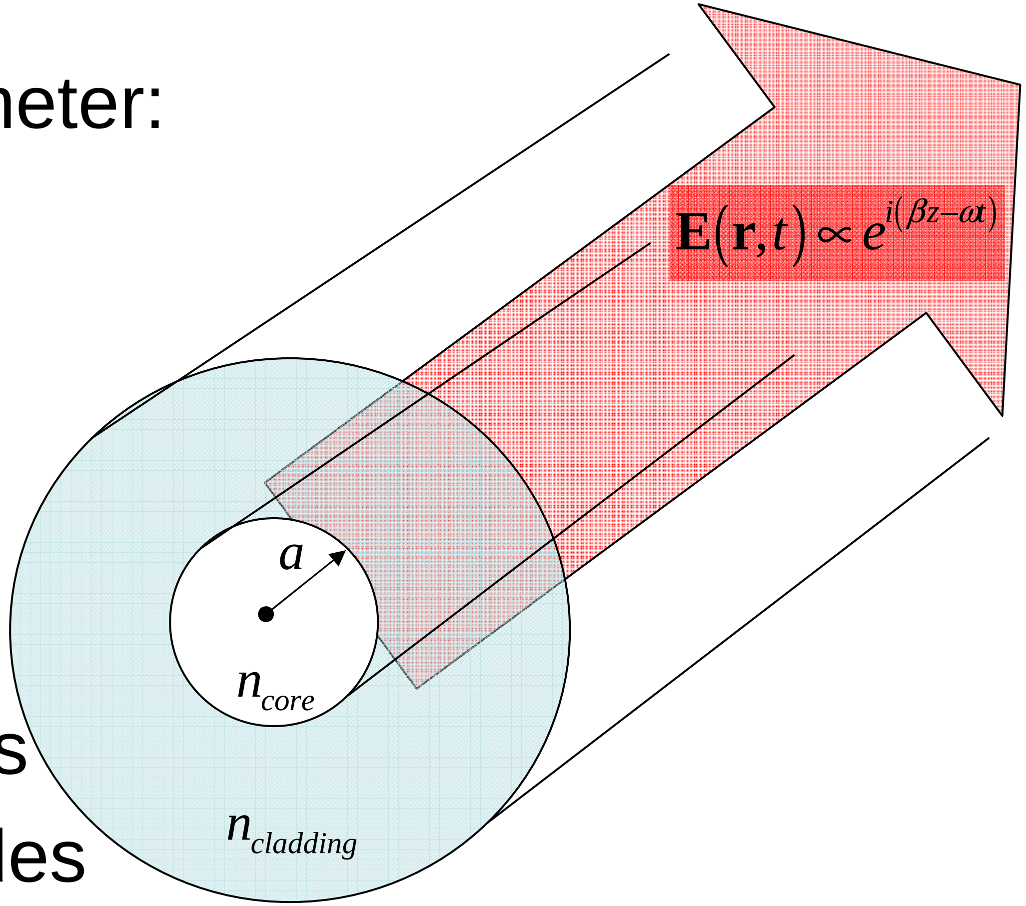


The spin-orbit coupling effect

- Field in fiber proportional to $\mathbf{E}(\mathbf{r},t) \propto e^{i(\beta z - \omega t)}$
- Define the fiber V parameter:

$$V \equiv \frac{\omega a}{c}\sqrt{n_{core}^2 - n_{cladding}^2}$$

- Assume the far-from-cutoff limit: $V >> 1$
- Solve Maxwell equations to obtain fiber eigenmodes



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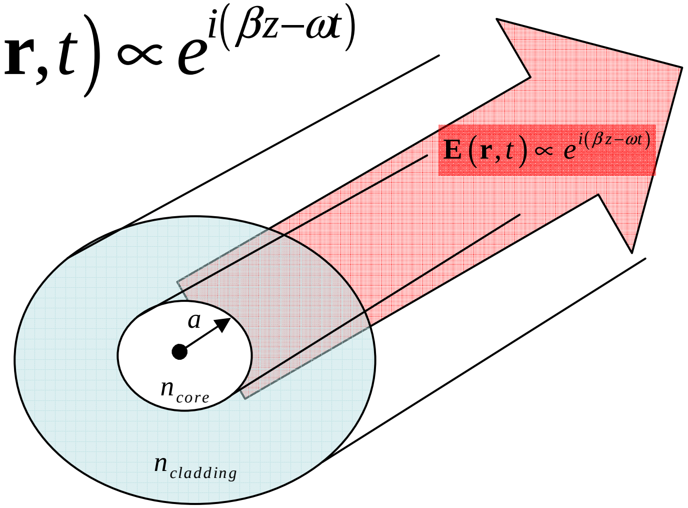


- $V \equiv \frac{\omega a}{c}\sqrt{n_{core}^2 - n_{cladding}^2}$

- **The effect:**
  - **Photon eigenmodes have well defined values of both spin σ and orbital angular momentum m_ℓ along *z* axis**
  - **Modal propagation constants β split according to**

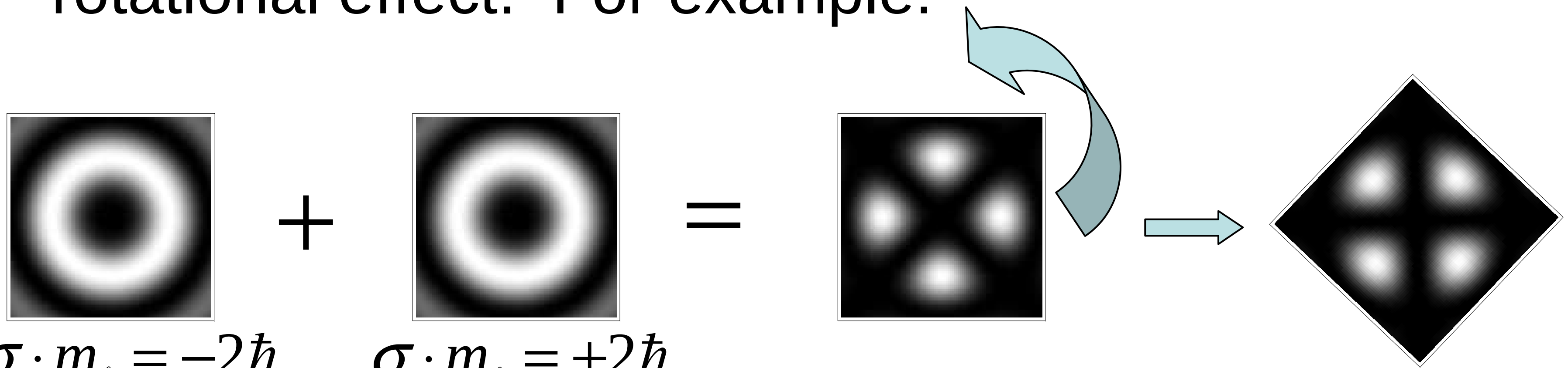
$$\beta \approx k\left\{1 - \frac{f_1}{V^2} + \frac{f_2}{V^3} - \frac{f_3}{V^4}(\sigma \cdot m_\ell)\right\}$$

when $n_{core}^2 \approx n_{cladding}^2$

(the "f" functions depend on simple fiber parameters)

Observable consequence of SOC

- If two fiber photon eigenmodes with different values of the quantity $\sigma \cdot m_\ell$ propagate in superposition, the relative phase between them will vary as the photon field propagates, due to their velocity mismatch.
- This phase shift gives rise to a σ-dependent rotational effect. For example:



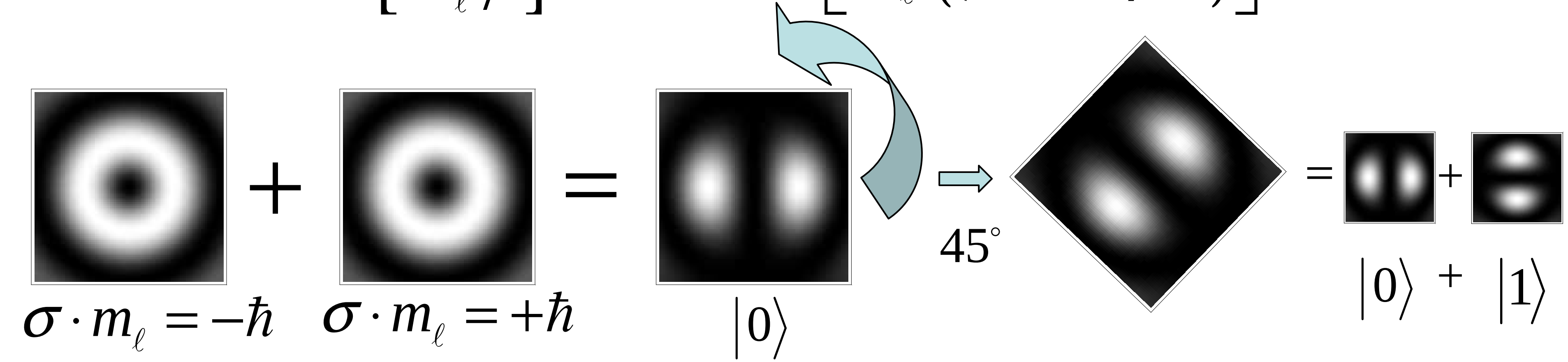
$\sigma \cdot m_\ell = -2\hbar$ $\quad$ $\sigma \cdot m_\ell = +2\hbar$

The superposition mode field rotates clockwise or counterclockwise, as determined by the sign of σ

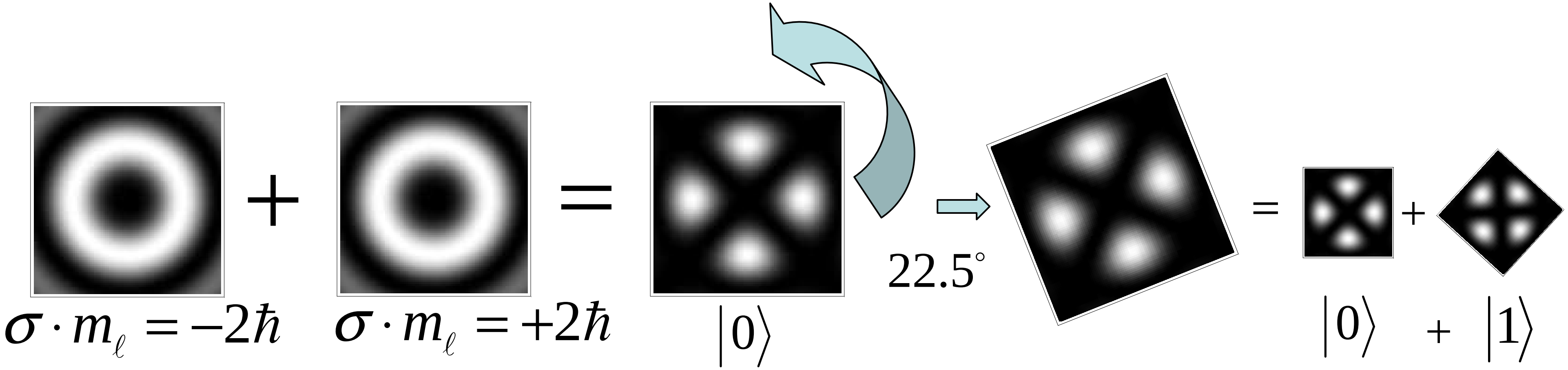
- **This is a spin-controlled spatial-mode Hadamard gate**

Spin-controlled Hadamard gate

$$\mathbf{E} \propto \cos\left[m_\ell \varphi\right] \Longrightarrow \cos\left[m_\ell\left(\phi + \sigma\Delta\beta z\right)\right]$$



Flipping the photon spin (circular polarization) also flips the direction of rotation of the superposition spatial mode.



How does it work?

Physics of spin-orbit coupling

How does it work?
Physics of spin-orbit coupling

- It is the inhomogeneity of the medium gives rise to the effect– there is no paraxial free-space SOC

- B. Zeldovich (PRA ’91) first mentioned photon SOC:
  - He treats a many-mode fiber with a parabolic index profile
  - Rotation of speckle pattern observed, but not of single modes
  - Kapany and Burke (’72) mention mode rotation, but not it the context of single photons or of spin-orbit coupling.

- We consider individual fiber modes propagating in a step-index few-mode fiber
  - The SOC effect is strongest for the step-index case
  - This is due to the $-\nabla\left[\mathbf{E}\cdot\nabla\left(\ln\varepsilon(\mathbf{r})\right)\right]$ term in the Helmholtz eqn

Photon angular momentum quantum numbers

- Define orbital angular momentum operators and quantum numbers:

$$\hat{\vec{L}} \equiv -i\hbar\left(\mathbf{r}\times\nabla\right) \quad\longrightarrow\quad \hat{L}^2\left|\ell\right\rangle \equiv \left(\hat{\vec{L}}\cdot\hat{\vec{L}}\right)\left|\ell\right\rangle = -\hbar^2\ell\left(\ell+1\right)\left|\ell\right\rangle$$

$$\downarrow$$

$$\hat{L}_z = \hat{\vec{L}}\cdot\hat{\mathbf{z}} = -i\hbar\frac{\partial}{\partial\phi} \quad\longrightarrow\quad \hat{L}_z\left|m_\ell\right\rangle = \hbar m_\ell\left|m_\ell\right\rangle$$

- Define "spin-1" operators and quantum numbers:

$$\hat{\vec{S}} \equiv -i\hbar\varepsilon_{ijk}\hat{\mathbf{e}}_k \quad\longrightarrow\quad \hat{S}_z = \hat{\vec{S}}\cdot\hat{\mathbf{e}}_3 = -i\hbar\varepsilon_{ij3} = \begin{pmatrix} 0 & -i\hbar & 0 \\ +i\hbar & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad\longrightarrow\quad \hat{S}_z\left|\sigma\right\rangle = \hbar\sigma\left|\sigma\right\rangle$$

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The above are NOT generally good photon quantum numbers!

Photon angular momentum quantum numbers

$\hat{L}^2 |\ell\rangle = -\hbar^2 \ell(\ell+1) |\ell\rangle$ $\hat{L}_z |m_\ell\rangle = \hbar m_\ell |m_\ell\rangle$ $\hat{S}_z |\sigma\rangle = \hbar\sigma |\sigma\rangle$

The above are NOT generally good photon quantum numbers!

- However, in the aforementioned paraxial and far-from-cutoff limits, m_ℓ and σ **are** good quantum numbers for the photon fields in a step-index fiber:

$$\hat{L}_z \mathbf{E}(\mathbf{r},t) \rightarrow -i\hbar \frac{\partial}{\partial \phi} \mathbf{E}(\mathbf{r},t) = \hbar m_\ell \mathbf{E}(\mathbf{r},t)$$

$$\hat{S}_z \mathbf{E}(\mathbf{r},t) \rightarrow \begin{pmatrix} 0 & -i\hbar & 0 \\ +i\hbar & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \mathbf{E}(\mathbf{r},t) = \hbar\sigma \mathbf{E}(\mathbf{r},t)$$

Fiber photon eigenmodes

- Fiber photon eigenmodes can be labeled as follows:

$$\mathbf{E} \propto J_{m_\ell}\left(\kappa r\right) e^{im_\ell \phi} e^{i(\beta z - \omega t)} \mathbf{e}_\sigma \leftrightarrow \left| n, m_\ell, \omega, \sigma \right\rangle$$

$$n = 1, 2, 3, \ldots \qquad \omega \in \mathbb{R}$$

$$m_\ell = 0, \pm\hbar, \pm 2\hbar, \ldots \qquad \sigma = \pm\hbar$$

$$\mathbf{e}_\sigma \equiv \hat{\mathbf{x}} + i\sigma\hat{\mathbf{y}}$$

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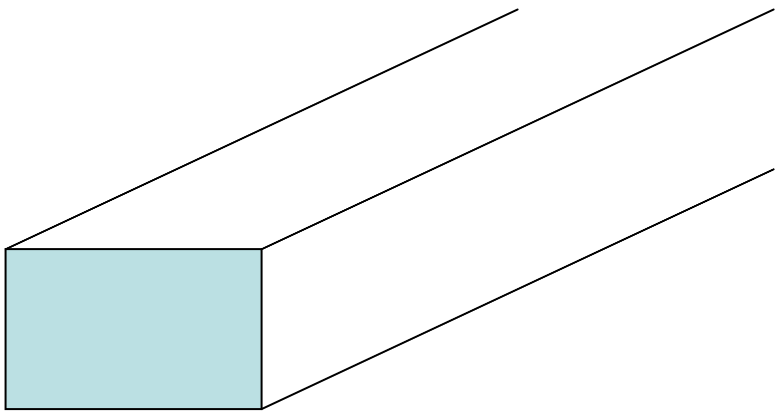

$$\left| k_x, k_y, k_z, \alpha \right\rangle$$

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$$n = 1, 2, 3, \ldots \qquad \omega \in \mathbb{R}$$

$$m_\ell = 0, \pm\hbar, \pm 2\hbar, \ldots \qquad \sigma = \pm\hbar$$

- Propagation constant $\beta \equiv \sqrt{k^2 - \kappa^2} \approx k\left(1 - \frac{1}{2}\left(\frac{\kappa}{k}\right)^2\right)$

- Transverse wavenumber $\kappa(n, m_\ell, \omega, \sigma)$

Fiber photon eigenmodes

- The roles of m_ℓ and σ are now explicit:

$$\mathbf{E} \propto J_{m_\ell}\left(\kappa r\right) e^{i m_\ell \phi} e^{i(\beta z - \omega t)} \mathbf{e}_\sigma \leftrightarrow \left| n, m_\ell, \omega, \sigma \right\rangle$$

$$-i\hbar \frac{\partial}{\partial \phi} \mathbf{E}(\mathbf{r}, t) = \hbar m_\ell \mathbf{E}(\mathbf{r}, t)$$

$$\begin{pmatrix} 0 & -i\hbar & 0 \\ +i\hbar & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} E\left(\mathbf{r}, t\right) \begin{pmatrix} 1 \\ i\sigma \\ 0 \end{pmatrix} = \hbar \sigma E\left(\mathbf{r}, t\right) \begin{pmatrix} 1 \\ i\sigma \\ 0 \end{pmatrix}$$

$$\boxed{\beta \approx k\left\{1 - \frac{f_1}{V^2} + \frac{f_2}{V^3} - \frac{f_3}{V^4}\left(\sigma \cdot m_\ell\right)\right\}}$$

Eigenmode pictures

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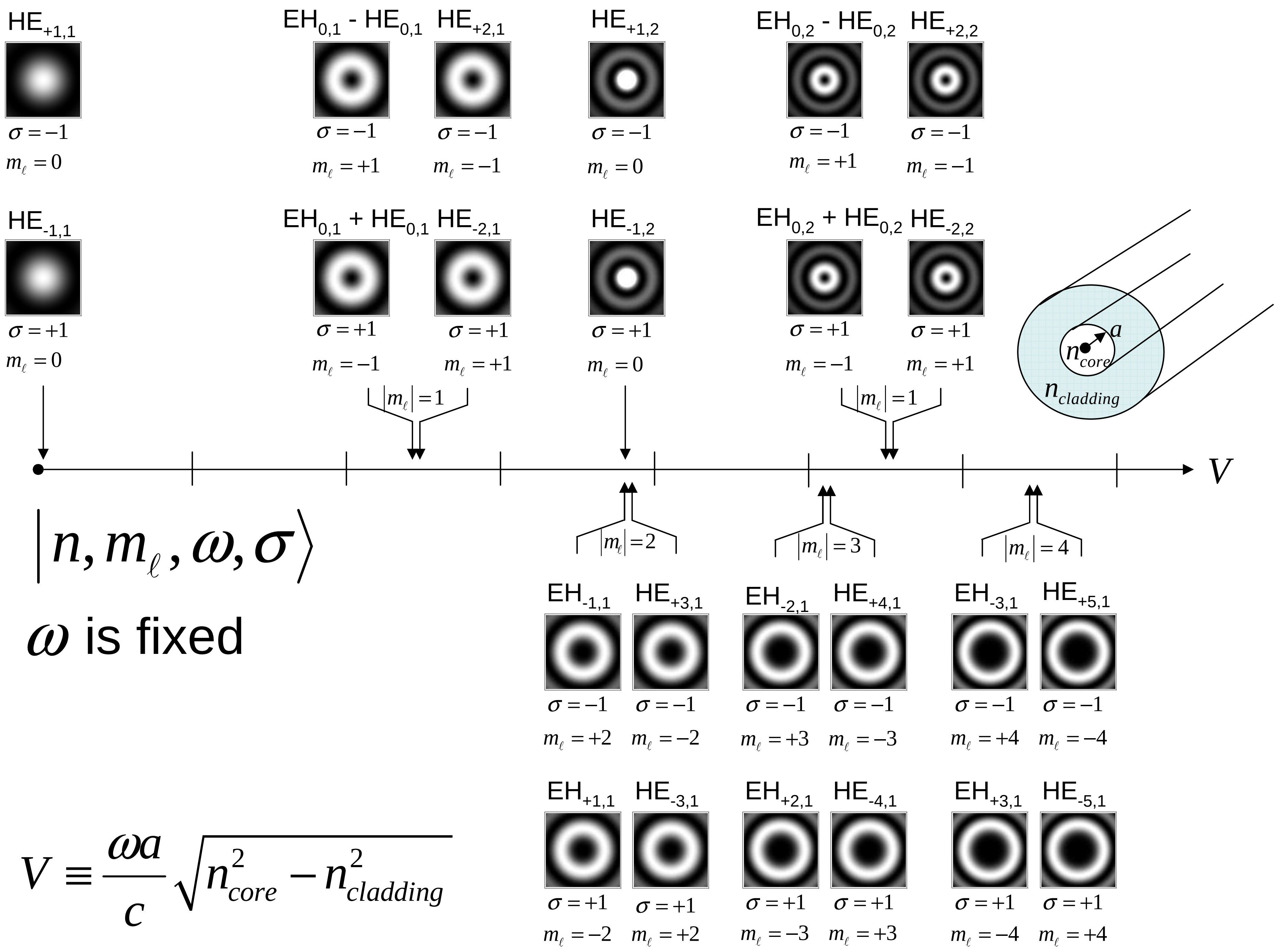
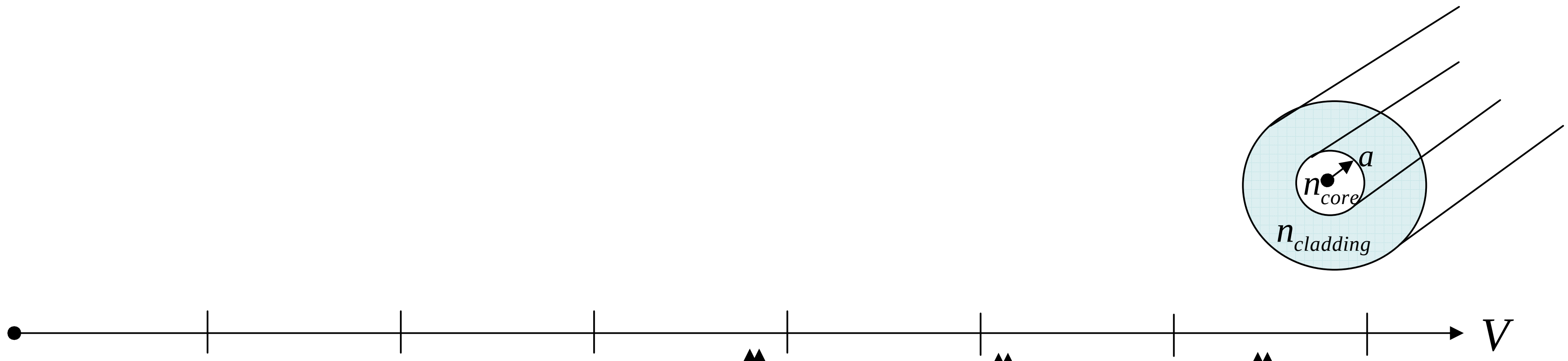


$$\left| n, m_\ell, \omega, \sigma \right\rangle$$

ω is fixed

$$V \equiv \frac{\omega a}{c}\sqrt{n_{core}^2 - n_{cladding}^2}$$



$$|n, m_\ell, \omega, \sigma\rangle$$

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$$|m_\ell| > 1$$

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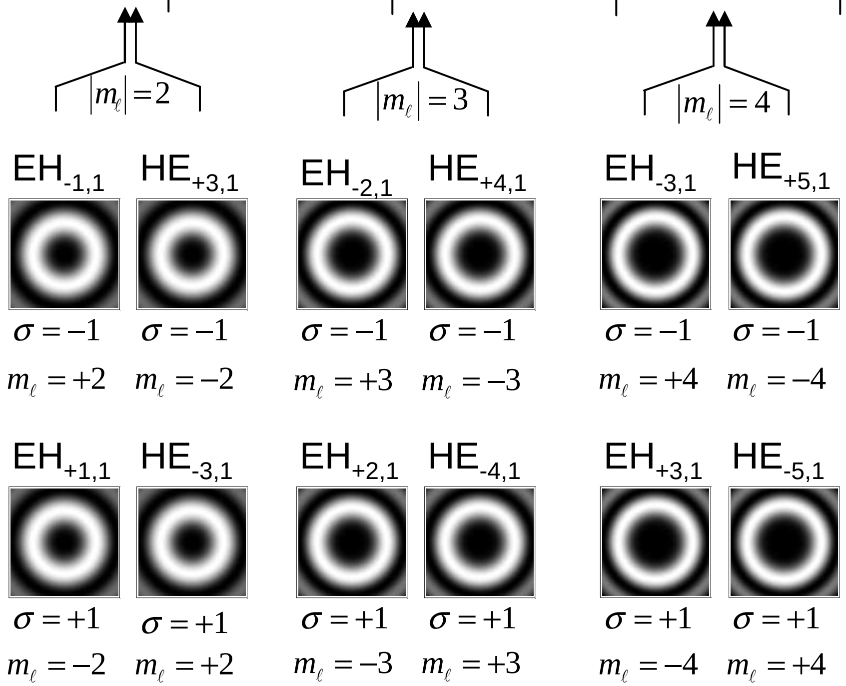
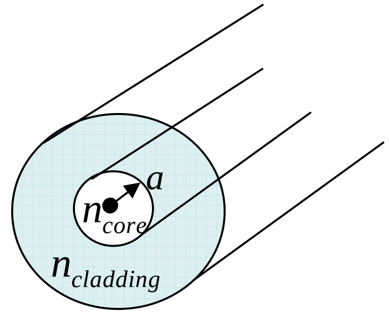


- Eigenmodes have cylindrical symmetry



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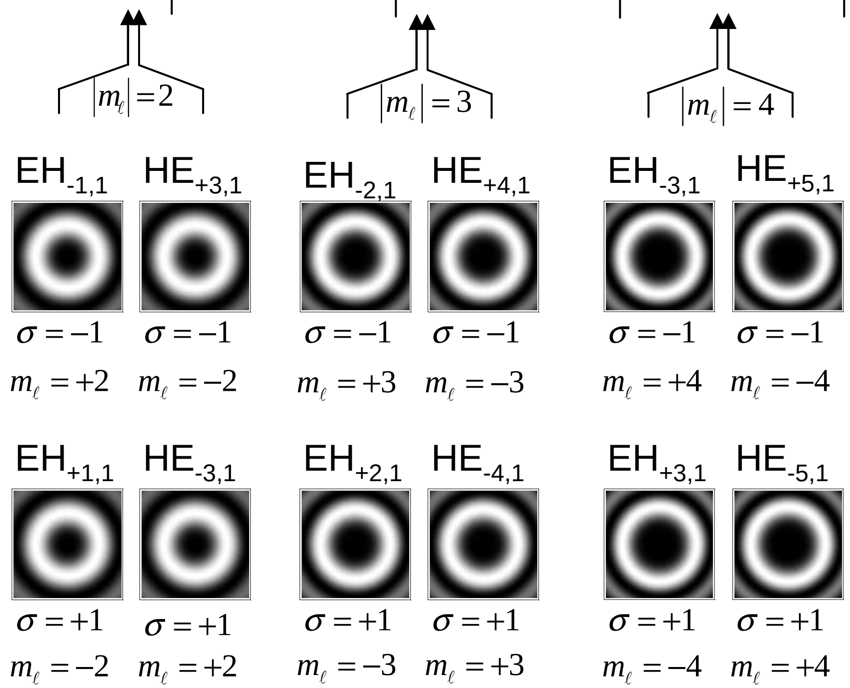
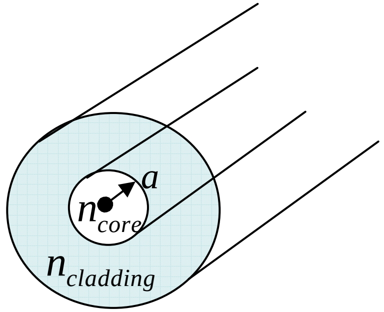
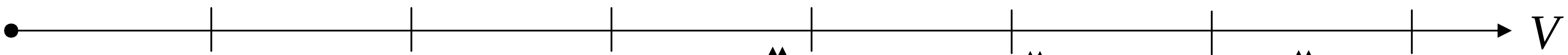


- Eigenmodes have cylindrical symmetry
- Grouped into families of $|m_\ell|$





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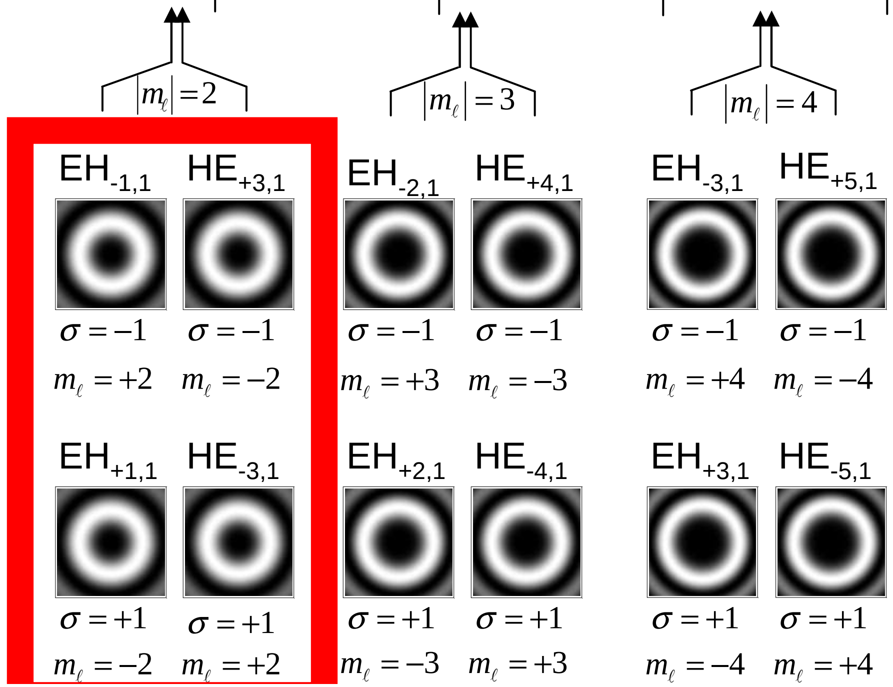

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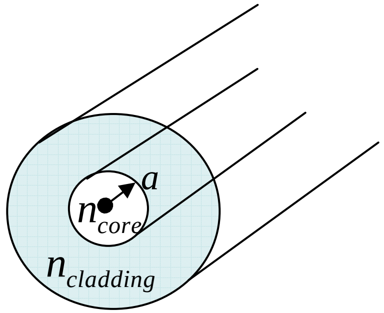

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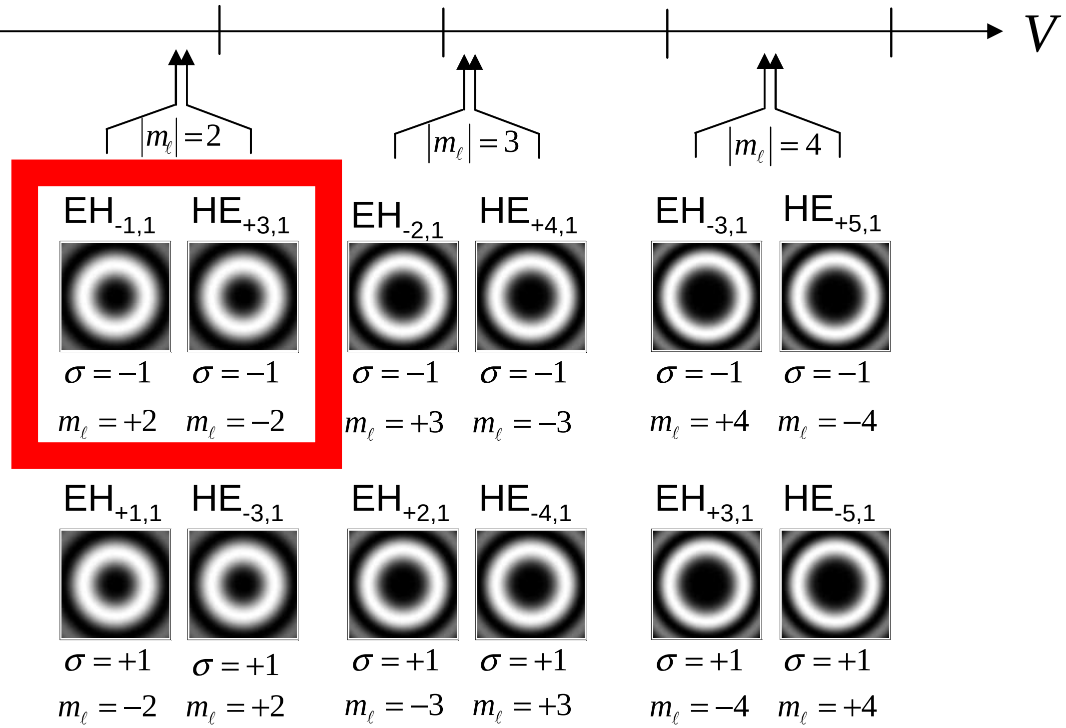

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- Grouped into families of $|m_\ell|$
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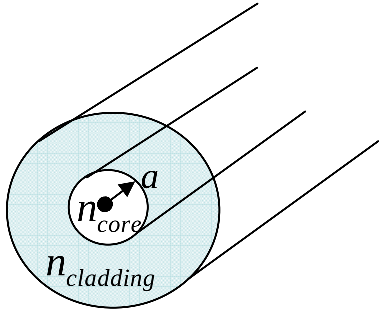
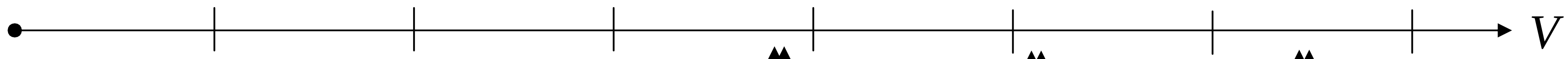
- Each mode has well defined spin and orbital angular momentum
- The modes of each family have **identical field distributions**
- Parallel vs. anti-parallel momenta: $\sigma \cdot m_\ell = \pm 1$
- Propagation constant $\sigma \cdot m_\ell$ dependent; mode pairs have a small degeneracy lifting in propagation constant





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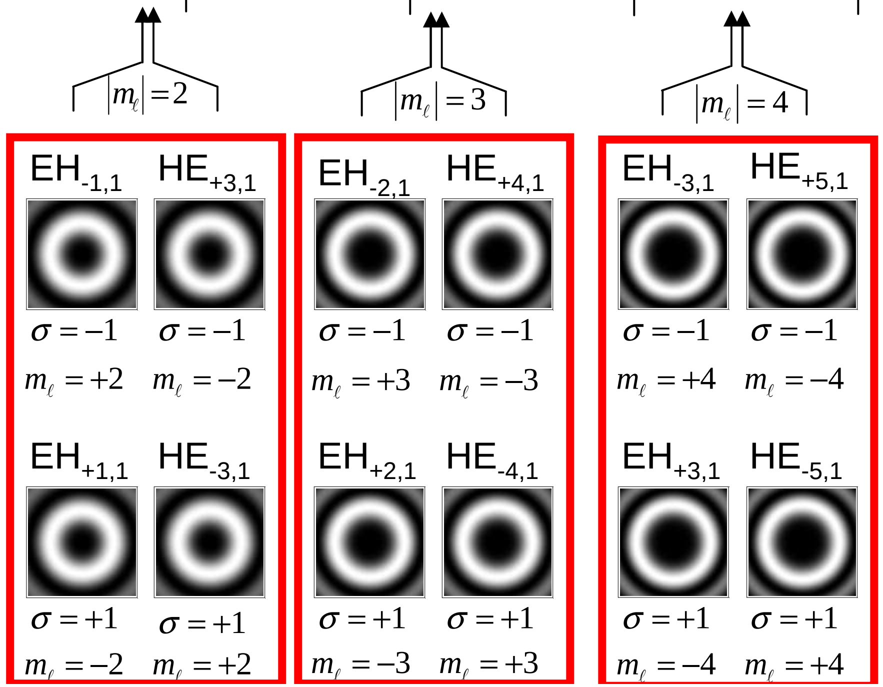

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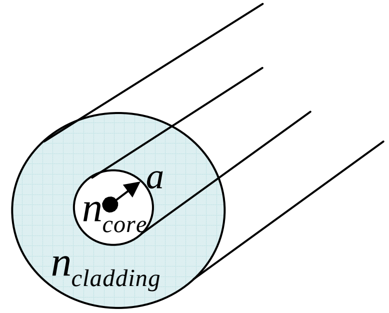

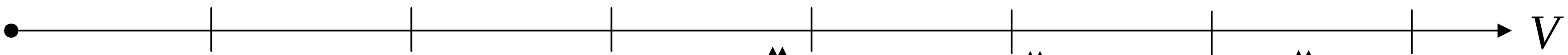

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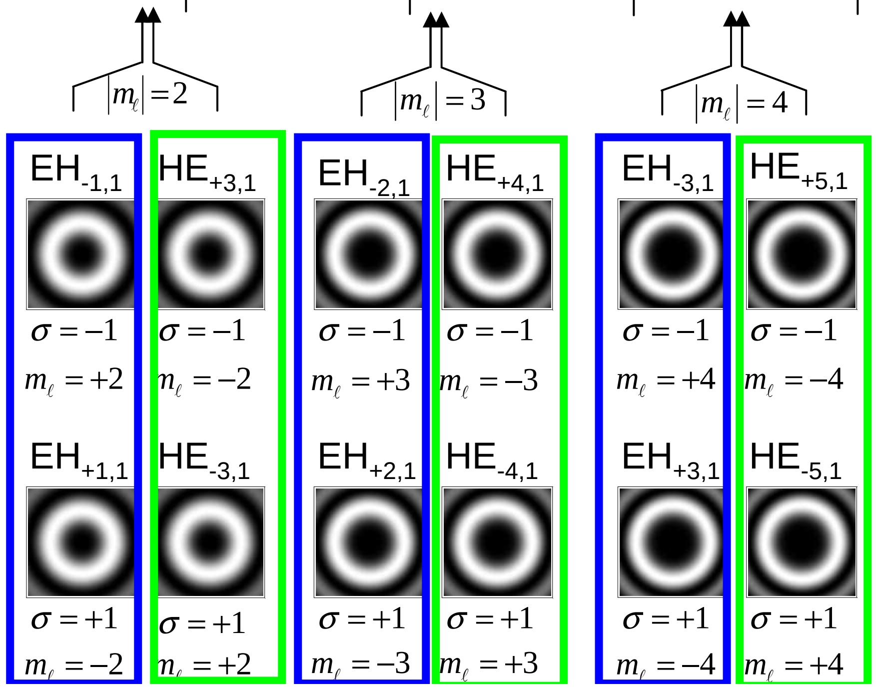

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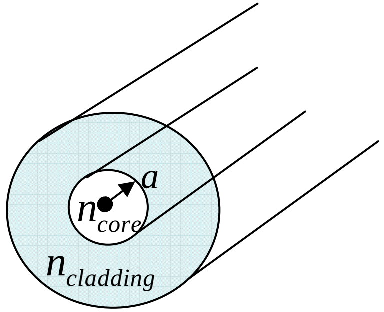
- **Superposition modes exhibit spin-controlled rotation**



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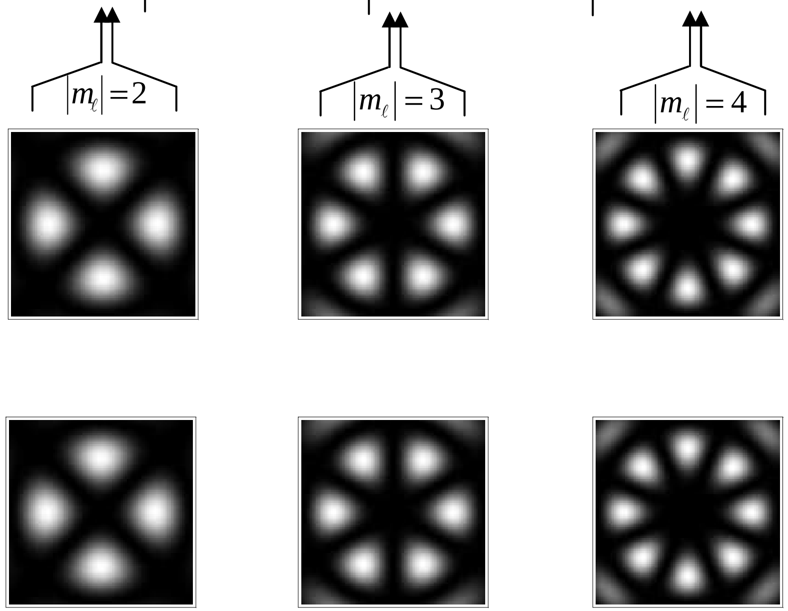
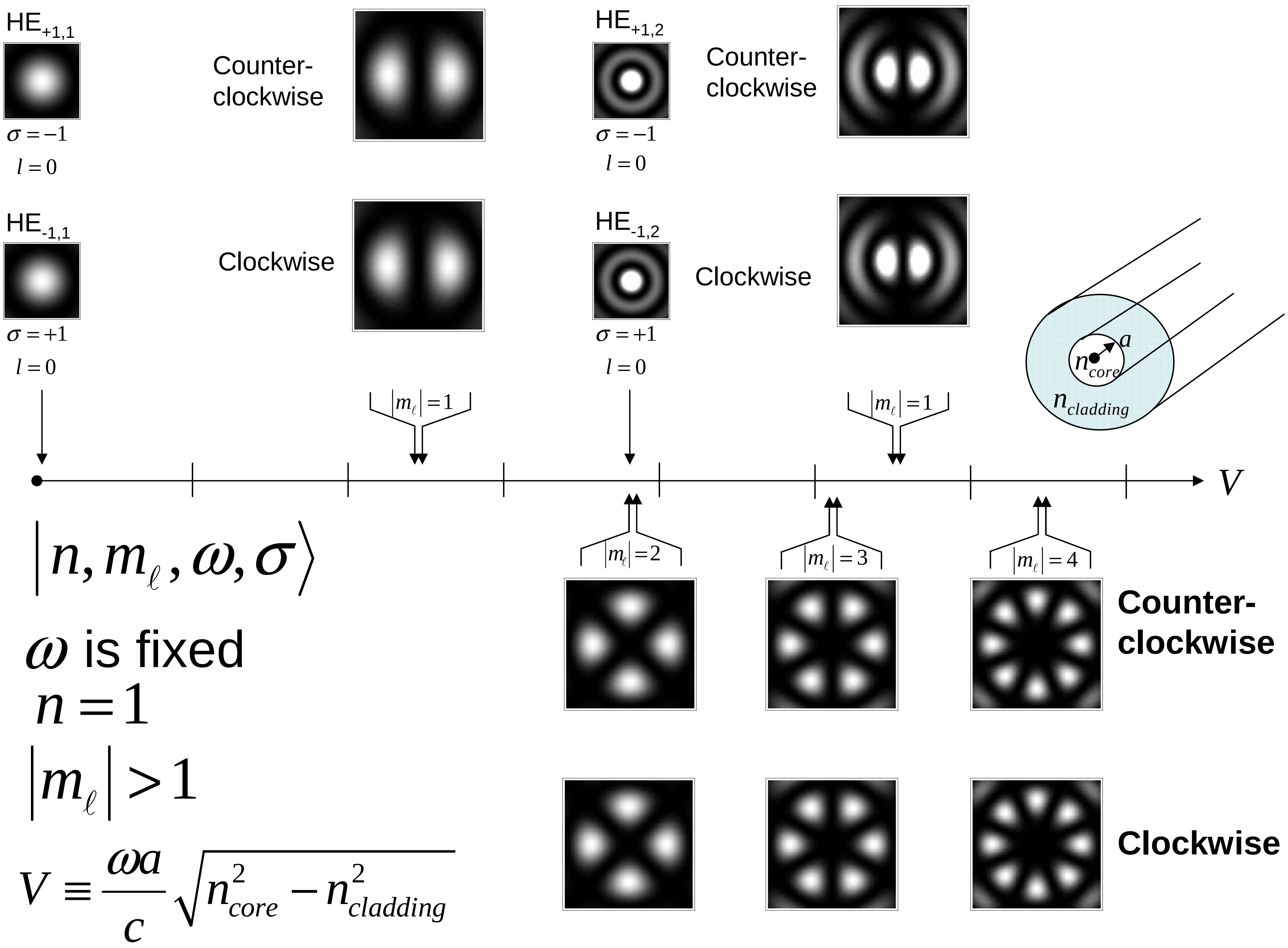
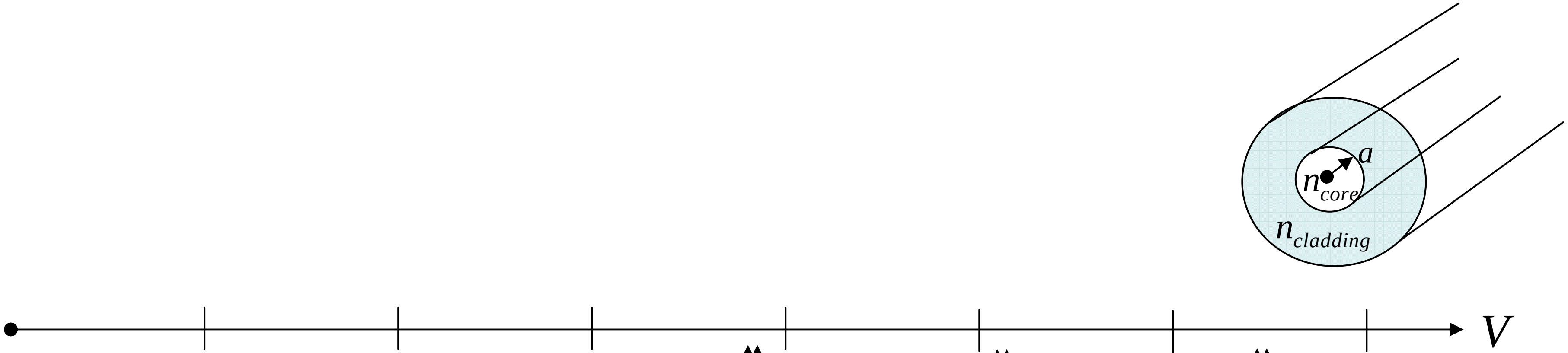


Counter-clockwise

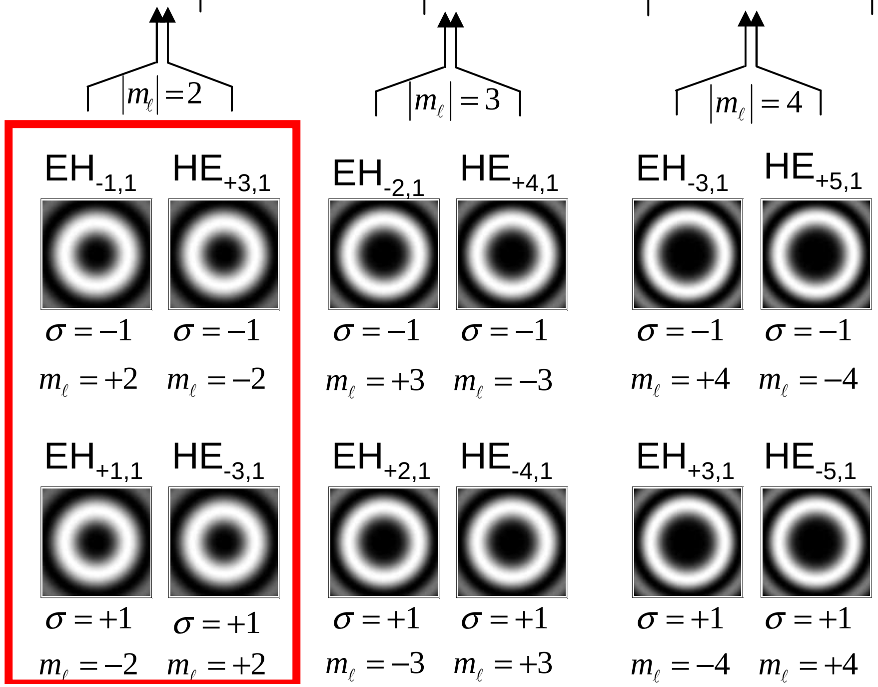
Clockwise



$HE_{+1,1}$
$\sigma = -1$
$l = 0$
$HE_{-1,1}$
$\sigma = +1$
$l = 0$
Counter-clockwise
Clockwise
$HE_{+1,2}$
$\sigma = -1$
$l = 0$
$HE_{-1,2}$
$\sigma = +1$
$l = 0$
Counter-clockwise
Clockwise
$|m_\ell| = 1$
$|m_\ell| = 1$
a
n_{core}
$n_{cladding}$
V
$|m_\ell| = 2$
$|m_\ell| = 3$
$|m_\ell| = 4$
Counter-clockwise
Clockwise
$|n, m_\ell, \omega, \sigma\rangle$
ω is fixed
$n = 1$
$|m_\ell| > 1$
$V \equiv \frac{\omega a}{c}\sqrt{n_{core}^2 - n_{cladding}^2}$



We focus next on the subset of modes where $|m_\ell| = 2$

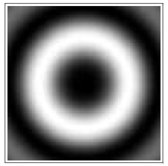


How does it work?

Propagation depends on absolute m_j

$$\mathbf{E} \propto J_{m_\ell}(\kappa r)\, e^{i m_\ell \phi} e^{i(\beta z - \omega t)} \mathbf{e}_\sigma \leftrightarrow |n, m_\ell, \omega, \sigma\rangle$$

$|1,+2,\omega,-1\rangle$



$\sigma = -1$

$m_\ell = +2$

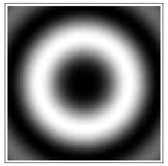
$\sigma \cdot m_\ell = -2$

(anti-parallel)

$|m_j| = 1$

(faster)

$|1,-2,\omega,-1\rangle$



$\sigma = -1$

$m_\ell = -2$

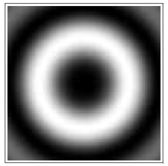
$\sigma \cdot m_\ell = +2$

(parallel)

$|m_j| = 3$

(slower)

$|1,-2,\omega,+1\rangle$



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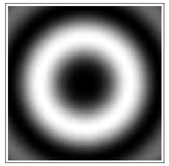


$\sigma = +1$

$m_\ell = +2$

$\sigma \cdot m_\ell = +2$

(parallel)

$|m_j| = 3$

(slower)

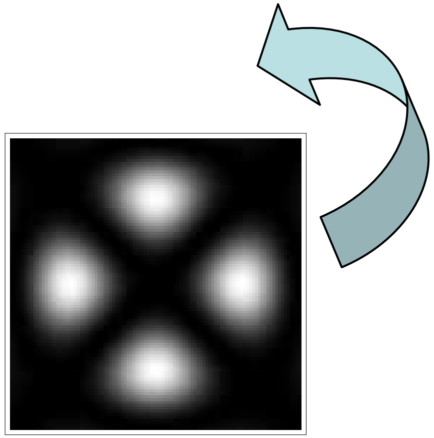
$$\hat{J}_z \equiv \hat{L}_z + \hat{S}_z \qquad m_j \equiv m_\ell + \sigma \qquad \hat{J}_z |n, m_\ell, \omega, \sigma\rangle = \hbar m_j |n, m_\ell, \omega, \sigma\rangle$$

How does it work?

Propagation depends on absolute m_j

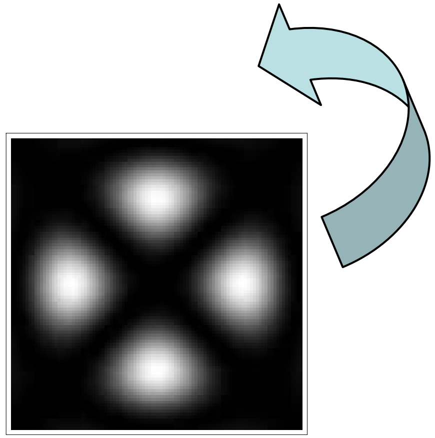
$$\mathbf{E} \propto J_{m_\ell}(\kappa r) e^{i m_\ell \phi} e^{i(\beta z - \omega t)} \mathbf{e}_\sigma \leftrightarrow |n, m_\ell, \omega, \sigma\rangle$$

$|1,+2,\omega,-1\rangle \quad + \quad |1,-2,\omega,-1\rangle$



Counter-clockwise

$|1,-2,\omega,+1\rangle \quad + \quad |1,+2,\omega,+1\rangle$



Clockwise

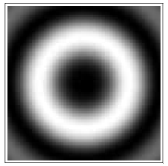
$$\hat{J}_z \equiv \hat{L}_z + \hat{S}_z \qquad m_j \equiv m_\ell + \sigma \qquad \hat{J}_z |n, m_\ell, \omega, \sigma\rangle = \hbar m_j |n, m_\ell, \omega, \sigma\rangle$$

How does it work?

Propagation depends on absolute m_j

$$\mathbf{E} \propto J_{m_\ell}(\kappa r)\, e^{i m_\ell \phi} e^{i(\beta z - \omega t)} \mathbf{e}_\sigma \leftrightarrow |n, m_\ell, \omega, \sigma\rangle$$

$|1,+2,\omega,-1\rangle$



$\sigma = -1$
$m_\ell = +2$

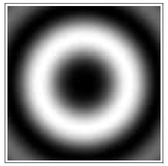
$\sigma \cdot m_\ell = -2$

(anti-parallel)

$|m_j| = 1$

(faster)

$|1,-2,\omega,-1\rangle$



$\sigma = -1$
$m_\ell = -2$

$\sigma \cdot m_\ell = +2$

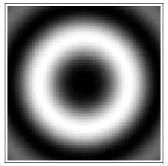
(parallel)

$|m_j| = 3$

(slower)

?

$|1,-2,\omega,+1\rangle$



$\sigma = +1$
$m_\ell = -2$

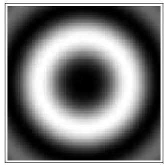
$\sigma \cdot m_\ell = -2$

(anti-parallel)

$|m_j| = 1$

(faster)

$|1,+2,\omega,+1\rangle$



$\sigma = +1$
$m_\ell = +2$

$\sigma \cdot m_\ell = +2$

(parallel)

$|m_j| = 3$

(slower)

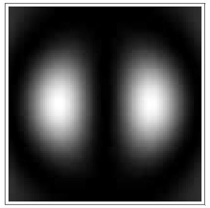
$$\hat{J}_z \equiv \hat{L}_z + \hat{S}_z \qquad m_j \equiv m_\ell + \sigma \qquad \hat{J}_z |n, m_\ell, \omega, \sigma\rangle = \hbar m_j |n, m_\ell, \omega, \sigma\rangle$$

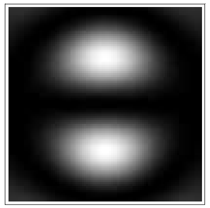
What is it good for?

Applications of SOC: cluster states

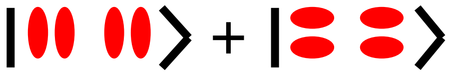
What is it good for?

Applications of SOC: Hermite-Gauss (HG) spatial-mode-entangled cluster states

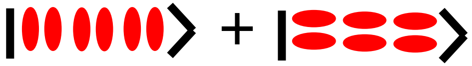
$|0\rangle =$ 

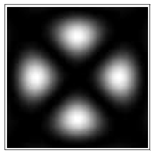
$|1\rangle =$ 

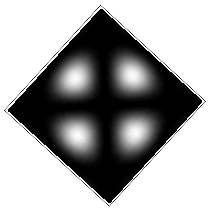
We denote the Bell state

$|00\rangle + |11\rangle$ by 

And the GHZ state

$|00\rangle + |11\rangle$ by 

$|0\rangle =$ 

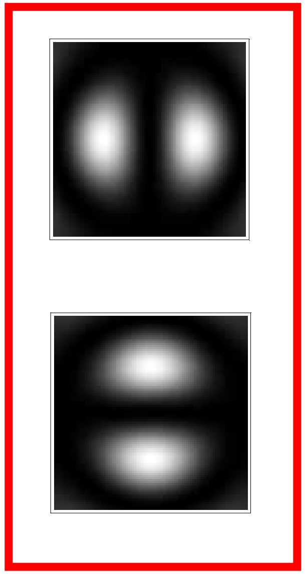
$|1\rangle =$ 

The following is applicable to either of the choices to the left: we focus on first order modes

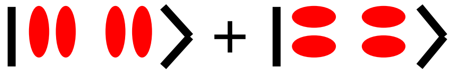
What is it good for?

Applications of SOC: Hermite-Gauss (HG) spatial-mode-entangled cluster states

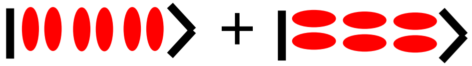
$|0\rangle =$, $|1\rangle =$

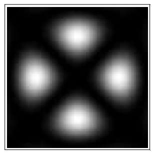


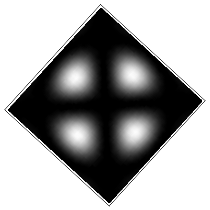
We denote the Bell state

$|00\rangle + |11\rangle$ by 

And the GHZ state

$|00\rangle + |11\rangle$ by 

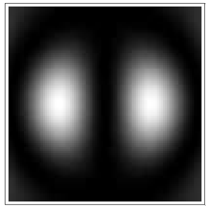
$|0\rangle =$ 

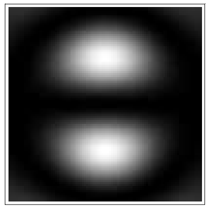
$|1\rangle =$ 

The following is applicable to either of the choices to the left: we focus on first order modes

What is it good for?

Applications of SOC: Hermite-Gauss (HG) spatial-mode-entangled cluster states

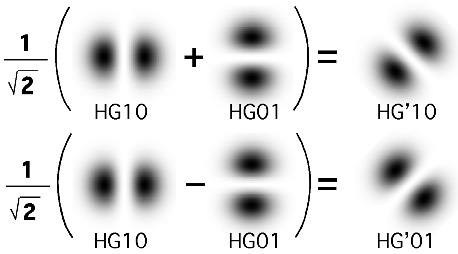
$|0\rangle =$ 

$|1\rangle =$ 

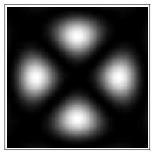
Our states have two key properties:

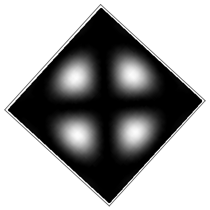
1.) Hadamard gate equivalent to a rotation

2.) They have opposing 1-D parities

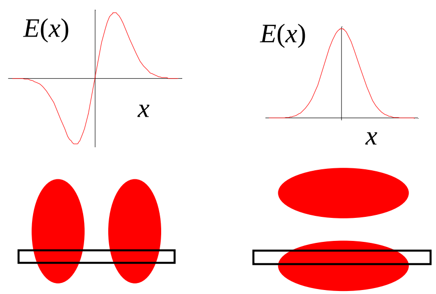


Sums/differences make rotations

$|0\rangle =$ 

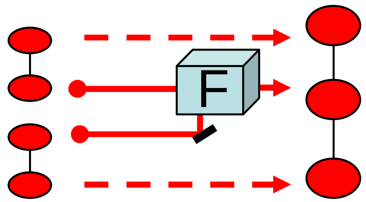
$|1\rangle =$ 

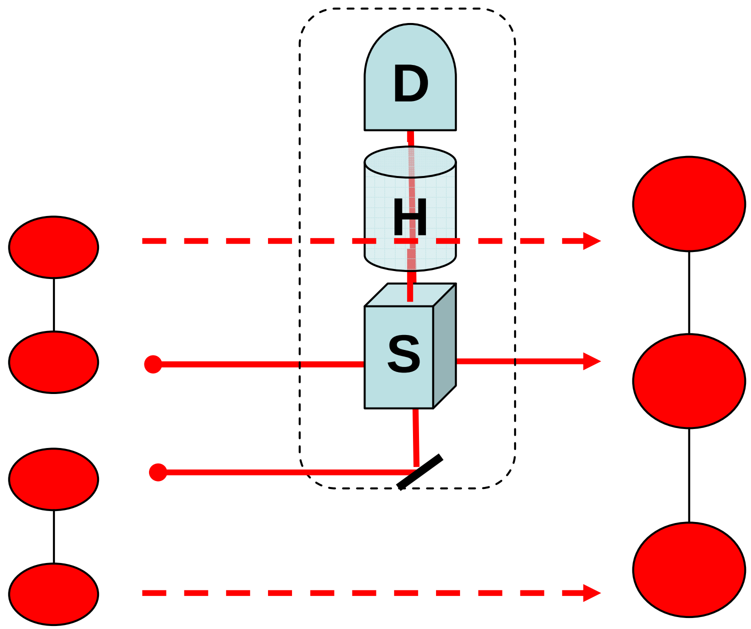
Odd/even upon y axis reflection

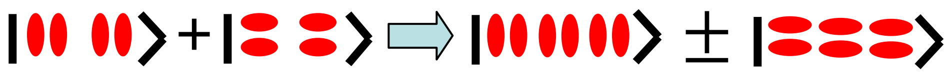


What is it good for?

The simplest example: type-I fusion (Brown et.al., 2005)

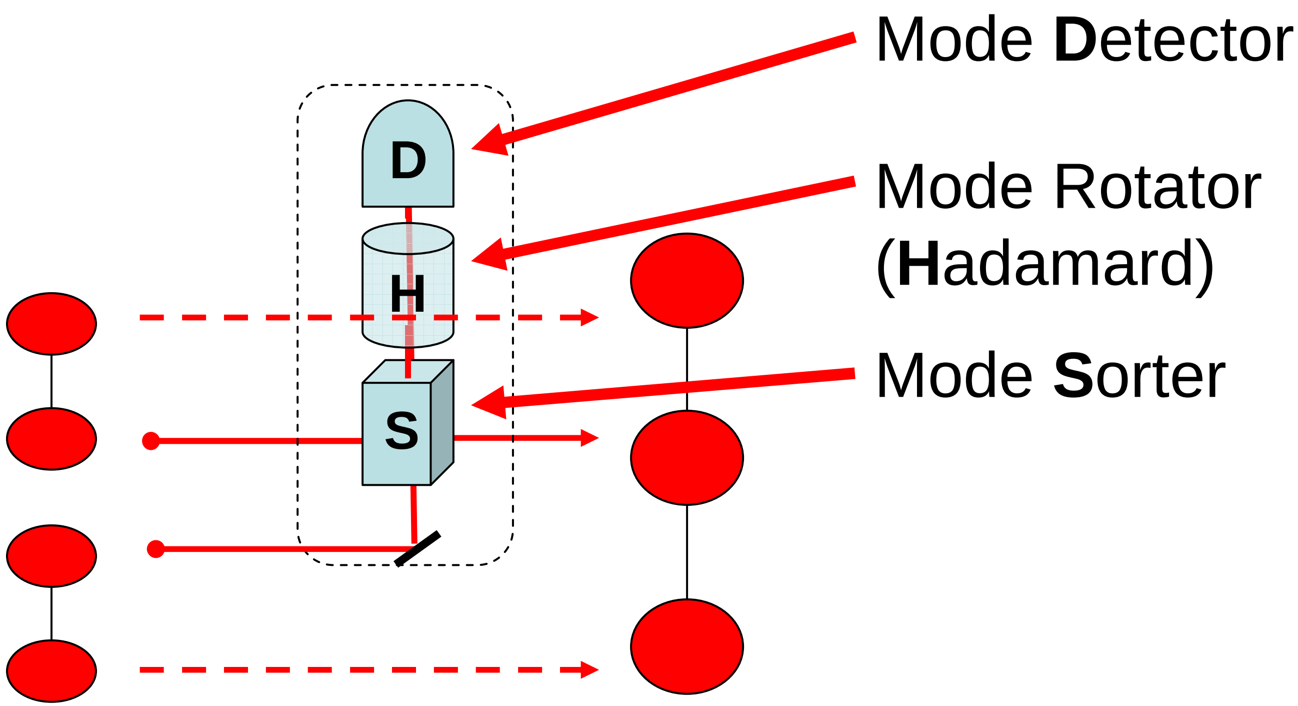




- Initial resource: two Bell states
- Input one photon from each Bell state
- The remaining two photons propagate freely
- One of the input photons is measured, the other exits the gate as output
- The result is an entangled three-qubit cluster state: 

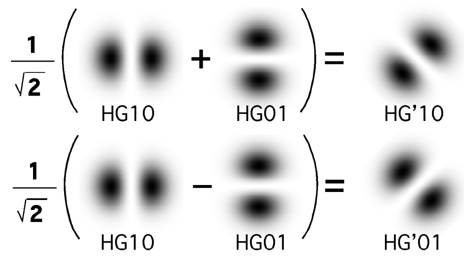
What is it good for?

Fusion gate elements



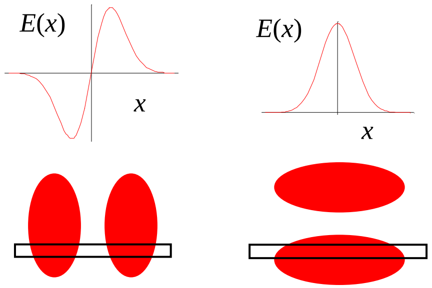
What is it good for?
fusion gate elements

Use transverse spatial modes as qubits

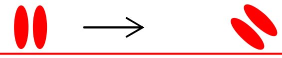


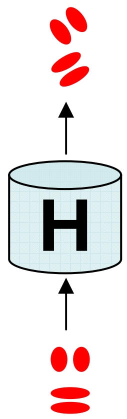
Sums/differences make rotations

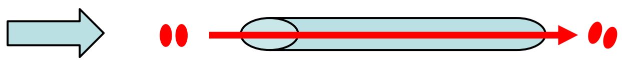
Odd/even upon y axis reflection



$$|0\rangle \to |0\rangle + |1\rangle$$

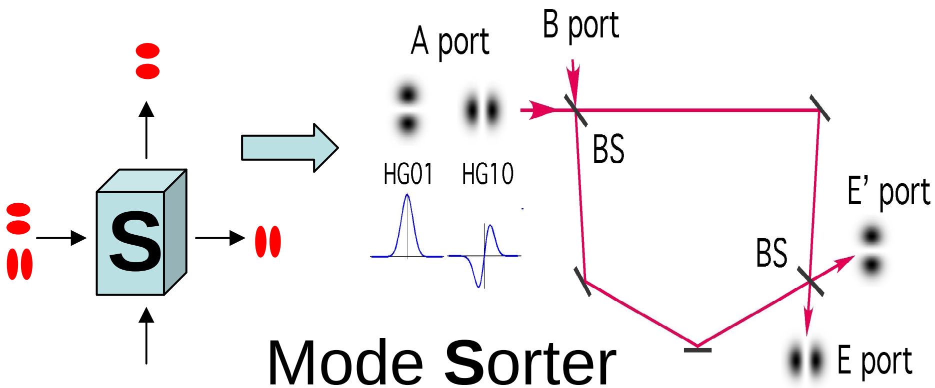




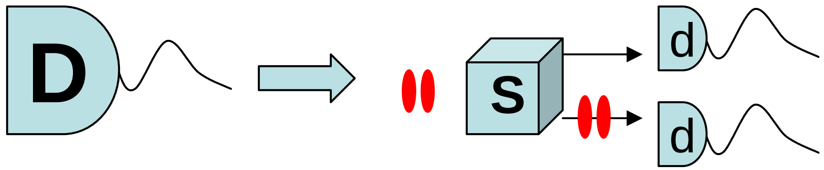


Step-index fiber

Mode Rotator (**H**adamard)



Mode **S**orter



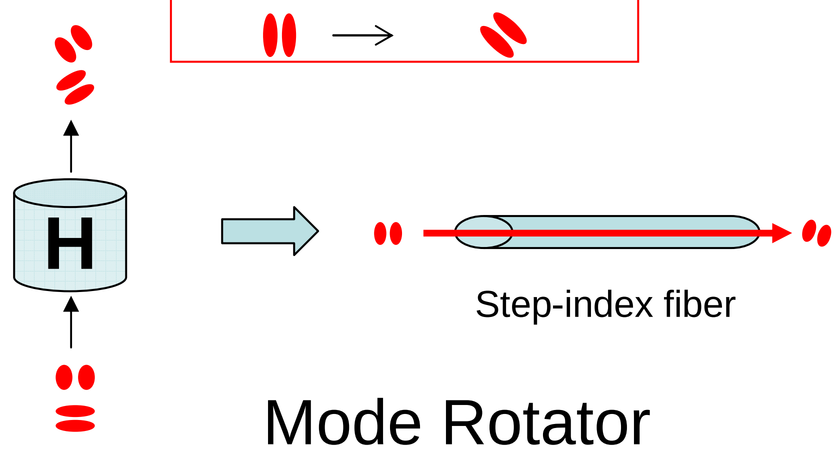
Mode **D**etector

What is it good for?

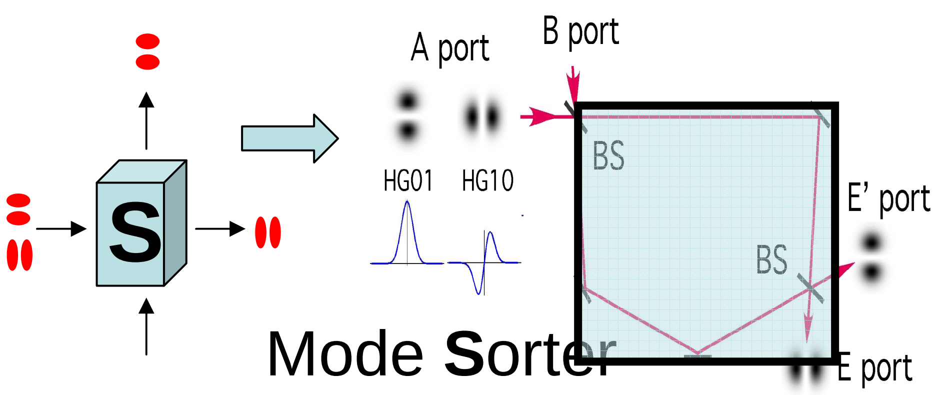
fusion gate elements

- The Mach-Zehnder style interferometer below is not stable, but we can overcome this by constructing a monolithic prism-like device
- The reflections and interference occur at internal interfaces in the “prism”

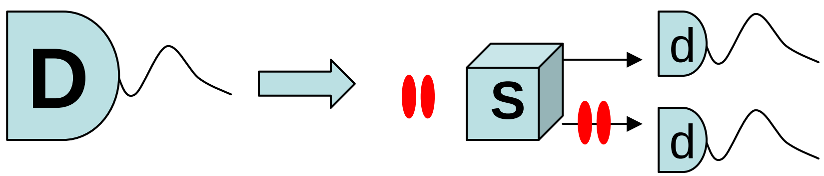
$$|0\rangle \rightarrow |0\rangle + |1\rangle$$



Mode Rotator (**H**adamard)



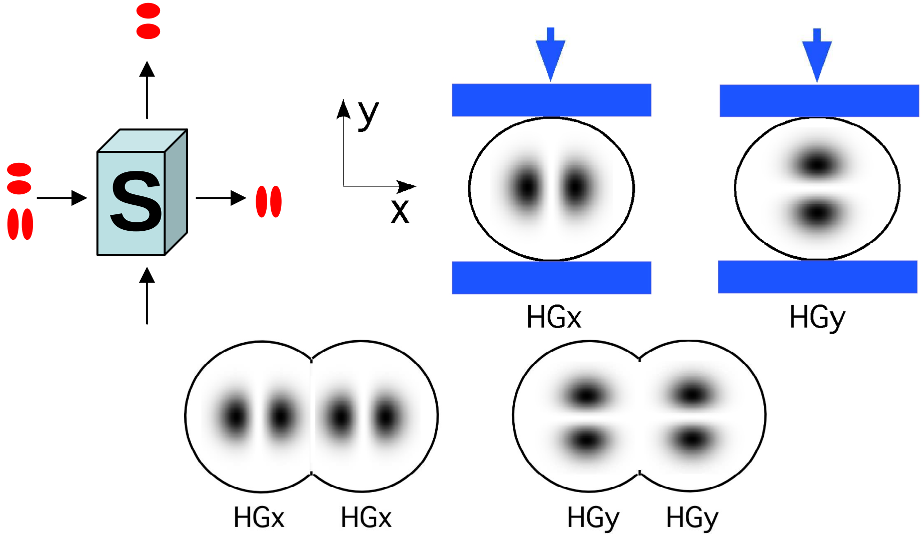
Mode **S**orter



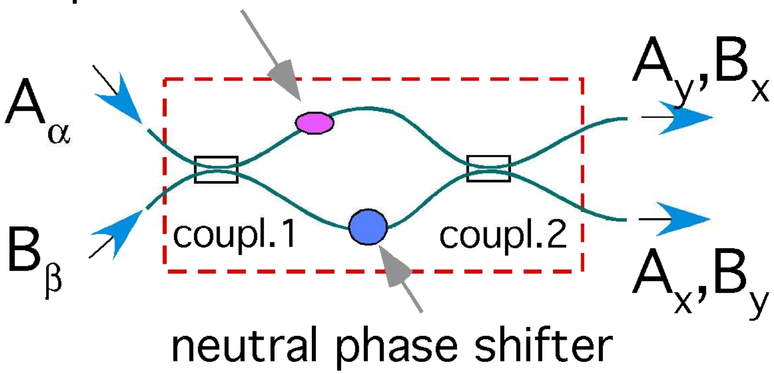
Mode **D**etector

What is it good for?

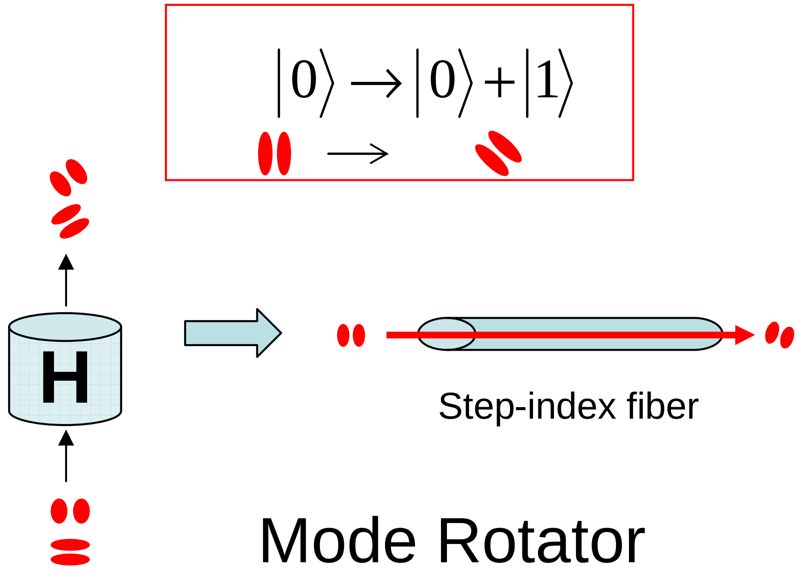
All fiber-based fusion gate elements



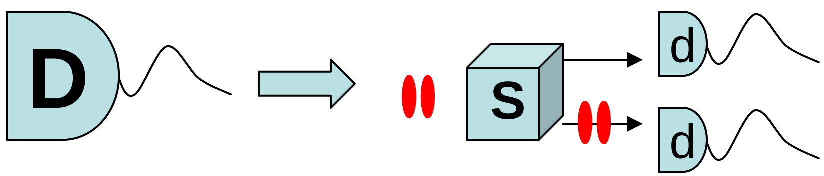
fiber compressor, relative HG-mode phase shifter



Mode **S**orter



Mode Rotator (**H**adamard)



Mode **D**etector

Outlook

Single-photon spin-orbit coupling

- No clear advantages to using photonic spatial modes over the standard polarization encoding for cluster states
- But there are physical differences!
  - Polarization “parity” is **local**, spatial “parity” is **global**
  - Spatial modes must be sorted via interferometry (not a PBS)
- Could this make spatial modes more robust in some situations?
- Interferometry could be in principle provide a less lossy way to sort qubits than polarizing beam splitters
- Fibers restrict the number of degrees of freedom for losses
- All-fiber devices are practically convenient to work with
- Encode **both** the photon’s spin and spatial degrees of freedom?

Conclusions

Single-photon spin-orbit coupling

- What is it?

β splitting due to degeneracy lifting in $\sigma \cdot m_\ell$: a larger $|m_j| = |m_l + \sigma|$ gives rise to a slower propagation speed

- How does it work?

$\sigma \cdot m_\ell$ -split modes have a varying relative phase

- What is it good for?

SOC produces a mode rotation effect that can be used to implement a spin-controlled Hadamard gate for multiple HG-entangled spatial modes.

- How will we observe it? Experiments are underway…