Transporting Data on the Orbital Angular Momentum of Light

Leslie A. Rusch
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Communications Systems Enabling the Cloud
FOR FURTHER READING ...

The IEEE Photonics Society is pleased to invite you to attend a special webinar entitled "Transporting Data on the Orbital Angular Momentum of Light," presented by Prof. Leslie A. Rusch, Université Laval, Quebec City, Canada.

Thursday, 26 April | 11:00 am - 12:00 pm EDT
Outline

- Motivation – overcoming the Shannon limit
- Space Division Multiplexing systems
- Fibers for SDM
  - Background on fibers
  - Eigenmodes & Few mode fibers
- Linearly polarized (LP) modes solution
  - Multiple input, multiple output (MIMO) processing
- Orbital angular momentum modes (OAM) solution
  - OAM fibers – why we like them & how we design them
  - OAM at UL
  - OAM transmission experiments
- Conclusion
Squeezing Shannon

- Coaxial cable to fiber optics
  - Increased distance & bandwidth
Squeezing Shannon

- Coaxial cable to fiber optics
  - Increased distance & bandwidth
- Fast electronics

Squeezing Shannon

- Coaxial cable to fiber optics
  - Increased distance & bandwidth
- Fast electronics
- Wavelength Multiplexing

Squeezing Shannon

- Coaxial cable to fiber optics
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- Fast electronics
- Wavelength Multiplexing
- Advanced modulation
  - polarization and I/Q

Squeezing Shannon

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- Fast electronics
- Wavelength Multiplexing
- Advanced modulation
  - polarization and I/Q

Nonlinear Effects

- Optical fibers are pretty thin ...
  - 8 micron cores
  - Many wavelengths means high power
    - Megawatts per square centimeter
    - Nonlinear effects

- Sending more power makes performance worse
  - Not part of Shannon’s limit

Nonlinear Effects

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  - 8 micron cores
  - Many waveler
    - Megawatts
    - Nonlinear e
- Sending more p ...
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Bandwidth growth and demand

Bandwidth growth and demand

Next wave of capacity increase

Next wave of capacity increase

Next wave of capacity increase

Next wave of capacity increase

Next wave of capacity increase

Outline

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Fiber bundles?

- Instead of electronic regeneration
- Use parallel fiber systems
Fiber bundles?

- Instead of electronic regeneration
- Use parallel fiber systems

Increased capacity, but
- not greener
- not cheaper

Integration drives down price per bit
Fiber bundles vs. fiber w/multiple channels
Fiber bundles vs. fiber w/multiple channels

- Requirements
  - Fiber with multiple channels
Fiber bundles vs. fiber w/multiple channels

- Requirements
  - Fiber with multiple channels
  - Integrate transceivers to higher capacity
Fiber bundles vs. fiber w/multiple channels

- Requirements
  - Fiber with multiple channels
  - Integrate transceivers to higher capacity
  - Amplifiers
Fiber bundles vs. fiber w/multiple channels

- Requirements
  - Fiber with multiple channels
  - Integrate transceivers to higher capacity
  - Amplifiers
  - Switches
Fiber bundles vs. fiber w/multiple channels

- Requirements
  - Fiber with multiple channels
  - Integrate transceivers to higher capacity
  - Amplifiers
  - Switches

- SDM offers
  - higher capacity
  - path to lower cost and power per bit
Spatial Multiplexing in New Fibers

- a single core, a single mode

56 Gbaud, 80 λs, DP-16QAM
Spatial Multiplexing in New Fibers

- a single core, a single mode
- multiple cores, each a single mode
Spatial Multiplexing in New Fibers

- a single core, a single mode
- multiple cores, each a single mode
- a single core, multiple modes
Spatial Multiplexing in New Fibers

- A single core, a single mode
- Multiple cores, each a single mode
- Ring core fiber
- A single core, multiple modes
Spatial Multiplexing in New Fibers

- a single core, a single mode
- multiple cores, each a single mode
- ring core fiber
- a single core, multiple modes
- and eventually ....
  multiple cores, multiple modes
What kind of fiber can support the most modes?

- a single core, multiple modes
Spatial Multiplexing in New Fibers

What kind of fiber can support the most modes?

- a single core, multiple modes

What kind of modes?
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Single mode vs. multimode

- Fibers used to come in two types...
  - Small core (single mode)
  - Large core (multimode)

**easy to couple, cheap**

**multimode**
- 60 micron core
- LED following multiple paths

**single-mode**
- 5.8 micron core
- Laser diode in straight path

high performance, long distance
Spatial division multiplexing

- A new kind of fiber
  - Larger distances & bit rate of SMF
  - Avoid the modal dispersion of MMF
  - Modes as independent, separate channels

- Need to control the modal interactions
  - Play with dimensions to limit the number of modes
  - Few mode fiber – not hundreds, not thousands
Few mode fibers

- Modes in fibers: solutions of Maxwell's equations

- Eigenmodes
  - Building blocks of derivative modes
  - Some solutions of Maxwell’s equation “flock” together
    - mode groups that are interrelated and that interact

- All depends on physical parameters of the fiber
SINGLE-MODE OPTICAL FIBER (SMF)

- Even in single mode fiber – two polarizations
- Gaussian shaped intensity profile
SINGLE-MODE OPTICAL FIBER (SMF)

- Even in single mode fiber – two polarizations
- Gaussian shaped intensity profile

![HE_{11a}](image1.png) ![HE_{11b}](image2.png)

Arrows are polarization
Few-mode-fiber (FMF)

Six spatial and polarization modes to place information.
Few-mode-fiber (FMF)

Six spatial and polarization modes to place information.
Few mode fibers

- Modes in fibers
- Eigenmodes
  - Building blocks of derivative modes
  - Some solutions of Maxwell’s equation “flock” together
    - mode groups that are interrelated and that interact
- All depends on physical parameters of the fiber
- Typical fibers have solutions called scalar modes
  - Solution of a simplified version of Maxwell’s equation
  - Called the “weakly guiding” solution

Refractive index of cladding $\approx$ Refractive index of core
Linear-Polarized (LP) Modes

- Six spatial and polarization paths
Linear-Polarized (LP) Modes

- Scalar approximation to vector modes
- Six spatial and polarization paths
- Boxes indicate near-degenerate modes – expect strong coupling
Linear-Polarized (LP) Modes

- Scalar approximation to vector modes
- Six spatial and polarization paths
- Boxes indicate near-degenerate modes – expect strong coupling

LP01 LP11a LP11b

HE11a TE01 HE21b TM01
Linear-Polarized (LP) Modes

- Scalar approximation to vector modes
- Six spatial and polarization paths
- Boxes indicate near-degenerate modes – expect strong coupling
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  - OAM at UL
  - OAM transmission experiments
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LP modes or scalar modes

- Studied for a long time

- Intensity profiles of light for each mode

- Degenerate modes ...
  - Same propagation speed in the fiber
  - Similar geometry to intensity profiles
LP modes or scalar modes

- LP for Spatial division multiplexing
- Modal interactions mix transmitted signals
- Digital signal processing at RX can undo this
  - Multiple input Multiple output (MIMO) processing
Demultiplexing
Electronic MIMO Demultiplexing

$I_1 = h_{11}O_1 + h_{12}O_2 + h_{13}O_3 + h_{14}O_4 + \ldots + h_{1N}O_N$
Electronic MIMO Demultiplexing

Need the complex filter (time varying amplitudes/phases) for each mode output

\[ I_1 = h_{11}O_1 + h_{12}O_2 + h_{13}O_3 + h_{14}O_4 + \ldots + h_{1N}O_N \]
Electronic MIMO Demultiplexing

Number of filters scales with the square of number of modes
**DSP requirements for LP mode multiplexing**

### IMPACT OF MODECOUPLING ON IMPULSE RESPONSE

- **Non mode coupling**
  - Modes are completely separated, light stays in the mode it was launched to.

- **Weak coupling**
  - Some of the light couples from one mode to another.
  - The impulse response is bound by the maximum DGD of the modes.
  - Crosstalk appears like random noise.
  - Time axis correspond to a location in propagation direction where the crosstalk occurs.
DSP requirements for LP mode multiplexing
DSP requirements for LP mode multiplexing

COHERENT MIMO DIGITAL SIGNAL PROCESSING

- The multiple-input multiple output (MIMO) digital signal processing (DSP) can be implemented by a network of $n \times n$ feed-forward equalizers (FFE).
- Number of taps $L$ required depend on modal differential group delay (DGD).
- Numerous algorithm are available to determine the equalizer coefficients $h_{ij}$.

Randel et. al., Opt. Exp., V. 19, N. 17, 2011
Different markets

- Long haul
  - Spectral efficiency being maxed out
  - DSP complexity high for dispersion compensation
  - MIMO complexity not significant
- Data centers
  - MIMO complexity would dominate
Different markets

- **Long haul**
  - Spectral efficiency being maxed out
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- **Data centers**
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Opportunities for **NEW** version of spatial multiplexing
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LP vs. OAM

Linearly polarized modes (LP)
- Well known & studied
- First solution for SDM
- Perturbations cause coupling

Orbital angular momentum modes (OAM)
- Recent subject of research
- New solution for SDM
- Robust to perturbations
Fiber modes are solutions to Maxwell equation

- **TE** (Transverse Electric) — no electric field in $z$
- **TM** (Transverse Magnetic) — no magnetic field in $z$

Hybrid modes are $EH$ or $HE$ whether electric or magnetic field dominates in $z$
Linearly polarized (LP) Modes

Linear combination of fiber eigenmodes
Linearly polarized (LP) Modes

Linear combination of fiber eigenmodes

\( \text{LP}_0^1 \)  \( \text{LP}_{11x} \)  \( \text{LP}_{11y} \)  \( \text{LP}_2^1 \)

\( \text{HE}_{11} \)  \( \text{TE}_{01} + \text{HE}_{21} \)  \( \text{TM}_{01} + \text{HE}_{21} \)  \( \text{EH}_{11} + \text{HE}_{31} \)
Linearly polarized (LP) Modes

Linear combination of fiber eigenmodes

- $LP_{01}$
- $LP_{11x}$
- $LP_{11y}$
- $LP_{21}$

- $HE_{11}$
- $TE_{01} + HE_{21}$
- $TM_{01} + HE_{21}$
- $EH_{11} + HE_{31}$

Crosstalk
Linearly polarized (LP) Modes

Different eigenmodes travel at different speeds

$\beta_1$

$\beta_2, \beta_3$

$\beta_4, \beta_3$

$\beta_5, \beta_6$

$\text{HE}_{11}$

$\text{TE}_{01} + \text{HE}_{21}$

$\text{TM}_{01} + \text{HE}_{21}$

$\text{EH}_{11} + \text{HE}_{31}$
Linearly polarized (LP) Modes

Different eigenmodes travel at different speeds

modal birefringence & crosstalk
Linearly polarized (LP) Modes

Eigenmodes combined differently for OAM ...

\[ \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6 \]

- \( \beta_1 \): \( \text{HE}_{11} \)
- \( \beta_2, \beta_3 \): \( \text{LP}_{11x} \)
- \( \beta_4, \beta_3 \): \( \text{LP}_{11y} \)
- \( \beta_5, \beta_6 \): \( \text{LP}_{21} \)

\( \text{OAM}(0) \) \( \text{OAM}(1) \) \( \text{OAM}(-2) \) \( \text{OAM}(+2) \)

\( \text{TE}_{01} + \text{HE}_{21} \)

\( \text{TM}_{01} + \text{HE}_{21} \)

\( \text{EH}_{11} + \text{HE}_{31} \)
OAM Modes

Eigenmodes combined differently for OAM ...

\[ \mathbf{H}_0 + j \mathbf{H}_1 + \mathbf{H}_2 + \mathbf{H}_3 \]

\[ \mathbf{E}_0 + j \mathbf{E}_1 + \mathbf{E}_2 + \mathbf{E}_3 \]
OAM Modes

Instead of propagation constant, consider mode effective index ...

$\mathbf{H}_{22} \mathbf{e} + j \mathbf{H}_{22} \mathbf{o} + \mathbf{H}_{32} \mathbf{e} + j \mathbf{H}_{32} \mathbf{o} + \mathbf{H}_{21} \mathbf{e} + j \mathbf{H}_{21} \mathbf{o} + \mathbf{H}_{11} \mathbf{e} + j \mathbf{H}_{11} \mathbf{o}$
Avoid LP modes and favor OAM modes

Instead of propagation constant, consider mode effective index...

“Fence off” modes
Keep effective index separation high to avoid coupling in the fiber...
Avoid LP modes and favor OAM modes

Instead of group velocity, think of effective index for the mode

“Fence off” modes

Keep effective index separation high to avoid coupling in the fiber...

\[ \Delta n_{\text{eff}} > 10^{-4} \]
FMF for LP modes cannot support OAM modes

FMF designed for LP modes violate this condition ...

Example: $OAM_{\pm 1}$
- $OAM_{\pm 1} (LG_{10})$ is formed of 2 $HE_{21}$
- However, $HE_{21}$ combines with $TM_{01}$ and $TE_{01}$ to give $LP_{11}$
- Thus, the presence of $TM_{01}$ and $TE_{01}$ modes in the fiber degenerates the $OAM_{\pm 1}$ modes.
Recap

- OAM modes can be fenced off from one another

- LP modes formed from overlapping eigenmodes
  - effective index cannot be shaped to avoid coupling
OAM characteristics

- Phase varies in time along propagation axis

OAM characteristics

- Phase varies in time along propagation axis

OAM example – 3rd order mode

- Annular field intensity profile \((m=1)\)
- Helical phase front \((e^{\pm il \varphi})\)
- Circular Polarization (±)
Why do we call it OAM?

- Electromagnetic radiation carries both energy and momentum
- The momentum may have both linear and angular contributions
- Angular momentum has a spin part associated with polarization and an orbital part associated with spatial distribution

**Spin Angular Momentum**
The *polarization vector* of electric field rotates around the beam axis.

- Associated with the photon spin
- Is manifest as circular polarization

**Orbital Angular Momentum**
The *phase structure* of the beam of light rotates around the beam axis.

- Associated with spatial distribution
Why do we call it OAM?

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Spin Angular Momentum

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OAM vs. LP

- Well known & studied
- First solution for SDM
- Perturbations cause coupling
- Recent subject of research
- New solution for SDM
- Robust to perturbations

conservation of momentum effect
OAM fibers

- Index profile matches OAM mode field intensity profile (ring shaped)
- Vector modes with well separated effective indices
  \[ \Rightarrow \text{avoid degeneracy into LP modes} \]
  (i.e. at least \(10^{-4}\))
- Effective index separation \( \Rightarrow \text{high refractive index contrast}\)
  (violates the weakly guiding approximation)
Designing a fiber for OAM

- Ring shaped
- Large effective index separation
"Vortex fiber" (2 OAM states)

\[ \Delta n_{\text{eff}} \approx 1.8 \times 10^{-4} \]


Ring core fibers at UL

- Inverse Parabolic Graded Index Fiber (IPGIF)
  - Smooth gradient profile

- Hollow core fiber
  - Hollow core to maximize index contrast
  - Probe maximum number of modes

- Ring core fiber
  - Analytical tools for designing step index OAM fiber

$\Delta n_{eff} > 10^{-4}$
Ring core fibers at UL

- Cladding: 23.2 µm
- Waveguide: 6 µm
- Air: 23.2 µm
- 2.4 µm core
- Hollow core: 5.6 µm
- Ring core: 1.8 µm
Inverse Parabolic Graded Index Fiber (IPGIF)

Inverse Parabolic Graded Index Fiber (IPGIF)

\[ \Delta n_{\text{max}} = n_a - n_2 \]

\[ \Delta = \frac{(n_1^2 - n_2^2)}{2n_1^2} \]

\[ \Delta n_{\text{eff}} \propto \sqrt[4]{\ln n_2^2} \propto \frac{|N|\Delta}{a} \]

N: curvature

a: core radius

IPGIF: Design

\[ \Delta n_{\text{eff}} = 2 \times 10^{-4} \]

\((a=3 \ \mu m)\)
IPGIF: Design

Minimum effective index separation

\[
\Delta n_{\text{eff}} = 2 \times 10^{-4}
\]

Curvature parameter (N)

Center refractive index (n_i)

(a=3 \ \mu m)

Average loss : 8.6 dB/km

LP_{01} loss : 6.5 dB/km
Ring core fibers at UL

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$\Delta n_{eff} > 10^{-4}$
Air-core fiber (12 OAM states)
\[ \Delta n_{\text{eff}} \approx 1.0 \times 10^{-4} \]

Hollow-Center Ring-Core Fiber: design

- Ring-core and trench indices
  - dictated by material constraints
  - highest possible index contrast

- Optimize
  - $\Delta n_{\text{eff}} > 10^{-4}$
  - Number of supported modes ($\geq 16$ OAM states)

Hollow-Center Ring-Core Fiber

The figure shows a graph plotting effective index ($n_{eff}$) against wavelength (µm) with a标注指出 "highest possible index contrast."
Hollow-Center Ring-Core Fiber

<table>
<thead>
<tr>
<th>Mode</th>
<th>OAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE 0,1</td>
<td></td>
</tr>
<tr>
<td>HE 1,1</td>
<td></td>
</tr>
<tr>
<td>HE 2,1</td>
<td>±1</td>
</tr>
<tr>
<td>HE 3,1</td>
<td></td>
</tr>
<tr>
<td>TM 0,1</td>
<td>±2</td>
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</tr>
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</tr>
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<td></td>
</tr>
<tr>
<td>EH 4,1</td>
<td>±6</td>
</tr>
<tr>
<td>HE 7,1</td>
<td>±7</td>
</tr>
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<td></td>
</tr>
<tr>
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<td>±8</td>
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</tr>
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<td></td>
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highest possible index contrast
Hollow-Center Ring-Core Fiber

The image shows a graph with the x-axis labeled as "wavelength (µm)" and the y-axis labeled as "effective index (n_{eff})". Various lines represent different modes such as TE 0,1, HE 1,1, HE 2,1, HE 3,1, TM 0,1, EH 1,1, etc., each with a specific range of OAM values. The graph indicates the highest possible index contrast for these modes.
Hollow-Center Ring-Core Fiber

9 OAM orders
17 OAM modes
36 information channels

highest possible index contrast
Hollow-Center Ring-Core Fiber

\[
\min \left[ \Delta n_{\text{eff}} \right] = 1.1 \times 10^{-4}
\]
Hollow-Center Ring-Core Fiber: 1 m transmission

Right circular polarization

Left circular polarization

loss few dB/m
Hollow-Center Ring-Core Fiber

Graph showing the effective index ($n_{eff}$) vs. wavelength (μm) for different modes: TE 0,1, HE 1,1, HE 2,1, HE 3,1, TM 0,1, HE 4,1, EH 1,1, HE 5,1, EH 2,1, HE 6,1, EH 4,1, HE 7,1, EH 5,1, HE 8,1, EH 6,1, with OAM values ±1 to ±8.

Cut-off at 1.52 to 1.57 μm wavelength range.
Ring core fibers at UL

- Inverse Parabolic Graded Index Fiber (IPGIF)
  - Smooth gradient profile

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- Ring core fiber
  - Analytical tools for designing step index OAM fiber

$\Delta n_{eff} > 10^{-4}$
Simple geometry

Ring Core Fiber – design tools

- Simple geometry

![Ring Core Fiber Cross Section](image.png)

**refractive index**

**fiber cross section**

- **I**: Core, $n_1$
- **II**: Cladding 1, $n_2$
- **III**: Cladding 2, $n_2$

$r$

- $a$, $b$ are the radii of the different layers.
Ring Core Fiber – design tools

- Simple geometry
- Analytical tools to choose dimensions
Ring Core Fiber – design tools

- Simple geometry
- Analytical tools to choose dimensions
  - OAM modes supported
  - Type
  - Number
  \[ \Delta n_{\text{eff}} > 10^{-4} \]
RCF Family – analytical tools for cutoff

Standard fiber

Annular fiber

$2b \rightarrow n_1$

$2b \rightarrow 2\rho b$

$2a = 2\rho b$

Fiber geometry
RCF Family – analytical tools for cutoff

Fiber geometry

Standard fiber

Annular fiber

LP

Modes mapped

Dimensions of modal map

Parameters of modal map

Solution of map boundaries

ID

V₀

analytical [13]

2D

V₀, ρ

analytical [10]

scalar equations
### RCF Family – analytical tools for cutoff

**Fiber geometry**

<table>
<thead>
<tr>
<th>LP</th>
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<tbody>
<tr>
<td>1D</td>
<td><strong>Dimensions of modal map</strong></td>
</tr>
<tr>
<td>( V_0 )</td>
<td><strong>Parameters of modal map</strong></td>
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<tr>
<td>2D</td>
<td><strong>Dimensions of modal map</strong></td>
</tr>
<tr>
<td>( V_0, n_0^2 )</td>
<td><strong>Parameters of modal map</strong></td>
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**Scalar equations**

- Standard fiber
  - \( 2b \)
  - \( n_1 \)
  - \( n_2 \)

- Annular fiber
  - \( 2b \)
  - \( 2\alpha = 2\rho b \)
  - \( n_2 \)
  - \( n_1 \)

**Vector equations**

- Standard fiber
  - \( 2b \)
  - \( n_1 \)
  - \( n_2 \)

- Annular fiber
  - \( 2b \)
  - \( 2\alpha = 2\rho b \)
  - \( n_2 \)
  - \( n_1 \)

---

*our work: analytical*
RCF Family – analytical tools for cutoff

Standard fiber

\[ 2b \quad n_1 \]

\[ n_2 \]

Annular fiber

\[ 2b \quad 2a = 2\rho b \]

\[ n_2 \]

\[ n_1 \]

Fiber geometry

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**vector equations**

**scalar equations**

RCF Family – modal maps

- Geometry \( \rho \triangleq \frac{a}{b} \)

- Normalized propagation constant

\[
\tilde{\beta} \approx \frac{n_{\text{eff}} - n_2}{n_1 - n_2}
\]

- Normalized frequency

\[
V_0 = k_0 b \sqrt{n_1^2 - n_2^2}
\]
Modal map

- Monomode region
- Modal labels: HE_{1,1}, TE_{0,1}, HE_{2,1}, TM_{0,1}, EH_{1,1}, HE_{3,1}, HE_{1,2}, HE_{2,1}, HE_{3,1}, HE_{4,1}, HE_{2,2}, HE_{3,2}, HE_{4,2}

Variables:
- \( \rho \): Dimensionless parameter
- \( V_0 \): Voltage parameter
Modal map

SCF fiber $\rho \to 0$
Modal map

LP mode group
Modal map

OAM mode “group”
Predicting $\Delta n_{\text{eff}}$

Predicting $\Delta n_{eff}$

SCF fiber $\rho \rightarrow 0$

Inner / outer radius ratio ($\rho = a / b$)

Normalized frequency ($V_0$)

- Monomode
- $OAM_{\pm 1,1}$
- $OAM_{\pm 2,1}$
- $m \geq 2$

No "fence" $\Rightarrow$ Vector modes mix to form LP
RCF family

Ring core

1.8µm

5.6µm

inner / outer radius ratio (\( \rho = a / b \))

monomode

OAM\(_{\pm1,1}\)

OAM\(_{\pm2,1}\)

m ≥ 2

Normalized frequency \( (V_0) \)

I

II

III

IV
Outline

- Motivation – overcoming the Shannon limit
- Space Division Multiplexing systems
- Fibers for SDM
  - Background on fibers
  - Eigenmodes & Few mode fibers
- Linearly polarized (LP) modes solution
  - Multiple input, multiple output (MIMO) processing
- Orbital angular momentum modes (OAM) solution
  - OAM fibers – why we like them & how we design them
  - OAM at UL
    - OAM transmission experiments
- Conclusion
First proof of concept

- Optical control of polarization
- Mode separation facilitated by this control
- No MIMO processing required

Electronic polarization demultiplexing

- Single port reception
- 1.4 km transmission
- Standard 2×2 MIMO
- No polarization tuning

Commercial Receivers & OAM Fiber

- Heterogeneous transmission (OOK/QPSK)
- OAM states separated by commercial 2x2 MIMO

Second order OAM

- OAM2 in IPGIF fiber

Higher order OAM


4x4 MIMO over one OAM |order|

8 channels
OAM |4|
OAM |5|

4x4 MIMO over one OAM |order|
Higher order OAM


Higher order OAM


no MIMO; stability once modes adjusted for TX

12 channels
OAM |5|
OAM |6|
OAM |7|
LP vs. OAM

- Rich set of components
  - coupling and muxing
- LP modes from eigenmodes that necessarily interact
  - high crosstalk
  - limited channel count
- Requires MIMO processing and multiplexed receivers

- Early stages of research
  - coupling issues still open
- OAM modes from eigenmodes that can be designed to avoid interaction
  - low crosstalk
  - better channel count
- DSP & RX simpler
  - No MIMO processing needed
  - Standard $2 \times 2$
LP vs. OAM

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Different Strategies

embrace strong fiber interactions to simplify components; exploit MIMO

/ target very low fiber interactions, but what about splices, etc.?
avoid MIMO
Some other promising directions

- a single core, a single mode
- ring core fiber
- a single core, multiple modes
Some other promising directions

- A single core, a single mode
- Ring core fiber
- A single core, multiple modes
- Elliptical core fibers
- Linearly polarized vector modes hold promise
Conclusion

• Transmission of OAM modes still very new
• Design and fabrication of optical fibers is challenging
• Need to better understand mode-coupling and cross-talk mechanisms
  - optimize designs
  - target most appropriate OAM modes
• Integrated components are needed as well as fibers
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