# Structured light with optical fibres: beams that can do what Gaussians cannot

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# Structured Light with Optical Fibres: Beams that Can Do What Gaussians Cannot

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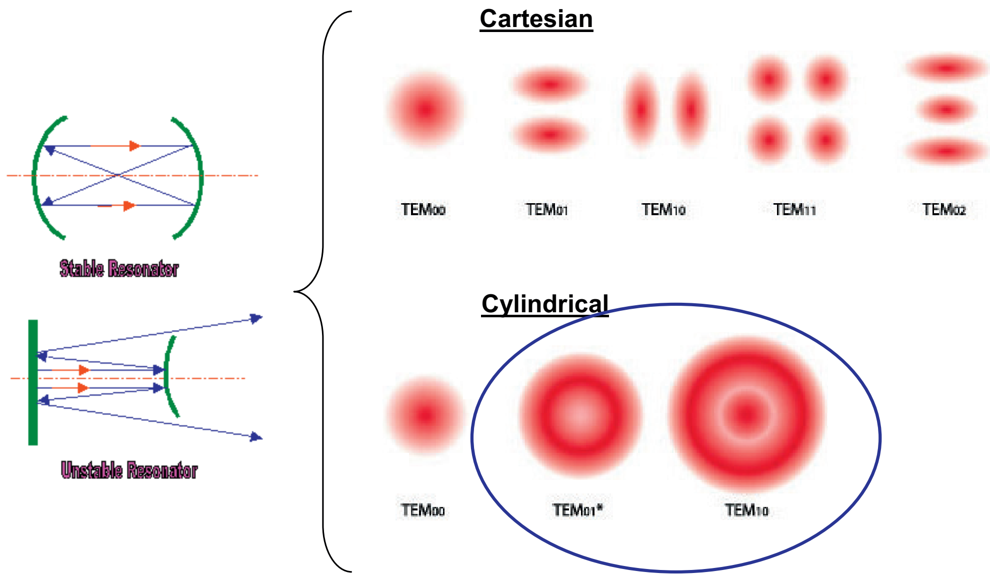
## Spatial modes

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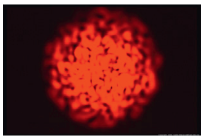
## Mode Stability

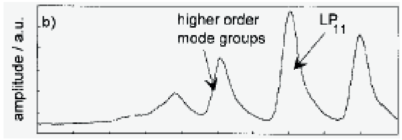
**Multimode Fiber**

**Spatial Output**

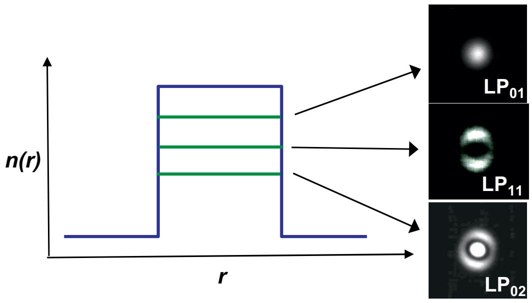


Vadim Makarov www.vad1.com

**Temporal Output**




Raddatz et al, PTL, v10, p534, 1998




$$\eta \sim \int E_1 \cdot P_{pert}(r,\varphi) \cdot E_2 \cdot dA$$

$$\delta(\lambda) = \frac{\Delta\beta(\lambda)}{2}$$

$$\delta \uparrow \Rightarrow coupling \downarrow$$

**To exploit other modes…**

- *Launch Purely*
- *Inhibit Coupling*

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## Outline

- Mode Conversion
  - The higher-order-mode schematic
  - How to access them –*gratings, tapered couplers, holograms*
- Dispersion control
  - High normal (-ve) dispersion… *telecom, fs pulse control*
  - Anomalous Dispersion……….. *nonlinear optics*
  - Multiple paths…………………. *adjustable delays*
- Mode area control
  - Anomalous stability criteria ⇔ large mode areas
  - Applications to high-power lasers
- Free space implications
  - Beam forming
  - Cylindrical vector beams, Vortices
  - Bessel beams

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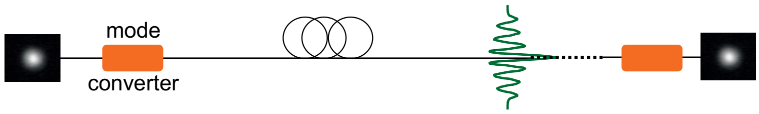
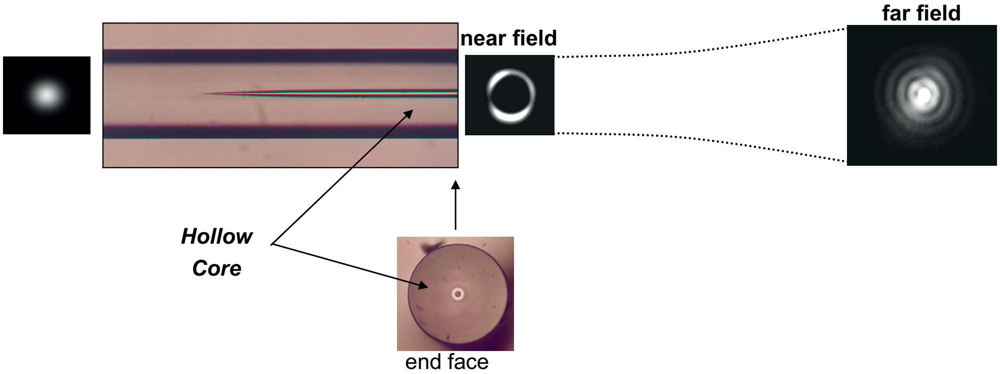
## The HOM Schematic

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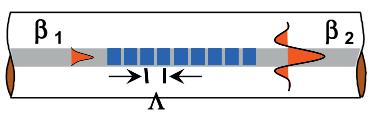
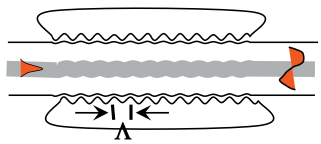
K. Oh et al, JLT, v23, p524, 2005

## Long-period Fiber-gratings

UV-induced index change




Microbends



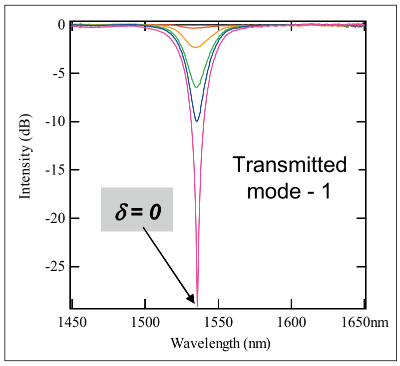

- Perturbation
  - break orthogonality between eigenmodes
  - symmetry of perturbation matters

$$\sim \int E_1 \cdot P_{pert}(r,\phi) \cdot E_2 \cdot dA$$

- Match phases
  - periodicity in real-space ⇔ singularity in k-space

$$\delta(\lambda) = \frac{\Delta\beta(\lambda)}{2} - \frac{\pi}{\Lambda}$$

  - maximum coupling for $\delta = 0$




J.N. Blake et al, OL, v11, p177, 1986
A.M. Vengsarkar, JLT, v14, p58, 1996

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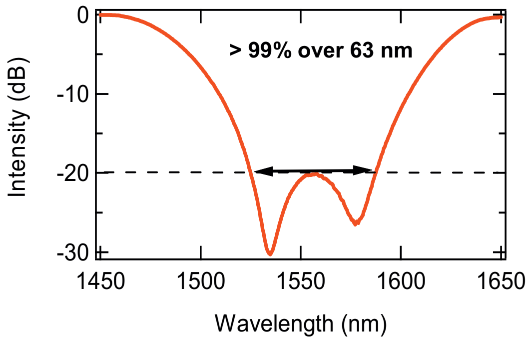
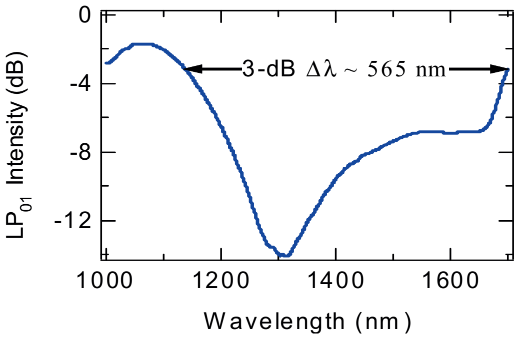
## Broadband Gratings




- Broadband Mode Conversion

(C.D. Poole et al, JLT, v9, p598, 1991)
(S. Ramachandran *et* al, OL, v27, p698, 2002)

$$\delta(\lambda)=\frac{1}{2}\left(\underbrace{\Delta\beta(\lambda)}_{0}\cdot\Delta\lambda+\frac{\Delta\beta''(\lambda)}{2!}\cdot\Delta\lambda^2+\frac{\Delta\beta'''(\lambda)}{3!}\cdot\Delta\lambda^3+\ldots\right)$$




- λ – insensitive coupling

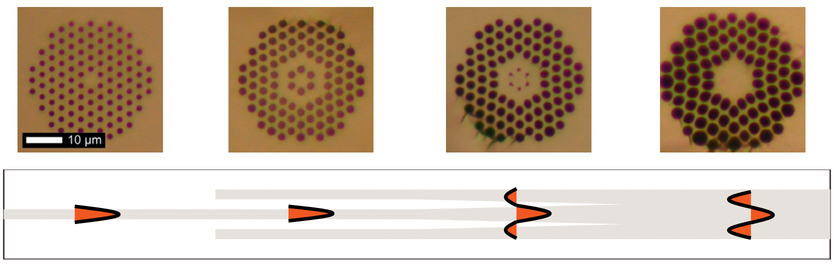
(S. Ramachandran *et* al, PTL, v15, p1561, 2003)

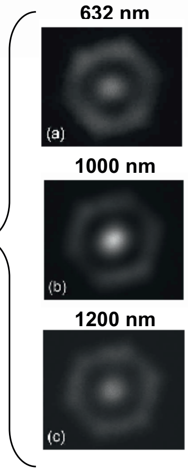
–**Match several dispersive orders**

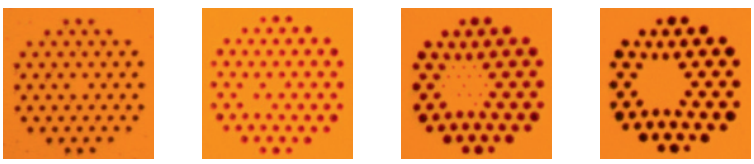
$$\delta(\lambda)=\frac{1}{2}\left(\underbrace{\Delta\beta(\lambda)}_{0}\cdot\Delta\lambda+\underbrace{\frac{\Delta\beta''(\lambda)}{2!}}_{0}\cdot\Delta\lambda^2+\underbrace{\frac{\Delta\beta'''(\lambda)}{3!}}_{0}\cdot\Delta\lambda^3+\ldots\right)$$

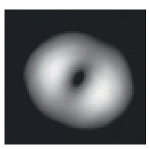
## Tapered Couplers

**K. Lai et al, OL, v32, p328, 2007**



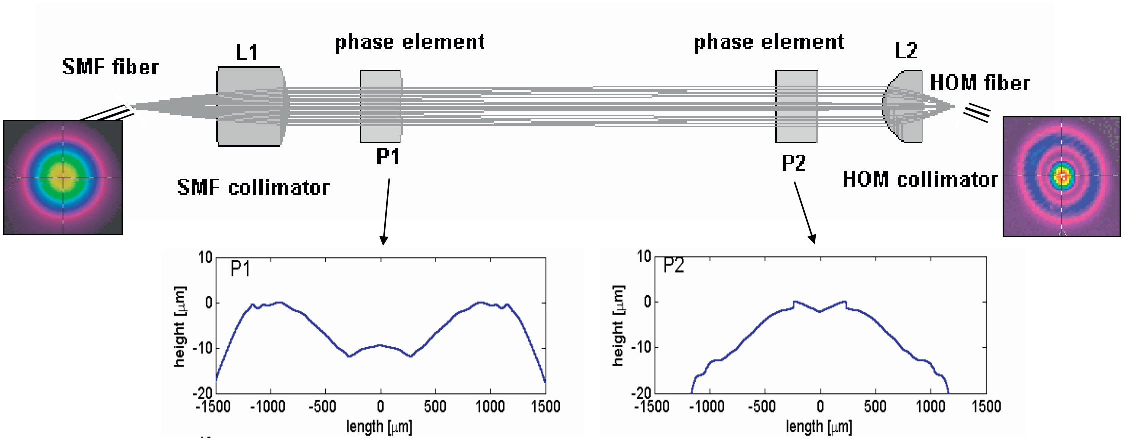


**A. Witkowska et al, OL, 33, p306, 2007**

## Phase Plates

**One Phase Element:**
*need |H(x,y)| ➔ absorptive elements ➔ loss*

***Two Phase Elements:***
*free space path ➔ convert phase variation at P1 to intensity variation at P2*

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**M. Tur et al, J. Opt. Fiber. Comm. (Springer), v4, p110, 2007**

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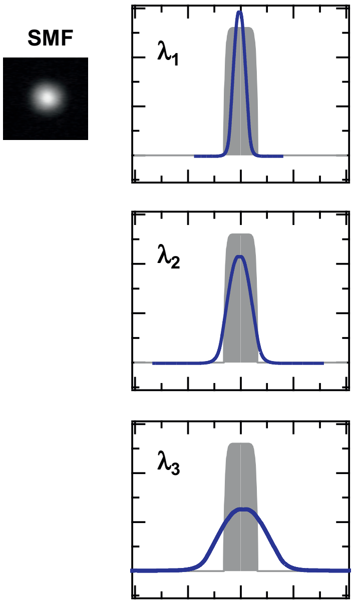
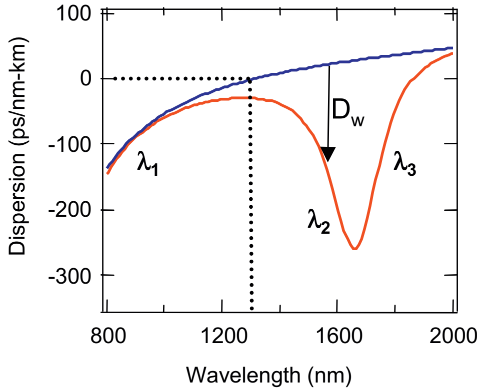
## Dispersion in fibers




$$D = D_m + D_w; \qquad D_w = \frac{d\tau}{d\lambda}$$




**Mode expands to ↓ n**
**⇒ $D_w < 0$**
**⇒ $D < D_m$**

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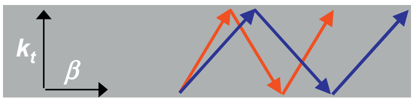
**L. Gruner-Nielsen *et al*, JLT, v23, p3566, 2005**

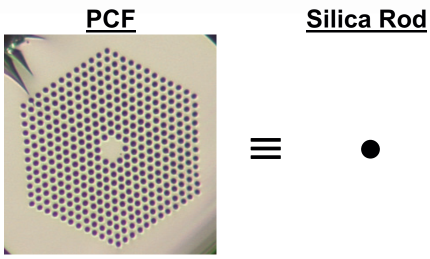
## Dispersion in fibers (2)



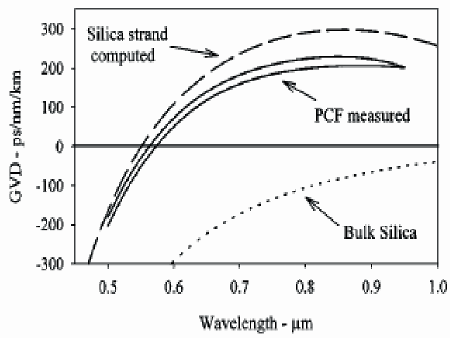

$$\beta^2 = \left(\frac{2\pi}{\lambda} n\right)^2 - k_t^2; \qquad k_t \cdot a = m\pi$$

$$\lambda \uparrow \Rightarrow \tau \uparrow$$

$$\therefore D_w = \frac{d\tau}{d\lambda} > 0$$




**+D ↑ with $A_{eff}$ ↓**

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**L. Gruner-Nielsen *et al*, JLT, v23, p3566, 2005**

**J.C. Knight *et al*, PTL, v12, p807, 2000**

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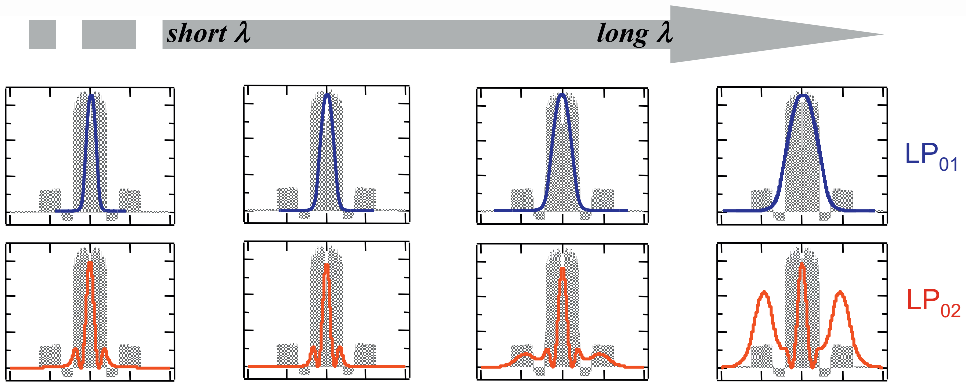
## Modal evolution in fibers




- Stable mode (e.g. $LP_{01}$)..................Mode profile expands **slowly** with λ
- Dispersive mode (e.g. $LP_{02}$)............Side lobes expand **rapidly** with λ

*Analogy to particle in a box*

- Core & Ring……competing attractive wells
- Trench…………..barrier for side-lobe movement

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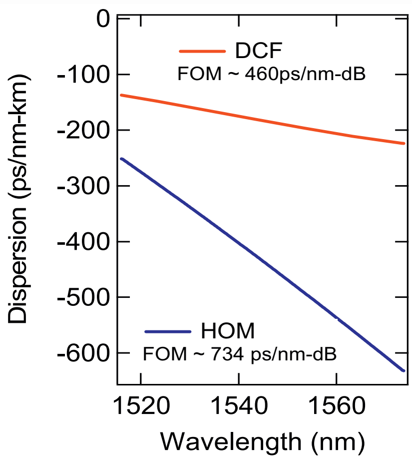
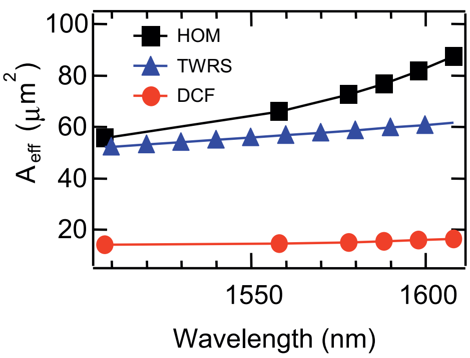
**S. Ramachandran, JLT, v23, p3426, 2005**

## -D from HOMs




- **Higher dispersion, slope possible**
  - *Lesser compensating fiber*
- **Higher FOM (d/α)**
  - *Lower loss modules*

- **$A_{eff}$ ~ 3x to 5x larger than DCF**

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**S. Ramachandran et al, J. Opt. Fiber. Comm. (Springer), v3, p159, 2006**

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## Dispersion compensation

### Dispersion Slope Matching

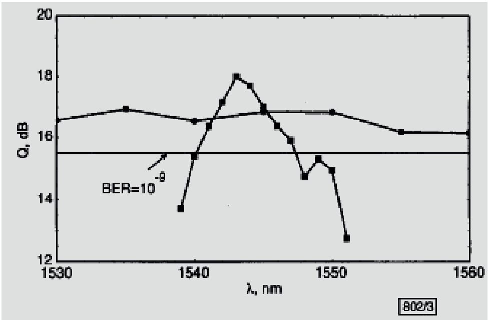
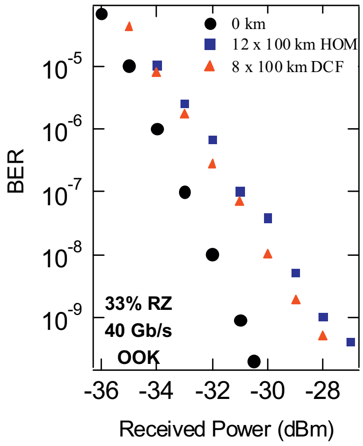



**Fig. 3** *Q-factor measurements against wavelength*
A 'Q' of 15.6 corresponds to a BER of $1 \times 10^{-9}$
—●— DMDs
—■— DCF

First slope-matched systems test over entire C-band with high-RDS fiber

**A. Gnauck et. al, OFC-2000, PD-8**

### Enhanced Nonlinear Threshold

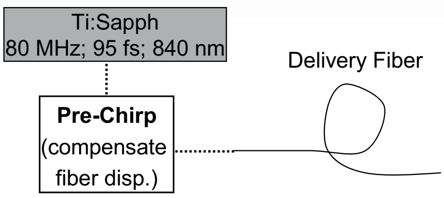



10 dBm higher input power in HOM vs. DCF
➔ 50% longer transmission

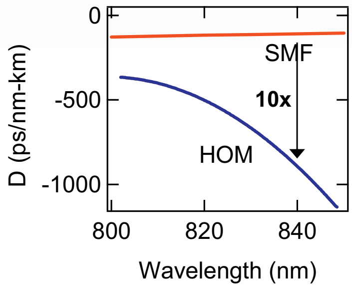
**S. Ramachandran et. al, ECOC-2000, PD-2.5**

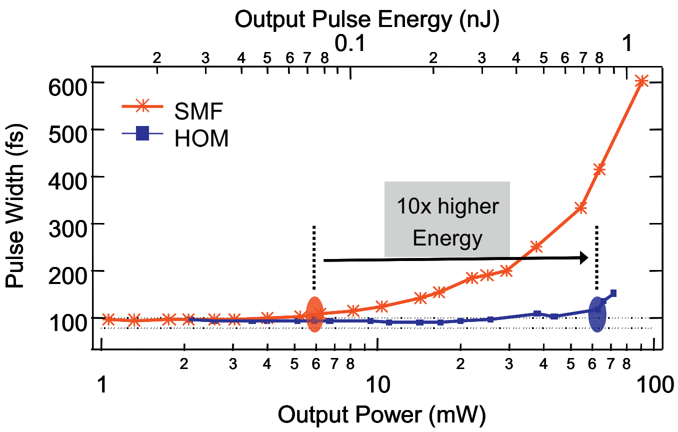


## Energetic Ultra-Short Pulse Delivery




$$nonlinearity \sim \frac{1}{D \cdot A}$$






**S. Ramachandran et. al, OL, v30, p3225, 2005**

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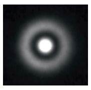
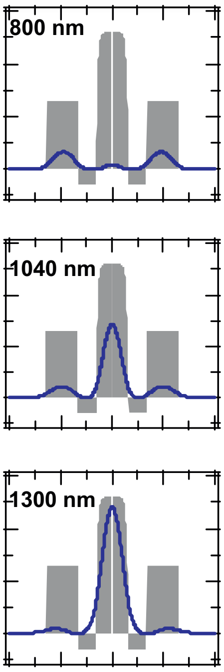
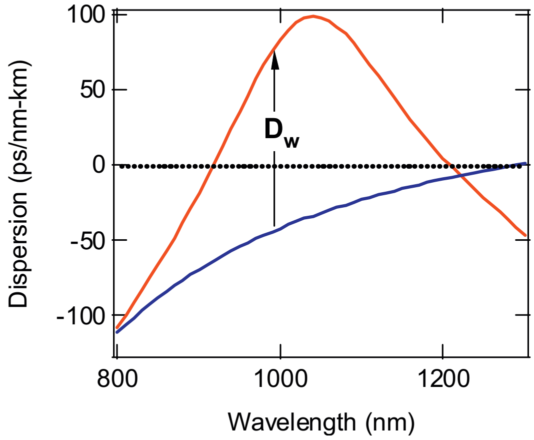
## "Anomalous" mode evolution in HOMs

$LP_{02}$






**Mode evolves in *opposite* direction => $D_w = d\tau/d\lambda > 0$**




**All silica fiber with ↑↑ +D**
**$A_{eff}$ ~ 10 to 100x higher than PCF**

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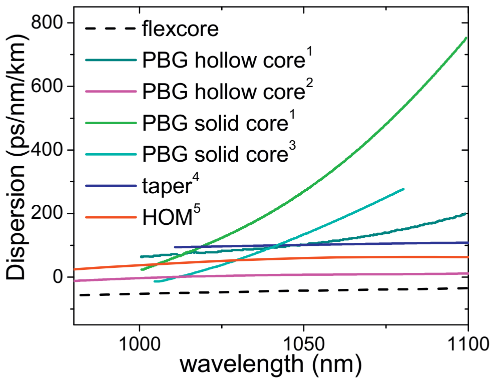
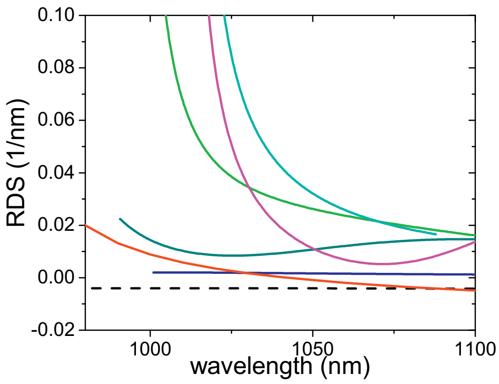
**S. Ramachandran et. al, OL, v31, p2532, 2006**

## Dispersion control at 1 μm




***+D HOMs in fs modelocked laser cavities***

- **88 fs output *all fiber*** (nonlinear pol. evolution)
  – M. Shultz et al, CLEO-Europe 2009
- **52 fs output** (nonlinear pol. evolution)
  – M. Shultz et al, OL-2007
- **137 fs output *all fiber*** (carbon nanotubes)
  – J.W. Nicholson et al, Opt. Exp.-2007

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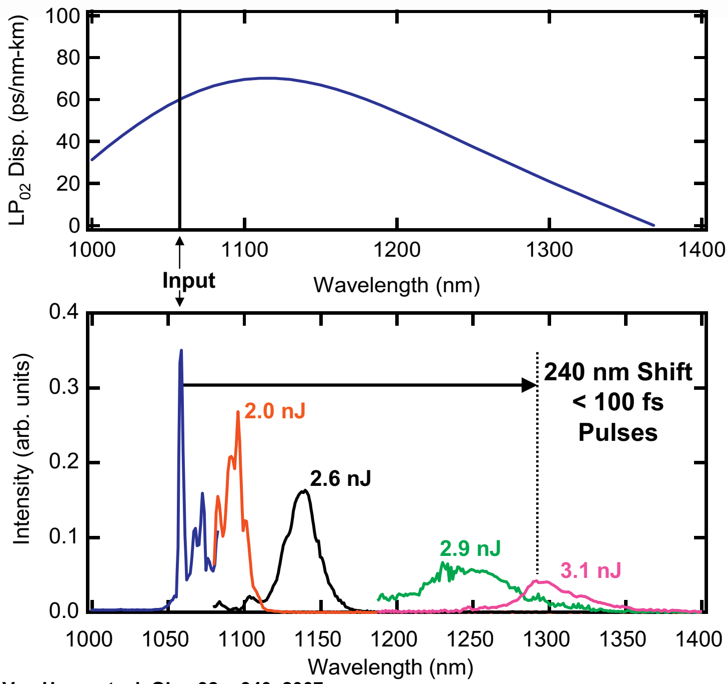
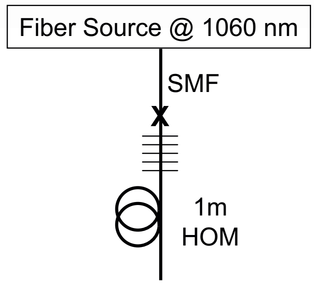
1 C.K. Nielsen et al. Opt. Exp. 14, pp 6063 (2006)
2 H. Lim et. al. Opt. Exp 12, pp 2231 (2004)
3 A. Isomaki et. al. Opt. Exp 14, pp 4368 (2006)
4 M. Rusu et. al. Opt. Lett. 31, pp 2257 (2006)
5 S. Ramachandran et. al. Opt. Lett. 31 pp 2532 (2006)

## Raman-Shifted Solitons ➔ fs tunable source



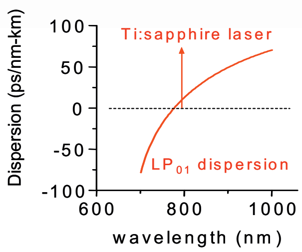



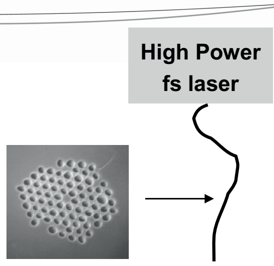

- Range ~ Ti:S + OPO
- Scale Energy by ↑ $A_{eff}$

J. Van Howe et. al, OL, v32, p340, 2007
J.H. Lee et. al, OFC-2007, Post-deadline

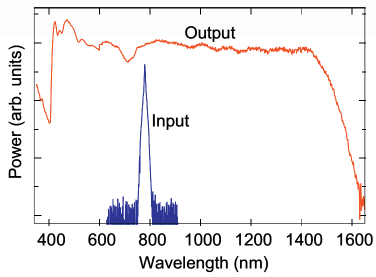


## Supercontinuum Generation




J.K. Ranka *et.* al, OL., v25, p25 , 2000




Center Launch

Offset Launch

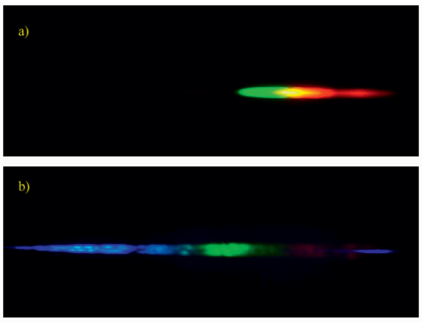
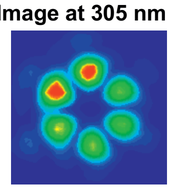



Image at 305 nm



- Anomalous dispersion in HOM
  - enhanced nonlinearities
  - new mode-conversion technique?



A. Efimov et al, Opt. Exp., v11, p910 , 2003

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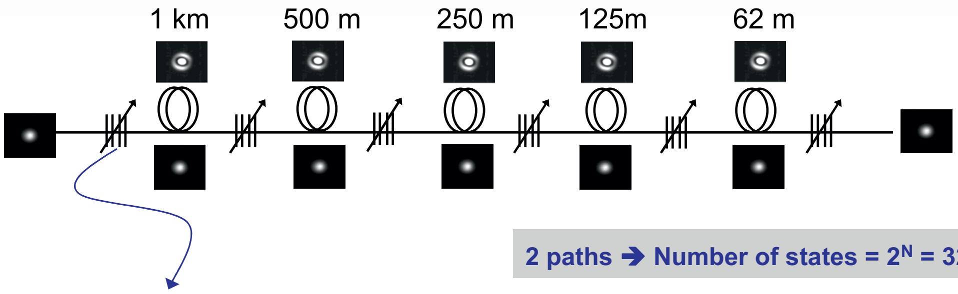
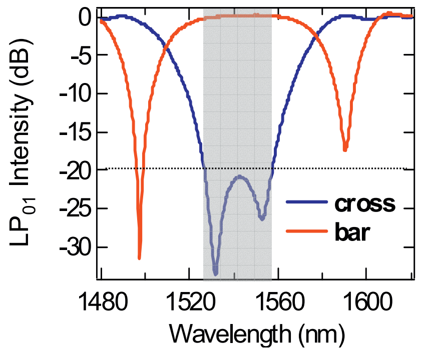
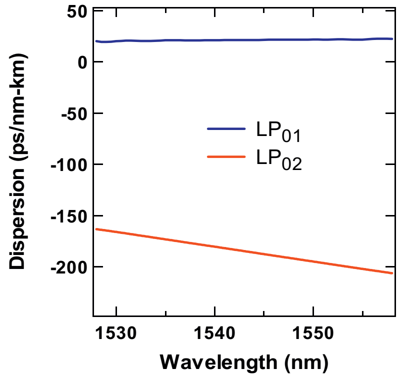
## Optical Path Diversity




**2 paths ➔ Number of states = $2^N$ = 32**

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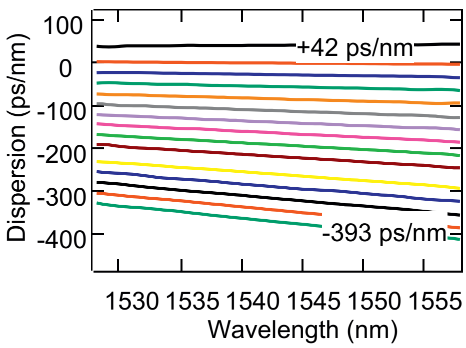
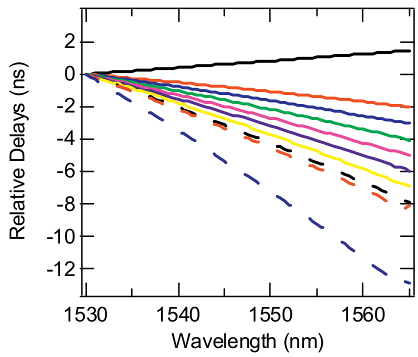
## Adjustable Delay/Dispersion

**Dispersion**




**Delay**

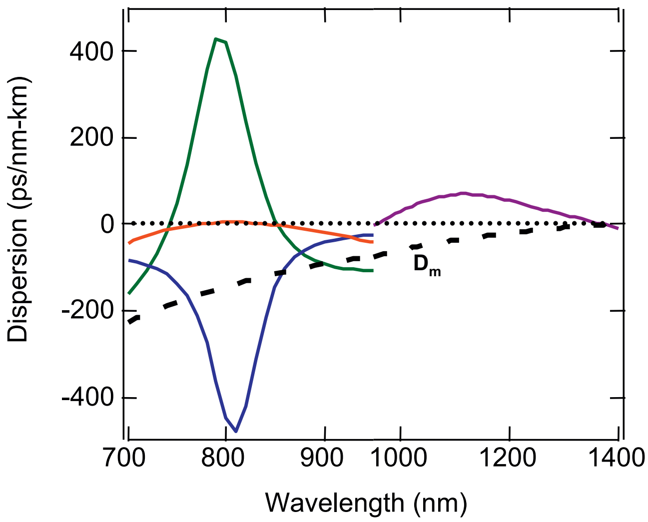



**Design Flexibility**

- Slope…………………HOM fiber design
- Range & Step size…..Segment lengths
- Bandwidth……………Grating design

**S. Ramachandran et. al, PTL, v15, p727, 2003**

## Dispersive design flexibility with other modes




**Control**
- D, $D_{slope}$, λ, $D_0$
  - *with range of $A_{eff}$*
- Low Loss (~0.1 – 0.5 dB)

**Applications**
- Tune λ range of source
- Disp. management of lasers
- High(er) energy ν-conversion

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S. Ramachandran et al, J. Opt. Fiber. Comm. (Springer), v3, p159, 2006

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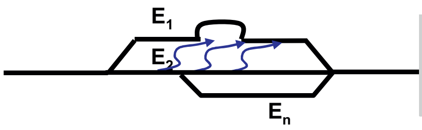
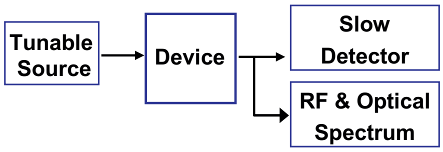
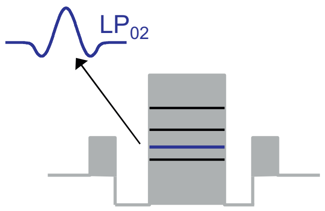
## Multi-Path Interference (MPI) or Modal Noise



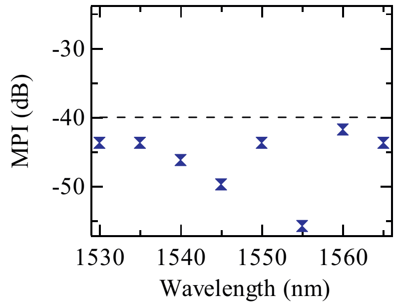

$$MPI = \left| \frac{E_{parasitic}}{E_{main}} \right|^2$$

**Testing technique**



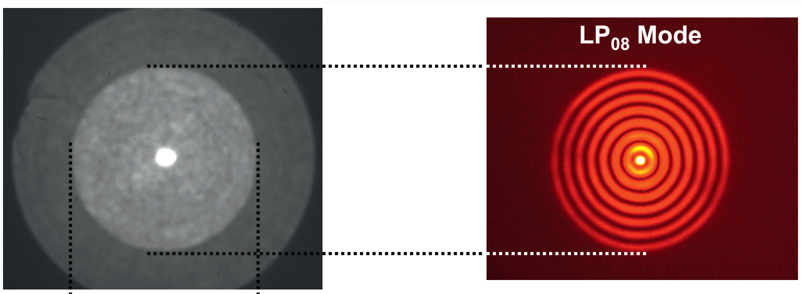



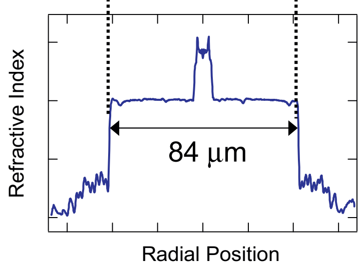

*Maximise $n_{desired} - n_{parasitic}$*
*➔ minimise coupling*




M.G. Taylor et al, ECOC-2003, 3.1.7
S. Ramachandran et. al, PTL, v15, p1171, 2003

## Large $A_{eff}$ modes




- $A_{eff}$ ~ 1750 µm²
- ***After 50 meters!***



S. Ramachandran et al, OL, v31, p1797 , 2006

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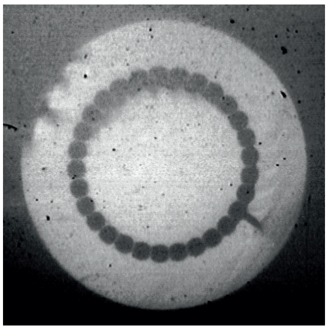
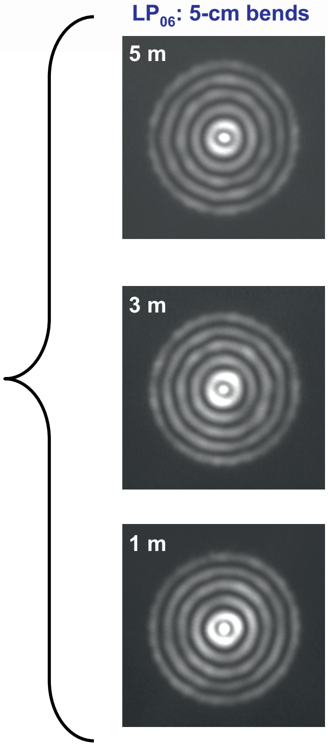
## Air-clad version

$A_{eff}$ ~ 2400 μm$^2$
Air Clad defines HOM waveguide



LP$_{06}$: 5-cm bends

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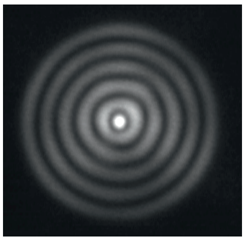
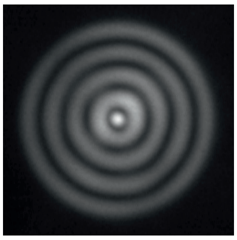
S. Ramachandran et al, J. Laser & Photonics Rev. , Dec. 2008

## Other modes (1550 nm)

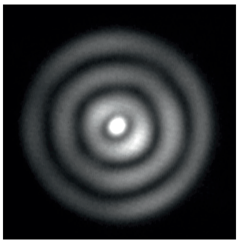
LP$_{06}$: 2 m; 7-cm bends



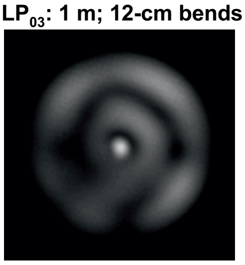
LP$_{05}$: 2 m; 7-cm bends



LP$_{04}$: 4 m; 7-cm bends



LP$_{03}$: 1 m; 12-cm bends

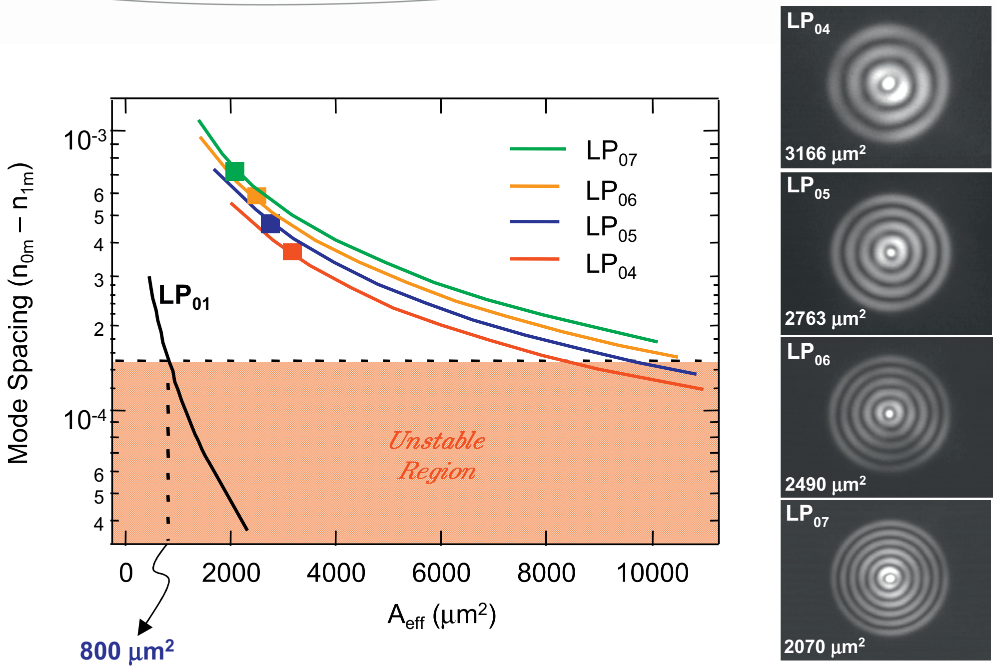


For higher mode orders:
– Stability ↑
– Bend Distortion ↓

Why?
Deeper Wells
⇒more states
⇒more coupling

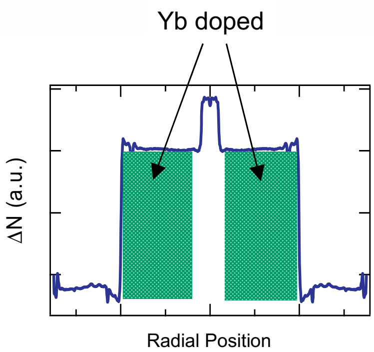
J.M. Fini & S. Ramachandran, OL, v32, p748, 2007

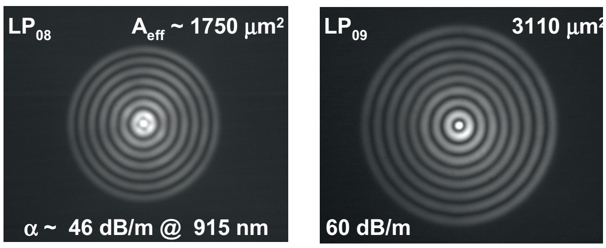
## LMA *flexible* Fibers

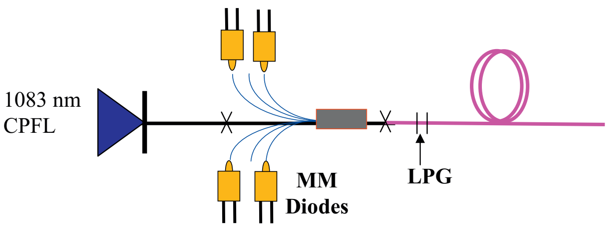



S. Ramachandran et al, J. Laser & Photonics Rev. , Dec. 2008
S. Ramachandran et al, OL, v31, p1797 , 2006
S. Ramachandran et al, Laser Focus World, Sept. 2007
S. Ramachandran et al, Photonics Spectra, Sept. 2006

## Cladding Pumped Amplifiers



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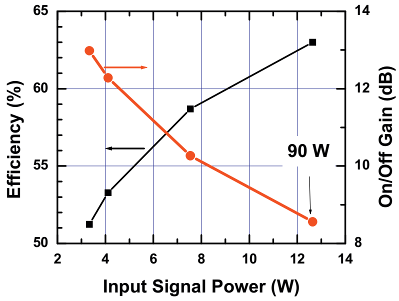
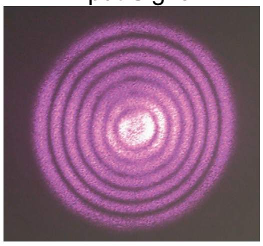
## HOMs for Power Amplification

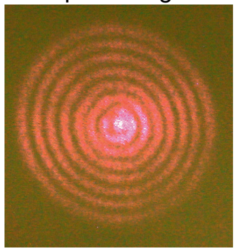
**1750 µm² LP$_{08}$ mode**



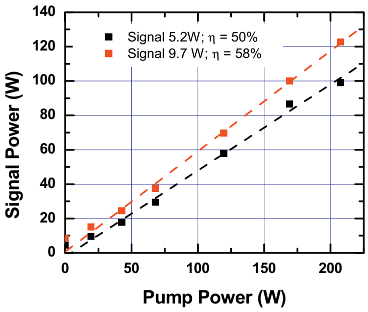

Input Signal

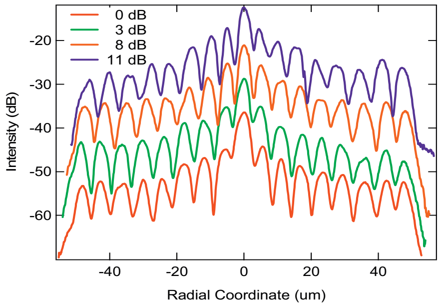


Amplified Signal



**3110 µm² LP$_{09}$ mode**

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# Single-mode fiber laser based on core-cladding mode conversion


Shigeru Suzuki,* Axel Schülzgen, and N. Peyghambarian
*College of Optical Sciences, University of Arizona, Tucson, Arizona 85721, USA*


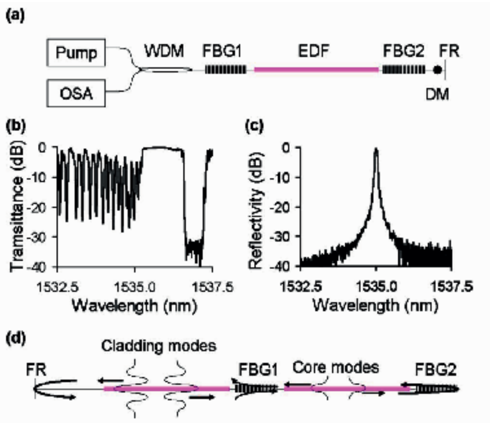


Fig. 1. (Color online) (a) Schematic of the fiber laser setup, (b) transmittance spectrum of FBG1, (c) reflectivity spectrum of FBG2, and (d) schematic of an unfolded cavity that is equivalent to the fabricated folded cavity with core-cladding mode conversion.

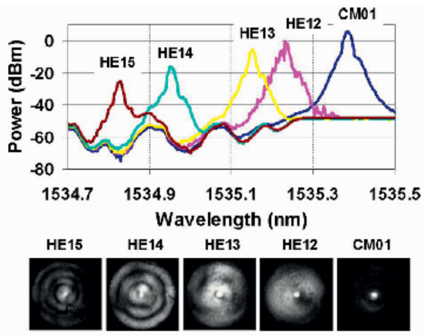


Fig. 3. (Color online) Lasing spectra and spatial profiles of the fiber laser at different temperatures of FBG2.

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S. Suzuki et al, OL, v33, p351, 2008

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# Phase locking and coherent combining of high-order-mode fiber lasers

Vardit Eckhouse,* Moti Fridman, Nir Davidson, and Asher A. Friesem
*Department of Physics of Complex System, Weizmann Institute of Science, Rehovot 76100, Israel*

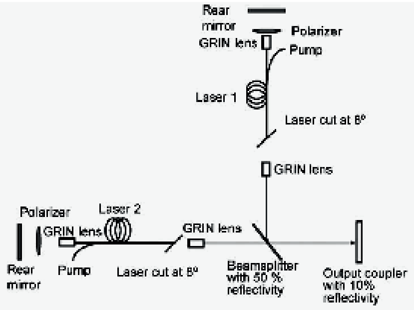


Fig. 5. Configuration for coherent addition of two fiber lasers each operating with a high-order mode.

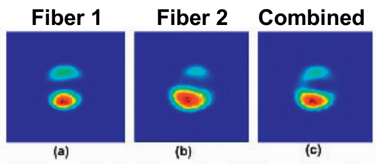


Fig. 6. (Color online) Coherent addition of two fiber lasers each operating with $LP_{11}$ mode. (a) Intensity distribution of one laser, (b) intensity distribution from the other laser, (c) intensity distribution of the combined output.

**Spatial distribution and polarisation of one laser imposed on the other**

**➔ feasible to lock in *any* mode?**

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**V. Eckhouse et al, OL, v33, p2134, 2008**

# Outline

- Mode Conversion
  - The higher-order-mode schematic
  - How to access them –*gratings, tapered couplers, holograms*
- Dispersion control
  - High normal (-ve) dispersion… *telecom, fs pulse control*
  - Anomalous Dispersion……….. *nonlinear optics*
  - Multiple paths…………………. *adjustable delays*
- Mode area control
  - Anomalous stability criteria ⇔ large mode areas
  - Applications to high-power lasers
- Free space implications
  - Beam forming
  - Cylindrical vector beams, Vortices
  - Bessel beams

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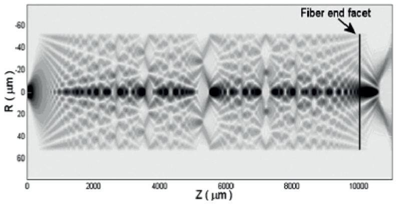
# Multimode Beam Forming

## Re-imaging in Multimode fibers

(W.S. Mohammed et al, JLT, v22, p469, 2004)




## Fiber lens: couple multiple modes to $LP_{01}$

(G. Nemova et al, Opt. Comm., v261, p249, 2006)

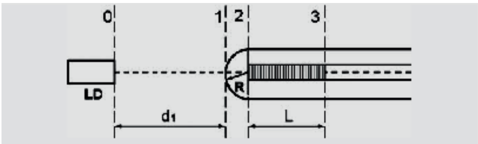
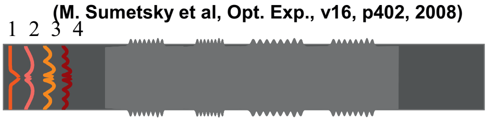



Fig. 1. Schematic diagram of the proposed coupling scheme with the hemispherical lens.

## Sequential or Superimposed LPG

(M. Sumetsky et al, Opt. Exp., v16, p402, 2008)




– Sharp beam edge, longitudinally
– Flat transverse beams

## X. Gu et al, PTL, v20, p1130, 2008

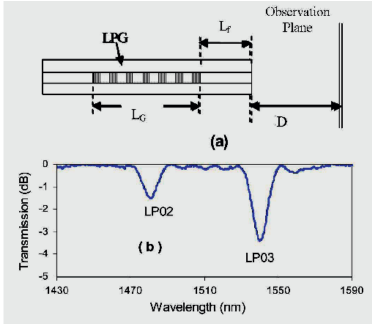



Fig. 1. (a) The schematic of the beam shaping device and (b) transmission spectrum of the $LP_{03}$ and $LP_{02}$ cladding modes of LPG.

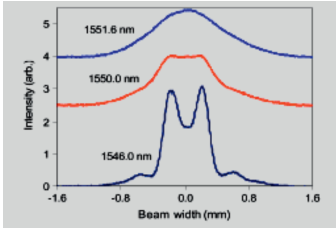



Fig. 4. The beam intensity profiles measured at 12 mm from the fiber facet at three different wavelengths. The Gaussian and top-hat beam profiles are displaced to improve visibility.

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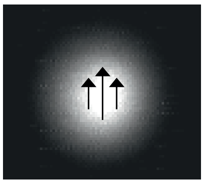
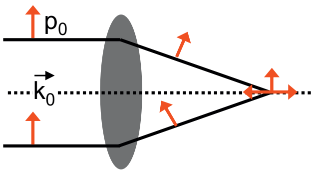
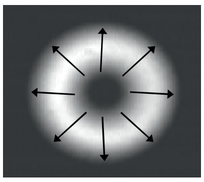
# Cylindrical Vector Beams

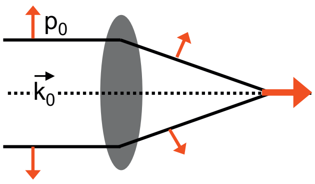
Gaussian






Radially Polarised






## Radially polarised beam

- Intense $E_Z$ with ↑↑ gradient, No $S_Z$!
  - resembles atomic states
    (Novotny et al, PRL **86**, 5251, 2001)
    - Quantum information
    - Probe atomic states
  - electron acceleration
    (Salamin, Phys. Rev. A **73**, 43402, 2005)
    - Free-electron lasers
  - super-resolved spots
    (Dorn et al, PRL, **91**, 233901, 2003)
    - Microscopy, Lithography
  - efficient tweezers
    (Q. Zhan, *Opt. Exp.* **12**, 3377, 2004)
- Machining of metals
  - 2x more efficient
    (Nesterov et al, *Phys. D* **33**, 1817, 2000)

***Not easy to generate***

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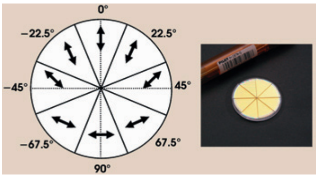
## Generation of non-uniform polarisation patterns

- **Segmented waveplates**
  - restricted λs
  - low efficiency, high loss




**Machavariani et al, OL 32, 1468, 2007**

- **Resonator modes**
  - unstable
  - Limited λ

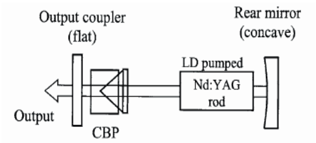
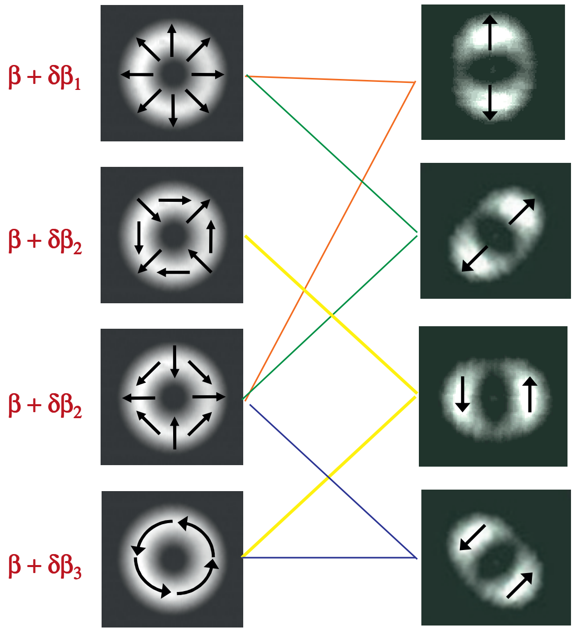


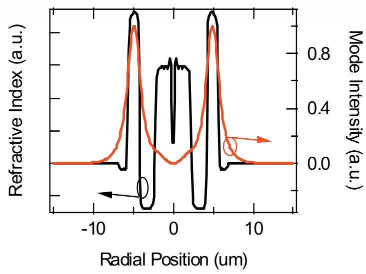

Fig. 2. Block diagram of the experimental setup. CBP, conical Brewster prism; LD, laser diode.

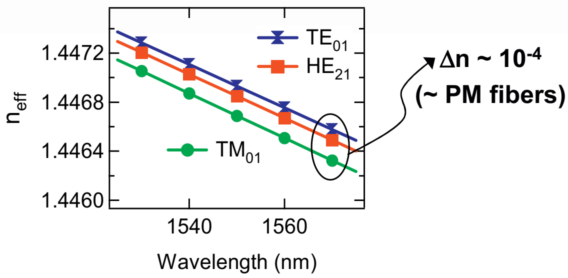
**Y. Kozawa et al, OL 30, 3063, 2005**
**J-L. Li et al, OL 31, 2969, 2006**

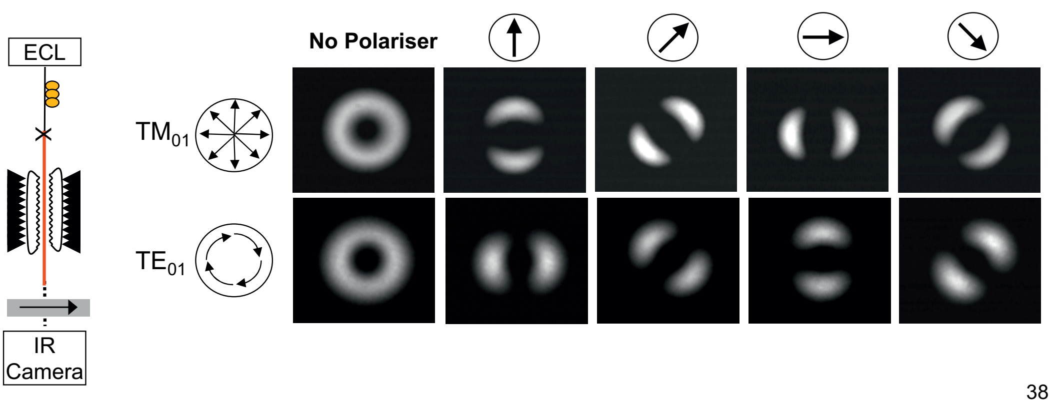





## Phase Engineered Fiber






**S. Ramachandran et al, OL, v34, 2009**

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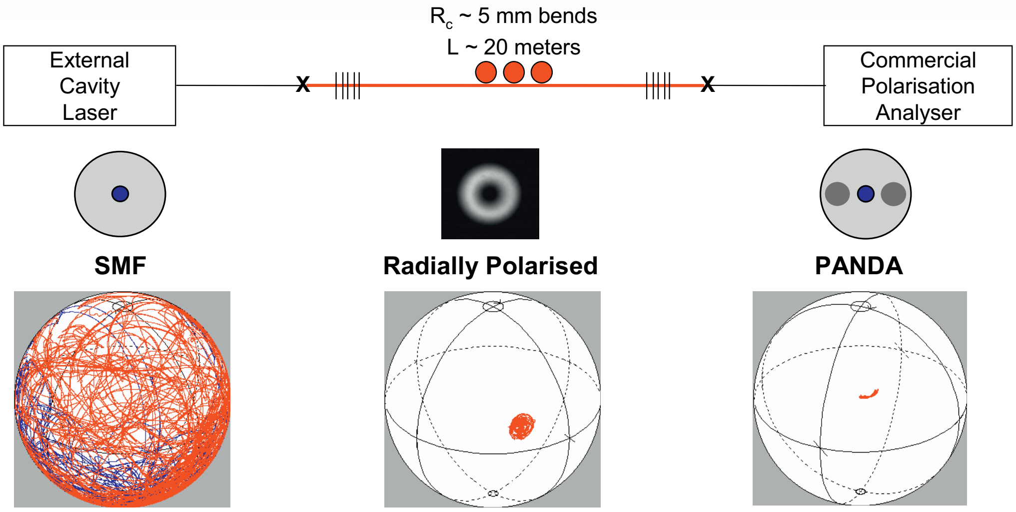
## Polarisation Preservation




**PER = 0 dB** **PER = 29 dB** **PER = 35 dB**

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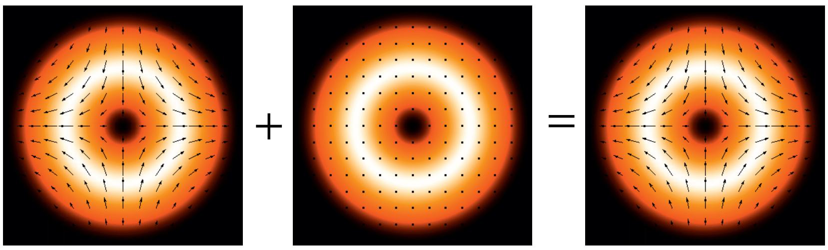
S. Ramachandran and M.F. Yan, CLEO-2008, CThV2

## Helical Gratings

C.D. Poole et al, JLT, v9, p598, 1991

P. Z. Dashti et al, PRL, v 96, 043604, 2006



***Output is a Vortex Beam (Spiral Phase)***

$$HE_{21}{}^{e} + \left(-iHE_{21}{}^{o}\right) = HE_{21}{}^{e} - iHE_{21}{}^{o}$$

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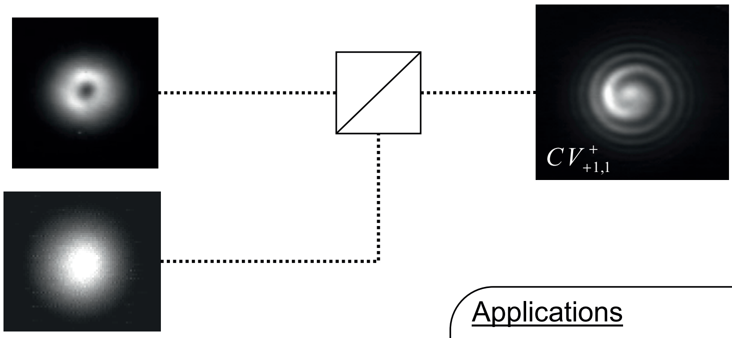
## Vortex Beams

P. Z. Dashti et al, PRL, v 96, 043604, 2006




***Carries Orbital Angular Momentum***

Applications

**"Optical Angular Momentum,"**
**Ed. Allen, Barnett & Padgett, Taylor & Francis (2003)**

- Torque on microscopic objects
- Quantum Cryptography key distribution
- Atom optics
- Nonlinear optics with chiral symmetry

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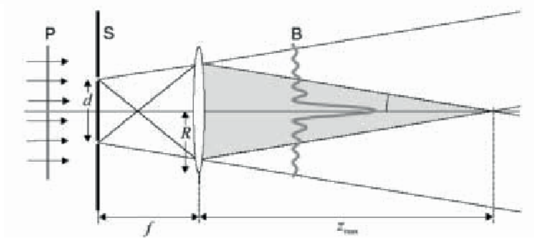
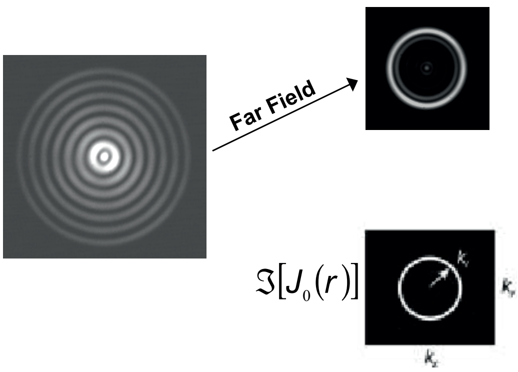
## Bessel Beams

***Thin Ring***




**Conical Plane Waves**

- Diffraction free!
- Navigate past opaque obstructions

**Applications**

- Large depth of focus
  - –Enhanced nonlinear interactions
  - –Atom guides
- Transmit in turbid media
  - –Simultaneous cell manipulation
  - –LIDAR & space communications

**Durnin et. al, PRL, v58, p1499, 1987**
**Dholakia et al, Contemporary Phys., v46, p15, 2005**

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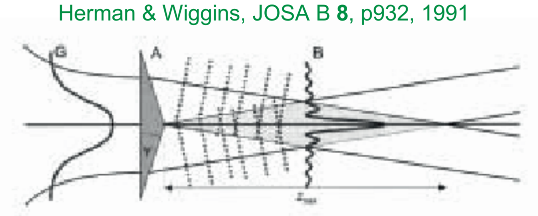
## Generation Techniques

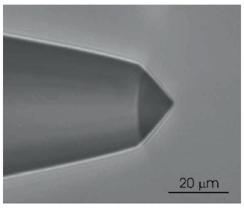
***Axicons***

Herman & Wiggins, JOSA B **8**, p932, 1991



***Fiber microaxicon***

T. Grosjean, Appl. Opt. **46**, p8061, 2007




***Limited aperture => Limited diffraction-resistance***
***Not efficient for higher order Bessel Beams***

**Other free-space techniques**

- Holograms
  - T. Turunen et al, Appl. Opt. **27**, p3959, 1988
- Mode selection in laser resonator
  - K. Uehara et al, Appl. Phys. B **48**, p125, 1989
- Spatial light modulators
  - N.Chattrapiban et al, Opt. Lett. **28**, p2183, 2003
- Whispering gallery mode resonators
  - V.S. Ilchenko et al, Opt. Exp. **15**, p5866, 2007

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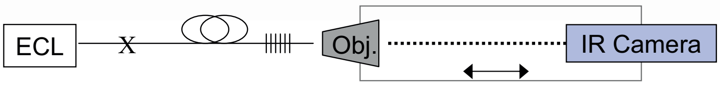
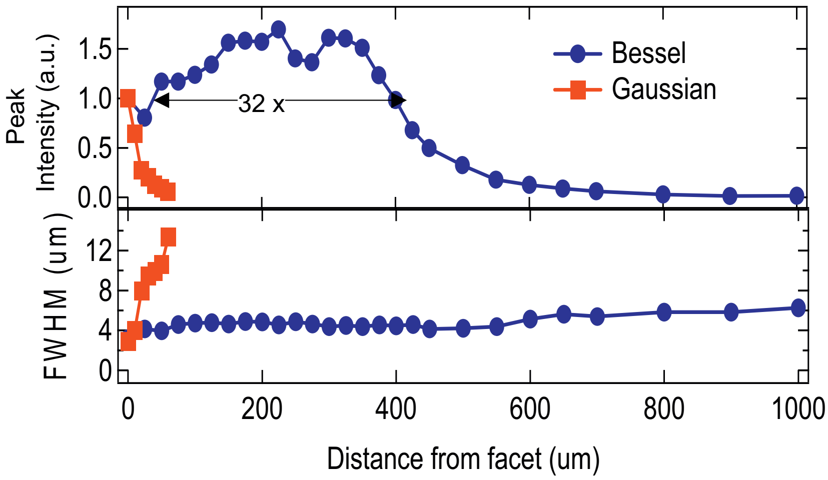
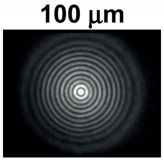
## Diffraction resistant behaviour



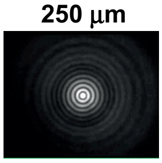




**~3 µm Central Spot**

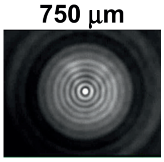
**100 µm**



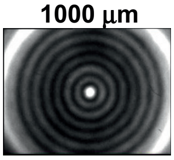
**250 µm**



**750 µm**



**1000 µm**



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**S. Ramachandran and S. Ghalmi, CLEO-2008, Postdeadline, CPDB5**

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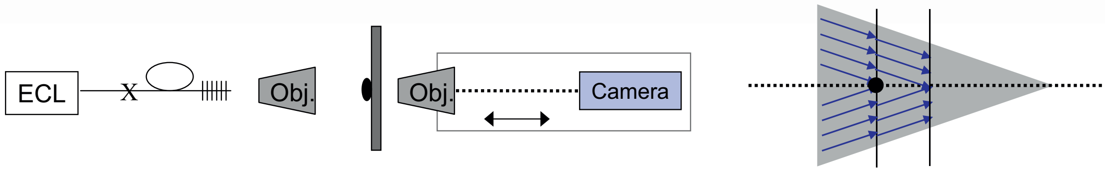
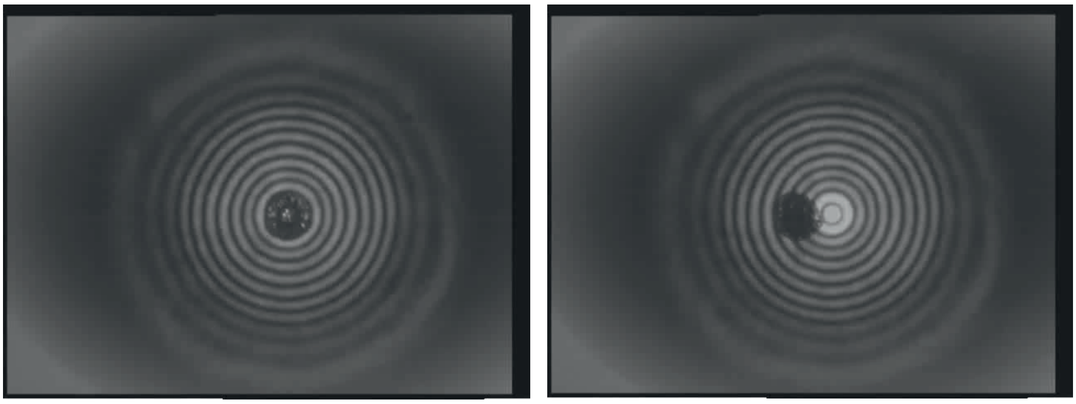
## Self-healing behaviour



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S. Ramachandran and S. Ghalmi, CLEO-2008, Postdeadline, CPDB5

## *Spatially Structured Light offers new possibilities…*

- **Unprecedented control of optical parameters…**
  - –interaction between light-paths with gratings
  - –record *D* and $A_{eff}$ control
- **…enabling new classes of devices**
  - –ultra-high power lasers
  - –novel colour sources
  - –nonlinear switches and devices
- **Light–matter interactions*… spatial & polarisation control with a fiber***
  - –fundamental sciences… quantum state tailoring; electron acceleration
  - –biology.......................... endoscopic imaging; cell manipulation
  - –technology……………… lithography; machining; telecom

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