Spatiotemporal Dynamics of Optical Pulse Propagation in Multimode Fibers

Presented by:

OSA Nonlinear Optics Technical Group

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- Mission
  - To benefit ***YOU***
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  - Prof. Takuro Ideguchi, “Molecular Spectroscopy with Optical Frequency Combs”
  - www.osa.org/tgwebinars/#tab_ondemand

- Spatiotemporal Dynamics of Optical Pulse Propagation in Multimode Fibers
  - Prof. Frank Wise of Cornell University
  - Theoretical and experimental studies of the basic properties and spatiotemporal behavior of complex nonlinear dynamics in multimode fiber will be presented.

Spatiotemporal Dynamics of Optical Pulse Propagation in Multimode Fibers

F. W. Wise
Department of Applied Physics
Cornell University

Spatiotemporal Dynamics…

Introduction to nonlinear pulse propagation

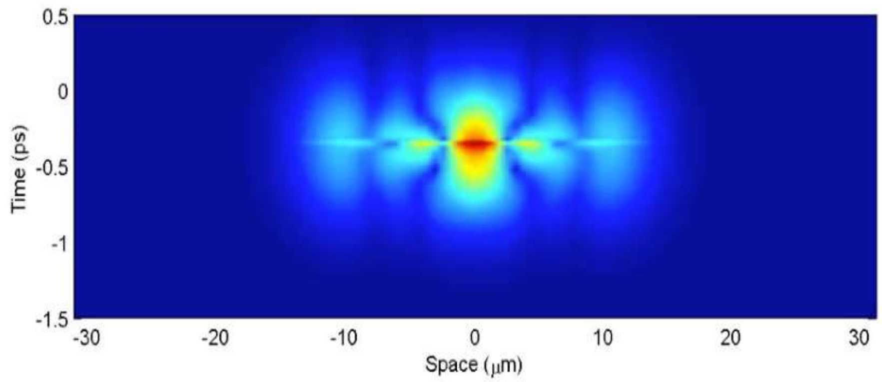
Recent progress in multimode nonlinear propagation

- Solitons in multimode GRIN fiber: formation and fission
- Multimode continuum generation
- Spatiotemporal dispersive waves
- Spatiotemporal modulation instability
- Beam self-cleaning

Future directions / toward applications

Spatiotemporal Dynamics…

- Pulse propagation in multimode fiber is spatiotemporally complex
- 4D vector field



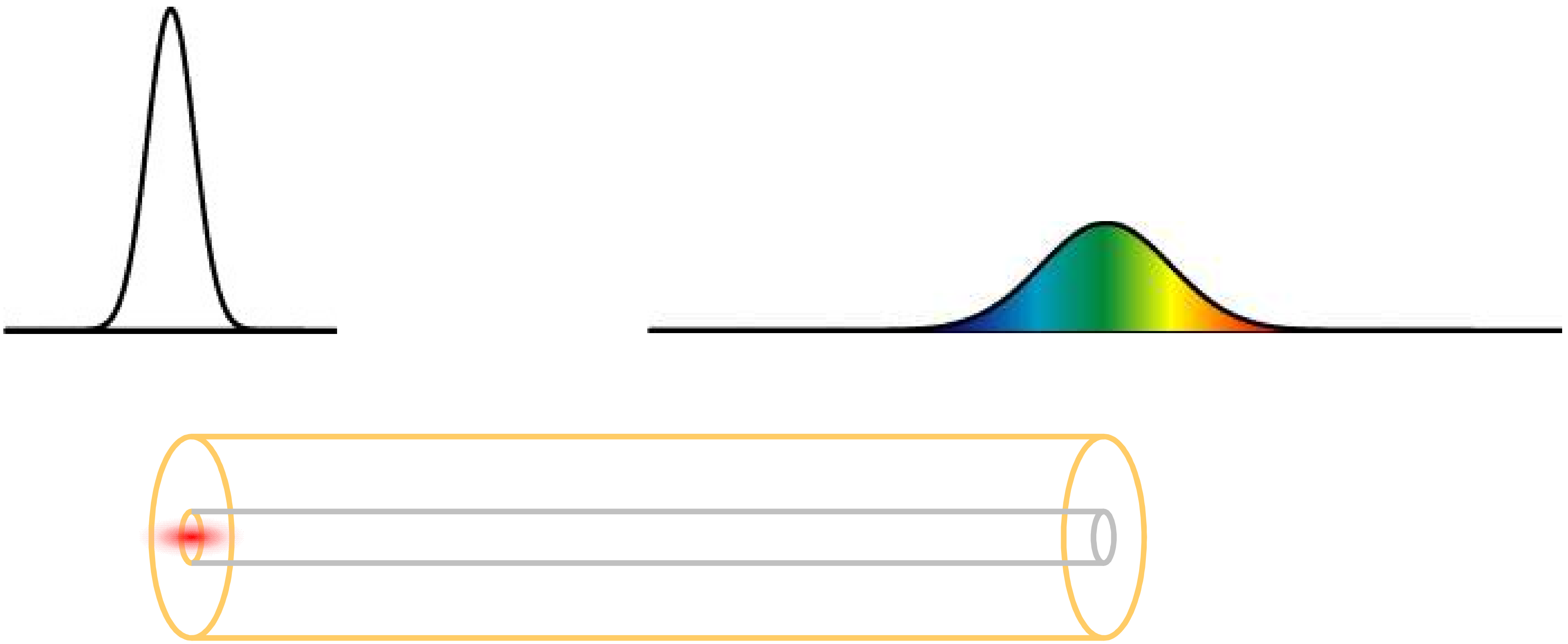
- Our job is to figure out basic processes, building blocks, and “rules”

Introduction to Nonlinear Wave Propagation

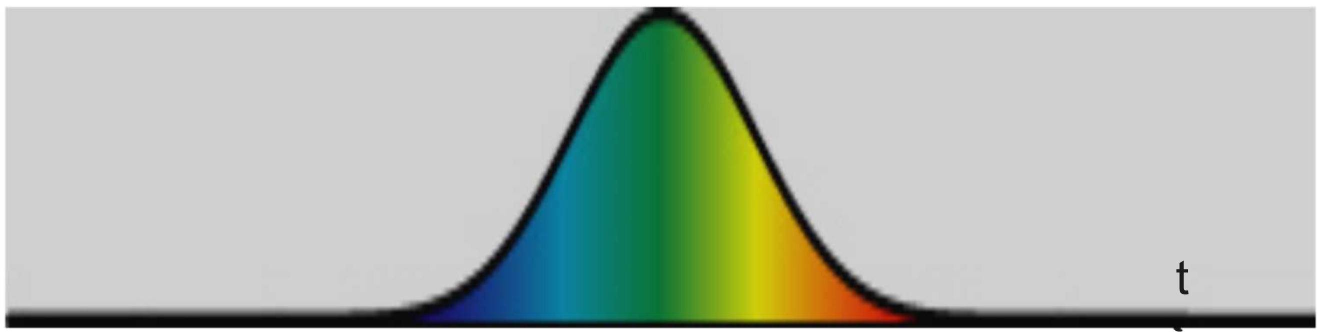
Short pulses: dispersion

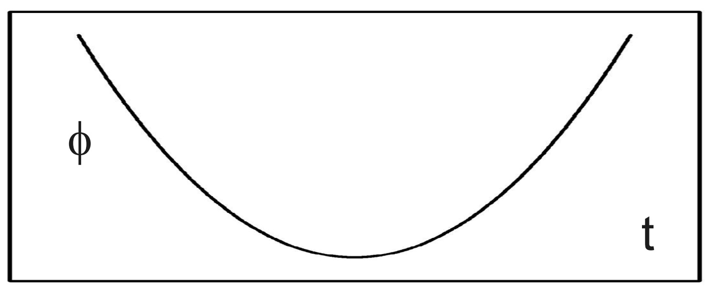
$n = n(\omega)$

$v(\omega) = c/n(\omega)$



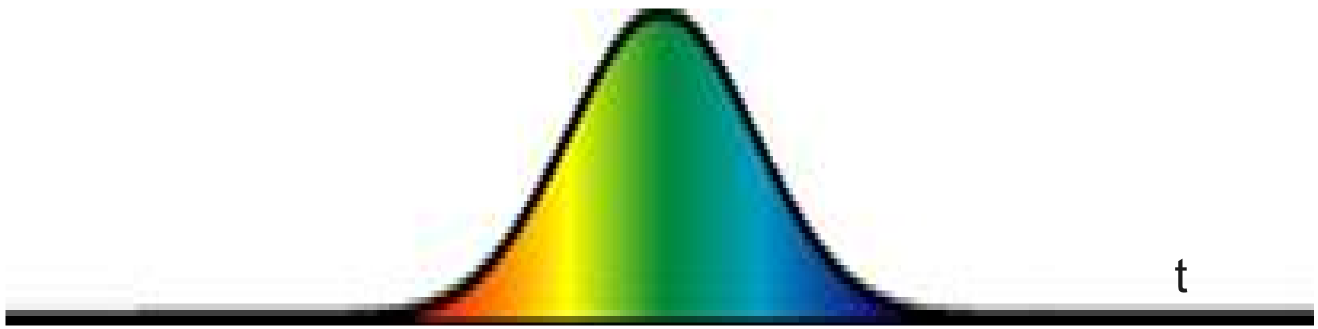
Dispersive phase accumulation

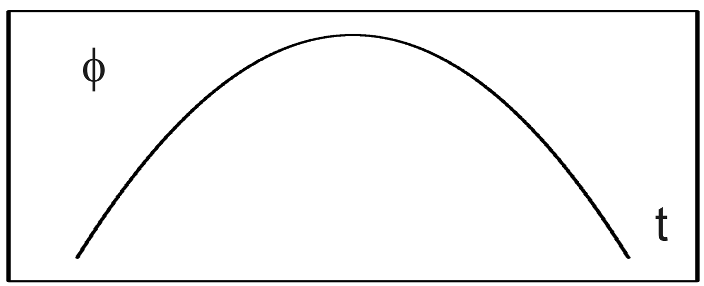




anomalous dispersion
λ > 1300 nm for silica

Dispersive phase accumulation



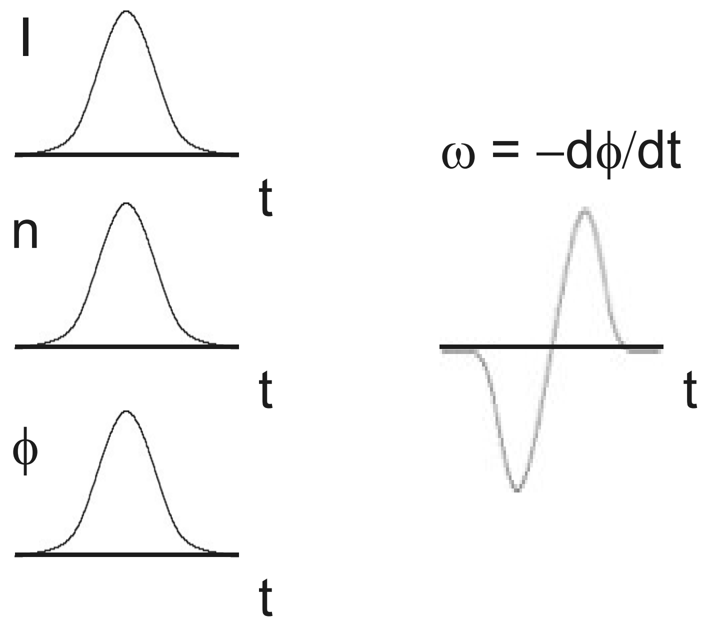


normal dispersion

λ < 1300 nm for silica

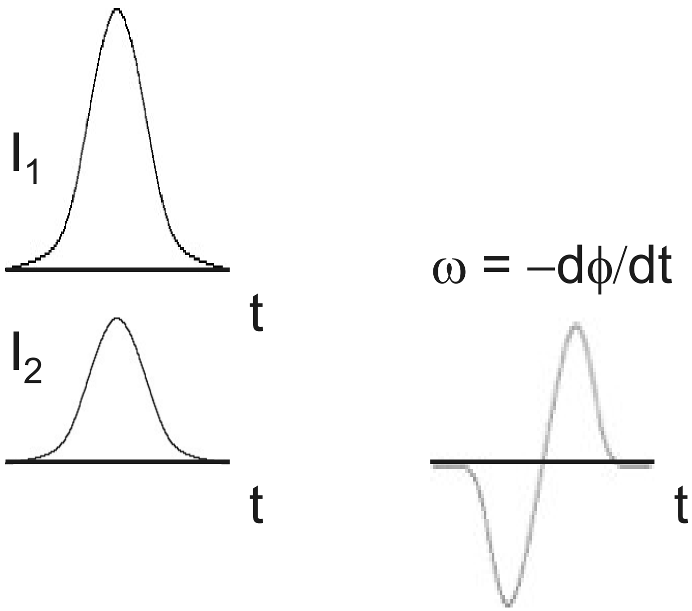
Nonlinear propagation ($\chi^{(3)}$)

- $n = n_0 + n_2 I$



self-phase modulation produces new frequencies

Nonlinear propagation ($\chi^{(3)}$)

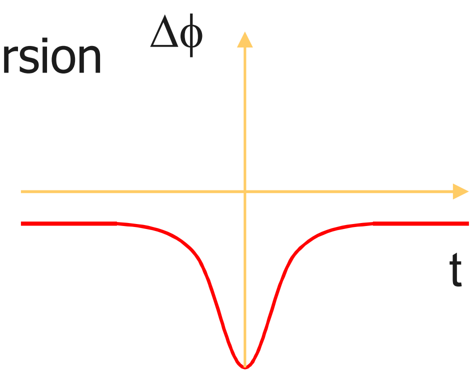


cross-phase modulation produces new frequencies

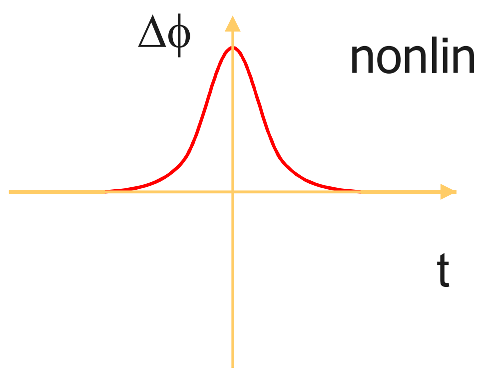
Soliton formation

$$\frac{\partial A(z,t)}{\partial z} + i\frac{\beta^{(2)}}{2}\frac{\partial^2 A(z,t)}{\partial t^2} = i\gamma\,|A(z,t)|^2\,A(z,t)$$

dispersion



nonlinearity

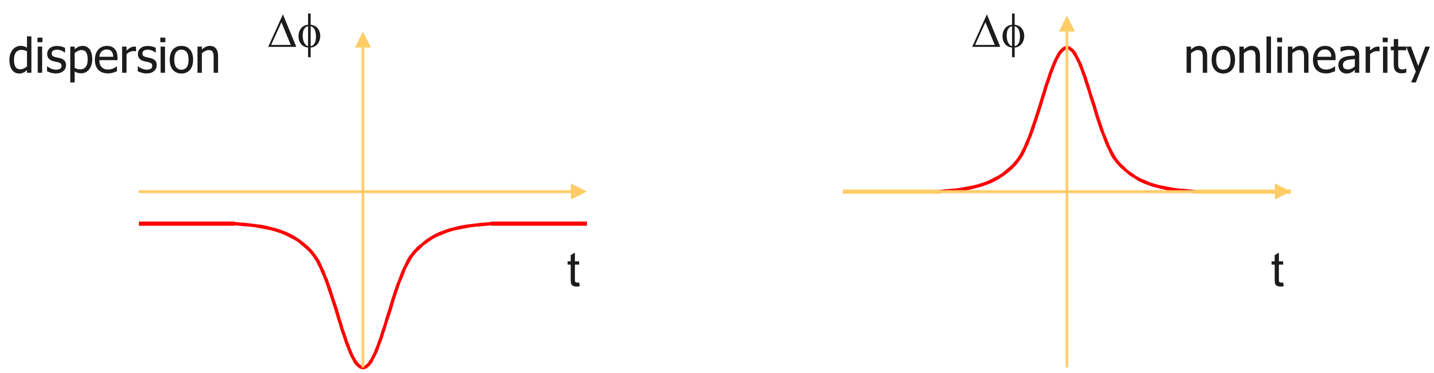


(anomalous) dispersion cancels nonlinearity for

$$A(t) = A_0\,\mathrm{sech}(t/\tau_p)\exp(iz/z_{sol})$$

Soliton formation

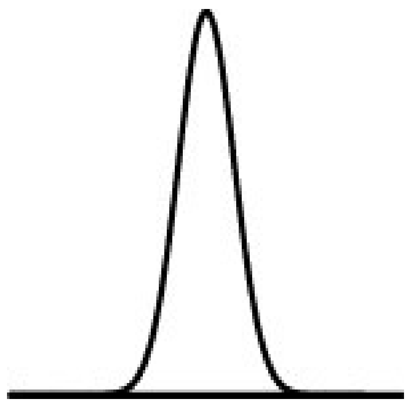
$$\frac{\partial A(z,t)}{\partial z} + i\,\frac{\beta^{(2)}}{2}\,\frac{\partial^2 A(z,t)}{\partial t^2} = i\gamma\,|\,A(z,t)\,|^2\;A(z,t)$$

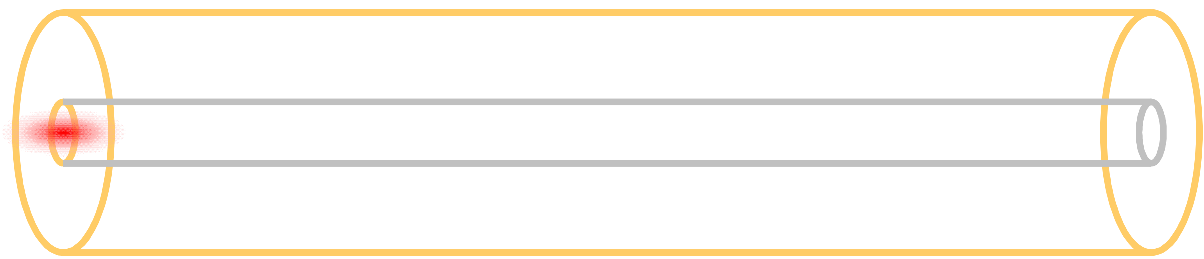


(anomalous) dispersion cancels nonlinearity for

$$A_0\tau_p = \sqrt{\frac{\beta_2}{\gamma}}$$

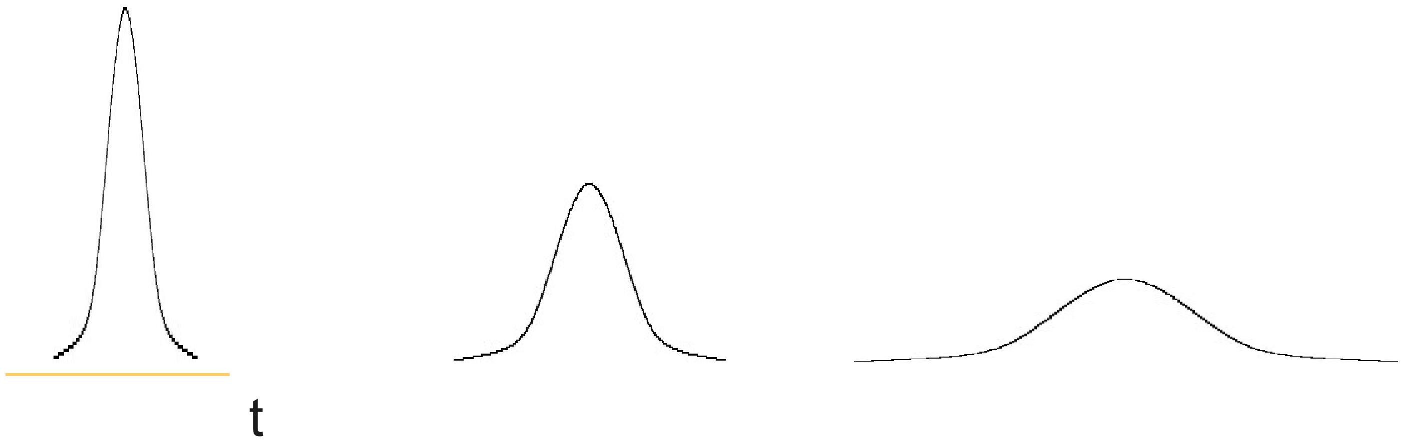
Soliton formation



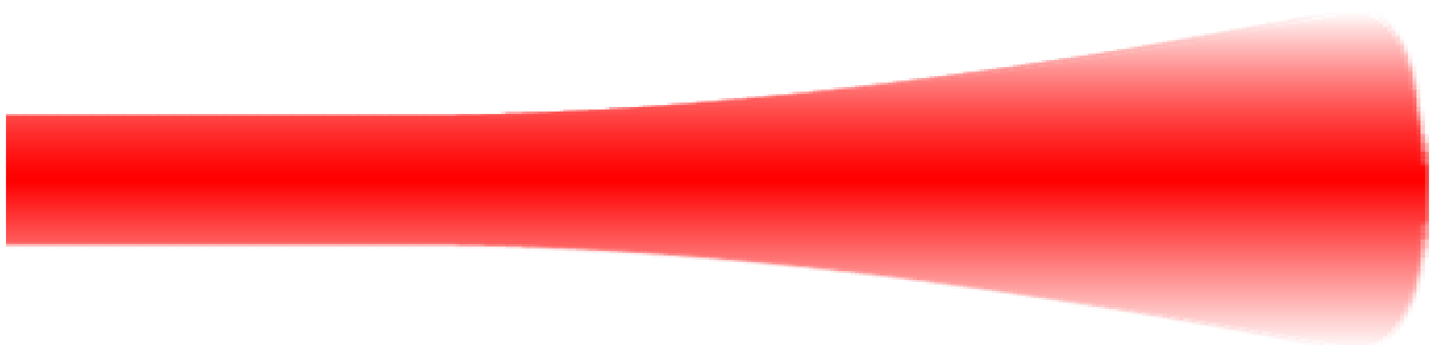


Linear wave propagation

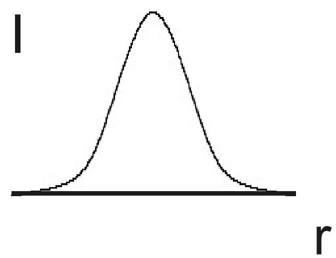
• pulse spreads owing to group-velocity dispersion



• beam spreads owing to diffraction



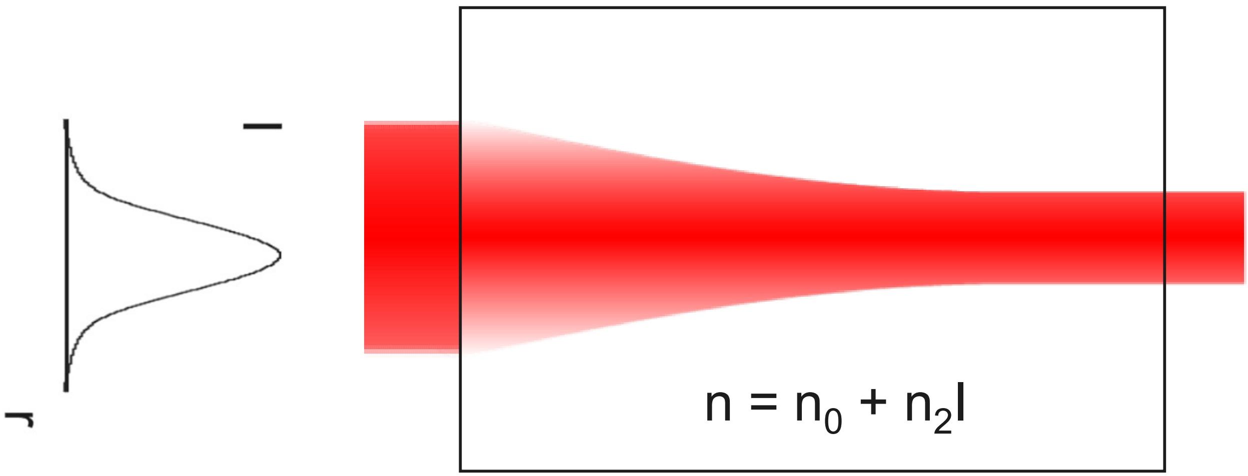
Nonlinear propagation ($\chi^{(3)}$)



$$n = n_0 + n_2 I$$

nonlinear phase shift produces self-focusing

Nonlinear propagation ($\chi^{(3)}$)

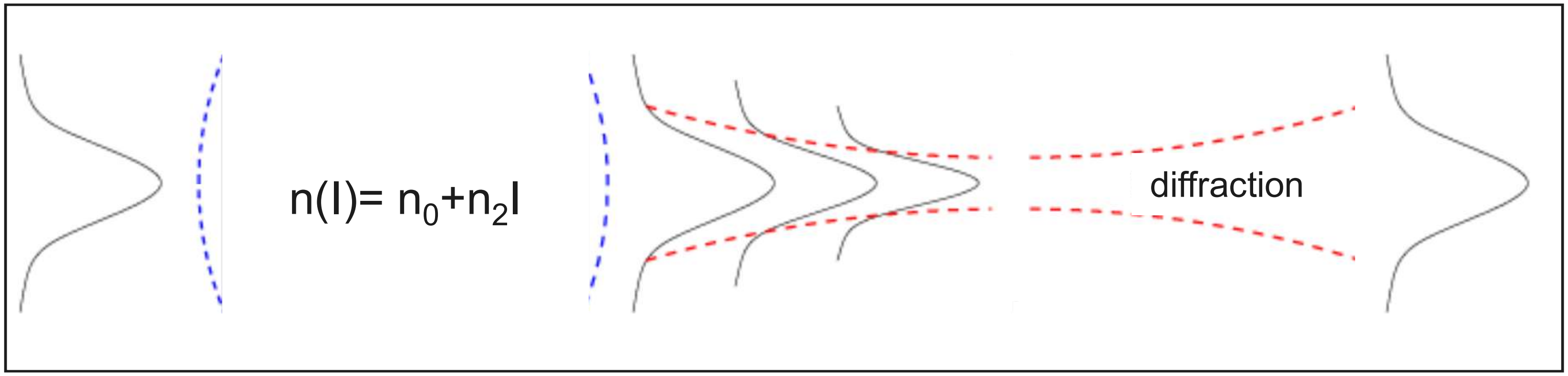


nonlinear phase shift produces self-focusing

Critical power

- diffraction balances self-focusing for

$$P = P_{cr} \sim 5 \text{ MW in glass}$$



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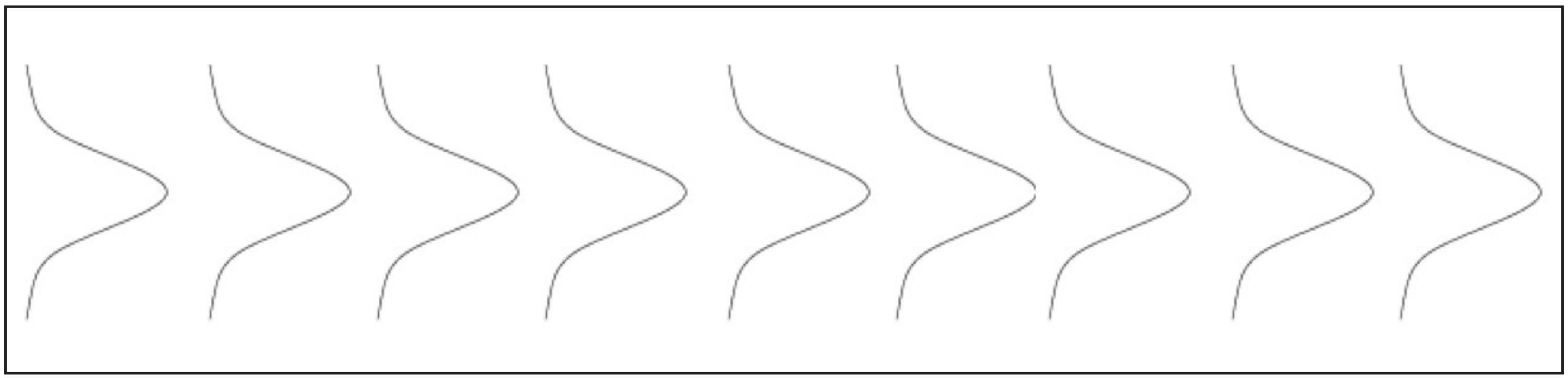
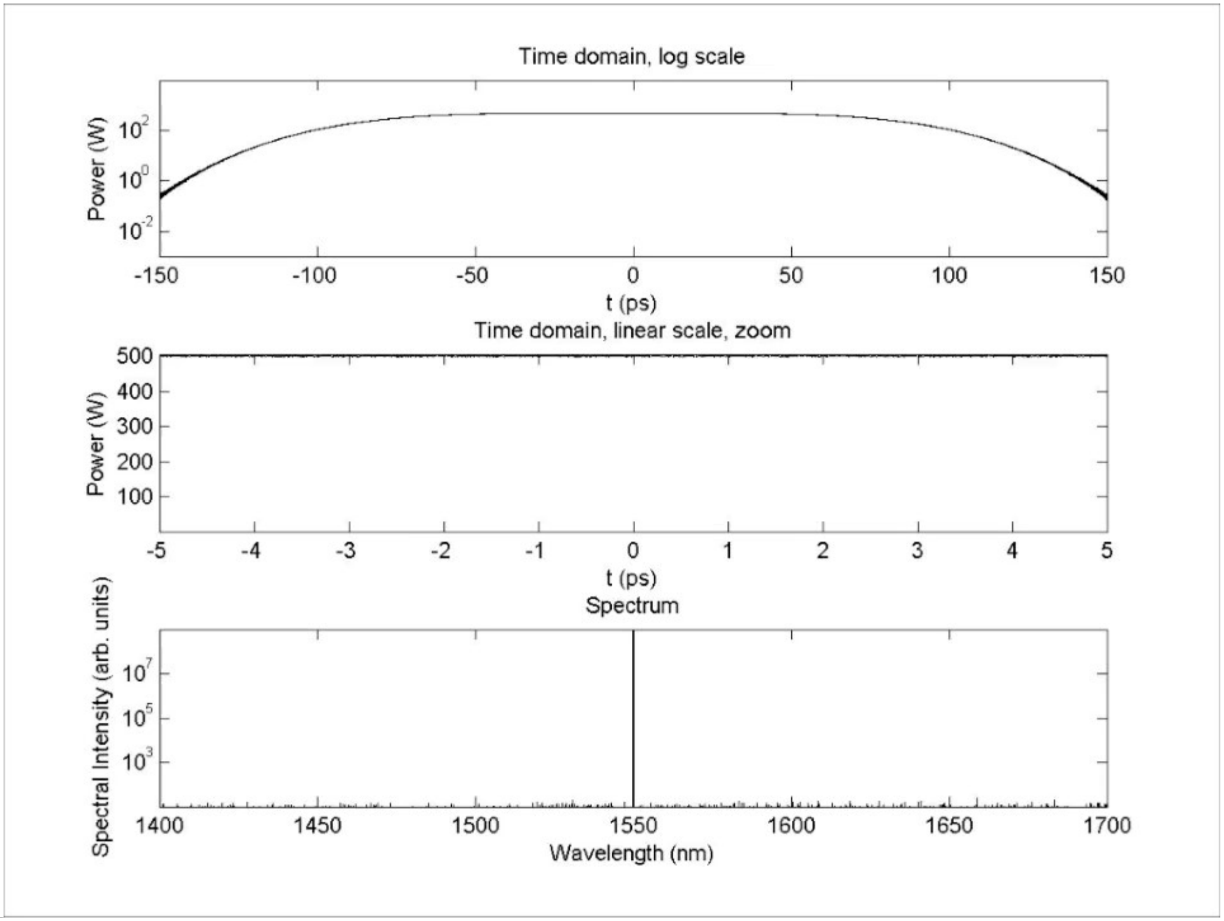


- 2D: unstable against collapse

Why are solitons so important?

- A continuous wave breaks into temporal components



Why are solitons so important?

- In general, waves in nonlinear media are unstable

Modulation Instability

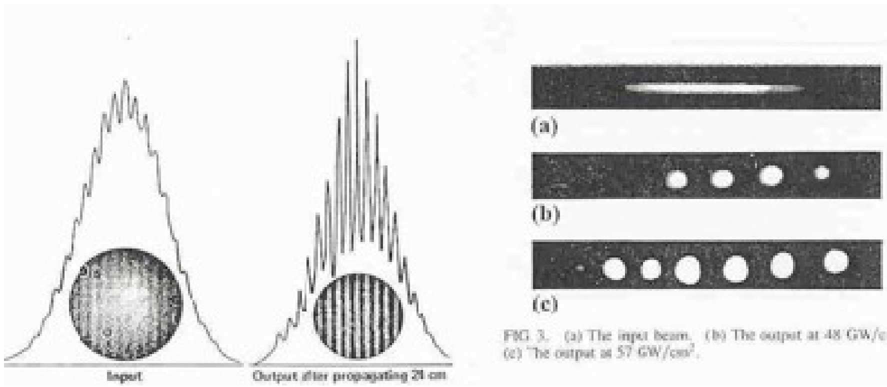


FIG 3. (a) The input beam. (b) The output at 48 GW/c
(c) The output at 57 GW/cm².

- A beam breaks into its component solitons

- Stable products of instability are “eigenmodes” of nonlinear systems

Why are solitons so important?

If they exist, solitons are important

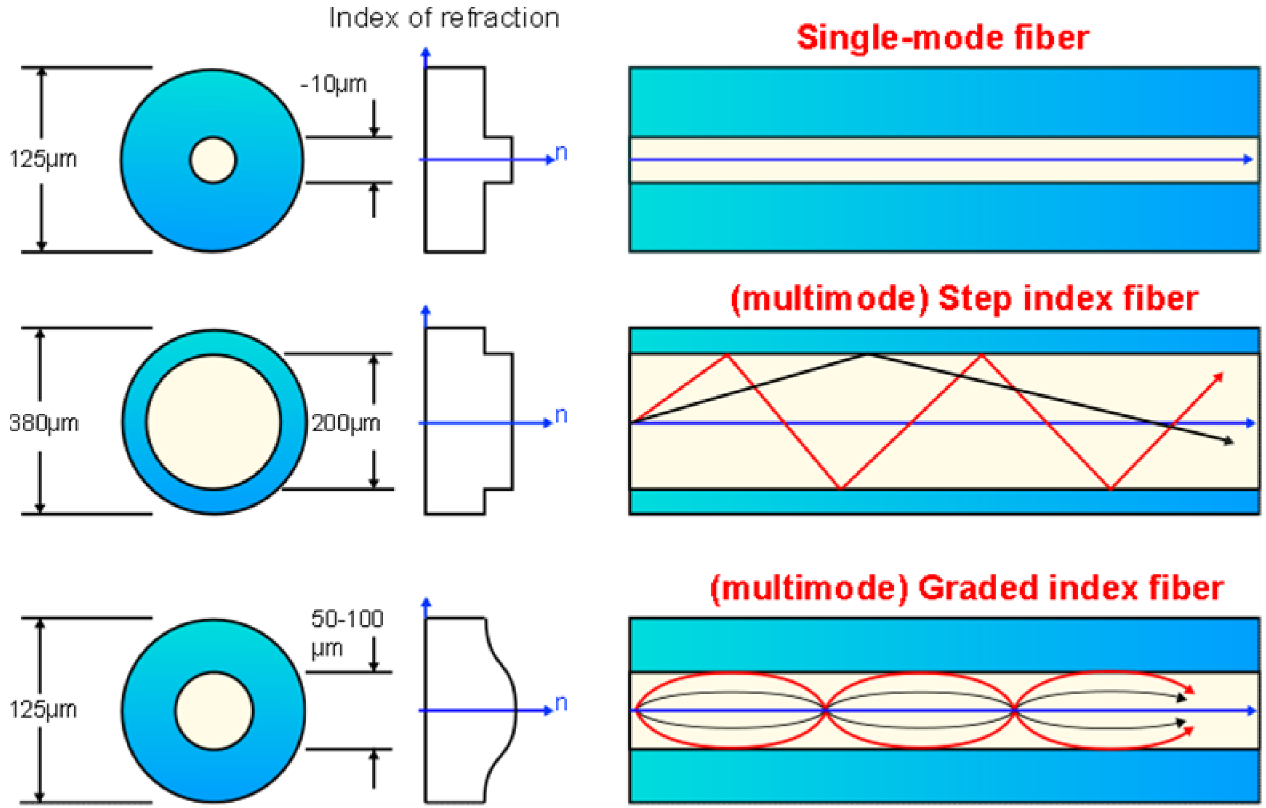
- as stable wave packets (sometimes nonlinear attractors)
- as components of arbitrary fields

In 1D solitons underlie

- modelocked lasers
- continuum generation
- breathers, Peregrine soliton
- rogue waves
- …

2D and 3D: solitons are unstable

Multimode waveguides: between 1- and 3-D



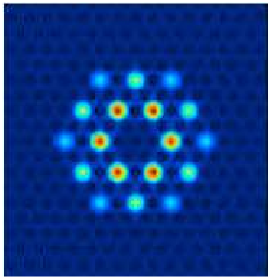
https://commons.wikimedia.org/wiki/File:Optical_fiber_types.svg

Why study propagation in multimode fiber now?

- Little work on multimode nonlinear pulse propagation before 2013

- Recent theoretical, computational advances
  e.g., transfer matrix, principal modes,…

- Relevance to multicore fibers

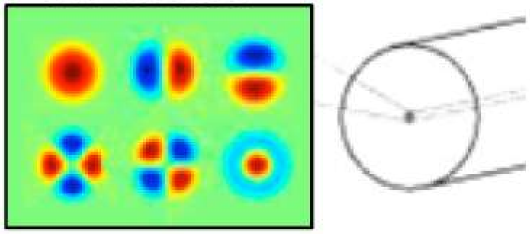


Huang et al., Opt Exp 2014

Why study propagation in multimode fiber now?

- Laser/ amplifier / transmission applications

- Spatial division multiplexing in telecom

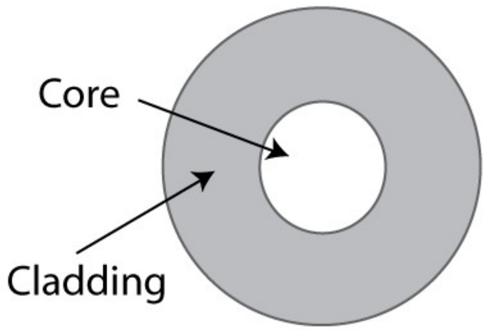


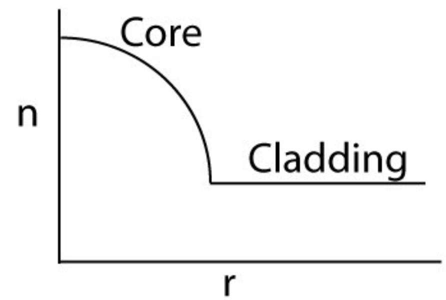
Agrell et al., J Opt 2016

- Imaging through multimode fiber/ complex media

Ploschner et al., Nature Photon 2015

Graded-index (GRIN) multimode fiber

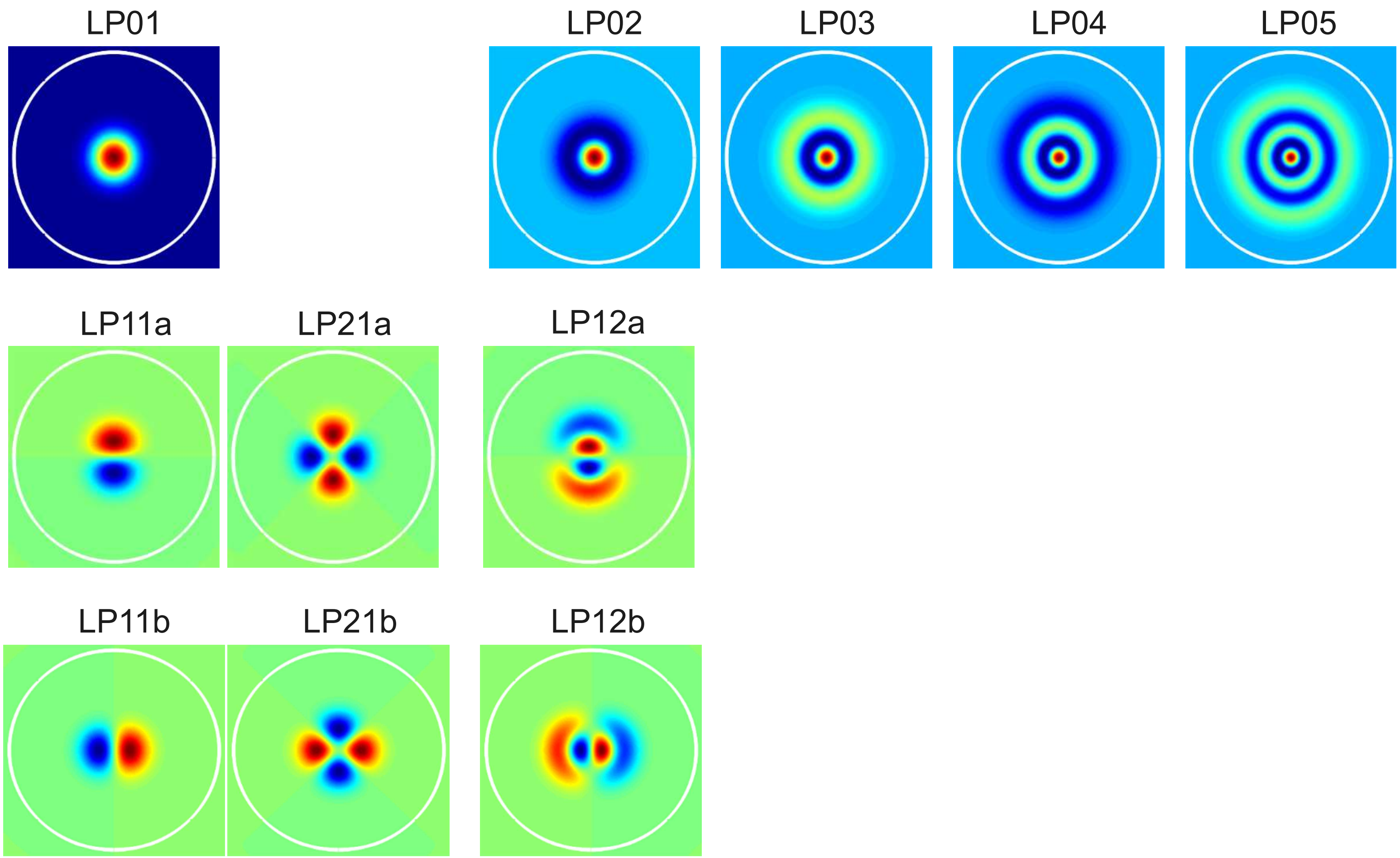




$$n^2(\rho) = n_0^2\left[1 - 2\Delta\left(\frac{\rho}{R}\right)^{\alpha}\right], \quad \rho \le R$$

$$= n_0^2(1 - 2\Delta), \quad \rho > R$$

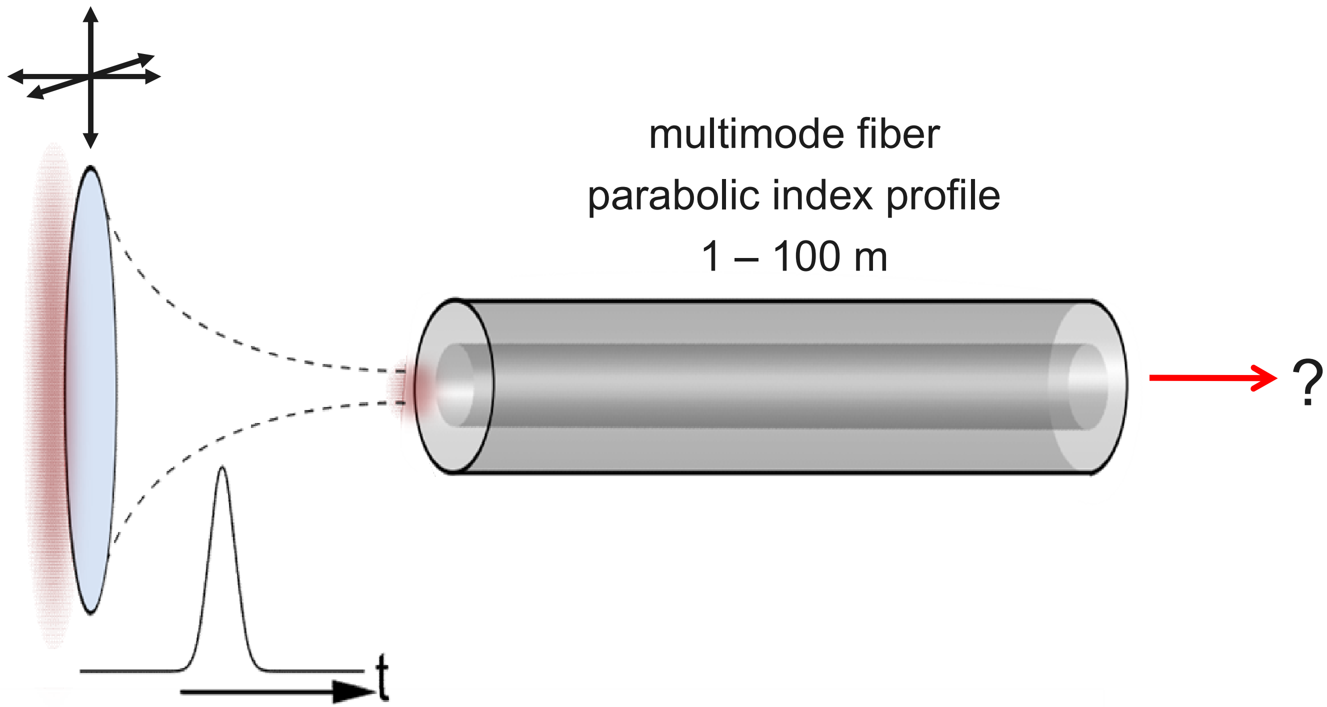
Modes of GRIN fiber



Modes of GRIN fiber

- Propagation constants equally-spaced
- Velocities of modes vary much less than in step-index fiber

Experiments



fs or ns pulses

energy up to 1 μJ

peak power kW to MW

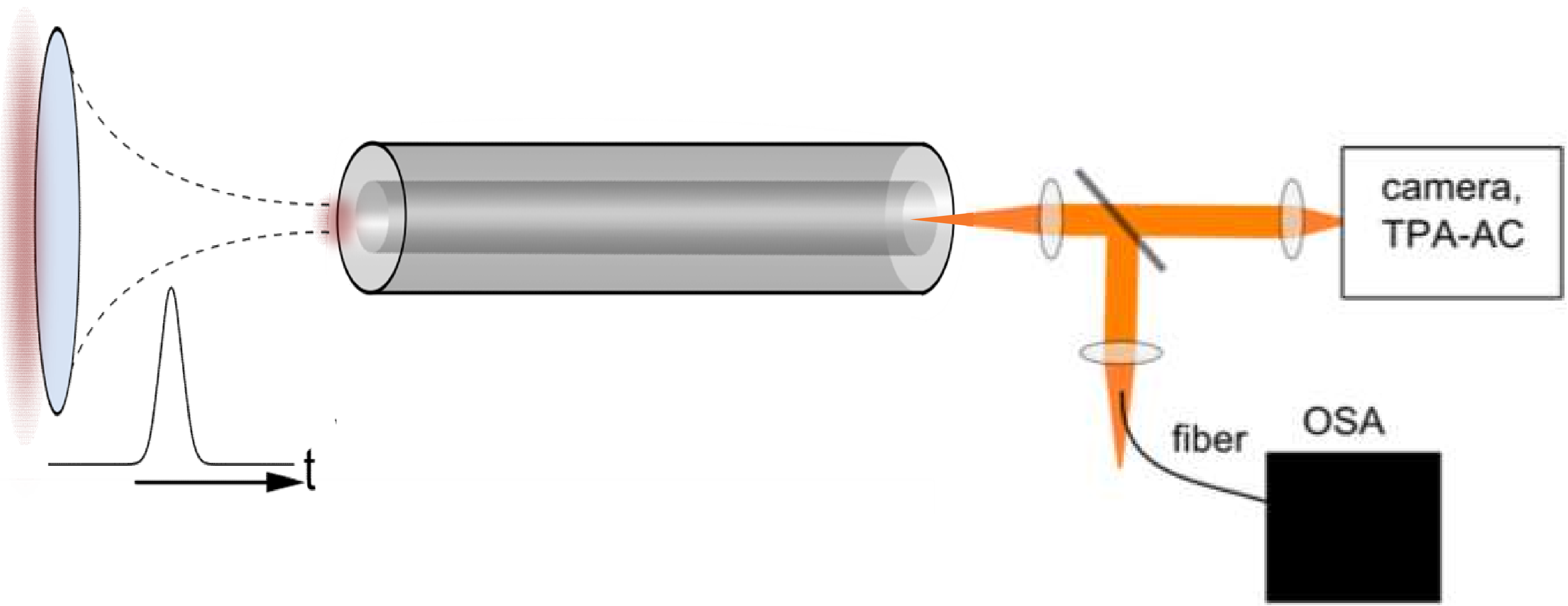
1550 nm

1050 nm

532 nm

What should we measure?

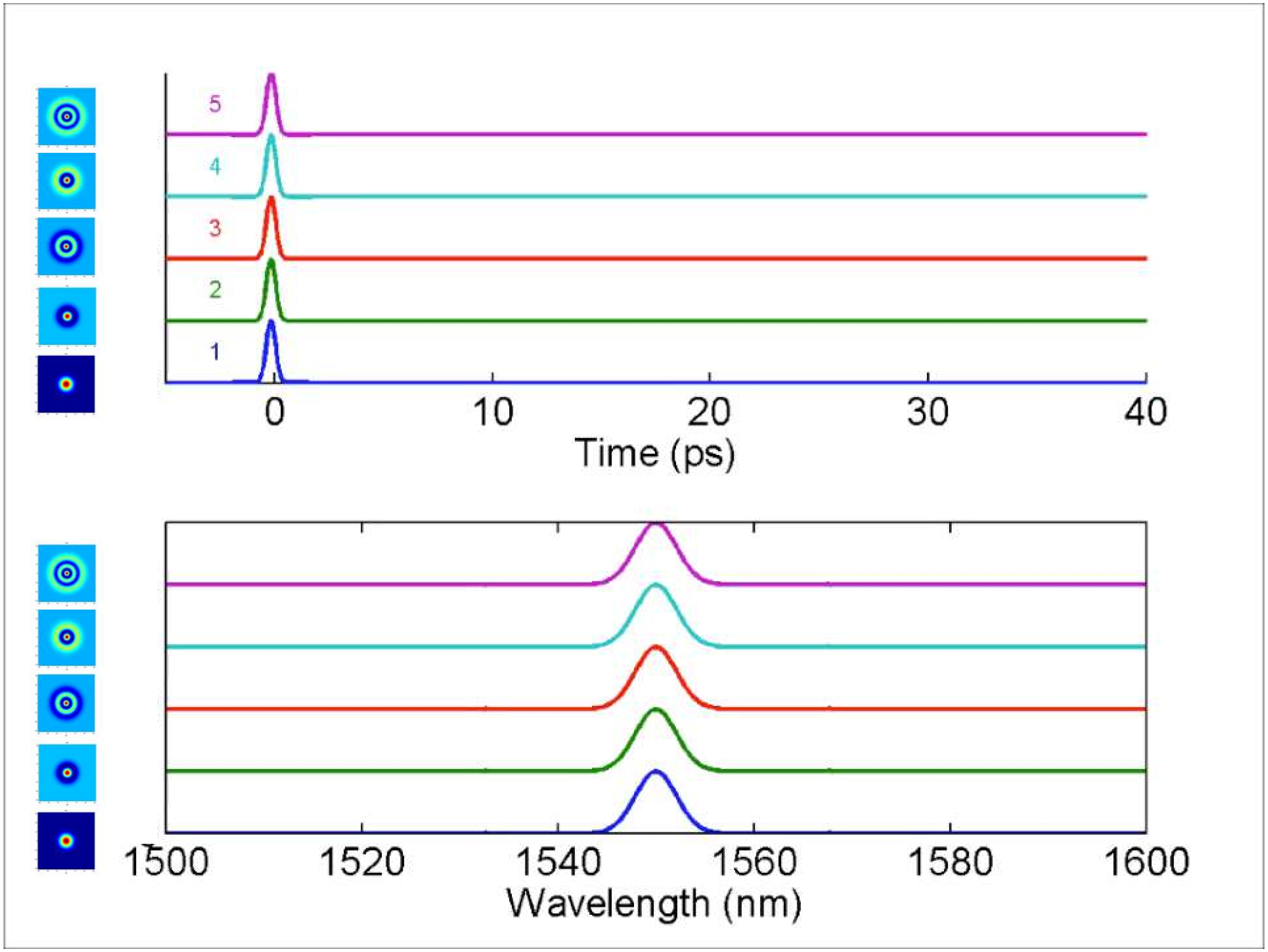
- Broadband space-time diagnostic does not exist



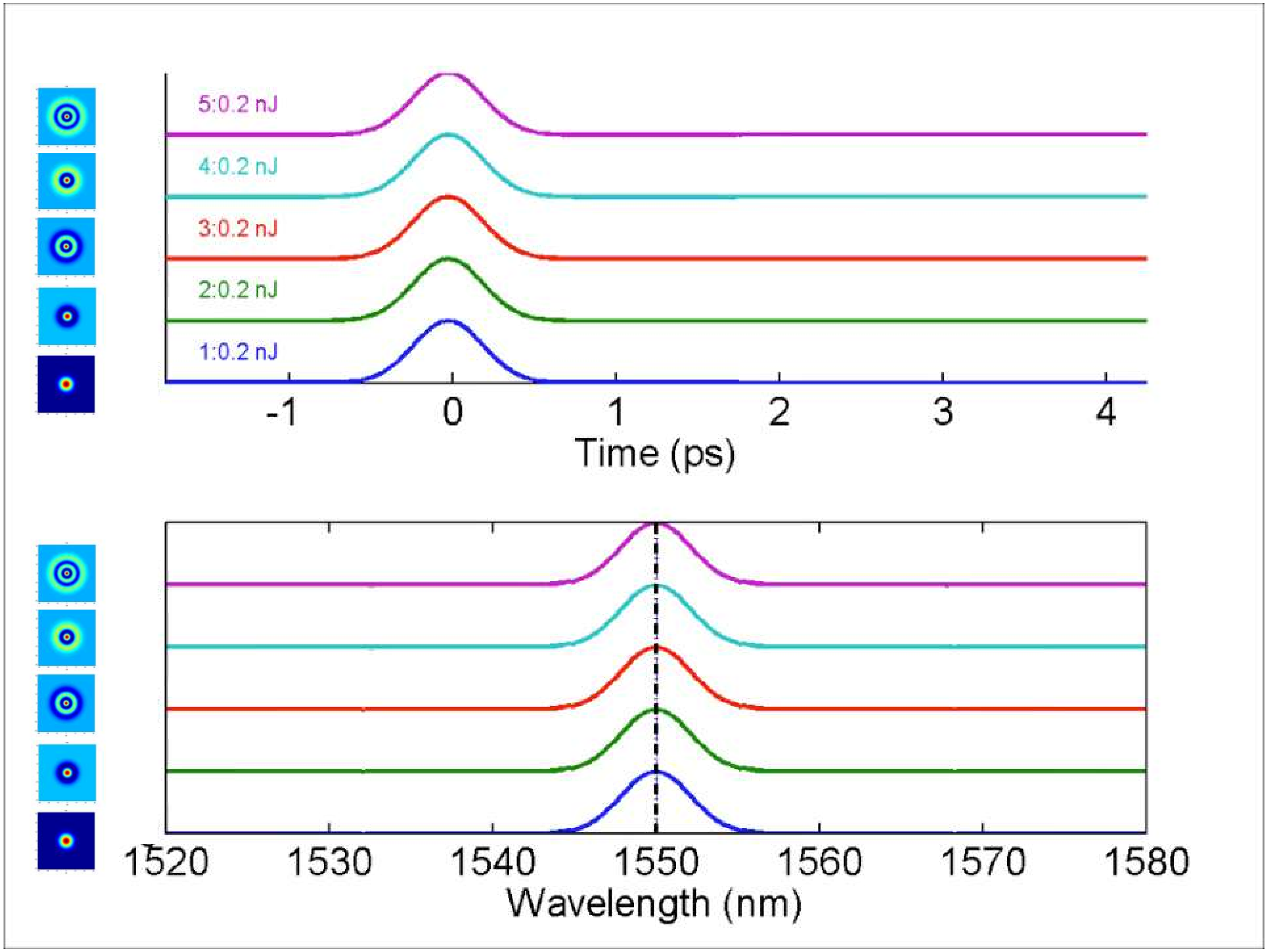
- Record overall average spectrum to compare to calculated
- Image near-field on autocorrelator
- Compute spatiotemporal autocorrelation for comparison

Multimode Solitons

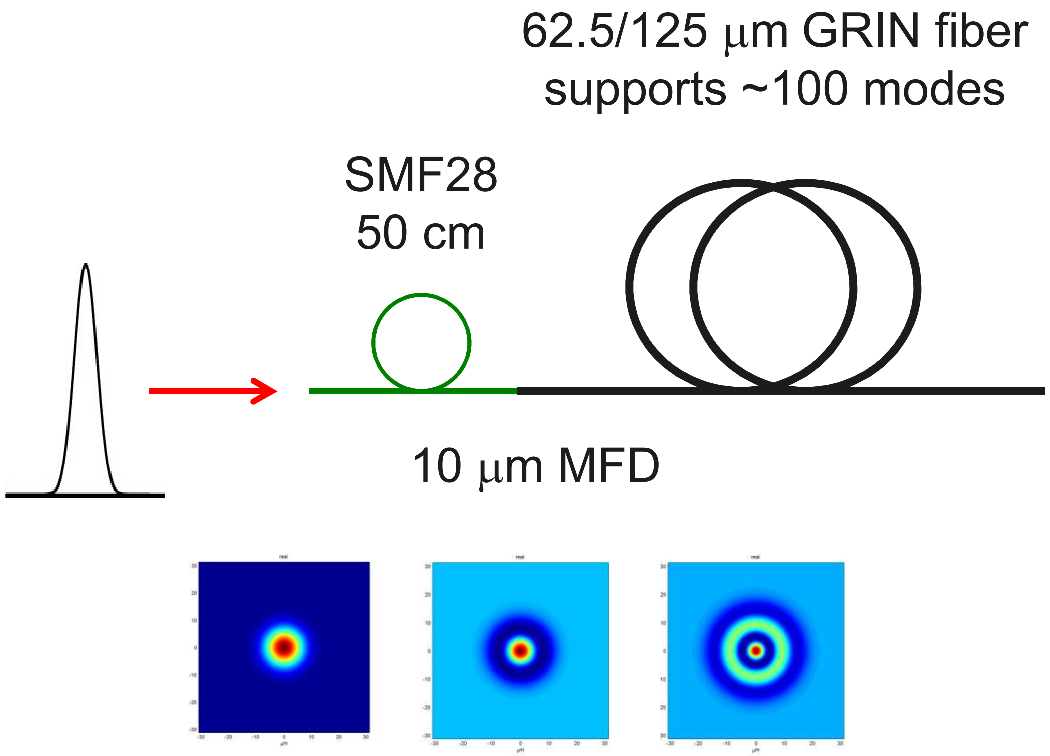
Linear propagation



Multimode soliton formation

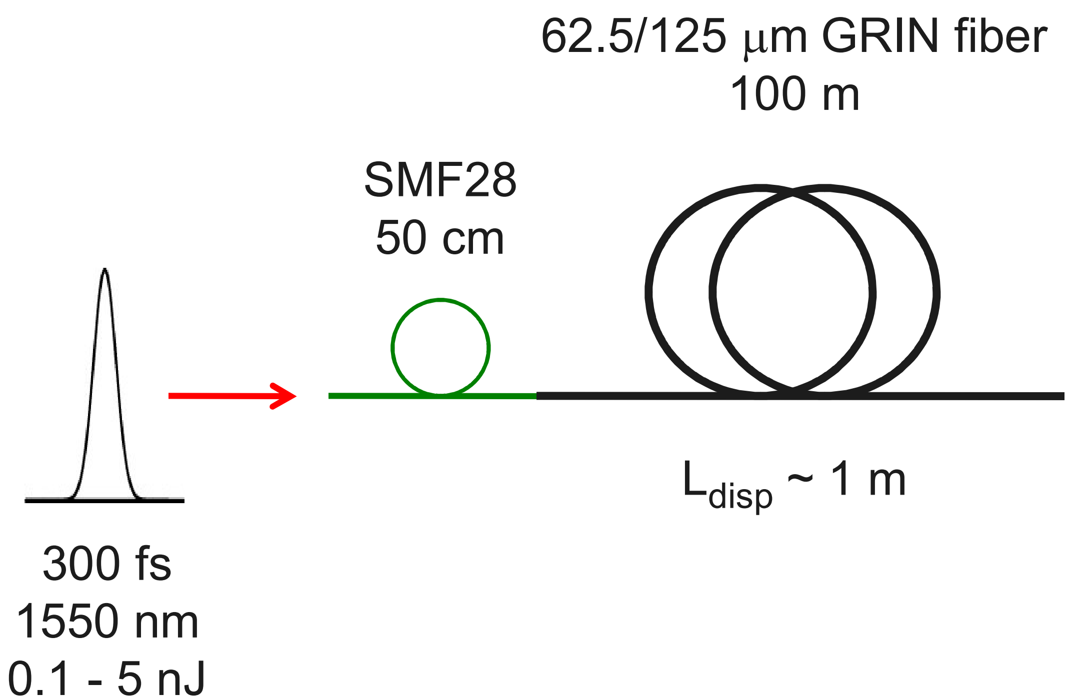


First steps: 3 modes



- Excite 3 lowest modes

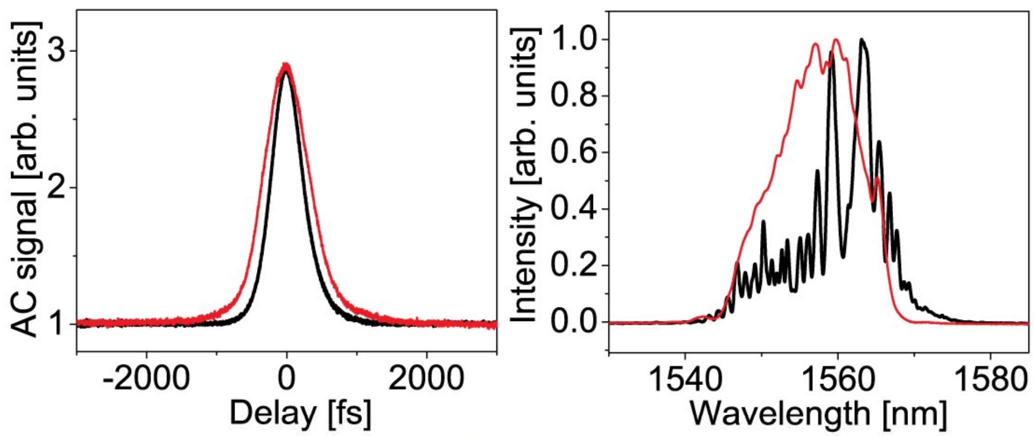
Experiment


62.5/125 μm GRIN fiber
100 m
SMF28
50 cm
L_{disp} ~ 1 m
300 fs
1550 nm
0.1 - 5 nJ

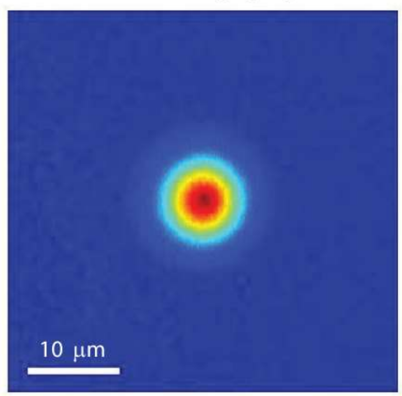
Experimental results

- For E < 0.1 nJ pulse disperses

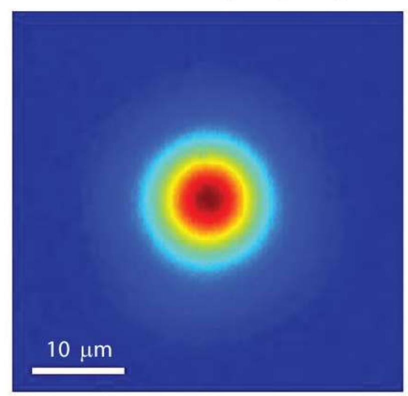
- 0.5 nJ pulse energy



input
output



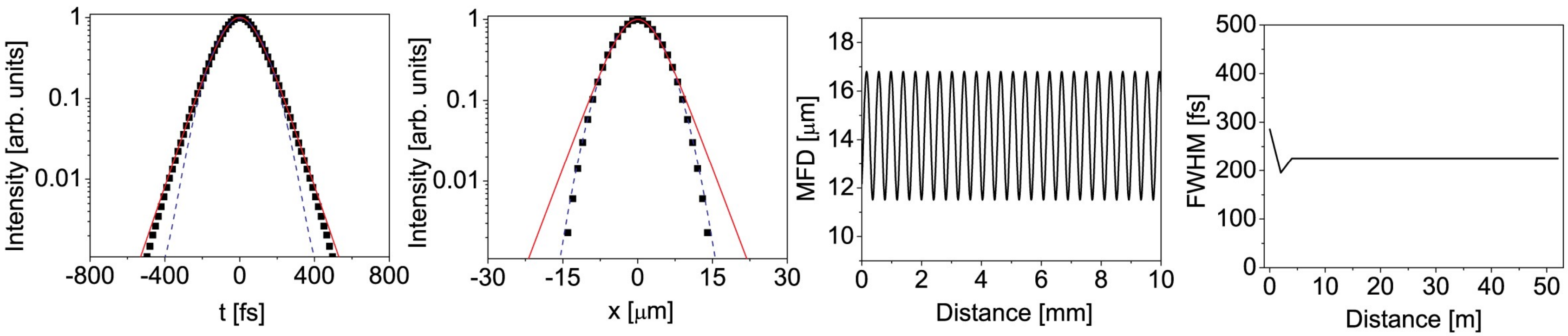
input



output

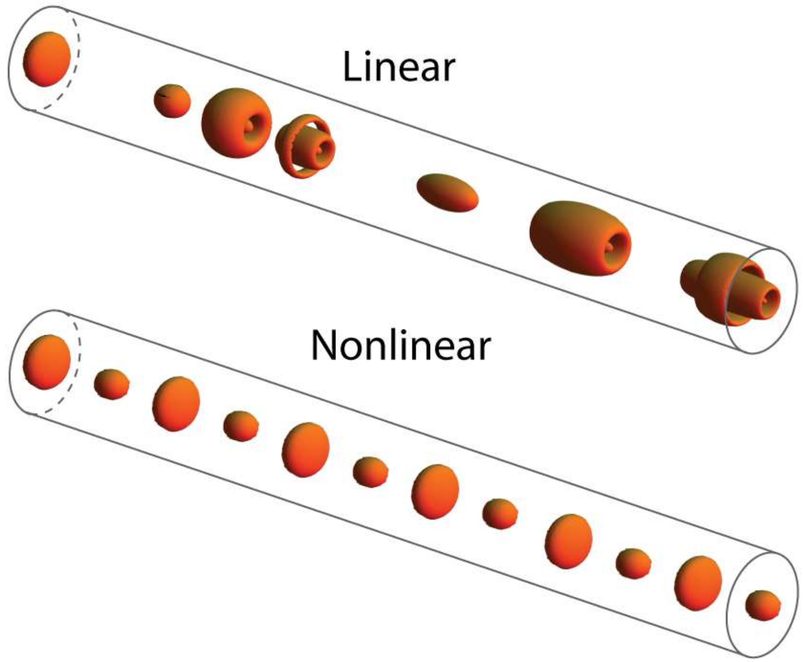
3 modes: theory

- Launch 0.5 nJ / 300 fs



- Coupled-mode theory and beam-propagation give similar results

Intuitive picture

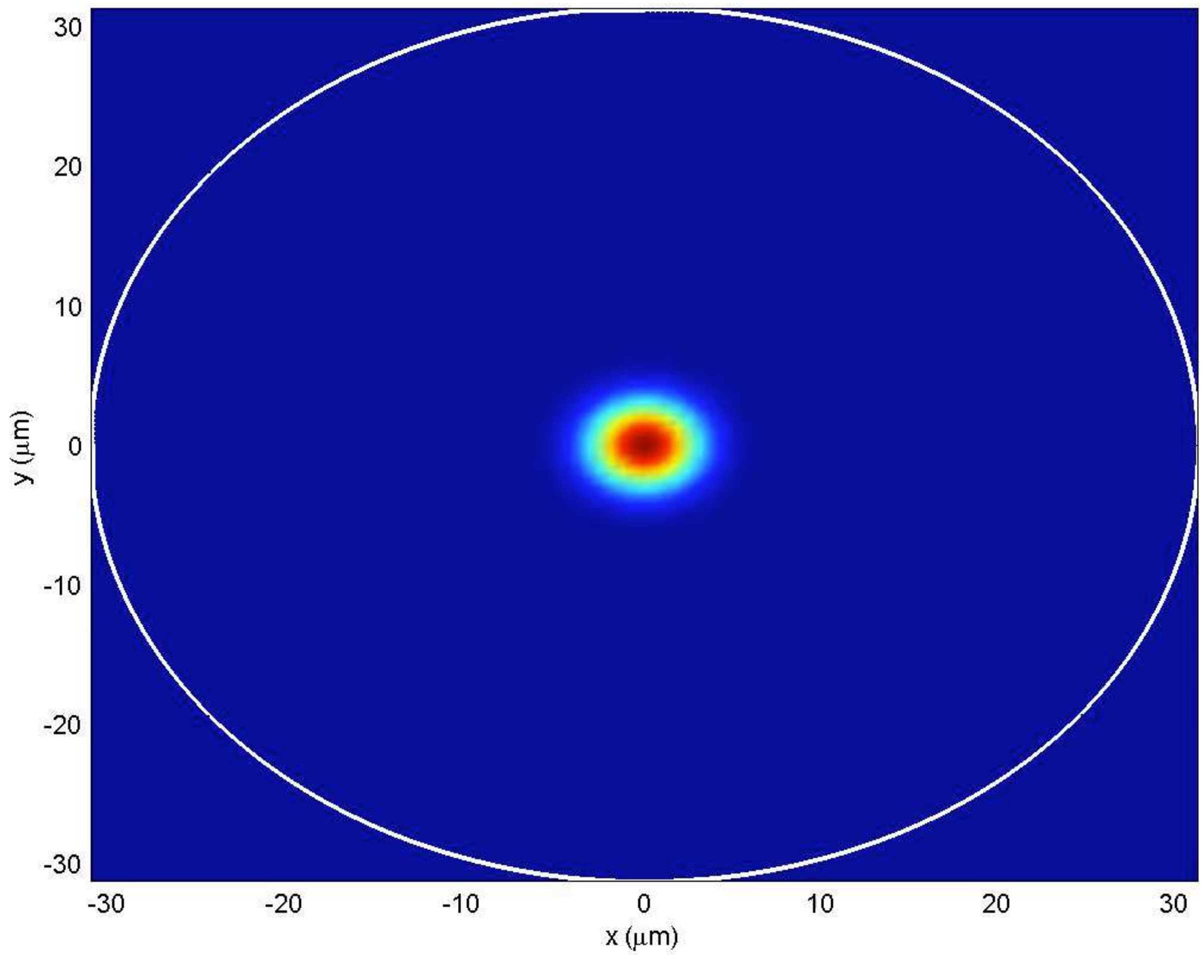


Renninger *et al., Nature Commun 2013*

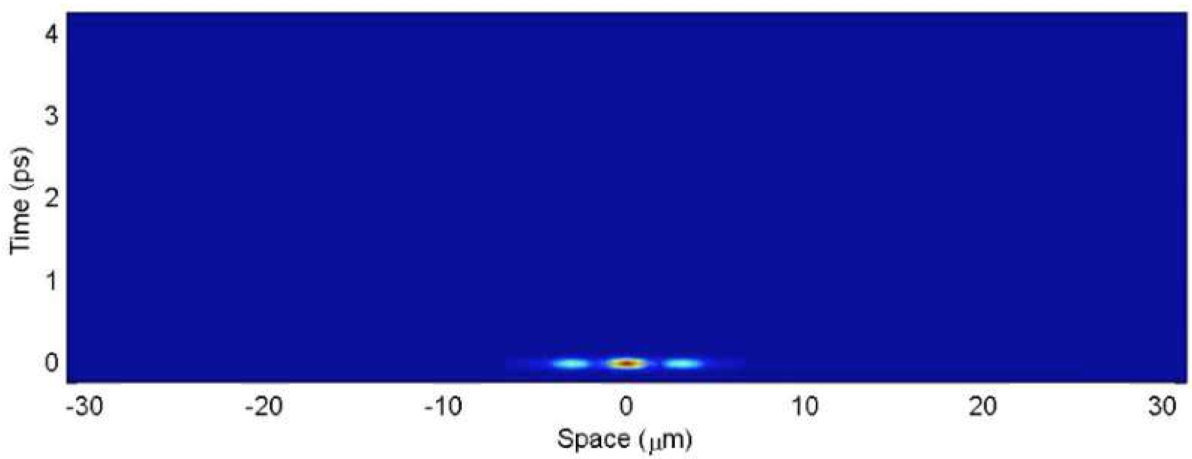
- Solitons with more modes require greater nonlinear phase / energy
- Solitons with up to 10 modes generated

Wright et al., Opt Exp 2015

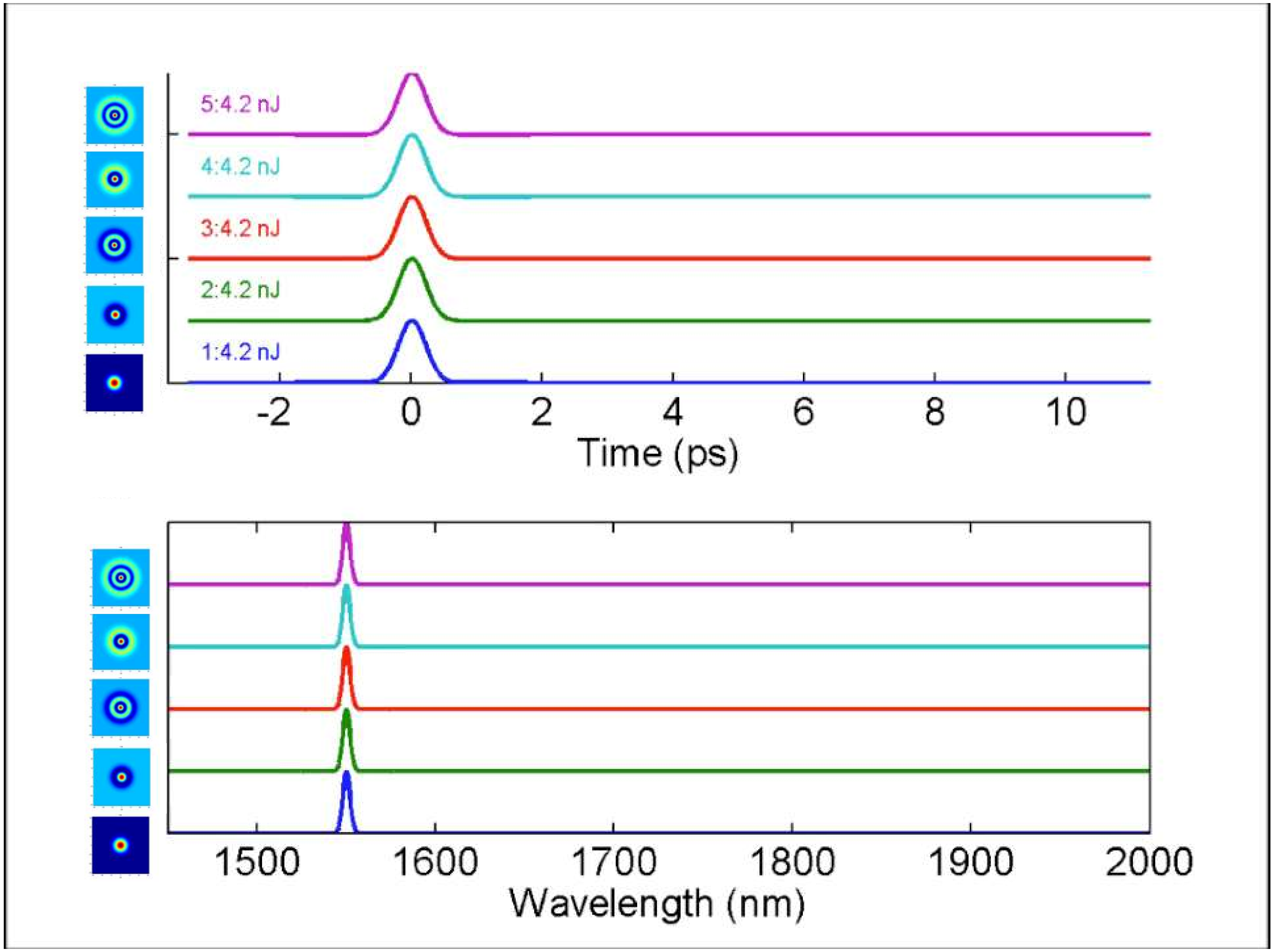
Multimode soliton formation



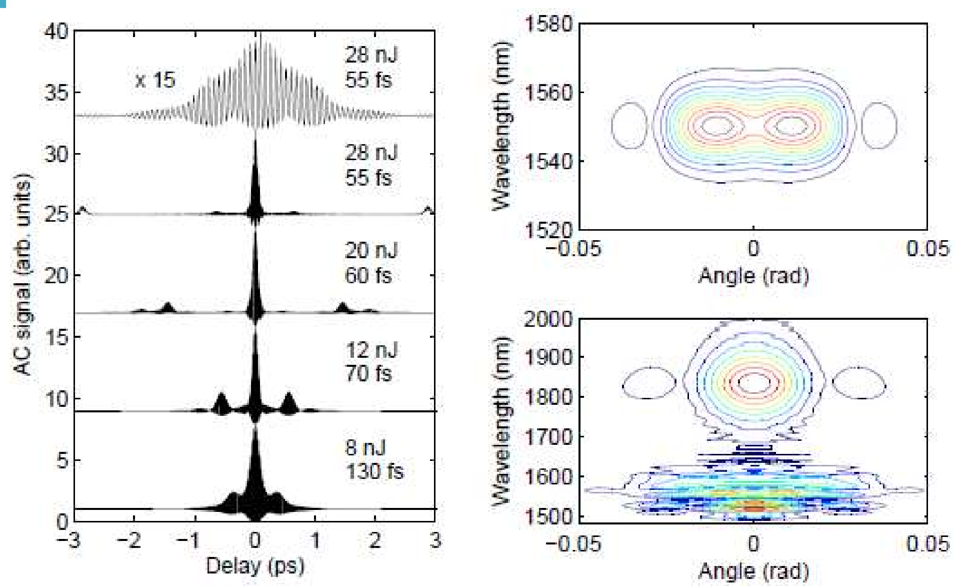
Multimode soliton formation



Multimode soliton fission

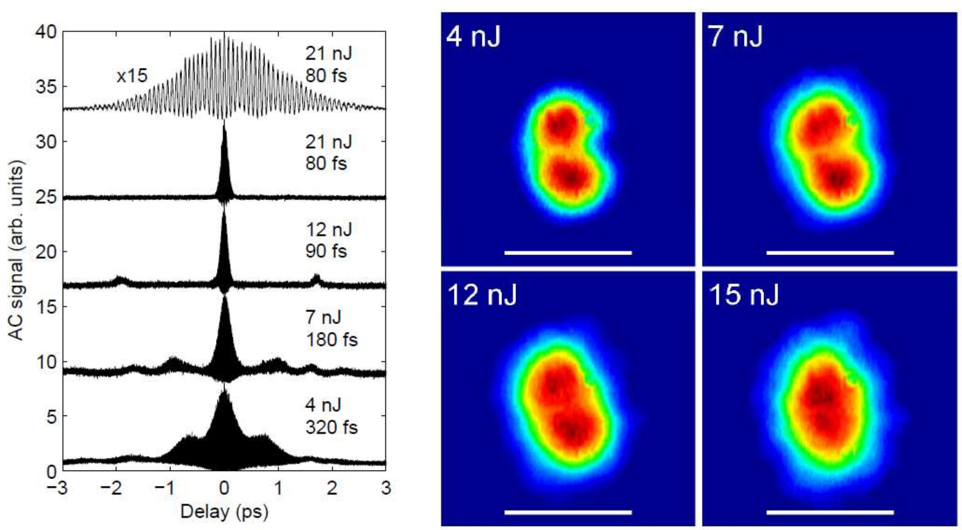


Multimode soliton fission: experiment



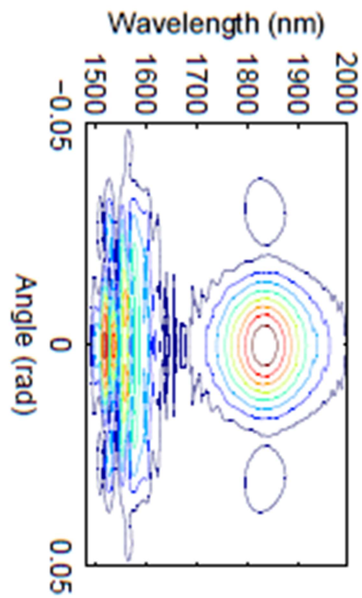
Simulation

- Smaller peaks in AC from
  less-localized modes
- Intermodal energy transfer during, after fission

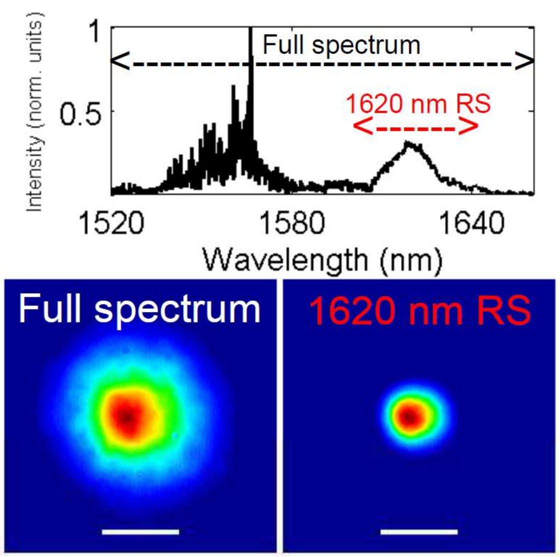


Experiment

Multimode soliton fission: experiment



Simulation



Experiment

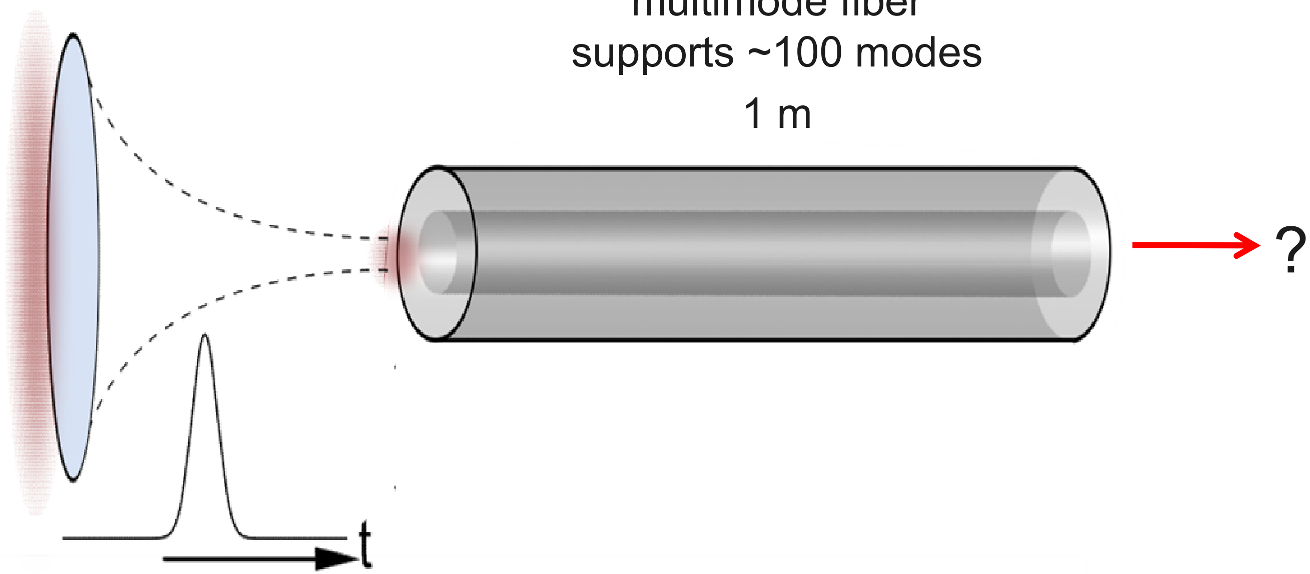
Multimode soliton fission

- Fission produces multiple MM solitons and MM dispersive waves
- Fission is spatiotemporal
- Raman “focuses” energy into the low-order mode

Wright et al., Opt Express 2015

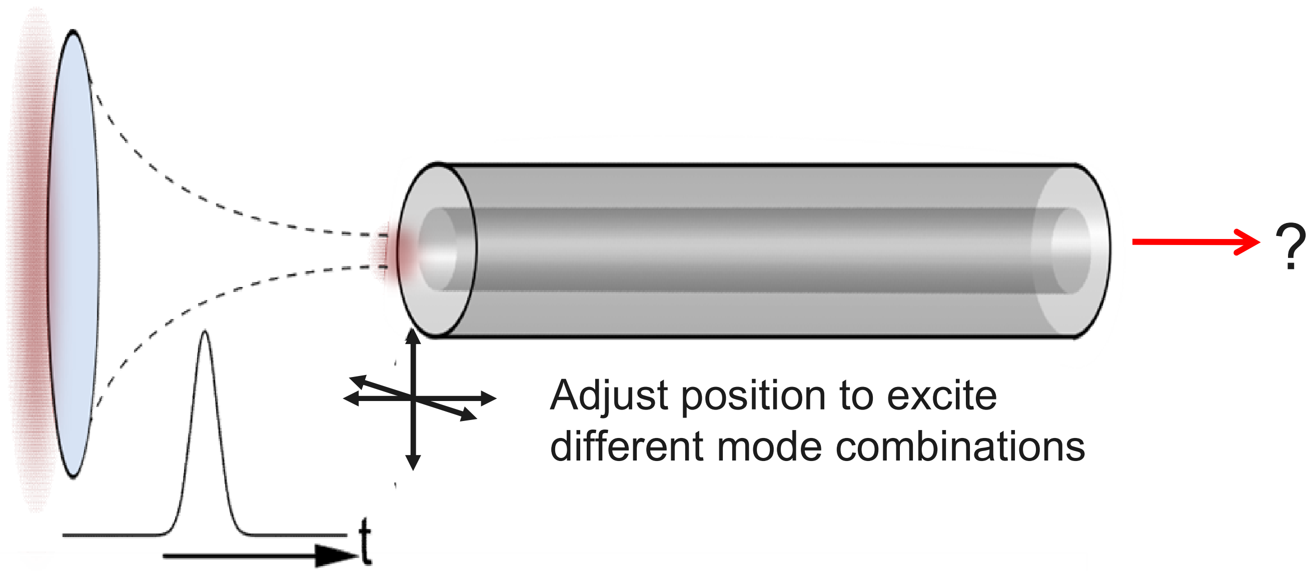
Continuum Generation

Experiments



500 fs
energy up to 1 μJ
peak power up to MW
1550 nm

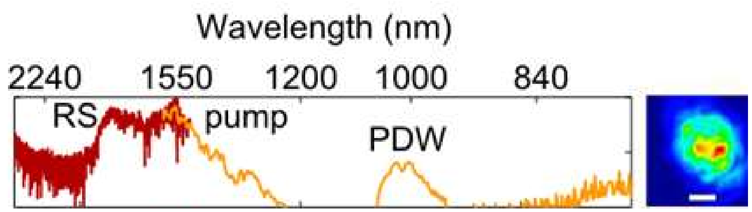
Experiments



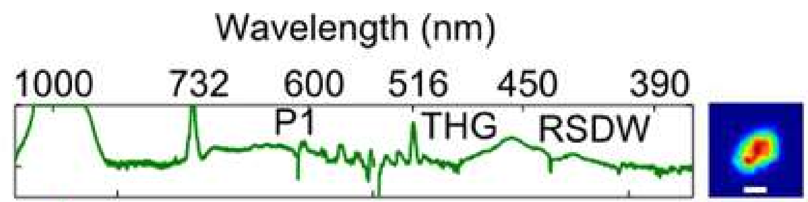
Adjust position to excite different mode combinations

Spatial conditions determine the continuum

Typical
IR

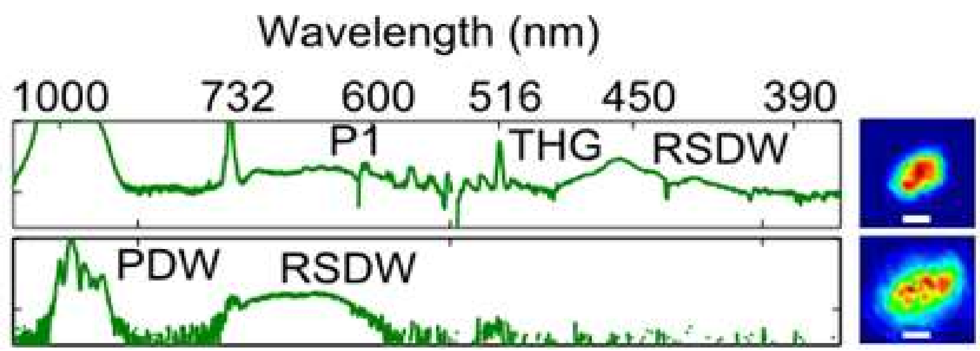


Typical
visible

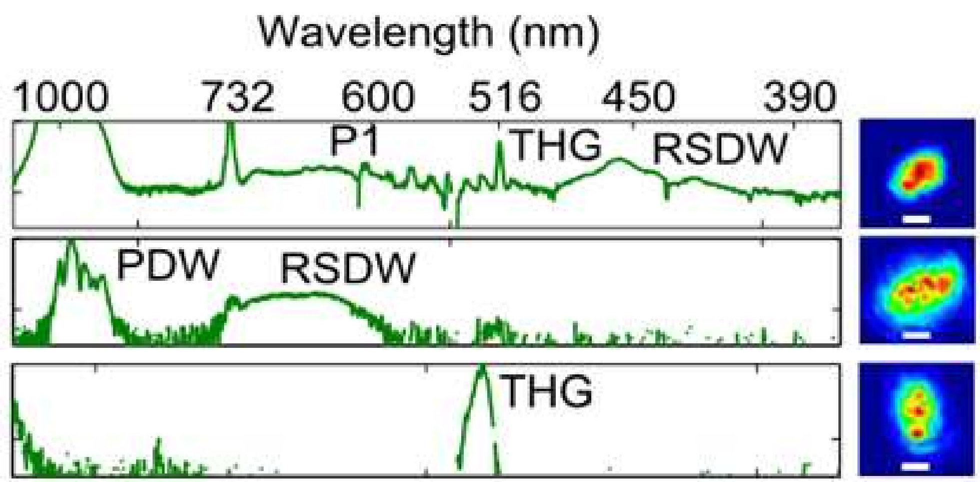


Spatial conditions determine the continuum

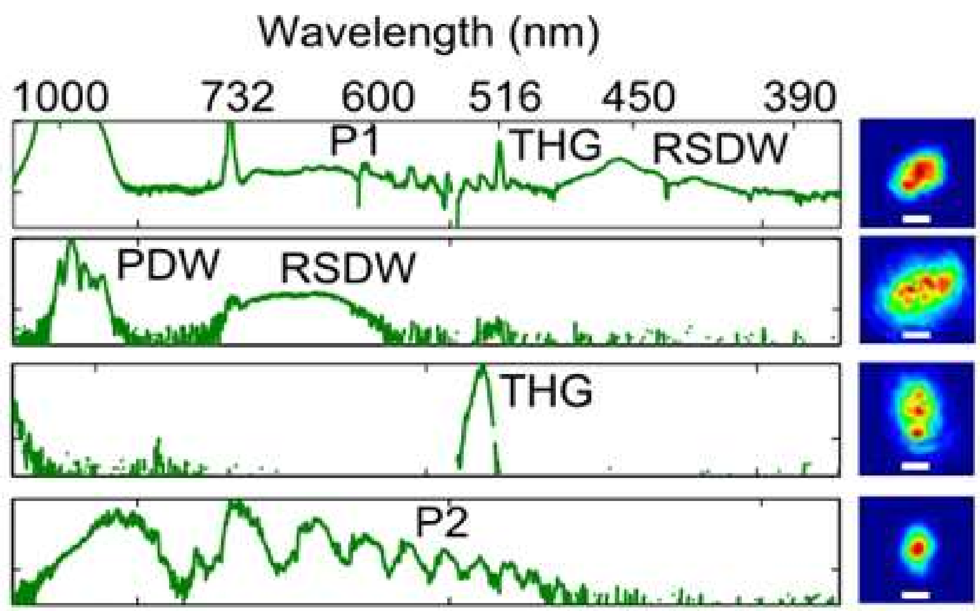
Spatial conditions determine the continuum



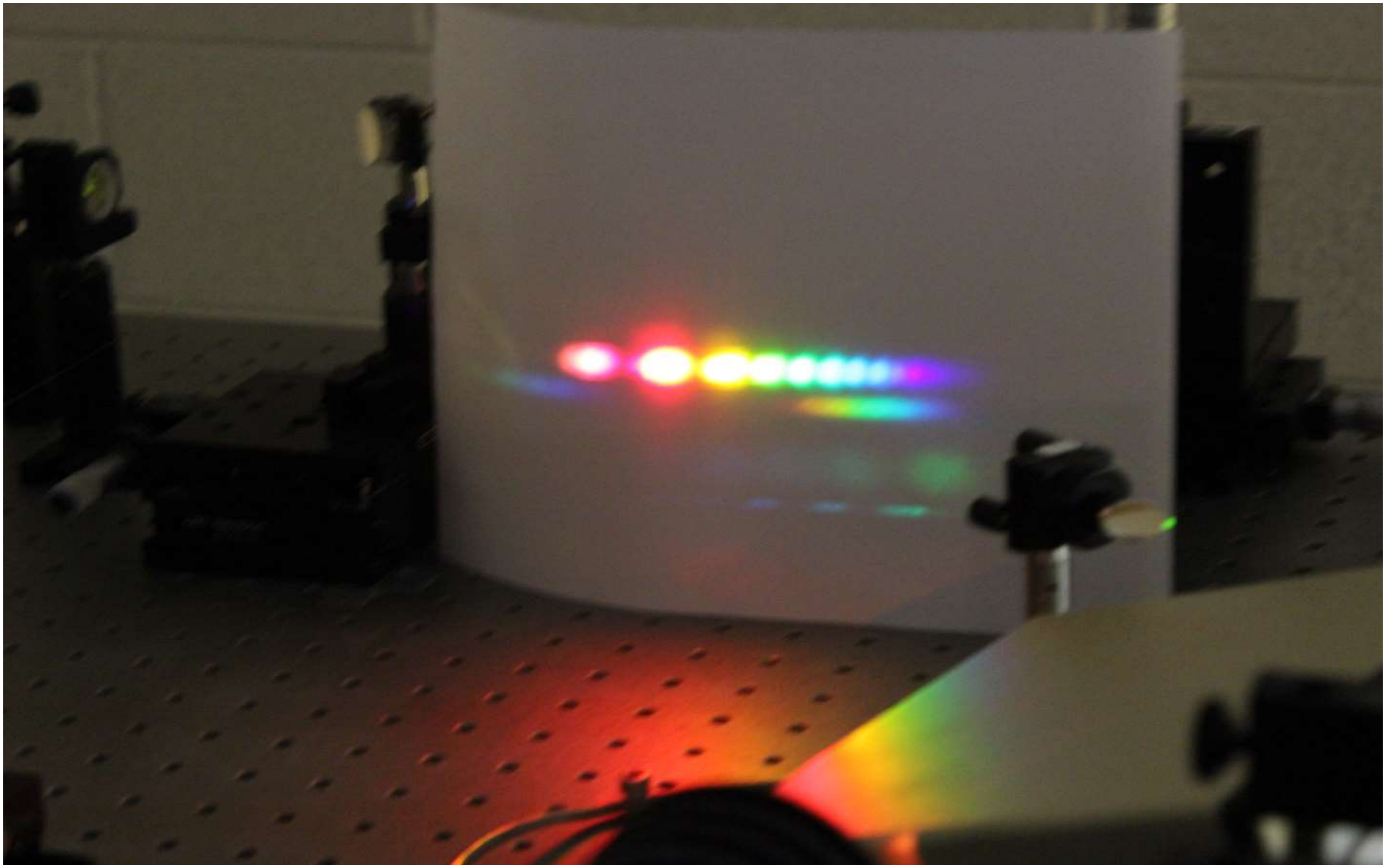
Spatial conditions determine the continuum



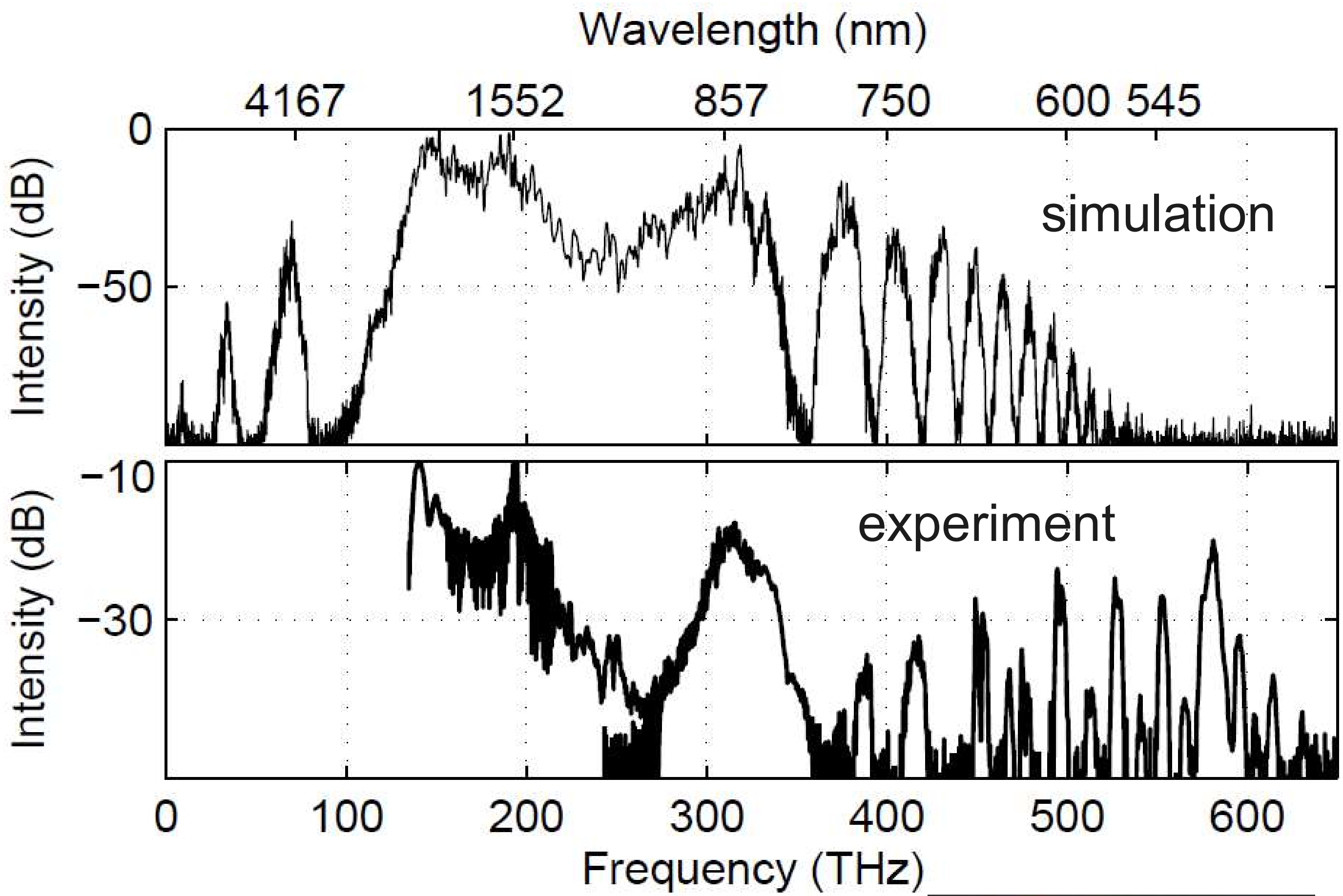
Spatial conditions determine the continuum



Spatial conditions determine the continuum



What is the origin of bright visible peaks?



Perturbation of solitons (1D tutorial)

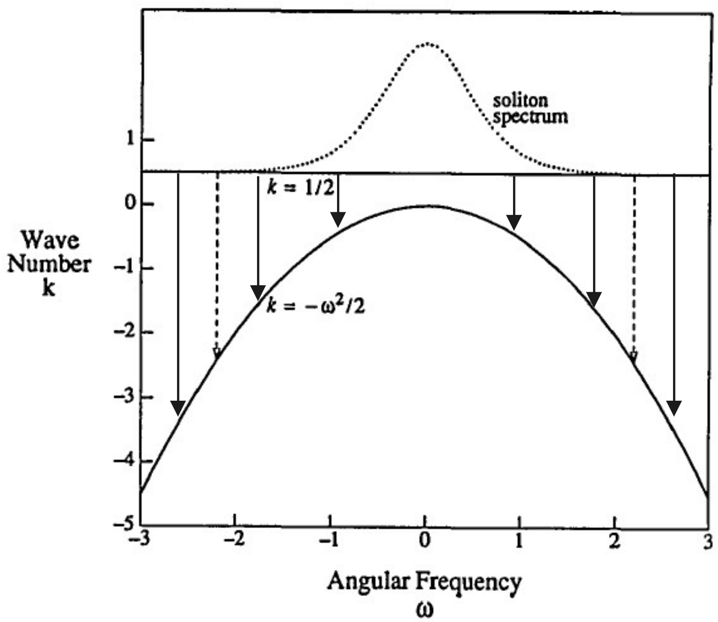
- Perturbed soliton adjusts to reach $A_0\tau_p = \sqrt{\frac{\beta_2}{\gamma}}$

  and radiates dispersive wave

- Periodic perturbation (period = Z_c)
  Resonant energy transfer when wave vectors match

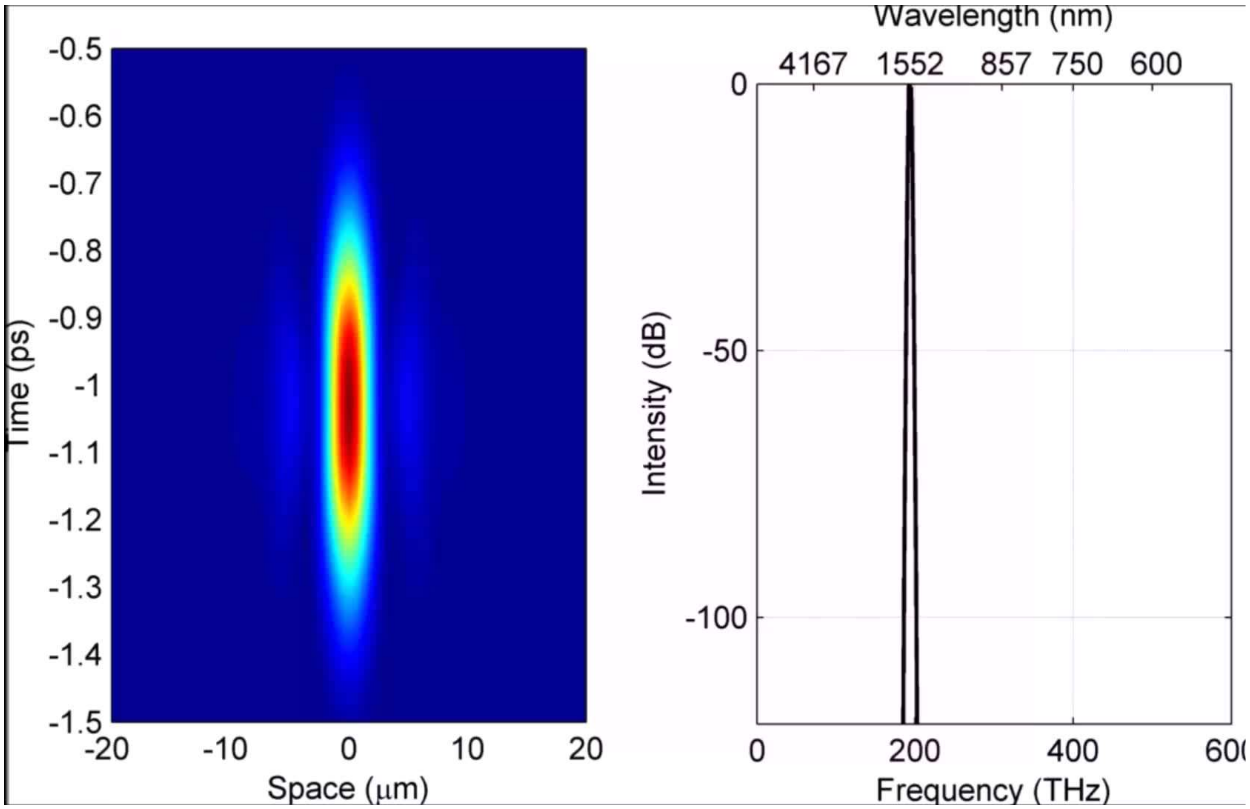
$$(k_{sol} - k_{dis}) = 2m\pi/Z_c$$

$$\Omega_{res} = \frac{1}{\tau}\sqrt{\frac{8Z_o m}{Z_c} - 1}$$

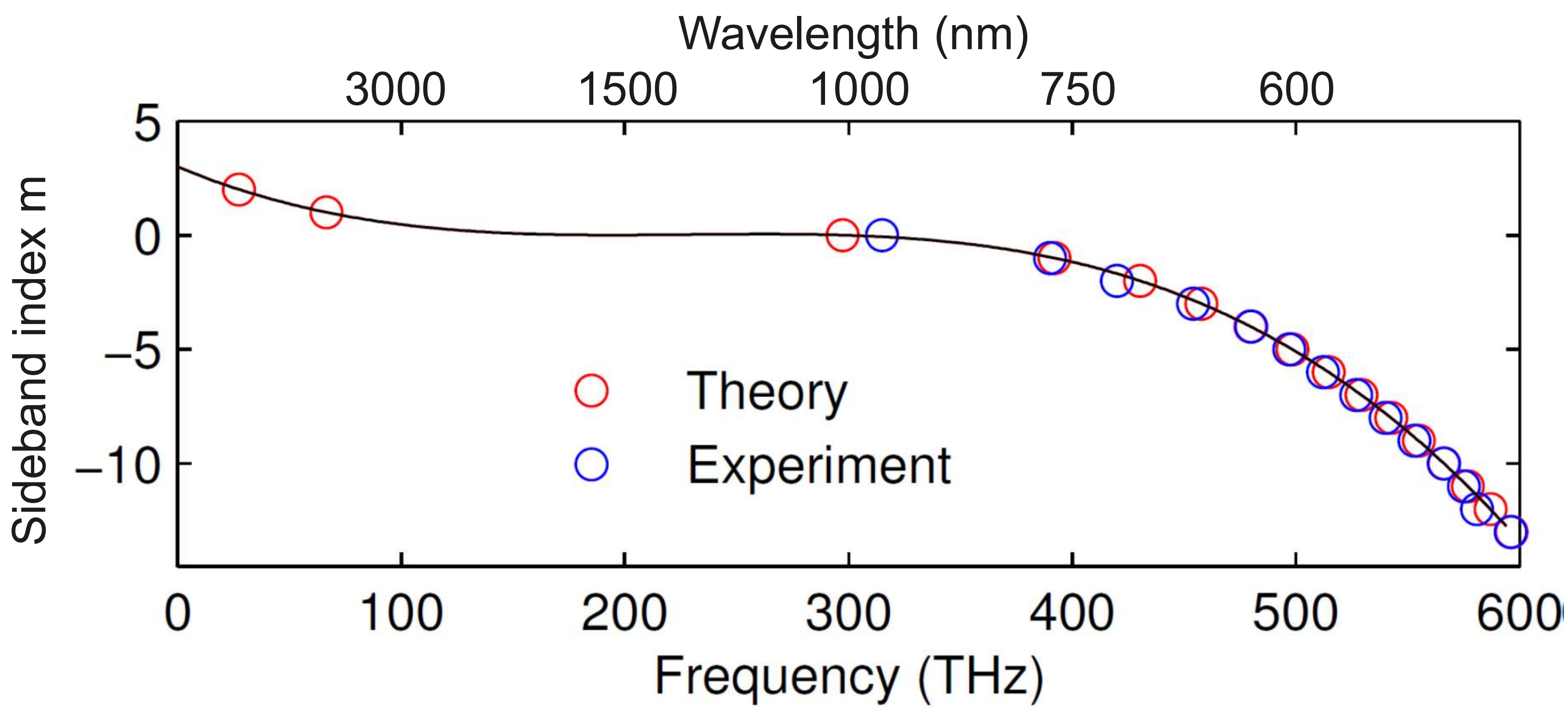


Gordon, J Opt Soc Am B 1992

Spatiotemporal oscillations



Theory and experiment



- Simulation, experiment and analytic theory agree well

Wright et al., Phys Rev Lett 2015

Oscillations about equilibrium as an instability: why more degrees of freedom matters

- Continuum is controllable through launched spatial modes
- Spatiotemporal oscillation leads to the generation of multimode dispersive waves
- Phenomenon understood in terms of multimode soliton dynamics

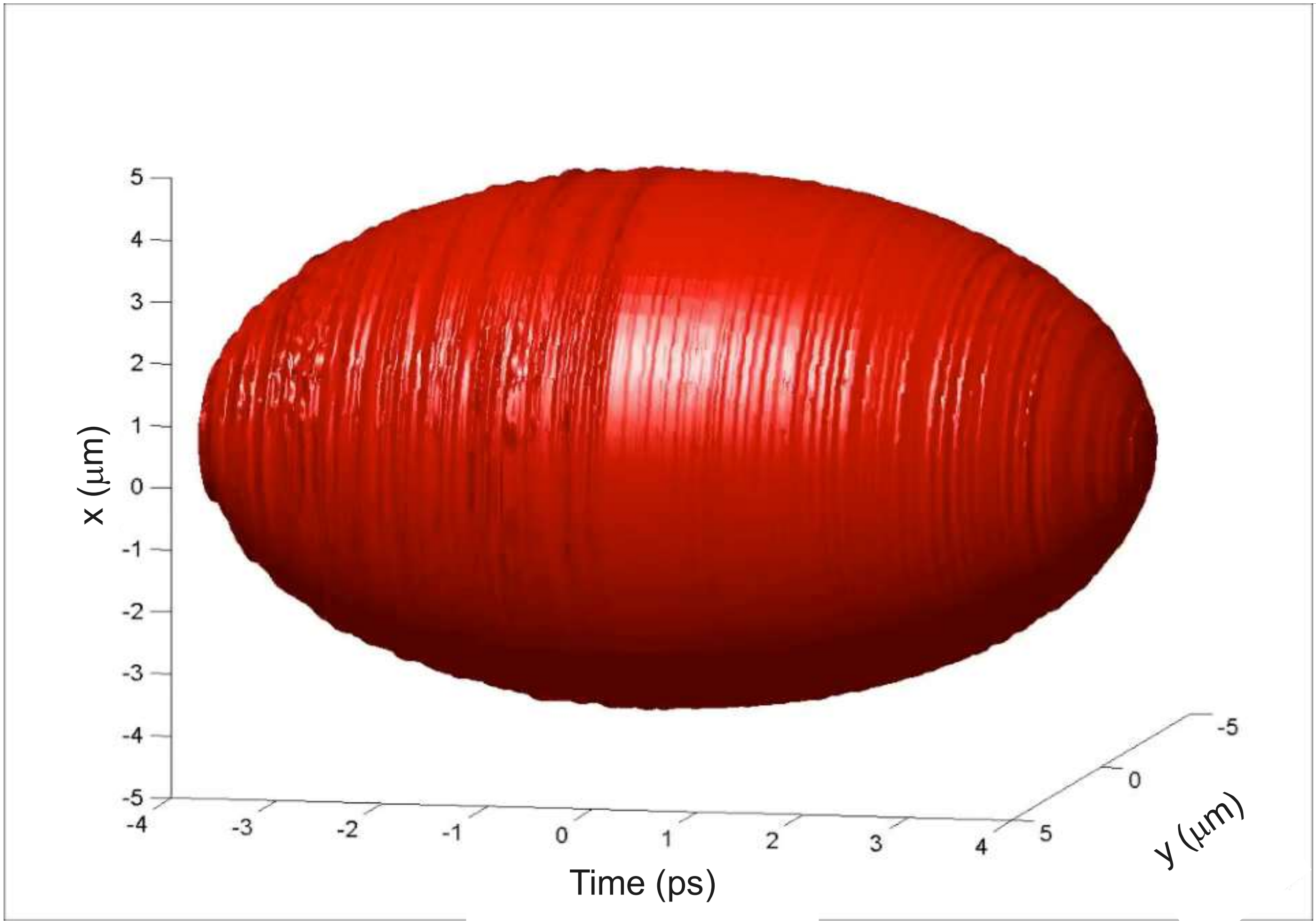
Wright et al., Nature Photon 2015

Wright et al., Phys Rev Lett 2015

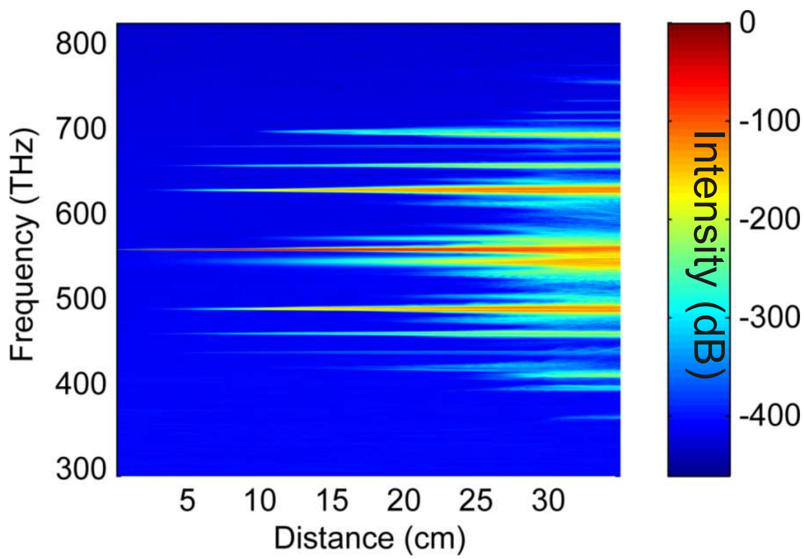
Spatiotemporal Modulation Instability

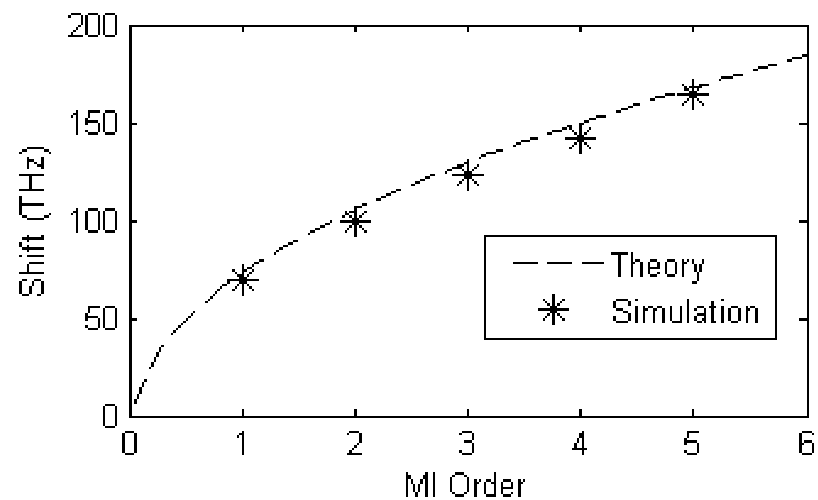
Spatiotemporal modulation instability

- Launch continuous wave or long pulse at normal dispersion



Spatiotemporal modulation instability

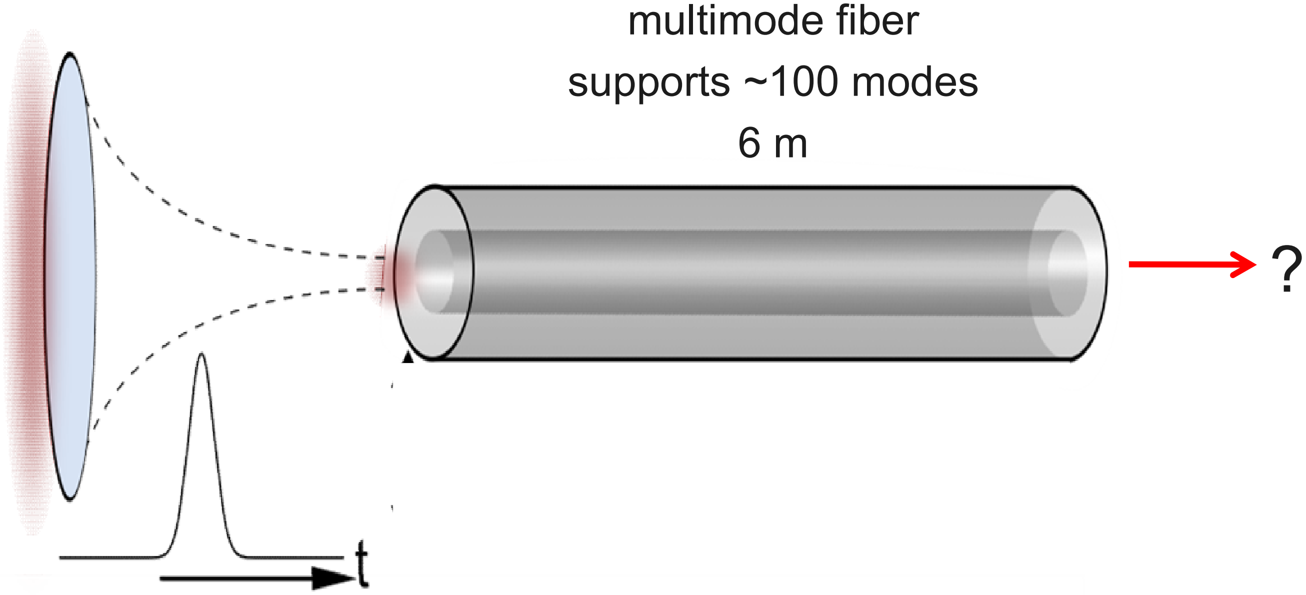




- Periodic self-imaging plays a role
- Instability occurs for either sign of dispersion

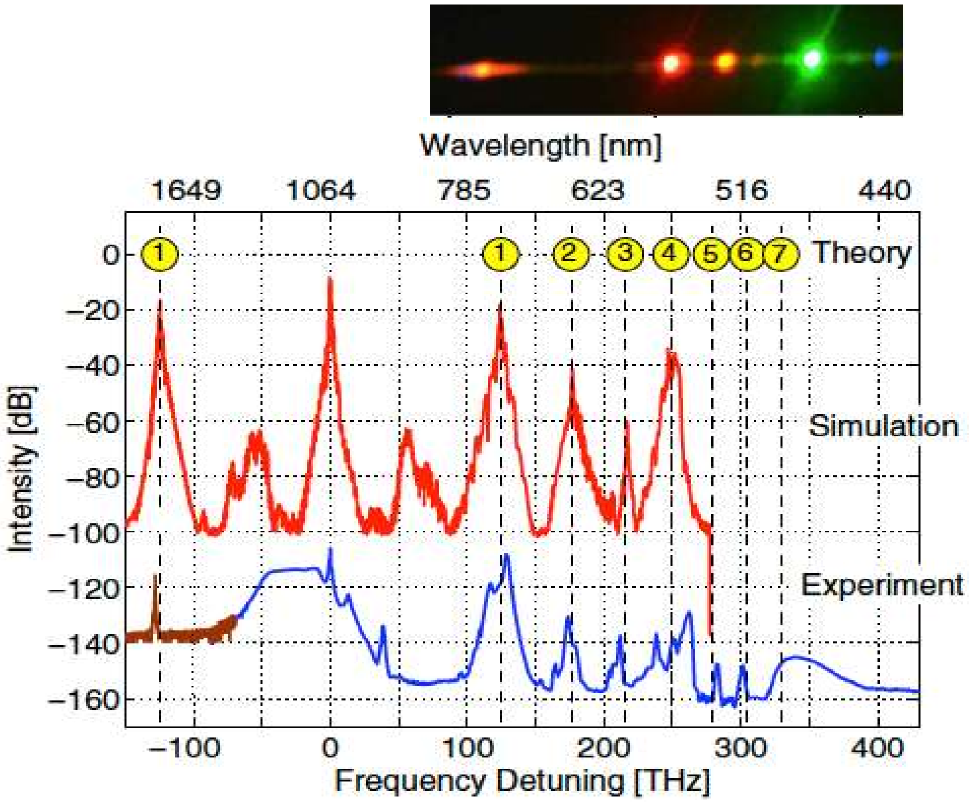
Longhi, Opt Lett 2003
Matera et al., Opt Lett 1993
Nazemosadat et al., JOSA B 2016

Spatiotemporal MI in GRIN fiber



Krupa et al., Phys Rev Lett 2016

Spatiotemporal MI in GRIN fiber

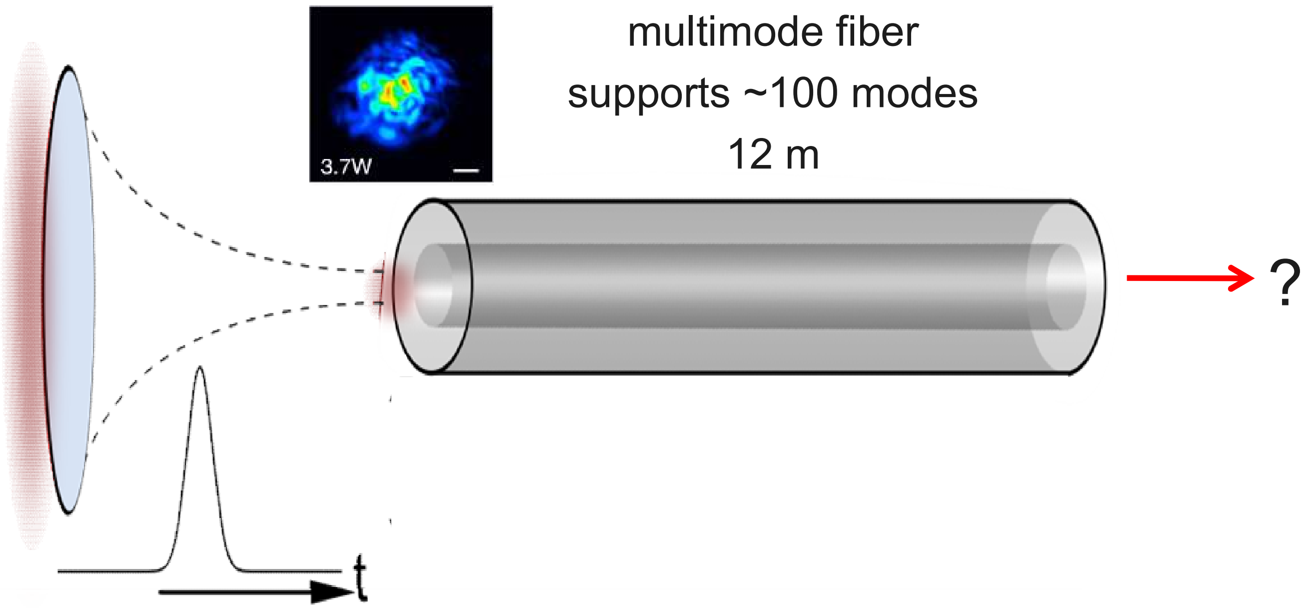


- Geometric parametric instability: periodic self-imaging of field allows quasi-phase-matching of 4WM sidebands

Krupa et al., Phys Rev Lett 2016

Beam Self-Cleaning in Multimode Fiber

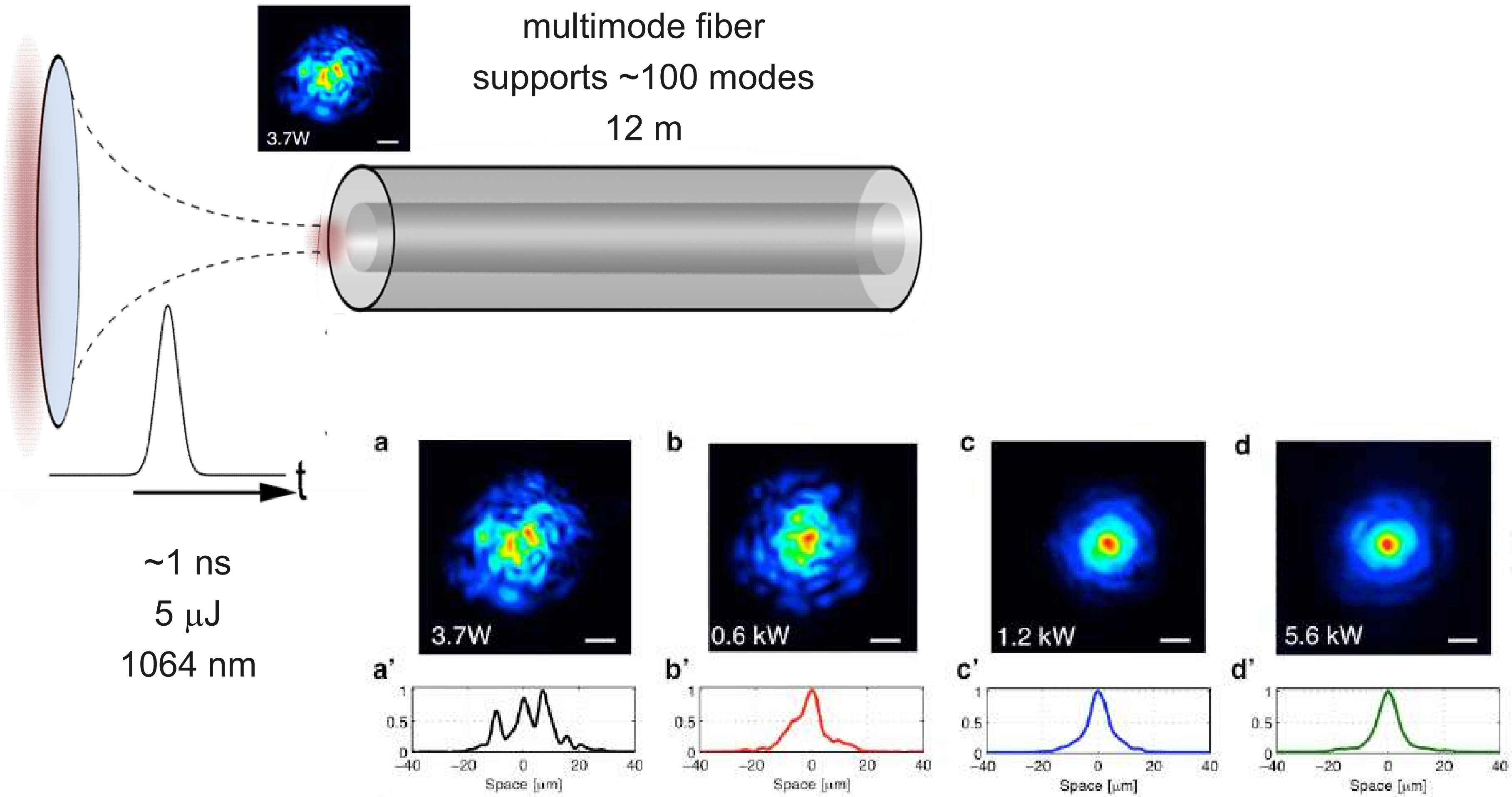
Beam self-cleaning in GRIN fiber



~1 ns
5 μJ
1064 nm

Krupa et al., arXiv 2016

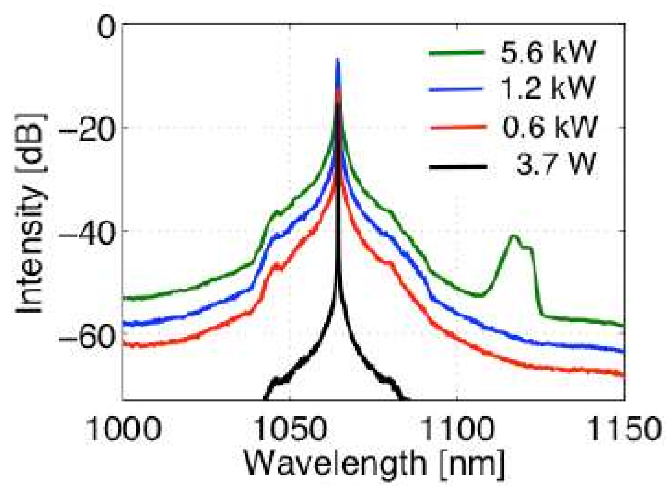
Beam self-cleaning in GRIN fiber

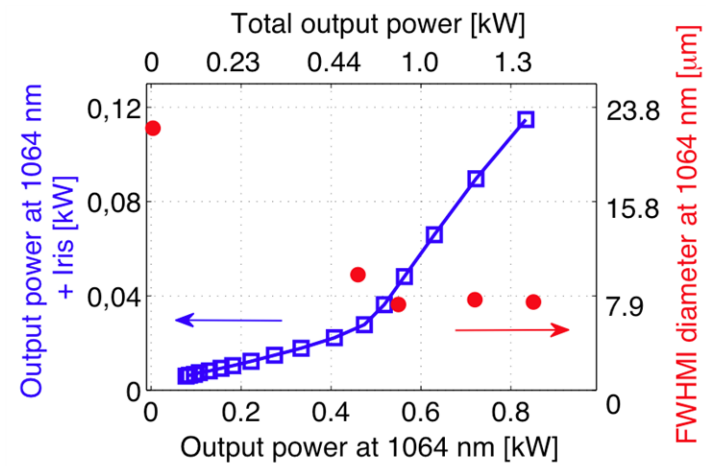


Krupa et al., arXiv 2016

Beam self-cleaning in GRIN fiber

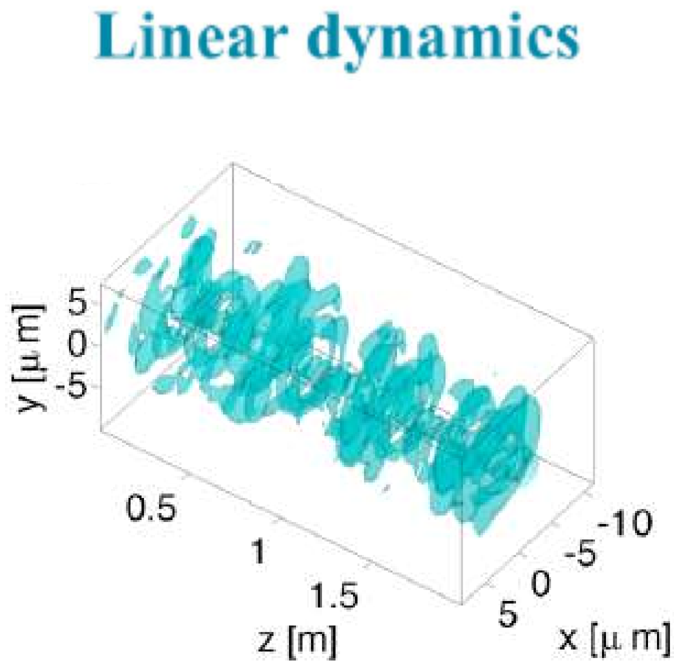
- P << P_{cr}
- Negligible dissipation
- Spatial coherence enhancement

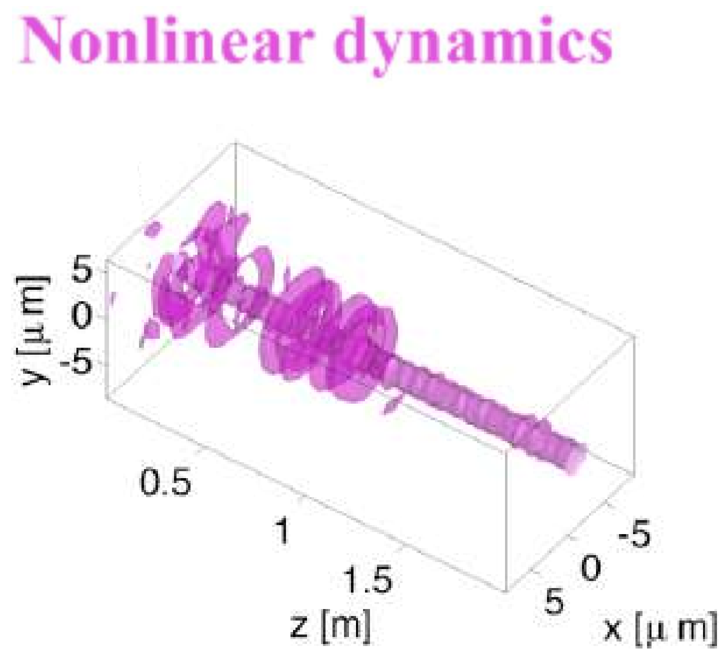




Krupa et al., arXiv 2016

Beam self-cleaning in GRIN fiber



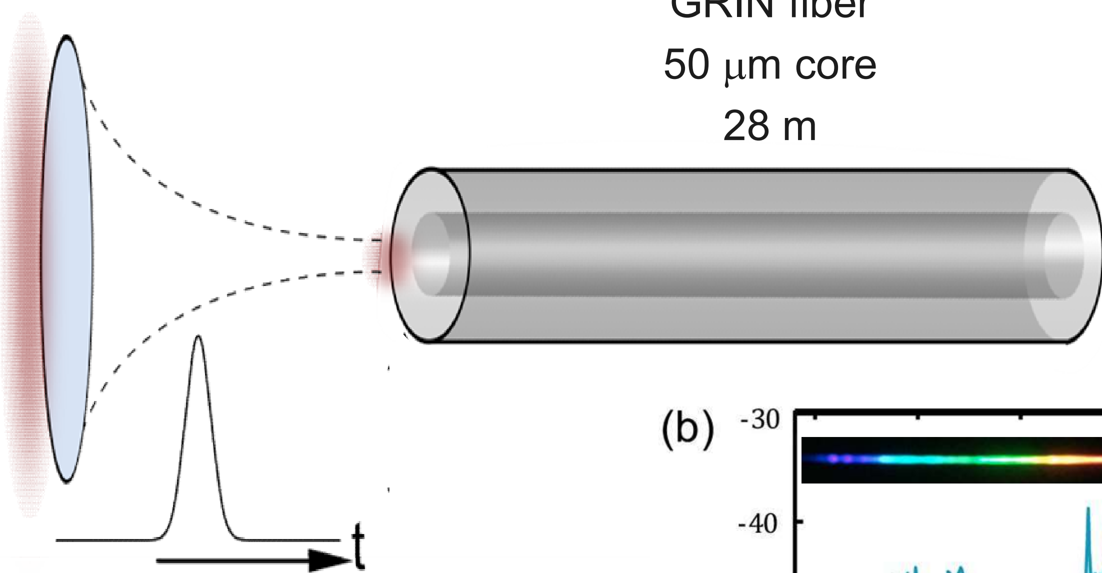


- Simulations show that Kerr nonlinearity underlies self-cleaning

Krupa et al., arXiv 2016

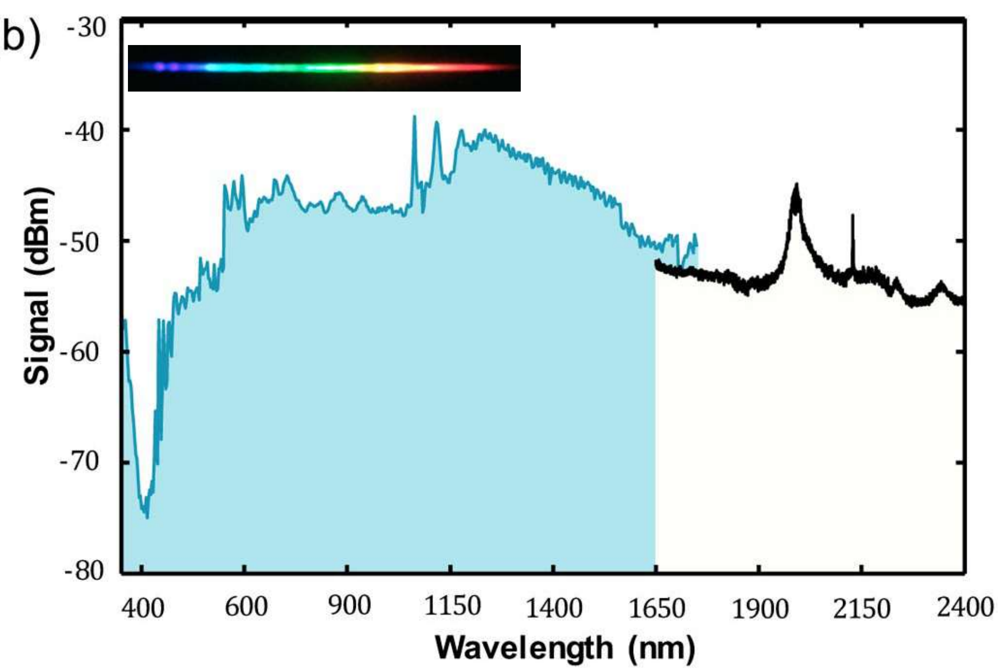
High-power continuum

GRIN fiber
50 μm core
28 m



400 ps
100 μJ
1064 nm

(b)



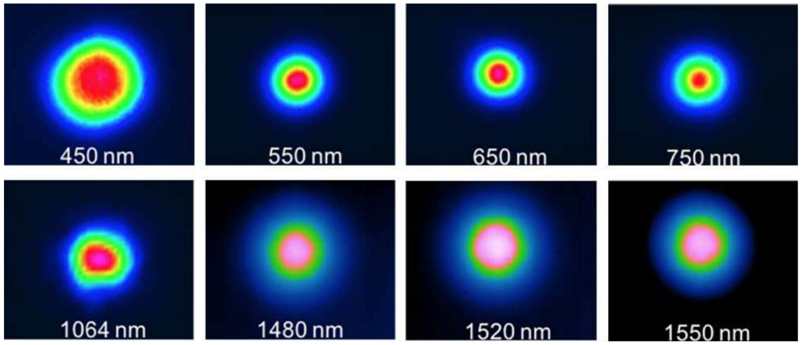
Lopez-Galmiche et al., Opt Lett 2016

High-power continuum

- Continuum from spatiotemporal MI, geometric parametric instability, Raman, and other 4-wave mixing processes

- Self-cleaning confirmed

- Speckle-free output with moderate M^2

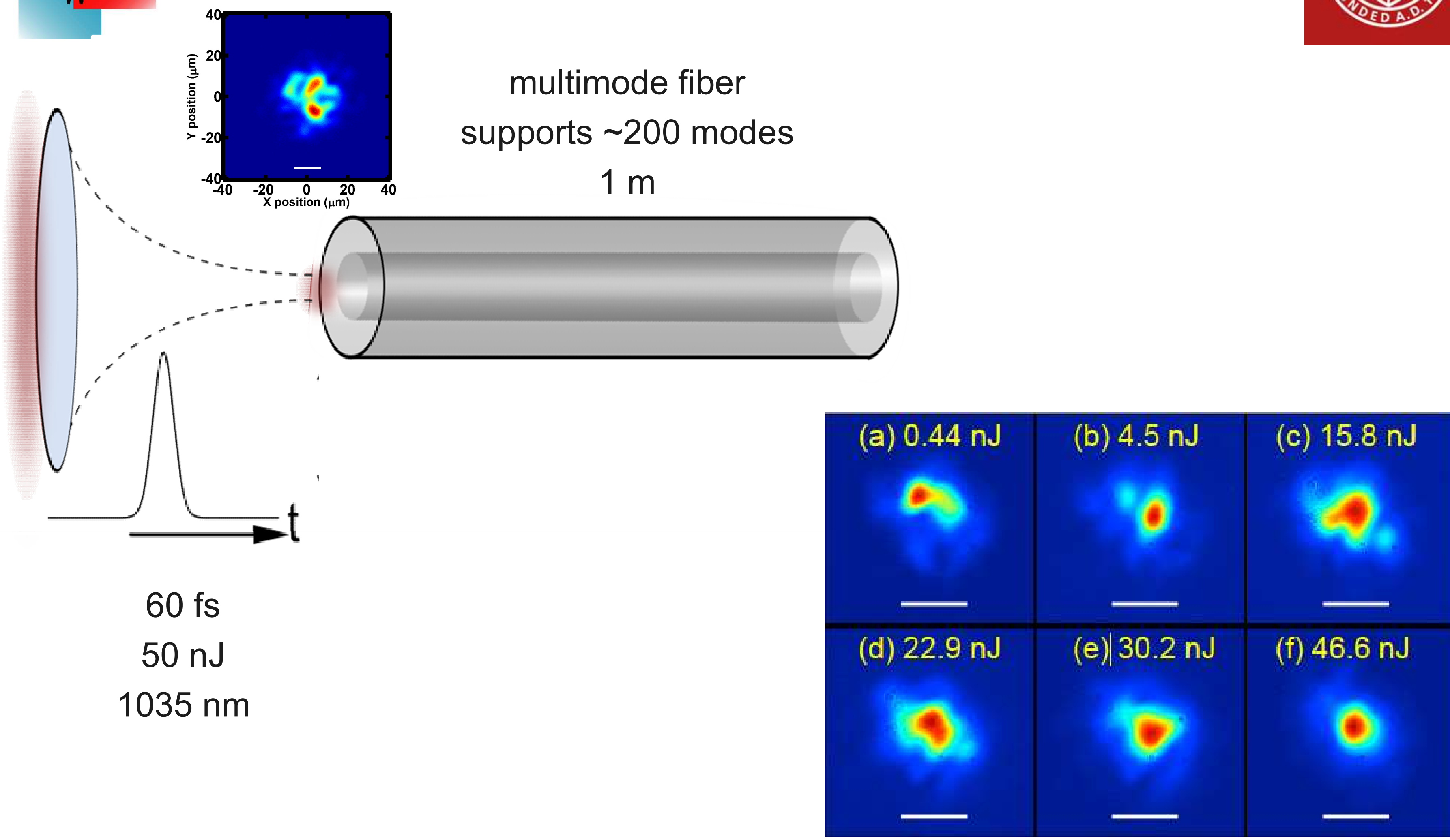


- 80 μJ pulse energy

- Route to compact, bright, multi-octave continuum

Lopez-Galmiche et al., Opt Lett 2016

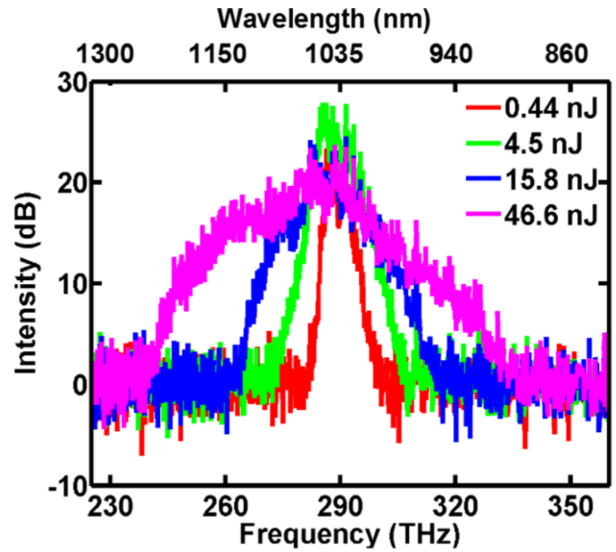
Self-cleaning of femtosecond pulsed beams



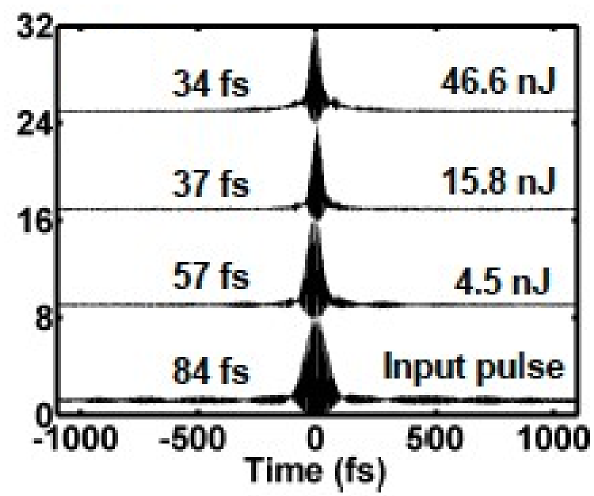
Z. Liu et al., 2016

Self-cleaning of femtosecond pulsed beams

- $P < P_{cr}$
- Negligible dissipation

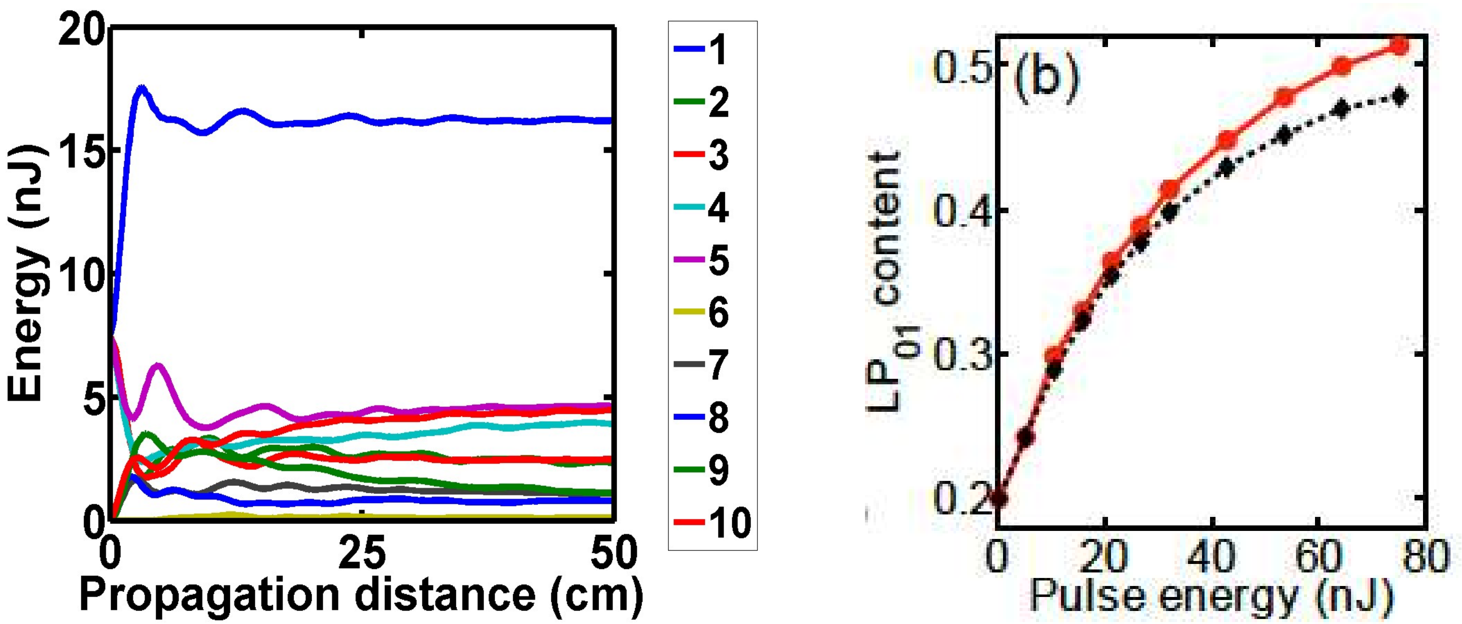


- Temporal coherence maintained



Z. Liu et al., 2016

Self-cleaning of femtosecond pulsed beams



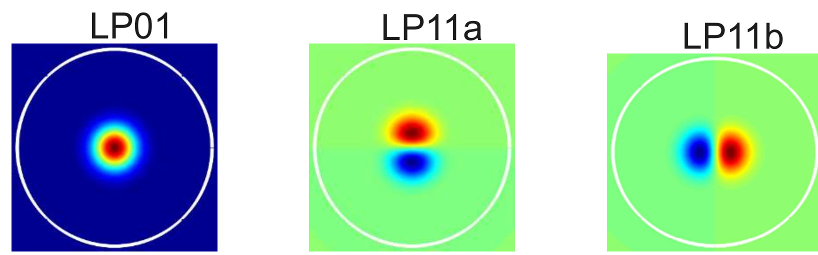
- Kerr nonlinearity underlies self-cleaning
- Process independent of pulse duration

Z. Liu et al., 2016

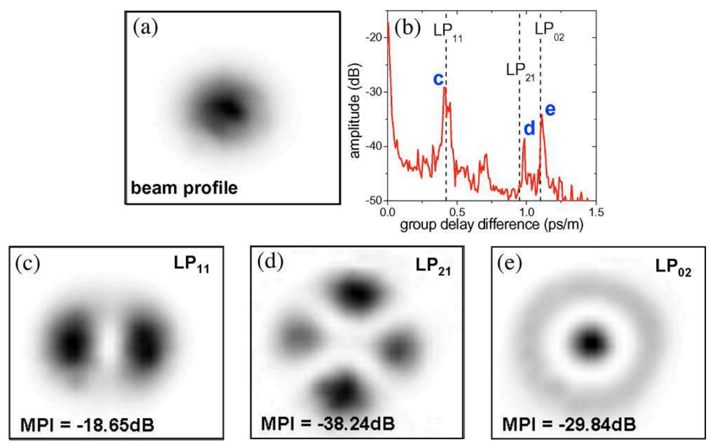
Implications / Future Directions

Multimode solitons

- Solitons in few-mode fibers



- Mode-resolved studies

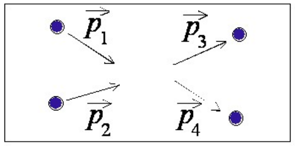


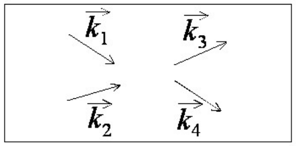
Nicholson et al., JSTQE 2009

Classical wave condensation

Wave turbulence theory

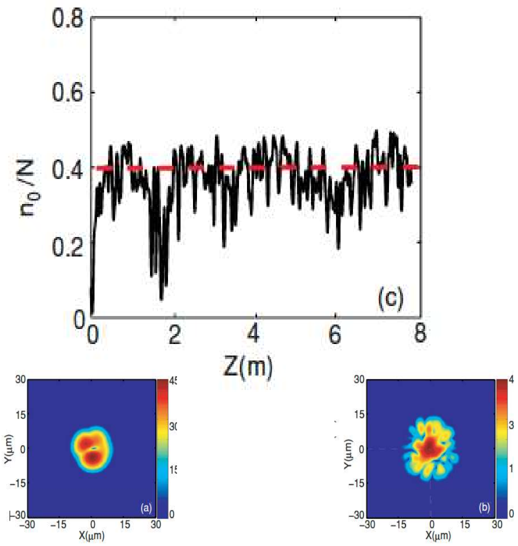
- random optical waves can "thermalize"





- initial *incoherent* field self-organizes to form large coherent structure
- equipartition of energy in higher-order modes

- 2D + parabolic waveguide:
  condensation predicted theoretically



Aschieri et al., Phys Rev A 2011

Optical turbulence

nature photonics LETTERS
PUBLISHED ONLINE: 22 SEPTEMBER 2013 | DOI: 10.1038/NPHOTON.2013.246

The laminar–turbulent transition in a fibre laser

E. G. Turitsyna[1], S. V. Smirnov[2], S. Sugavanam[1], N. Tarasov[1], X. Shu[1], S. A. Babin[2,3], E. V. Podivilov[2,3], D. V. Churkin[1,2,3], G. Falkovich[4,5] and S. K. Turitsyn[1,2]*

1362 OPTICS LETTERS / Vol. 39, No. 6 / March 15, 2014

Optical turbulence in fiber lasers

Stefan Wabnitz
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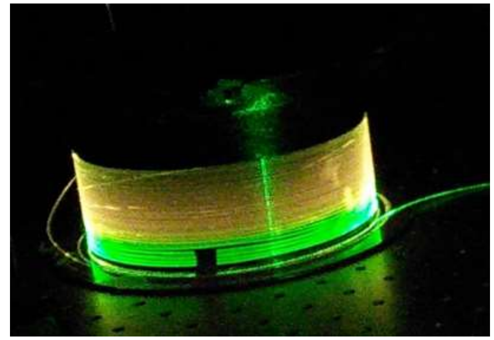
ELSEVIER
Physics Reports
Volume 542, Issue 1, 1 September 2014, Pages 1–132
Optical wave turbulence: Towards a unified nonequilibrium thermodynamic formulation of statistical nonlinear optics

Optical wave turbulence: Towards a unified nonequilibrium thermodynamic formulation of statistical nonlinear optics

A. Picozzi[a], J. Garnier[b], T. Hansson[c], P. Suret[d], S. Randoux[d], G. Millot[a], D.N. Christodoulides[e]

- Optical wave turbulence studied in 1D systems
- True turbulence requires 3D

Effects of disorder and dissipation

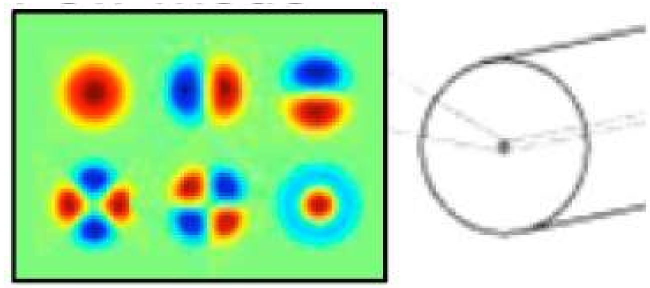


- Introduce
  - random mode coupling
  - gain, loss
- Complex system
- Controllable and measurable
- Testbed for
  - cooperative phenomena
  - self-organized critical behavior

Wright et al., arXiv 2016

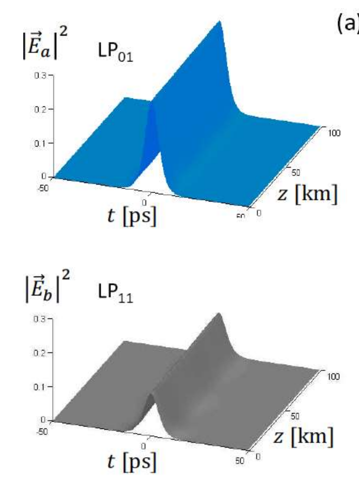
Relevance to telecommunications

- N modes → N channels



- Multimode solitons *versus* independent channels

- Strongly-coupled mode groups: Manakov solitons



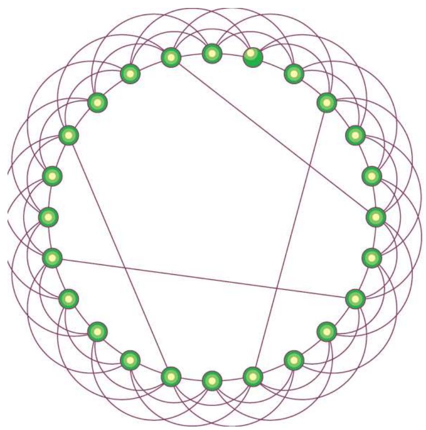
Mecozzi et al., Opt Exp 2012

- Instabilities may limit transmission

Relevance to telecommunications

Multimode fibers are small-world networks

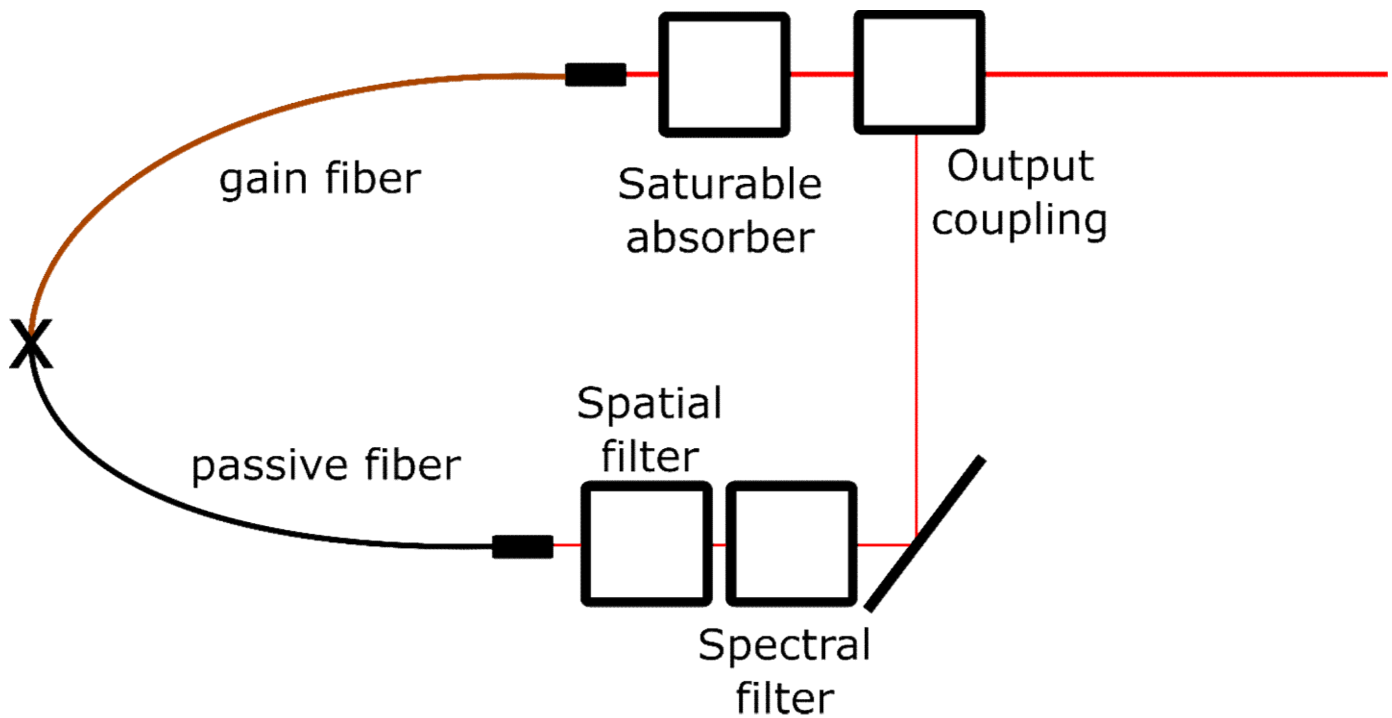
- Coupling is primarily between nearest neighbors
- "Shortcut" links can lead to a strong-coupling transition, many-mode self-organization



A small-world network
Strogatz, Nature 2001

- Need to understand many-mode nonlinear interactions
  - Mode-dependent gain and loss
  - Mode-dependent, longitudinally-varying disorder

Multimode soliton lasers



A multimode fiber laser is a new environment for nonlinear waves. It adds

- spatially-dependent gain, saturable absorption
- spatial and spectral filtering

Multimode soliton lasers

Multimode fiber lasers can have much higher energy than single-mode fiber lasers

- Larger mode area

Multimode soliton lasers

Multimode fiber lasers can have much higher energy than single-mode fiber lasers

- Larger mode area

$$E \sim A_{eff}$$

single mode fiber	A_{eff} = 50-100 μm^2
large-mode-area microstructure fiber	A_{eff} ~ 5,000 μm^2
single higher-order mode	A_{eff} ~ 3,000 μm^2
multimode fiber	A_{eff} > 30,000 μm^2

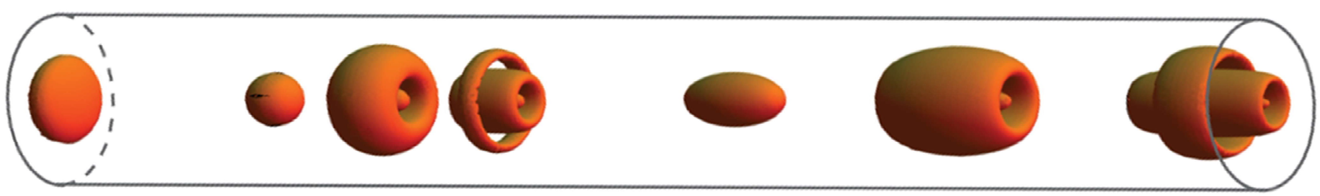
(1550 nm)

Multimode soliton lasers

Multimode fiber lasers can have much higher energy than single-mode fiber lasers

- Larger mode area
- Modal dispersion

$$E \sim \sum \text{dispersion}$$



Multimode soliton lasers

Multimode fiber lasers can have much higher energy than single-mode fiber lasers

- Larger mode area
- Modal dispersion
- New (spatiotemporal) pulse evolutions

Role of spatiotemporal instabilities?

Ultimate limit from self-focusing

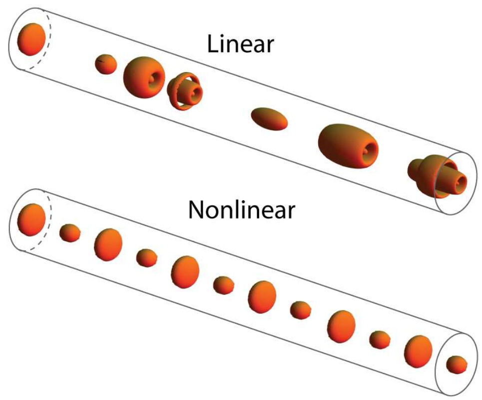
Overall Summary

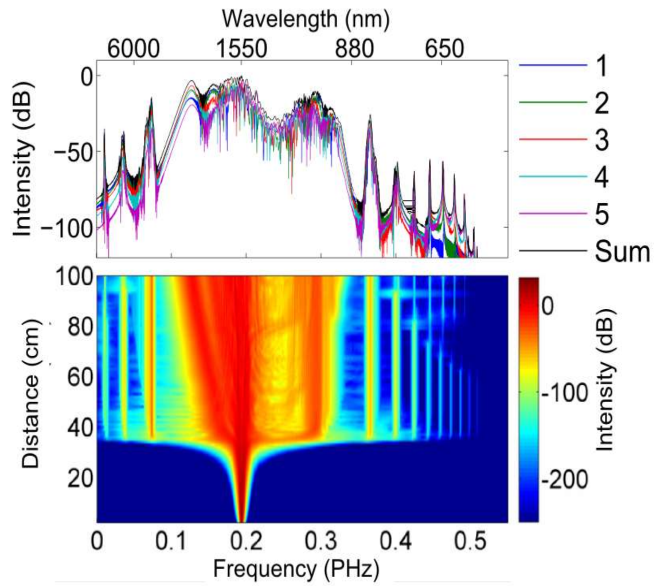
- Multimode fiber supports a variety of new spatiotemporal phenomena
- Initial results indicate that multimode solitons will
  help understand complex dynamics
- Relevance of nonlinear dynamics to applications
  - High-power, multi-octave continuua
  - Connection to optics of complex media
  - Space-division multiplexing in telecommunications
  - Laser / amplifier / transmission applications

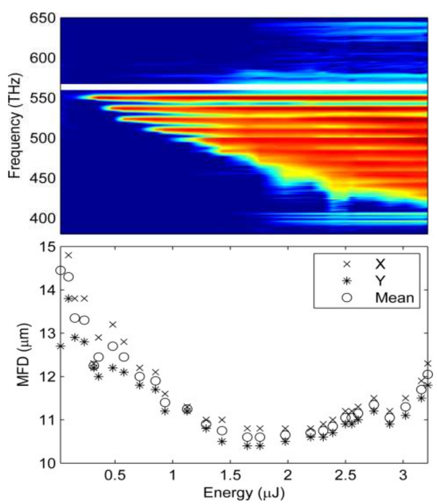
Office of Naval Research
ONR
Science & Technology

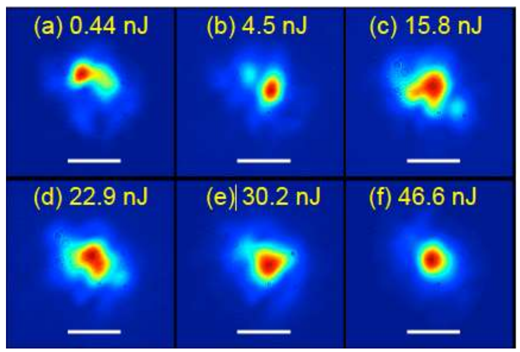
NSF

NSERC
CRSNG


Linear
Nonlinear


Wavelength (nm)
6000 1550 880 650
Intensity (dB)
0 −50 −100
1
2
3
4
5
Sum
Distance (cm)
100 80 60 40 20
0 −100 −200
Intensity (dB)
0 0.1 0.2 0.3 0.4 0.5
Frequency (PHz)


Frequency (THz)
650 600 550 500 450 400
MFD (μm)
15 14 13 12 11 10
X
Y
Mean
0.5 1 1.5 2 2.5 3
Energy (μJ)


(a) 0.44 nJ
(b) 4.5 nJ
(c) 15.8 nJ
(d) 22.9 nJ
(e) 30.2 nJ
(f) 46.6 nJ

Reserve slides

Theory of pulse propagation in MM fiber

F. Poletti and P. Horak, "Description of ultrashort pulse propagation in multimode optical fibers," J. Opt. Soc. Am. B 25, 1645 (2008).

P. Horak and F. Poletti, "Multimode Nonlinear Fiber Optics: Theory and Applications," in "Recent Progress in Optical Fiber Research," M. Yasin, ed. (2012), chap. 1, pp. 3–24.

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F. Poletti and P. Horak, "Dynamics of femtosecond supercontinuum generation in multimode fibers," Opt. Express 17, 6134 (2009).

G. Hesketh, F. Poletti, and P. Horak, "Spatio-Temporal Self-Focusing in Femtosecond Pulse Transmission Through Multimode Optical Fibers," J. Lightwave Technol. 30, 2764–2769 (2012).

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A. Mecozzi, C. Antonelli & M. Shtaif, Nonlinear propagation in multi-mode fibers in the strong coupling regime. Optics express 20.11, 11673-11678 (2012).

A. Mecozzi, C. Antonelli & M. Shtaif, Coupled Manakov equations in multimode fibers with strongly coupled groups of modes."Optics express 20.21, 23436-23441.(2012).

J. Andreasen and M. Kolesik, "Nonlinear propagation of light in structured media: Generalized unidirectional pulse propagation equations", *Phys. Rev. E* 86 (2012)

Theory: solitons in multimode fiber

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B. Crosignani and P. D. Porto, “Soliton propagation in multimode optical fibers,” Opt. Lett. 6, 329 (1981).

B. Crosignani, A. Cutolo, and P. D. Porto, “Coupled-mode theory of nonlinear propagation in multimode and single-mode fibers: envelope solitons and self-confinement,” J. Opt. Soc. Am. 72, 1136 (1982).

N. Akhmediev and A. Ankiewicz, “Multi-soliton complexes,” Chaos (Woodbury, N.Y.) 10, 600–612 (2000).

S. Buch and G. P. Agrawal, “Soliton stability and trapping in multimode fibers,” Opt. Lett 40, 225–228 (2015).

Graded-index fiber

- Predicted 3D wave-packets from analytical models

Yu, et al., Spatio-temporal solitary pulses in graded-index materials with Kerr nonlinearity. *Optics Communications 1995.*

S Raghavan and Govind P Agrawal. Spatiotemporal solitons in inhomogeneous nonlinear media. *Optics Communications 2000.*

- Experiments

P. L. Baldeck, F. Raccah, and R. R. Alfano, "Observation of self-focusing in optical fibers with picosecond pulses," Opt. Lett. 12, 588 (1987).

A. B. Grudinin, E. M. Dianov, D. V. Korbkin, A. M. Prokhorov, and D. V. Khaˇidarov, "Nonlinear mode coupling in multimode optical fibers; excitation of femtosecond-range stimulated-Raman-scattering solitons," J. Exp. Theor. Phys. 47 297–300 (1988).

H. Pourbeyram, G. P. Agrawal, and A. Mafi, "Stimulated Raman scattering cascade spanning the wavelength range of 523 to 1750 nm using a graded-index multimode optical fiber," Appl. Phys. Lett. 102, 201107 (2013).

K.O. Hill, D.C. Johnson & B.S. Kawasaki, Efficient conversion of light over a wide spectral range by four-photon mixing in a multimode graded-index fiber. Appl. Opt. **20,** 2769 (1981).

Hollow-core multimode nonlinear optics

P. St. J. Russell, P. Hölzer, W. Chang, A. Abdolvand & J. C. Travers, Hollow-core photonic crystal fibres for gas-based nonlinear optics, Nature Photonics **8**, 278–286 (2014)

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G. Fibich and A. L. Gaeta, “Critical power for self-focusing in bulk media and in hollow waveguides,” Opt. Lett. 25, 335–337 (2000)

Recent work on nonlinear optics in other multimode fibers

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J. Demas, P. Steinvurzel, B. Tai, L. Rishøj, Y. Chen, and S. Ramachandran, "Intermodal nonlinear mixing with Bessel beams in optical fiber," Optica 2, 14-17 (2015)

J. Demas, T. He, and S. Ramachandran, "Generation of 10-kW Pulses at 880 nm in Commercial Fiber via Parametric Amplification in a Higher Order Mode," in Conference on Lasers and Electro-Optics, OSA Technical Digest (2016) (Optical Society of America, 2016), paper STh3P.6.

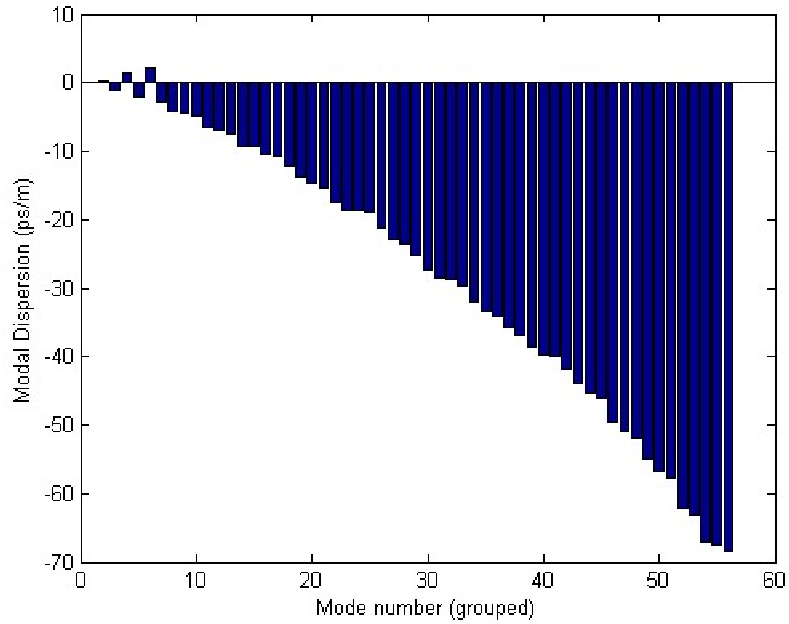
L. Rishoj, G. Prabhakar, J. Demas, and S. Ramachandran, "30 nJ, ~50 fs All-Fiber Source at 1300 nm Using Soliton Shifting in LMA HOM Fiber," in Conference on Lasers and Electro-Optics, OSA Technical Digest (2016) (Optical Society of America, 2016), paper STh3O.3.

J. Cheng, M.E. Pedersen, K. Charan, K. Wang, C. Xu, L. Grüner-Nielsen & D. Jakobsen, Intermodal four-wave mixing in a higher-order-mode fiber. Applied Physics Letters, 101(16), 161106 (2012)

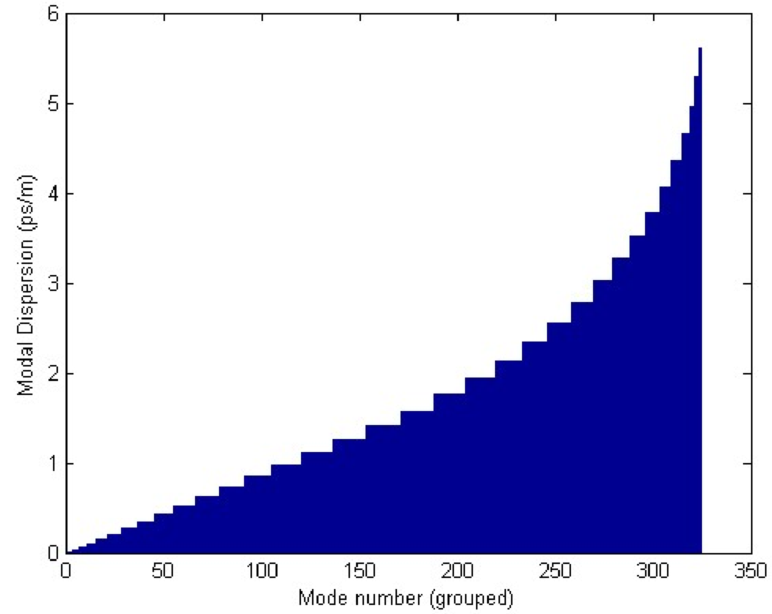
J. Cheng, M.E. Pedersen, K. Charan, K. Wang, C. Xu, L. Grüner-Nielsen & D. Jakobsen, Intermodal Čerenkov radiation in a higher-order-mode fiber, Optics letters 37 (21), 4410-4412 (2012).

Multimode fibers

Step-Index



GRIN



- In GRIN fiber, modes have similar group velocities

Single-field model for GRIN fiber

$$\frac{\partial A}{\partial z} = \frac{i}{2k_0}\left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\right) - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - i\frac{k_0 \Delta}{R^2}(x^2 + y^2)A + i\gamma|A|^2 A$$

diffraction dispersion index profile Kerr

Single-field model for GRIN fiber

$$\frac{\partial A}{\partial z} = \frac{i}{2k_0}\left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\right) - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - i\frac{k_0\Delta}{R^2}(x^2+y^2)A + i\gamma|A|^2 A$$

- Gross-Pitaevskii equation

Coupled mode analysis

"GMMNLSE"

$$\partial_z A_p(z,t) = i\left(\beta_0^{(p)} - \Re\left[\beta_0^{(0)}\right]\right)A_p - \left(\beta_1^{(p)} - \Re\left[\beta_1^{(0)}\right]\right)\frac{\partial A_p}{\partial t} + \sum_{m=2}^{3} i^{m+1}\frac{\beta_m}{m!}\partial_t^m A_p$$

modal wavenumber mismatch **modal velocity mismatch** **group velocity dispersion**

$$+i\frac{n_2\omega_0}{c}\left(1+\frac{i}{\omega_o}\partial_t\right)\sum_{l,m,n}\left\{(1-f_R)S_{plmn}^k A_l A_m A_n^* + f_R A_l S_{plmn}^R \int_{-\infty}^{t} d\tau A_m(z,t-\tau)A_n^*(z,t-\tau)h_R(\tau)\right\}$$

shock **Kerr** **Raman**

F. Poletti and P. Horak, "Description of ultrashort pulse propagation in multimode optical fibers," J. Opt. Soc. Am. B 25, 1645 (2008).

A. Mafi, "Pulse Propagation in a Short Nonlinear Graded-Index Multimode Optical Fiber," J. Lightwave Technol. 30, 2803–2811 (2012).

Relation between modes

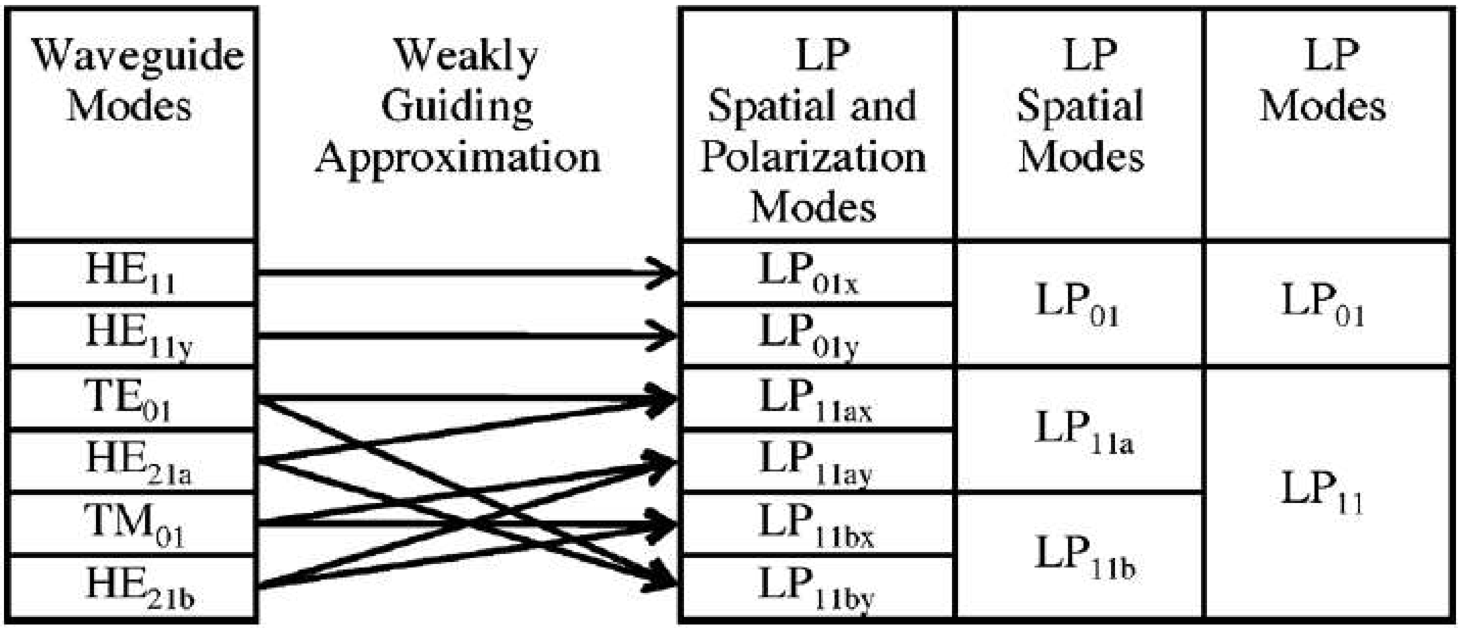


Fig. 1. Relation between the LP modes and the real waveguide modes HE_{11x}, HE_{11y}, TE_{01}, TM_{01}, HE_{21a}, and HE_{21b} of the six-mode FMF.

Ryf *et al., J. Lightwave Tech.* 30, 521 (2012)