Spatiotemporal Dynamics of Optical Pulse Propagation in Multimode Fibers

Presented by:

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• Past seminars
  – 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

$\lambda > 1300 \text{ nm for silica}$
Dispersive phase accumulation

normal dispersion

$\lambda < 1300 \text{ nm for silica}$
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

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

(anomalous) dispersion cancels nonlinearity for

\[
A(t) = A_0 \text{sech}(t/\tau_p) \exp(i z / z_{sol})
\]
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

- Soliton is a nonlinear attractor
Linear wave propagation

- pulse spreads owing to group-velocity dispersion

- beam spreads owing to diffraction
Nonlinear propagation $(\chi^{(3)})$

nonlinear phase shift produces self-focusing
Nonlinear propagation ($\chi^{(3)}$)

Nonlinear phase shift produces self-focusing

\[ n = n_0 + n_2 |I| \]
Critical power

- diffraction balances self-focusing for
  \[ P = P_{cr} \sim 5 \text{ MW in glass} \]

\[ n(I) = n_0 + n_2 I \]
Critical power

- diffraction balances self-focusing for
  \[ P = P_{cr} \approx 5 \text{ MW in glass} \]

- 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

- A beam breaks into its component solitons

- Stable products of instability are “eigenmodes” of nonlinear systems
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
  - Agrell et al., J Opt 2016

- Spatial division multiplexing in telecom

- Imaging through multimode fiber/ complex media
  - Ploschner et al., Nature Photon 2015
Graded-index (GRIN) multimode fiber

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

multimode fiber
parabolic index profile
1 – 100 m
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

62.5/125 μm GRIN fiber supports ~100 modes

SMF28 50 cm

10 μm MFD

- Excite 3 lowest modes
Experiment

300 fs
1550 nm
0.1 - 5 nJ

62.5/125 μm GRIN fiber
100 m

SMF28
50 cm

\( L_{\text{disp}} \sim 1 \text{ m} \)
Experimental results

- For $E < 0.1$ nJ pulse disperses

- 0.5 nJ pulse energy

![Input and output graphs](image-url)
3 modes: theory

- Launch 0.5 nJ / 300 fs

- Coupled-mode theory and beam-propagation give similar results
Solitons with more modes require greater nonlinear phase / energy

Solitons with up to 10 modes generated

Renninger et al., Nature Commun 2013

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 pulses
- Energy up to 1 µJ
- Peak power up to MW
- 1550 nm
- Multimode fiber supports ~100 modes over 1 m
Experiments

Adjust position to excite different mode combinations
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
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

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

\[
\Omega_{res} = \frac{1}{\tau} \sqrt{\frac{8Z_0m}{Z_c}} - 1
\]

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

multimode fiber supports ~100 modes
6 m

~1 ns
125 nJ
1064 nm

Krupa et al., Phys Rev Lett 2016
Spatialtemporal 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

multimode fiber
supports ~100 modes
12 m

~1 ns
5 μJ
1064 nm

Krupa et al., arXiv 2016
Beam self-cleaning in GRIN fiber

multimode fiber supports ~100 modes

~1 ns
5 μJ
1064 nm

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

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 $\mu$J pulse energy

- Route to compact, bright, multi-octave continuum

Lopez-Galmiche et al., Opt Lett 2016
Self-cleaning of femtosecond pulsed beams

multimode fiber supports ~200 modes

1 m

60 fs
50 nJ
1035 nm

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

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 \textit{incoherent} field self-organizes to form large coherent structure
- equipartition of energy in higher-order modes

- 2D + parabolic waveguide: condensation predicted theoretically

\textit{Aschieri et al., Phys Rev A 2011}
Optical turbulence

- 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 $\rightarrow$ N channels

- Multimode solitons *versus* independent channels

- Strongly-coupled mode groups: Manakov solitons

- Instabilities may limit transmission

*Mecozzi et al., Opt Exp 2012*
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

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

A small-world network
Strogatz, Nature 2001
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

\[ E \sim A_{eff} \]

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>( A_{eff} )</th>
</tr>
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<tbody>
<tr>
<td>Single mode fiber</td>
<td>( 50-100 \ \mu m^2 )</td>
</tr>
<tr>
<td>Large-mode-area microstructure fiber</td>
<td>( \sim 5,000 \ \mu m^2 )</td>
</tr>
<tr>
<td>Single higher-order mode</td>
<td>( \sim 3,000 \ \mu m^2 )</td>
</tr>
<tr>
<td>Multimode fiber</td>
<td>( &gt; 30,000 \ \mu m^2 )</td>
</tr>
</tbody>
</table>

(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
Reserve slides
Theory of pulse propagation in MM fiber


Theory: solitons in multimode fiber


**Graded-index fiber**

- Predicted 3D wave-packets from analytical models


- Experiments


Hollow-core multimode nonlinear optics


Recent work on nonlinear optics in other multimode fibers


In GRIN fiber, modes have similar group velocities
Single-field model for GRIN fiber

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

- diffraction
- dispersion
- index profile
- Kerr
Single-field model for GRIN fiber

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

- Gross-Pitaevskii equation
Coupled mode analysis

“GMMNLSE”

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

modal wavenumber mismatch  modal velocity mismatch  group velocity dispersion

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

shock  Kerr  Raman


Fig. 1. Relation between the LP modes and the real waveguide modes $\text{HE}_{11x}$, $\text{HE}_{11y}$, $\text{TE}_{01}$, $\text{TM}_{01}$, $\text{HE}_{21a}$, and $\text{HE}_{21b}$ of the six-mode FMF.

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