Soliton Dynamics in Multi-Core Fibers: Supermode Transitions and Raman-Shift Suppression

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Multi-Core Fibers

- Coupling among the cores reduces the impact of optical nonlinearities and benefits optical communication systems [1-3].

- Notably, a multi-core fiber can outperform an equivalent bundle of single-mode fibers [3].

- Multi-core fibers still exhibit nonlinear effects that can be useful for applications such as pulse compression and pulse combining [4].

[1] S. Mumtaz, R.-J. Essiambre, and G. P. Agrawal, IEEE Photon. Technol. Lett. **24**, 1574–1576 (2012)
[2] J. Sakaguchi *et al*., J. Light. Technol. **31**(4), 554–562 (2013)
[3] R. Ryf, *et al*., Proc. OFC, (Optical Society of America, 2019), paper Th4B.3.
[4] A. M. Rubenchik *et al*. Opt. Lett. **40**(5), 721–724 (2015)

Our Objectives

- Study evolution of femtosecond pulses in a 7-core fiber.
- Launch the input pulse into the central core.
- Include fully the wavelength dependence of the linear coupling among all cores of the fiber.
- Vary core spacing to study the impact of weak, moderate, and strong coupling among all neighboring cores.
- Consider the Raman effect fully and include both intrapulse and inter-supermodal Raman scattering.
- Study how the linear mode coupling affects intrapulse and inter-supermodal Raman scattering.
- Look for the possibility of supermode transition.

Numerical Model

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DISPERSION LINEAR COUPLING

$$\frac{\partial \tilde{A}_p(z,\omega)}{\partial z} = i\beta(\omega)\tilde{A}_p(z,\omega) + i\sum_{l\neq p}\kappa_{pl}(\omega)\tilde{A}_l(z,\omega)$$

$$+ i\gamma(\omega)\mathscr{F}\left\{\left[R(t) * |A_p(z,t)|^2\right]A_p(z,t)\right\}(\omega)$$

NONLINEARITIES

$A_p(z,t)$ = amplitude in the p-th core of the fiber

$\kappa(\omega)$ = linear coupling matrix, $\gamma(\omega)$ = nonlinear parameter

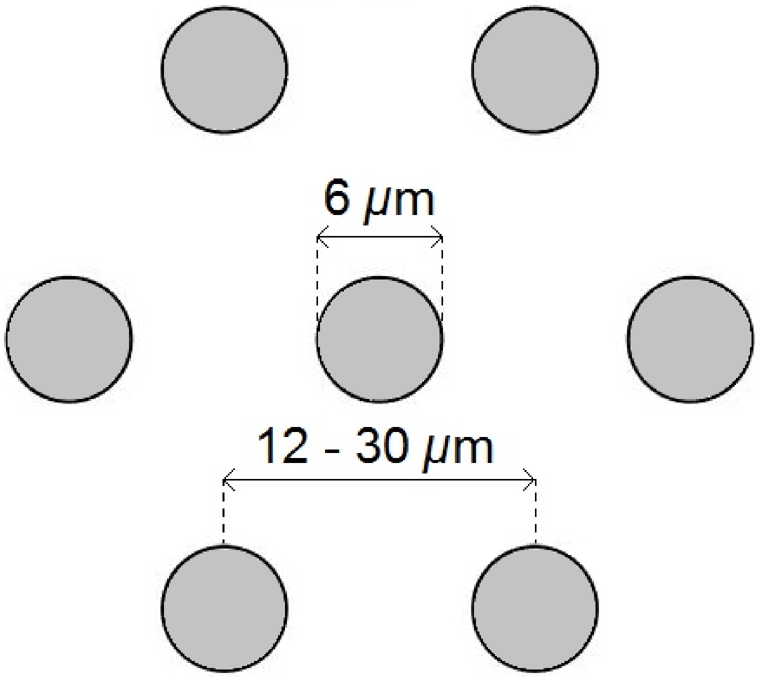
$\beta(\omega)$ = dispersive properties of the fiber

R(t) includes both the Kerr and Raman effects. [5].

[5] G. P. Agrawal, *Nonlinear Fiber Optics, 6th ed*. (Academic Press, 2019)

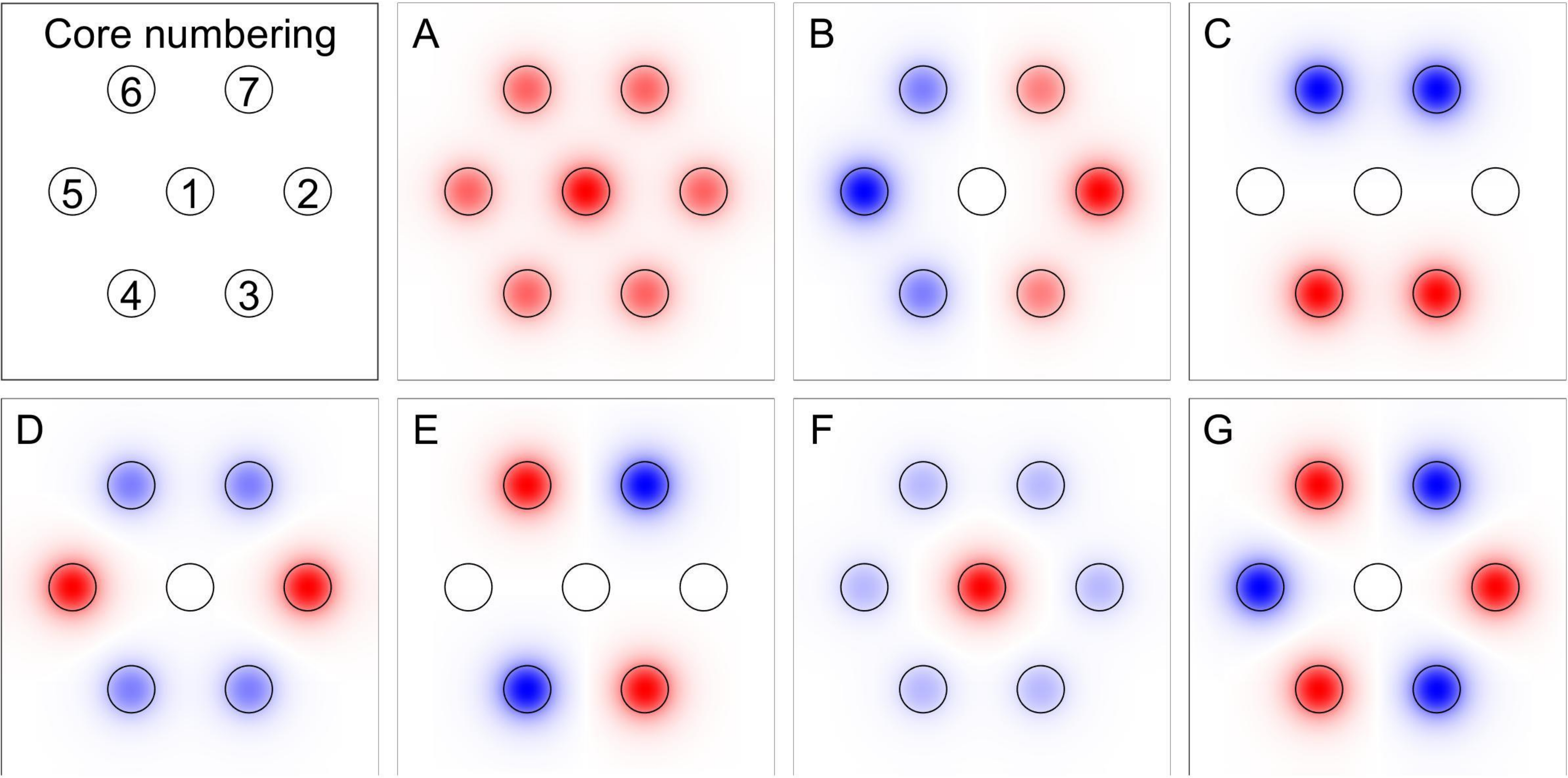
Seven-Core Fiber

- Seven-core fiber has 6 μm core diameter and its core separation is varied from 12 to 30 μm.
- Input pulse: T_{FWHM} = 100 fs, sech-shape, λ_0 = 1.55 μm
- $n_1(\lambda) = n_2(\lambda) + 0.01$
- Wavelength dependence of $n_2(\lambda)$ included through Sellmeier equation [6].
- Wavelength dependence of linear coupling included.



[6] I. H. Malitson, J. Opt. Soc. Am. **55** 1205–1209 (1965)

Supermodes of 7-Core Fiber

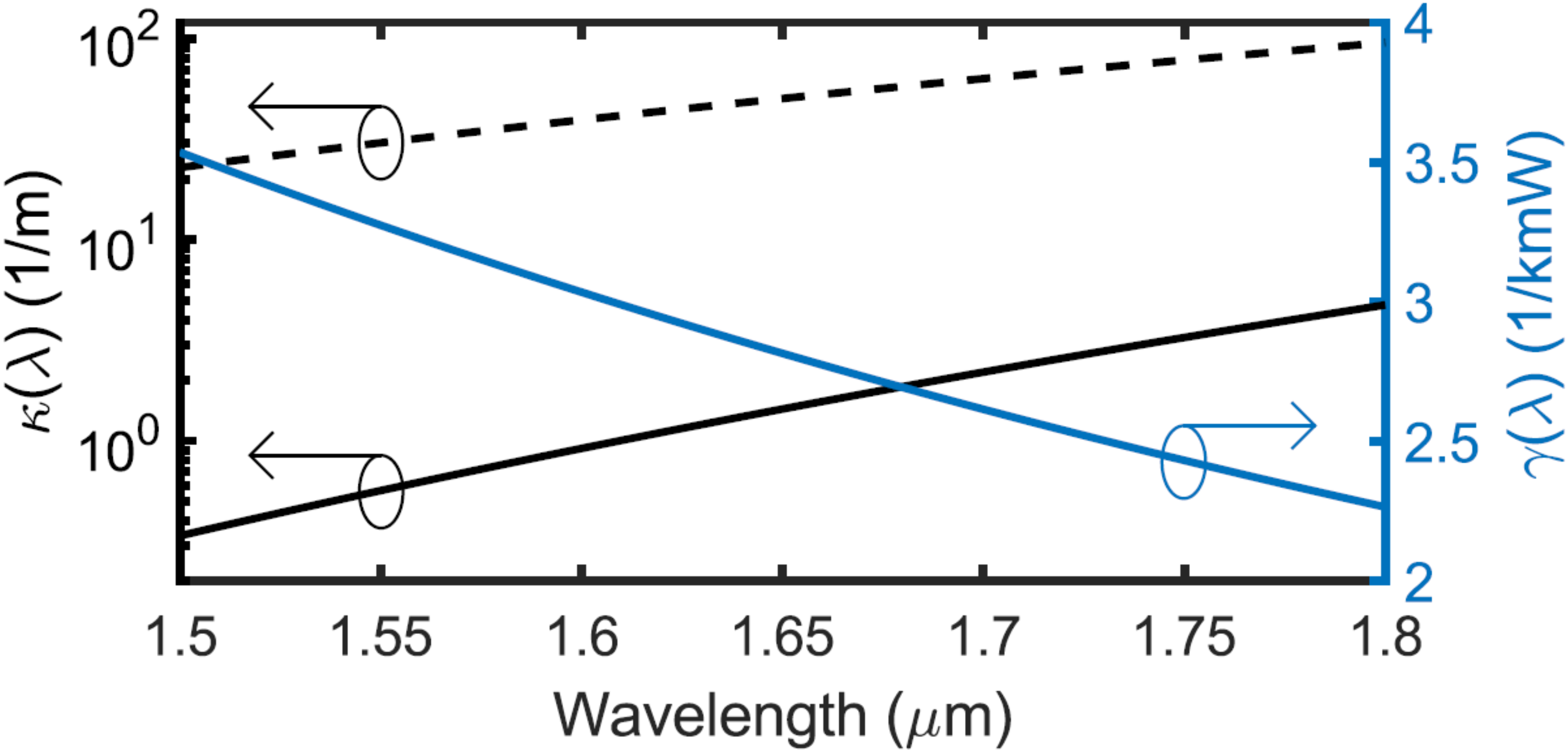


[7] A. Antikainen and G. P. Agrawal, J. Opt. Soc. Am. B, manuscript accepted 2. Sep. 2019

Supermodes of 7-Core Fiber

- Eigenvalues and supermodes were found analytically by diagonalizing a 7x7 matrix. Supermode pairs *B* and C and *D* and *E* are two-fold degenerate.
- Only supermodes *A* and *F* have energy in all cores with a six-fold symmetry. Other supermodes have energy in some cores but not others.
- Only *A* and *F* supermodes are excited when an input pulse is launched into the center core (31% of pulse energy in supermode *A* and 69% in supermode *F).*
- In the case of supermode *F,* the fields in outer cores are 180° out of phase with the central core. They are all in phase in the case of supermode *A.*

Weak and Moderate Coupling

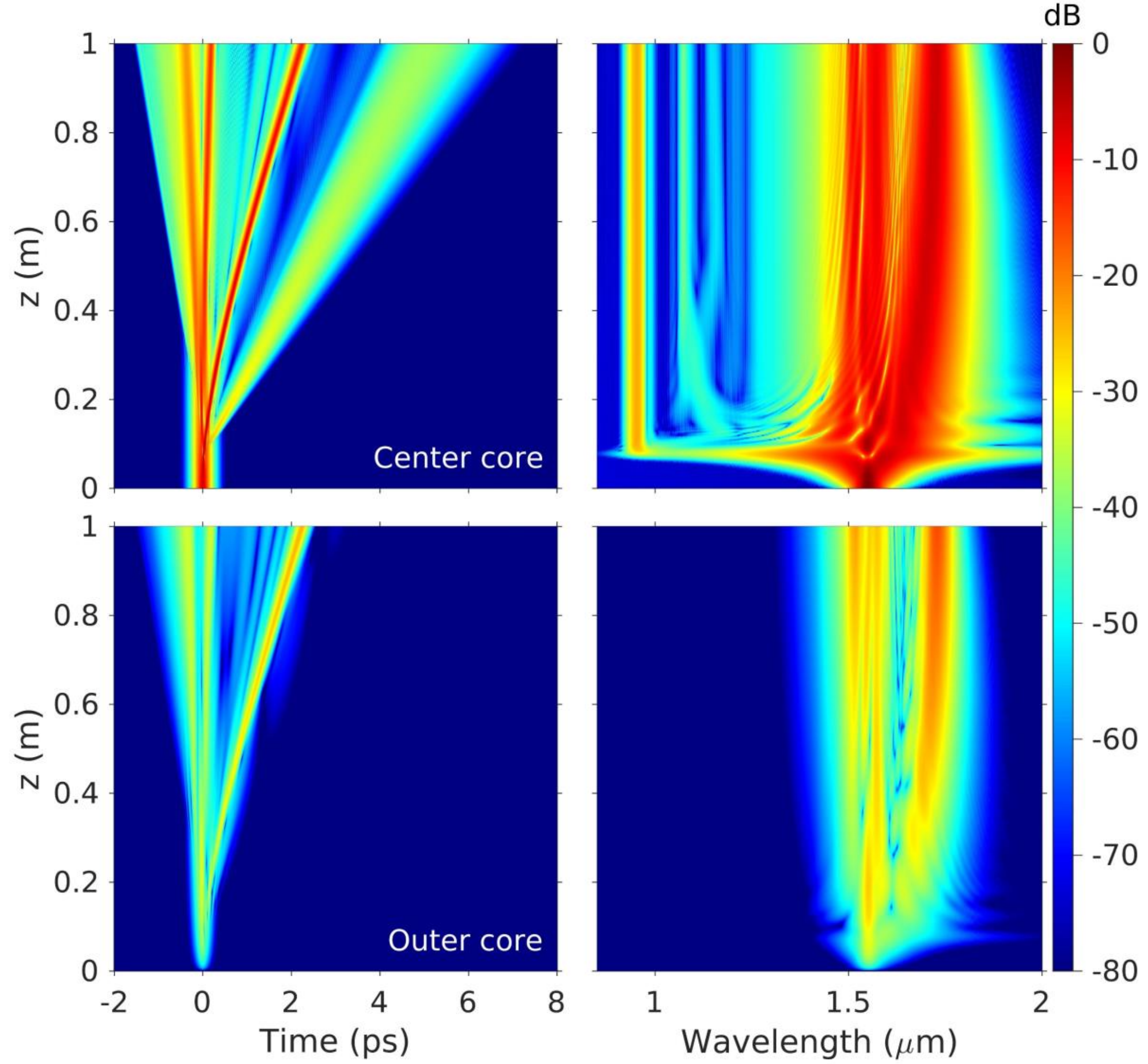


- Wavelength dependence of κ (black) and γ (blue)
- Solid line: weak coupling (25 μm core separation)
- Dashed line: strong coupling (16 μm core separation)

[8] A. Antikainen and G. P. Agrawal, Opt. Lett. **44**(17), pp. 4159–4162 (2019)

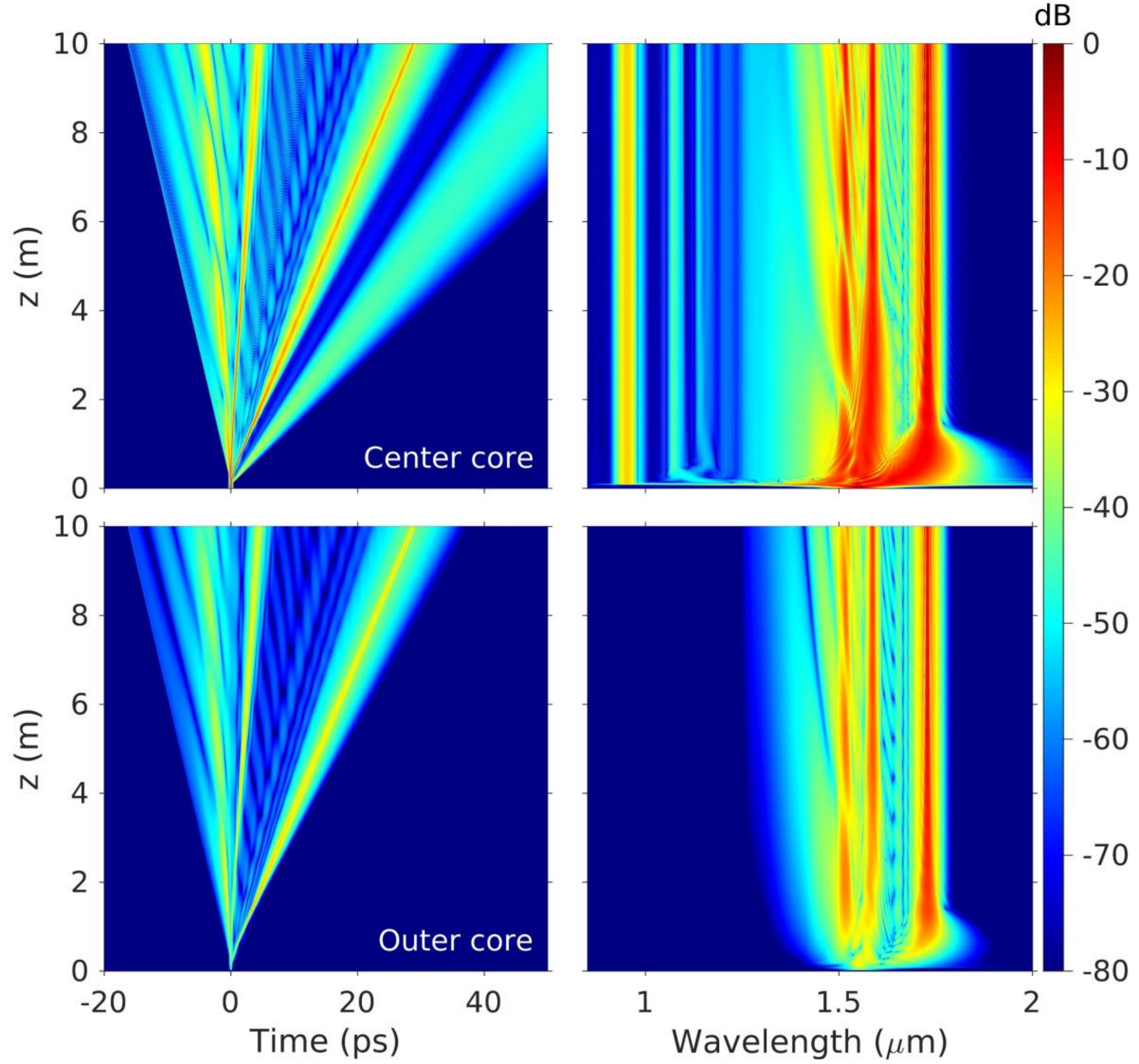
Weak coupling case

- 100-fs pulse with 15 kW peak power launched into the center core.
- Temporal and spectral evolution similar to that in a single-core fiber.
- Energy transfer is significant after 40 cm because of enhanced coupling at larger λ.



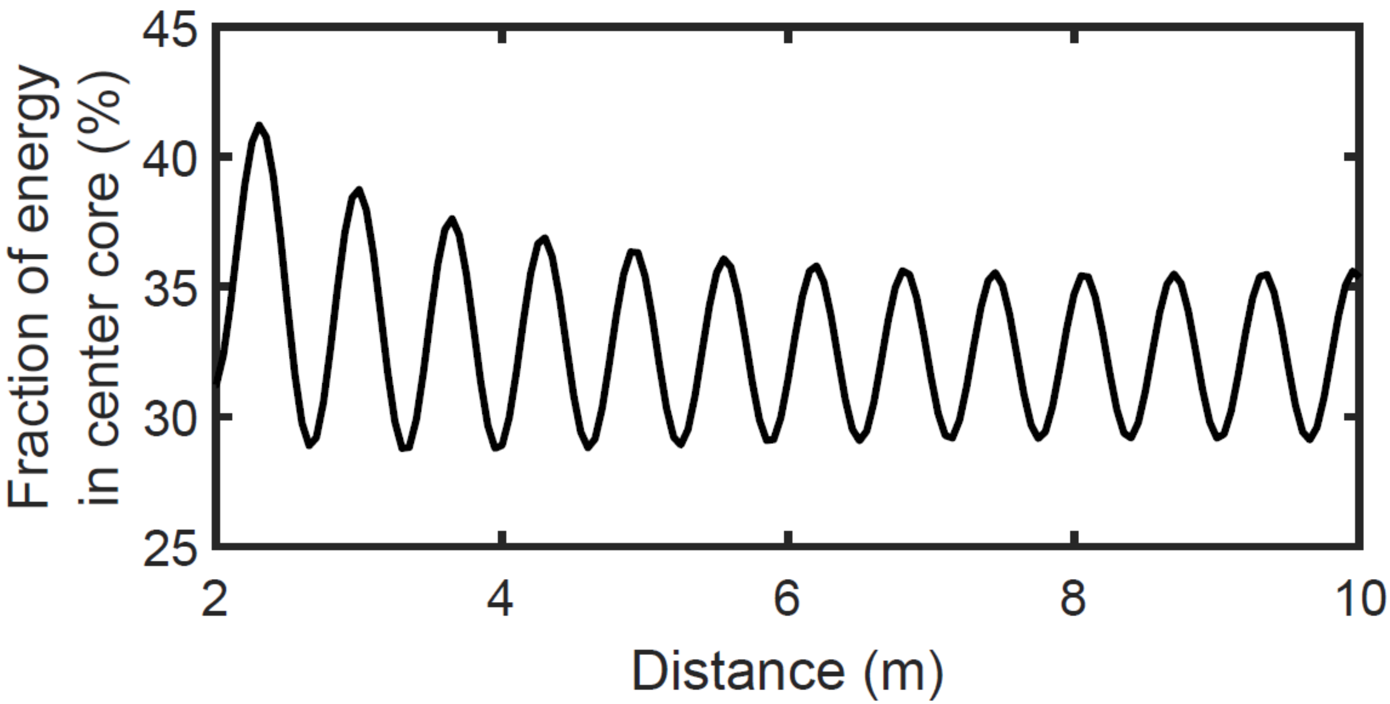
Weak coupling case

- Evolution over 10 m exhibits new features.
- More energy from central core is transferred to outer cores after 1 meter.
- In the central core:
  - P_0 decreases
  - T_0 increases
  - Raman shift is suppressed.



[7] A. Antikainen and G. P. Agrawal, J. Opt. Soc. Am. B, manuscript accepted 2. Sep. 2019

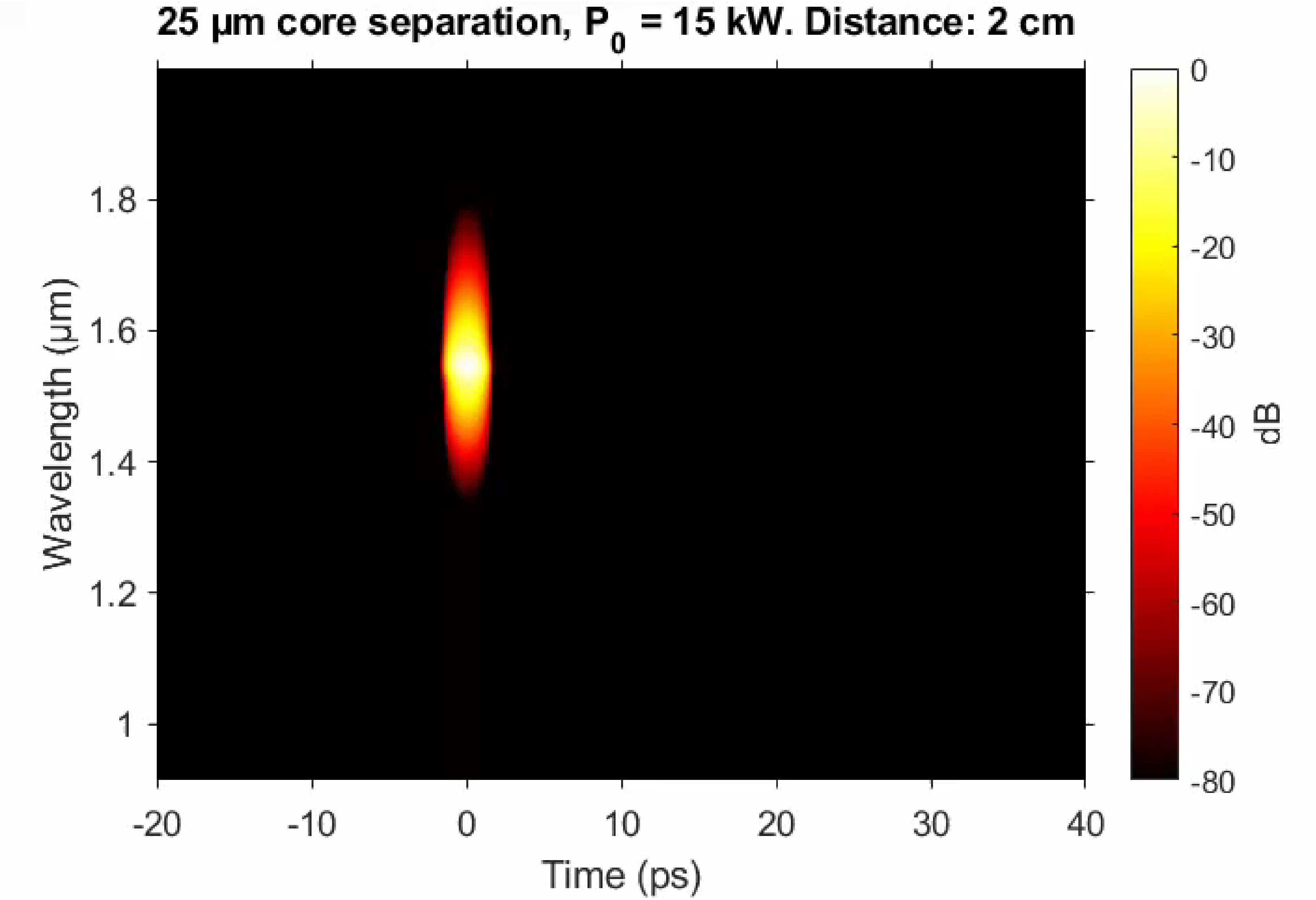
Multimode Solitons



- Fraction of energy in the center core after 2 m ~35%.
- Soliton-like evolution in multiple supermodes.
- Similar to multimode solitons in graded-index fibers [9].

[9] W. H. Renninger and F. W. Wise, Nat. Commun. **4**, 1719 (2013)

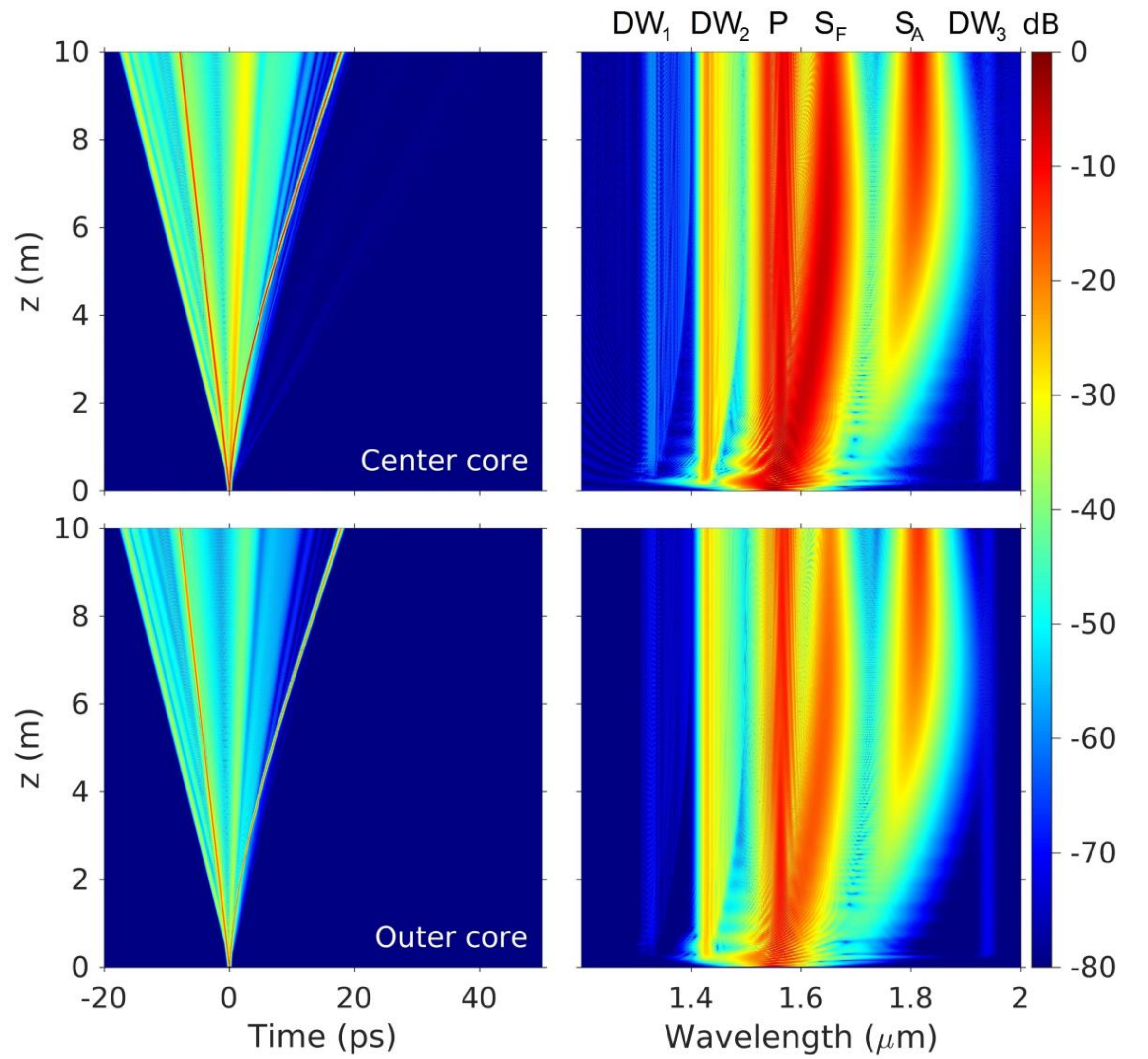
Weak coupling case



[7] A. Antikainen and G. P. Agrawal, J. Opt. Soc. Am. B, manuscript accepted 2. Sep. 2019

Moderate coupling

- Cores of the 7-core fiber are separated by 15.5 μm.
- 100-fs pulse with 15 kW peak power is launched into the central core.
- A new spectral peak appears after 2 meters.
- 13-THz jump indicates Stokes generation in a different supermode.



[7] A. Antikainen and G. P. Agrawal, J. Opt. Soc. Am. B, manuscript accepted 2. Sep. 2019

Supermode Transition

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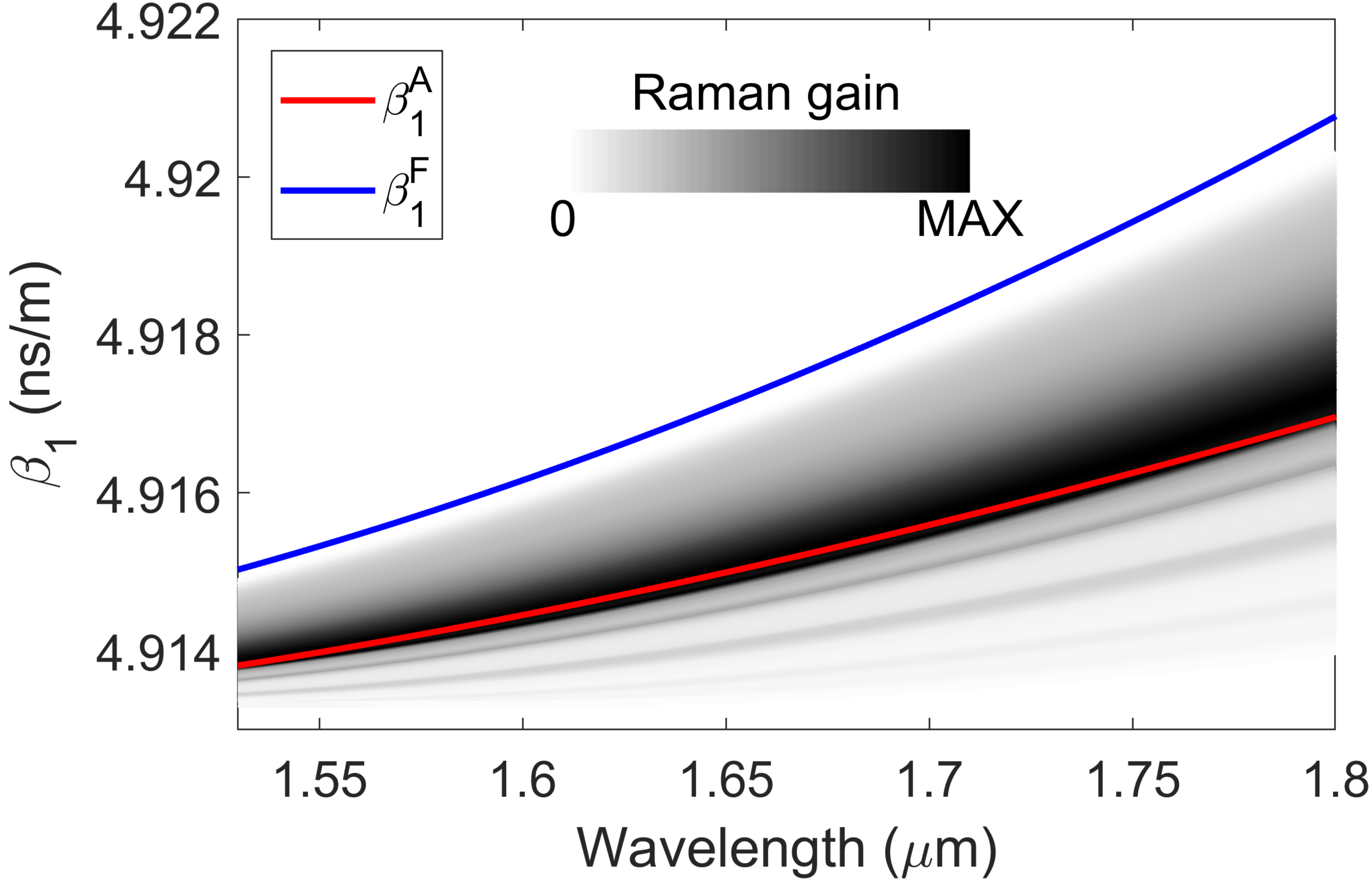
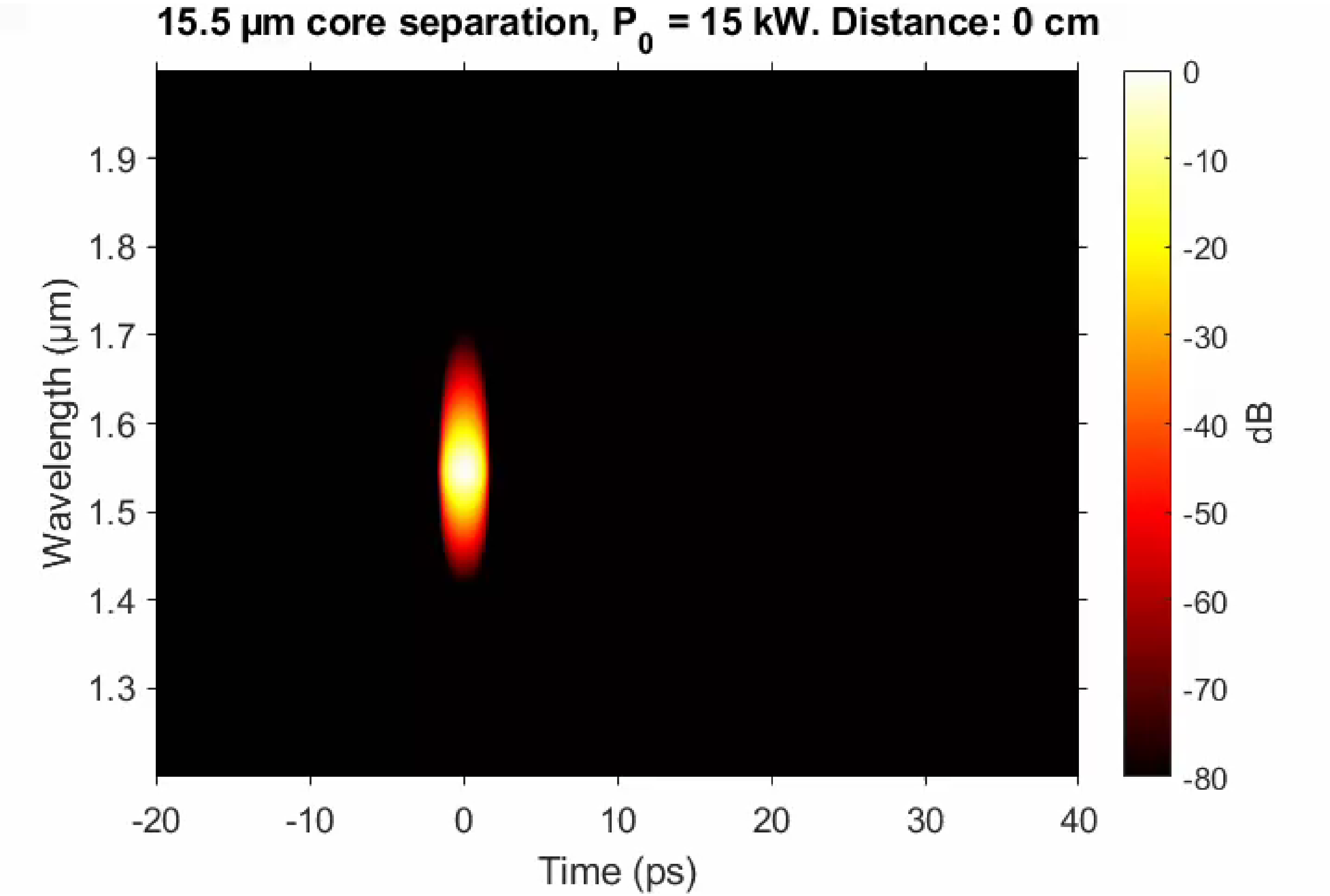
- Raman-induced red-shift occurs for a femtosecond soliton belonging to the supermode *F*.
- A new Stokes pulse appears in the supermode *A* through noise-seeded Raman scattering.
- Such a pulse is never generated in single-mode fibers because of a large group-velocity mismatch.
- Soliton self-mode conversion (SSMC) was recently observed in a step-index multimode fiber [10-11].
- We have discovered a multi-core analog of SSMC.
- Group velocities of *A* and *F* supermodes matched for a frequency separation near the Raman gain peak of silica (13.2 THz).

[10] L. Rishøj, B. Tai, P. Kristensen, and S. Ramachandran, Optica **6**(3), 304–308 (2019)
[11] A. Antikainen *et al.*, Phys. Rev. Lett. **122**, 023901 (2019)

Moderate coupling

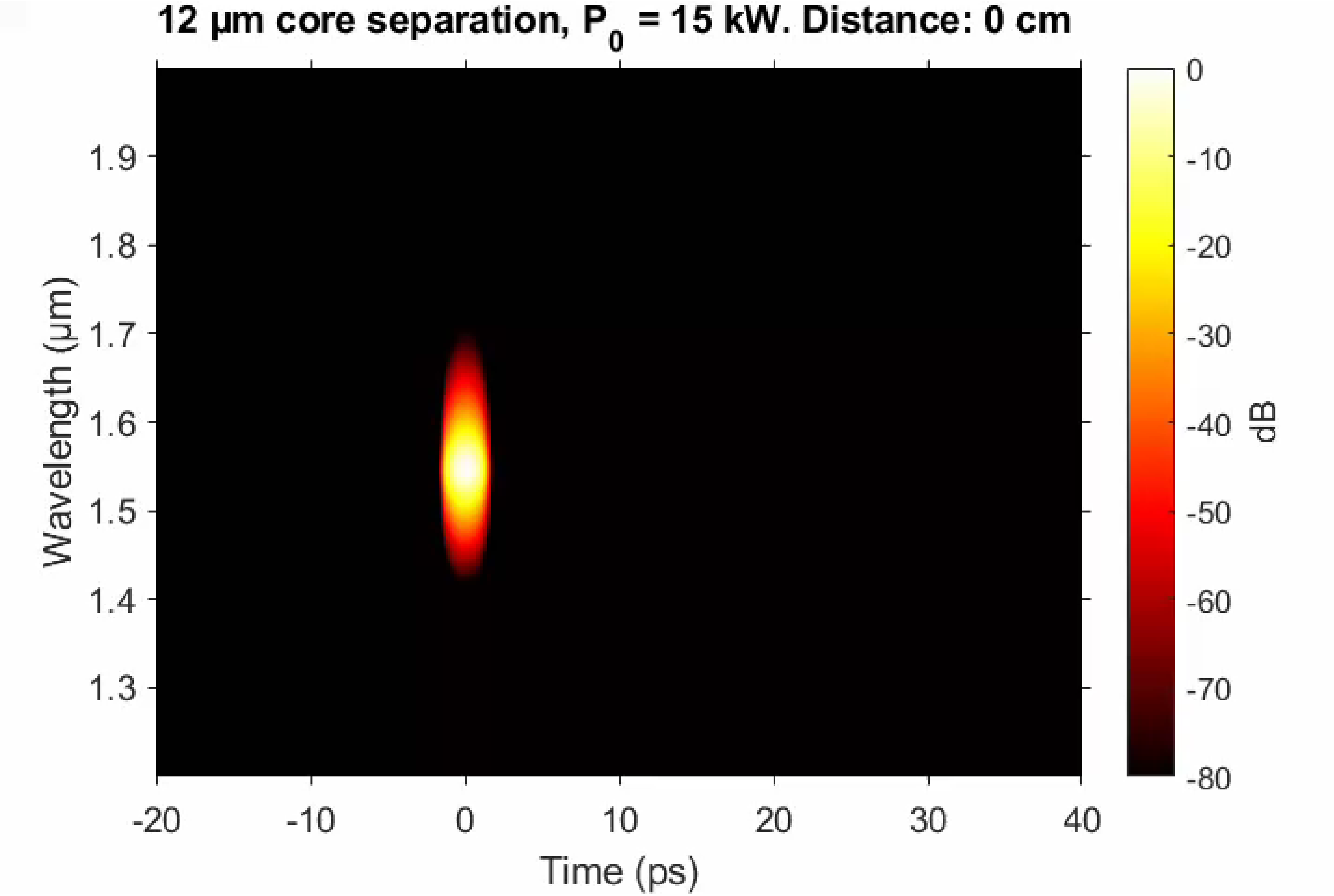


Moderate coupling



[7] A. Antikainen and G. P. Agrawal, J. Opt. Soc. Am. B, manuscript accepted 2. Sep. 2019

Strong coupling



[7] A. Antikainen and G. P. Agrawal, J. Opt. Soc. Am. B, manuscript accepted 2. Sep. 2019

Concluding Remarks

- Multicore fibers provide a new platform for studying a variety of nonlinear phenomena.
- Linear coupling among its cores depends on the core separation and plays a critical role in the nonlinear evolution of femtosecond pulses.
- It is important to include the wavelength dependence of this coupling in numerical modeling.
- We discussed suppression of the Raman-induced red shift and the formation of multi-supermode solitons.
- We also found a multi-core analog of soliton self-mode conversion occurring in step-index multi-mode fibers.
- A discrete jump of 13.2 THz occurred as the soliton switches from one supermode to another.

Thank you

Further Reading

A. Antikainen and G. P. Agrawal, ”Soliton Supermode Transitions and Total Red Shift Supression in Multi-Core Fibers,” Opt. Lett. **44**(17), pp. 4159–4162 (2019)

A. Antikainen and G. P. Agrawal, ”Supercontinuum Generation in Seven-Core Fibers,” J. Opt. Soc. Am. B, early posting (2019)