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Intermodal Raman Scattering of Ultrashort Pulses in Multimode Fibers

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Introduction

Raman scattering is an inelastic scattering process where the scattered photon has a different frequency than the incident photon [1]

Energy is transferred to (Stokes) or from (Anti-Stokes) the medium in the form of lattice vibrations (phonons)

Manifests as a delayed third-order optical nonlinearity:

$$P(t) = \ldots + E(t) \int_0^\infty h_R(t')|E(t-t')|^2 dt'$$

[1] G. P. Agrawal, *Nonlinear Fiber Optics, 5th ed.* (Academic Press, 2012)

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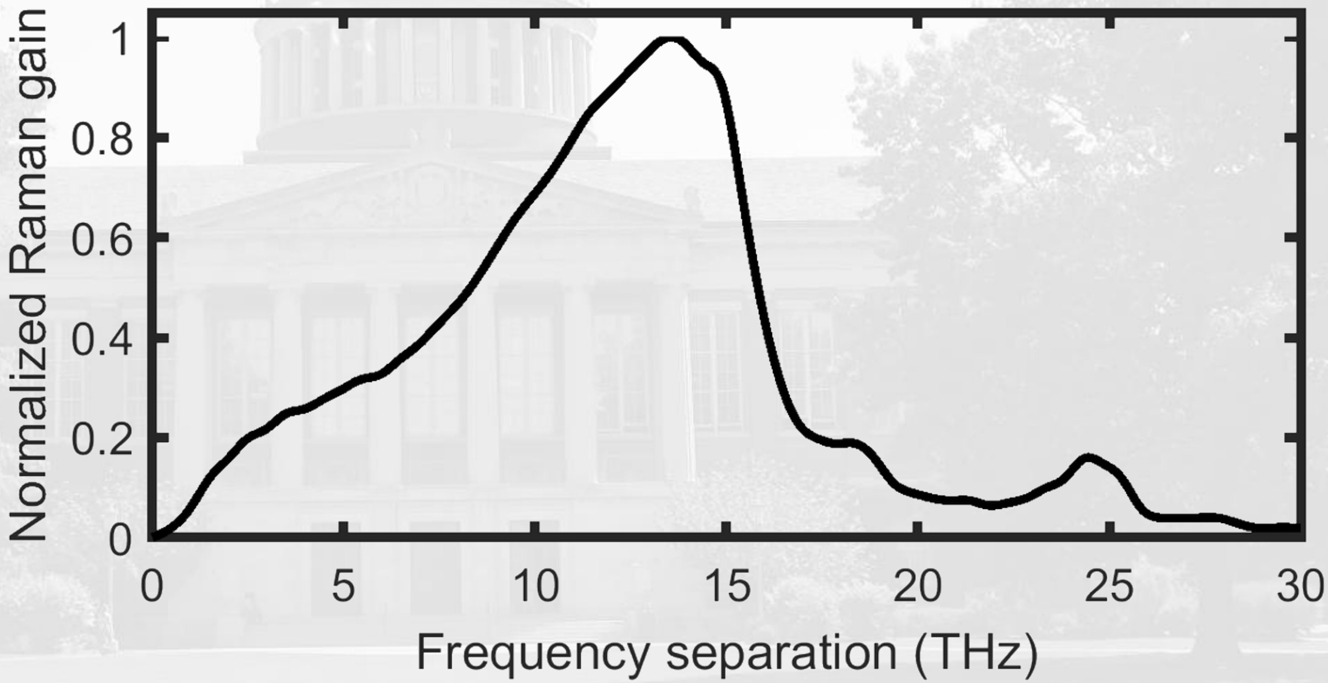
Introduction

The nonlinear response function *h(t)* depends on the material and determines the frequency of the scattered photons

Fused silica:



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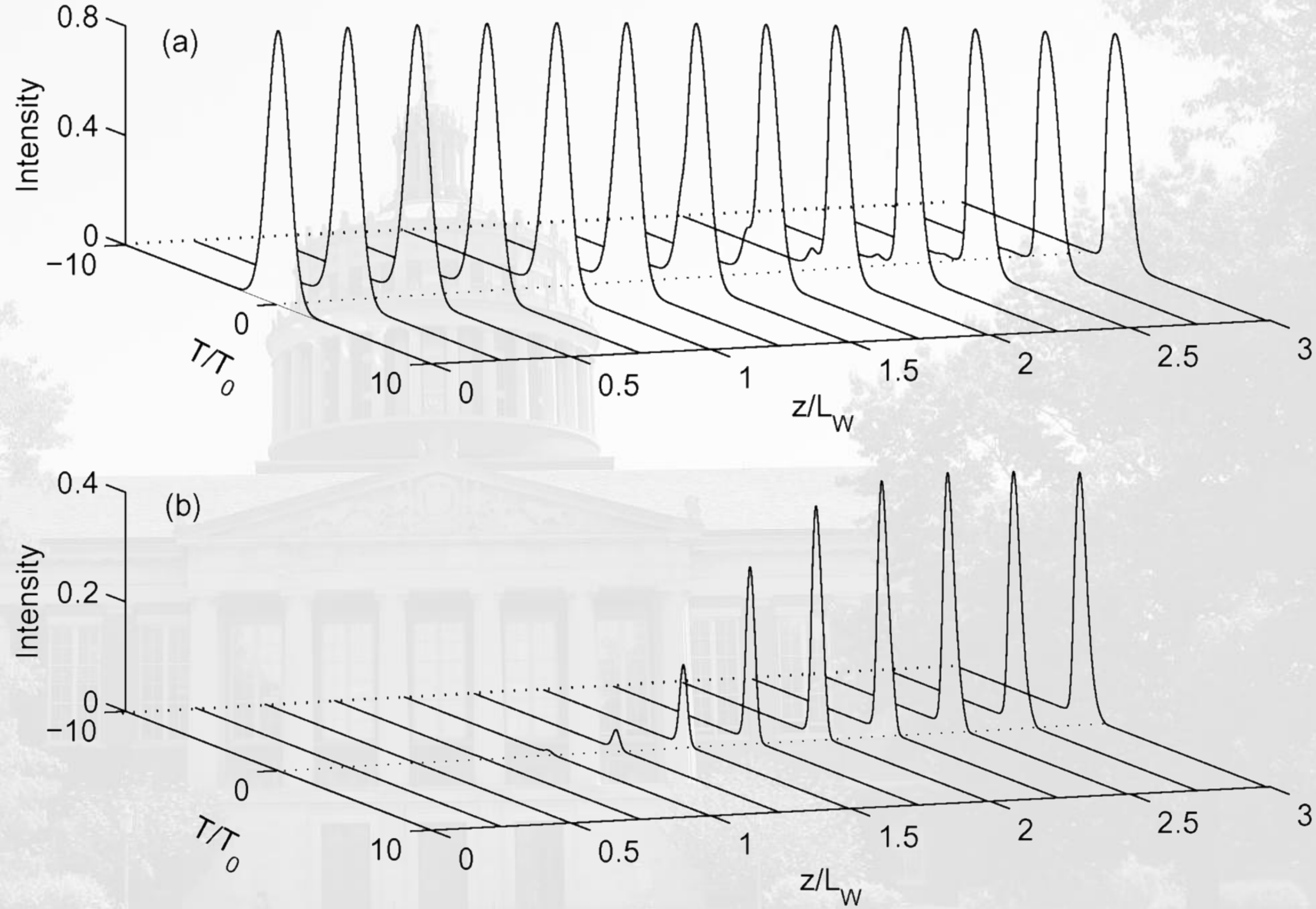
Raman effects in single-mode fibers

Generation of a Stokes pulse [1]



[1] G. P. Agrawal, *Nonlinear Fiber Optics, 5th ed.* (Academic Press, 2012)

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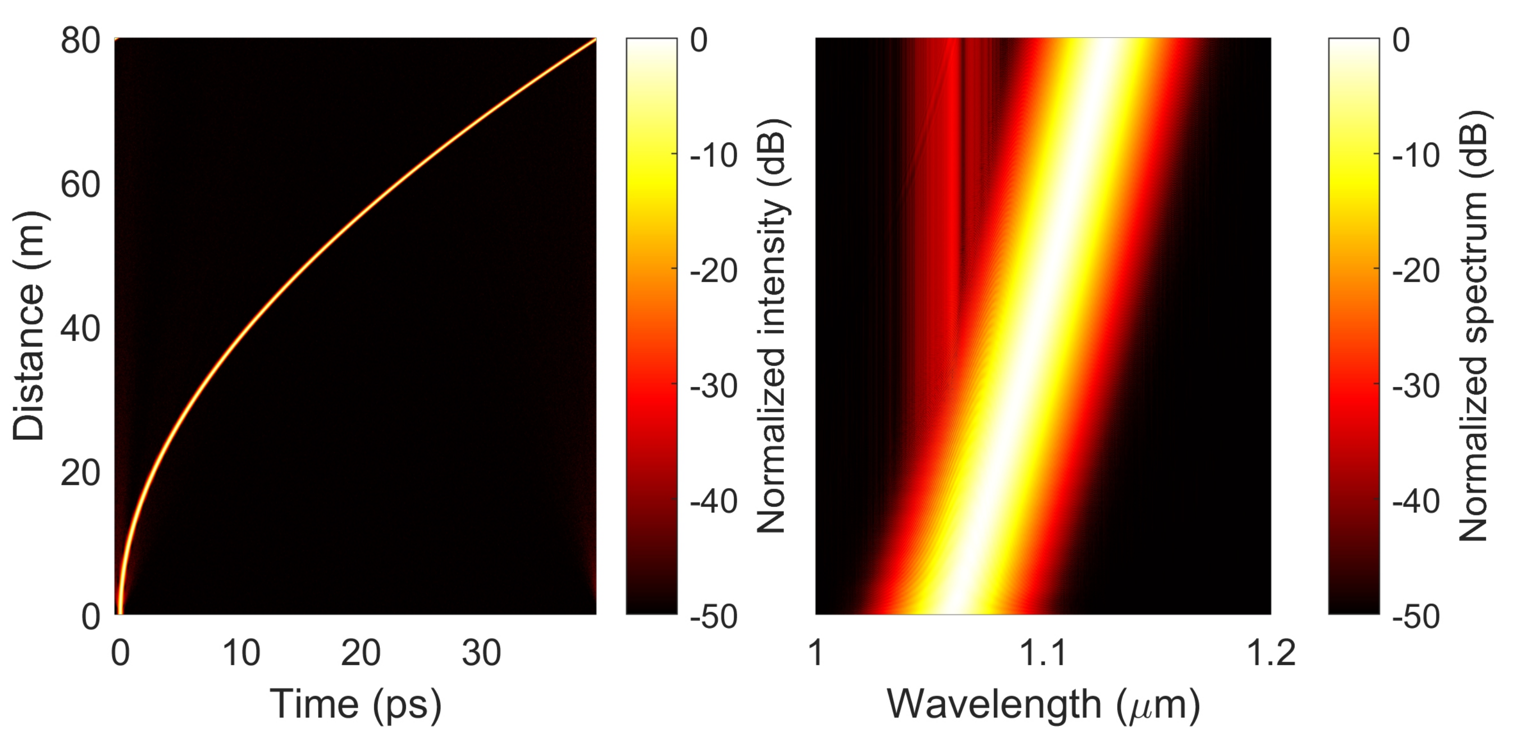
Raman effects in single-mode fibers

Soliton self-frequency shift [2]



[2] F. M. Mitschke and L. F. Mollenauer, Opt. Lett **11**(10) pp. 659-661 (1986)

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Raman effects in single-mode fibers

Stokes pulse generation suffers from differences in group velocities between the pump pulse and the Stokes pulse

Walkoff: ~ 10 ps^2/km * 13.2 THz = 132 ps/m

For short pulses the Stokes pulse essentially becomes part of the original pulse and the result is seen as a red shift of the pulse spectrum

The red side of a short pulse acts as a seed: Stimulated Raman scattering

Nonlinearities in multimode fibers

Each mode can have the same effects as the fundamental mode of a single-mode fiber (self-phase modulation, four-wave mixing, modulation instability, solitons, ...)

In addition: Intermodal four-wave mixing [3] and soliton interactions [4]

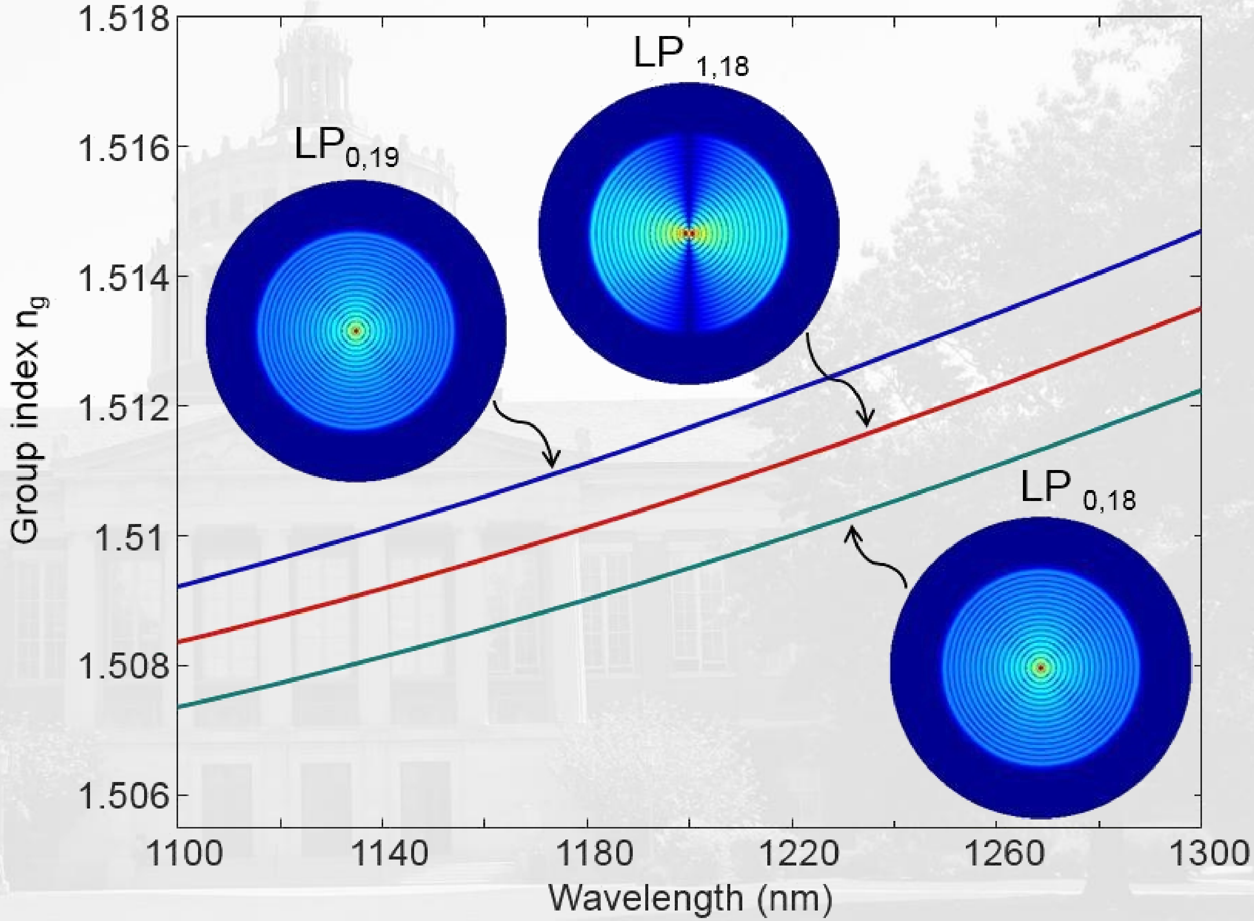
Intermodal nonlinear effects are generally weaker due to smaller mode overlap [5]:

$$f_{lmnp} \propto \int F_l F_m^* F_n F_p^* \, dA$$

[3] J. Demas, P. Steinvurzel, B. Tai, L. Rishøj, Y. Chen, and S. Ramachandran , Optica **2**(1) pp. 14-17 (2015)
[4] L. Rishøj, B. Tai, P. Kristensen, and S. Ramachandran, paper Sth3K.2 in CLEO 2017
[5] F. Poletti and P. Horak, JOSA B **25**(10), pp. 1645-1654 (2008)

Group velocity matching between modes

Different spatial modes have different group velocities
→ Two different wavelengths can propagate at the same speed if they are on different modes



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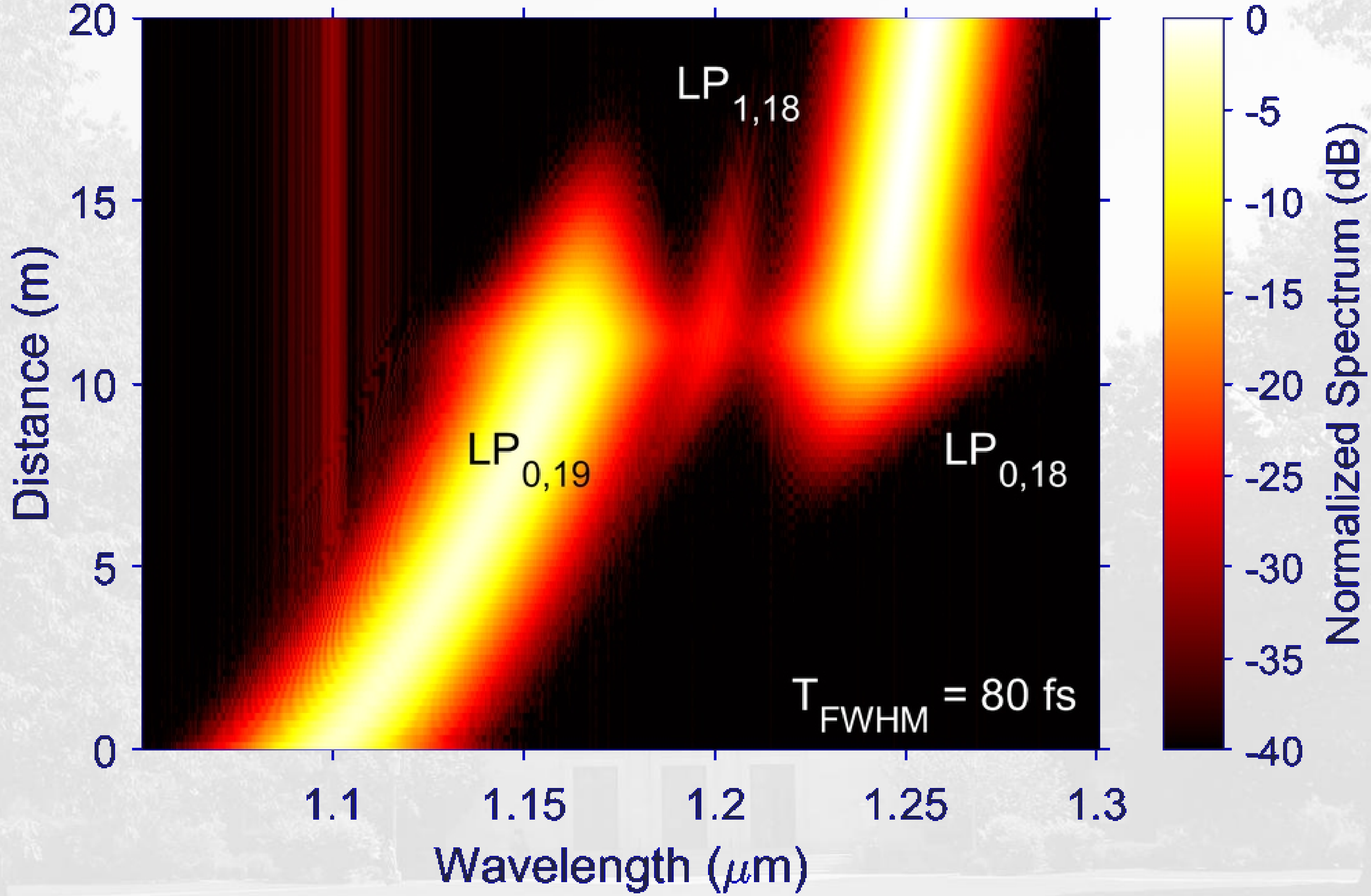
Intermodal Raman scattering



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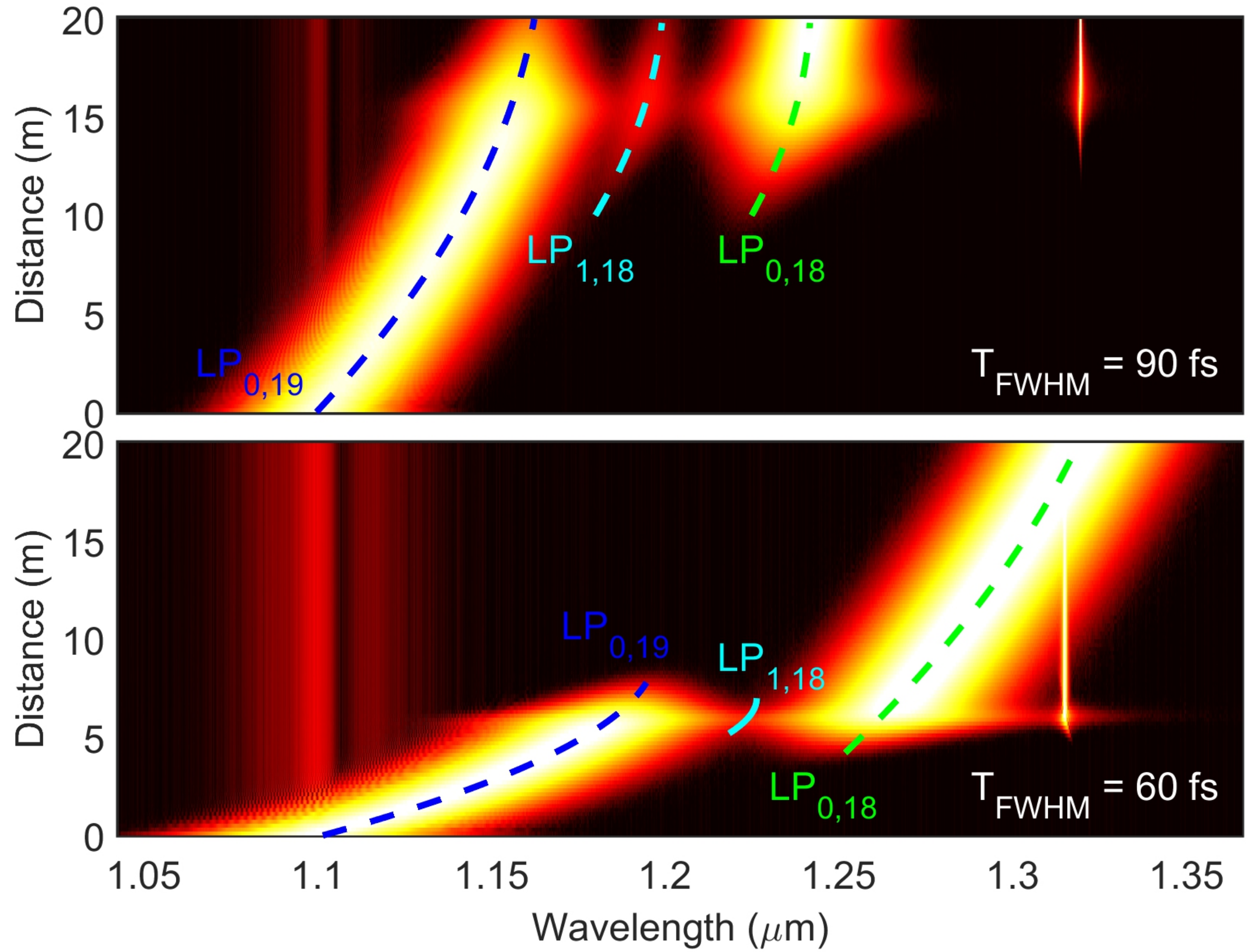
Intermodal Raman scattering



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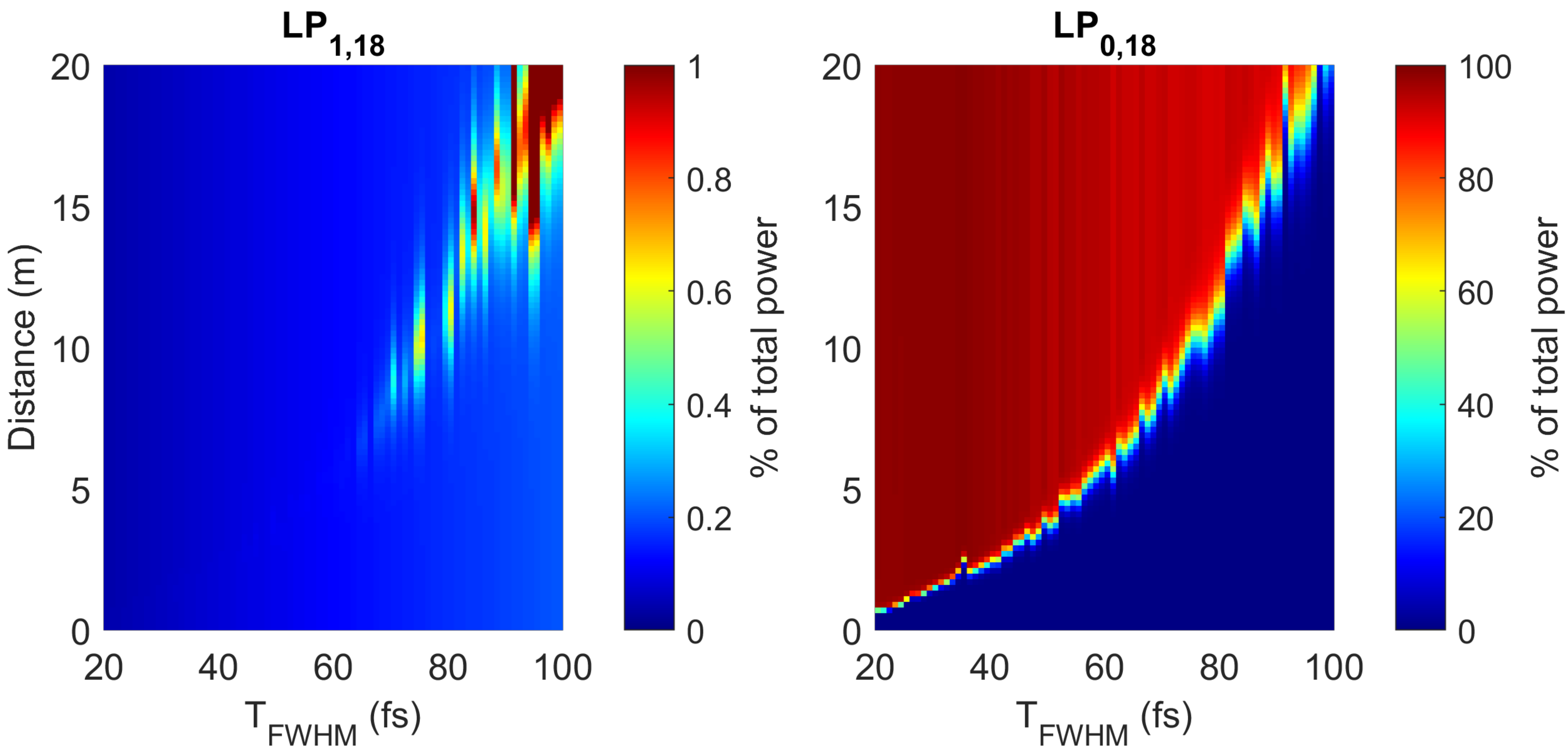
Intermodal Raman scattering



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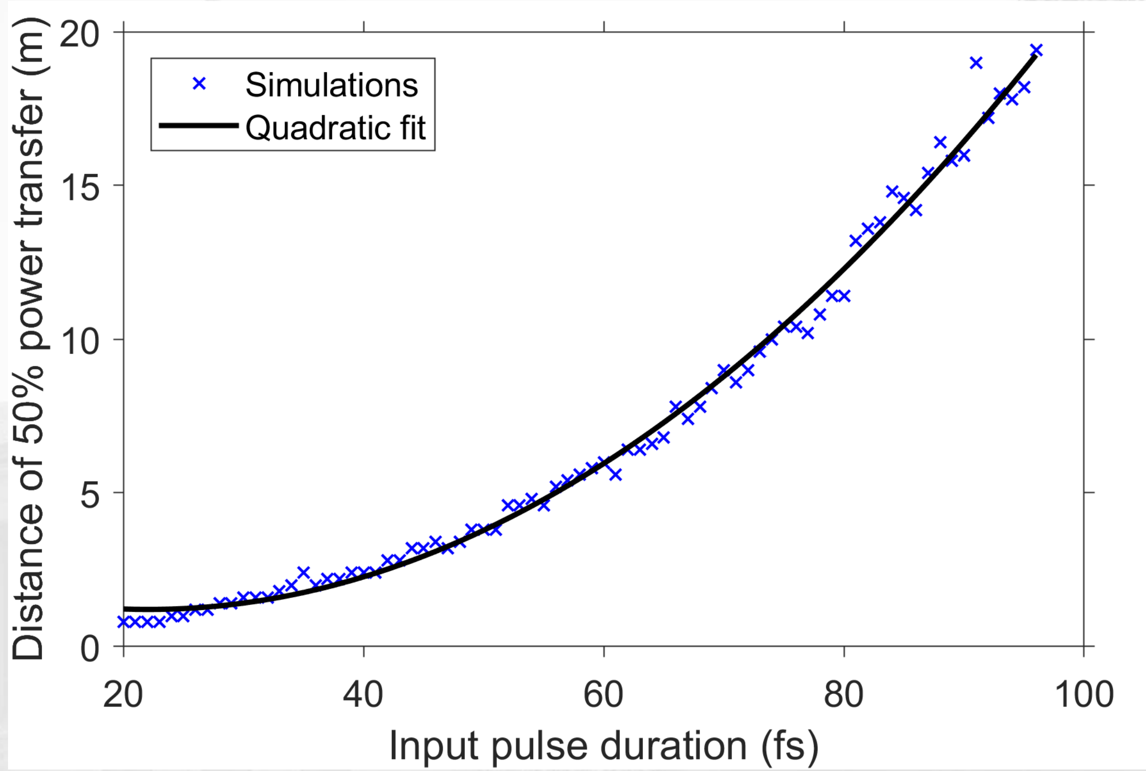
Intermodal Raman scattering

Power transfer from LP(0,19) to LP(0,18) happens over a short distance once it starts

Power transfer starting distance depends roughly quadratically On input pulse duration



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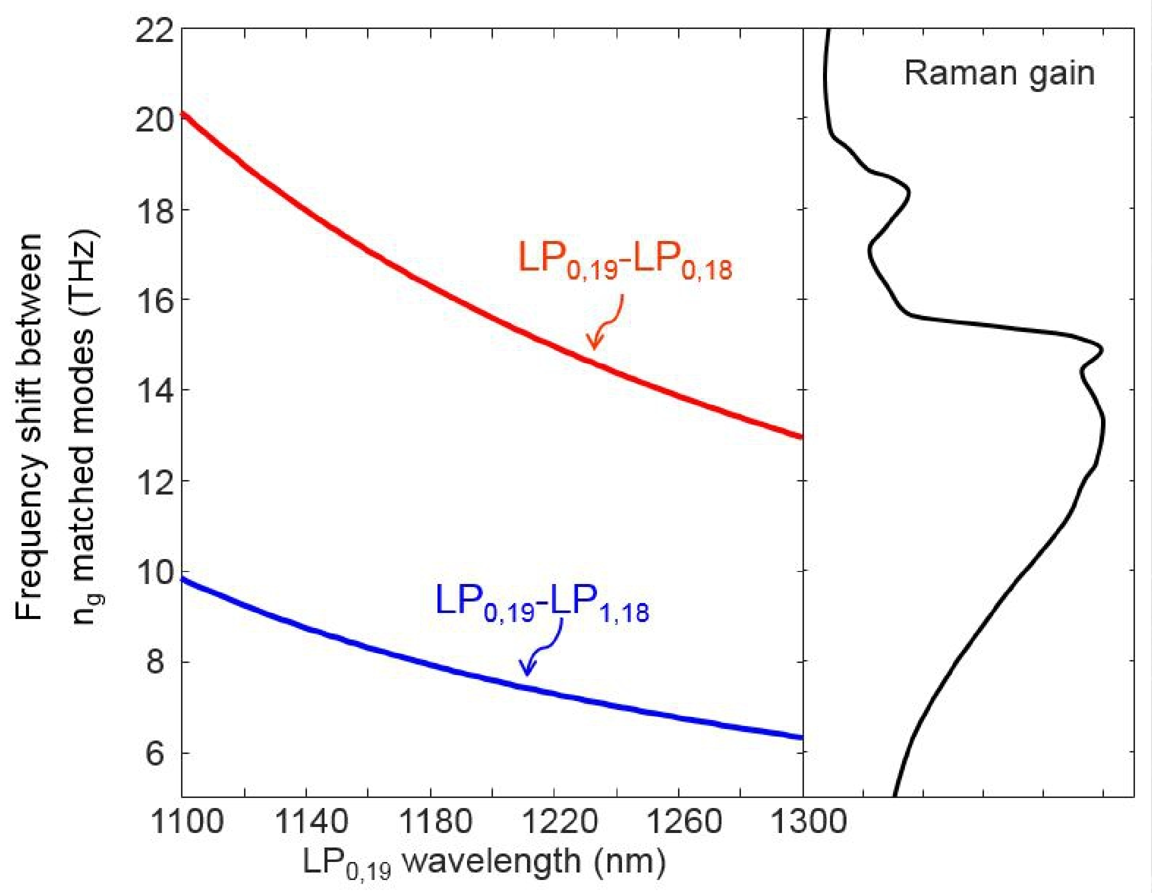
Group velocity matching and power transfer

No appreciable power builds up on LP(1,18)

Group velocity matched for small frequency separation

LP(1,18) is anti-symmetric
→ Nonlinear overlap factors are small or identically zero



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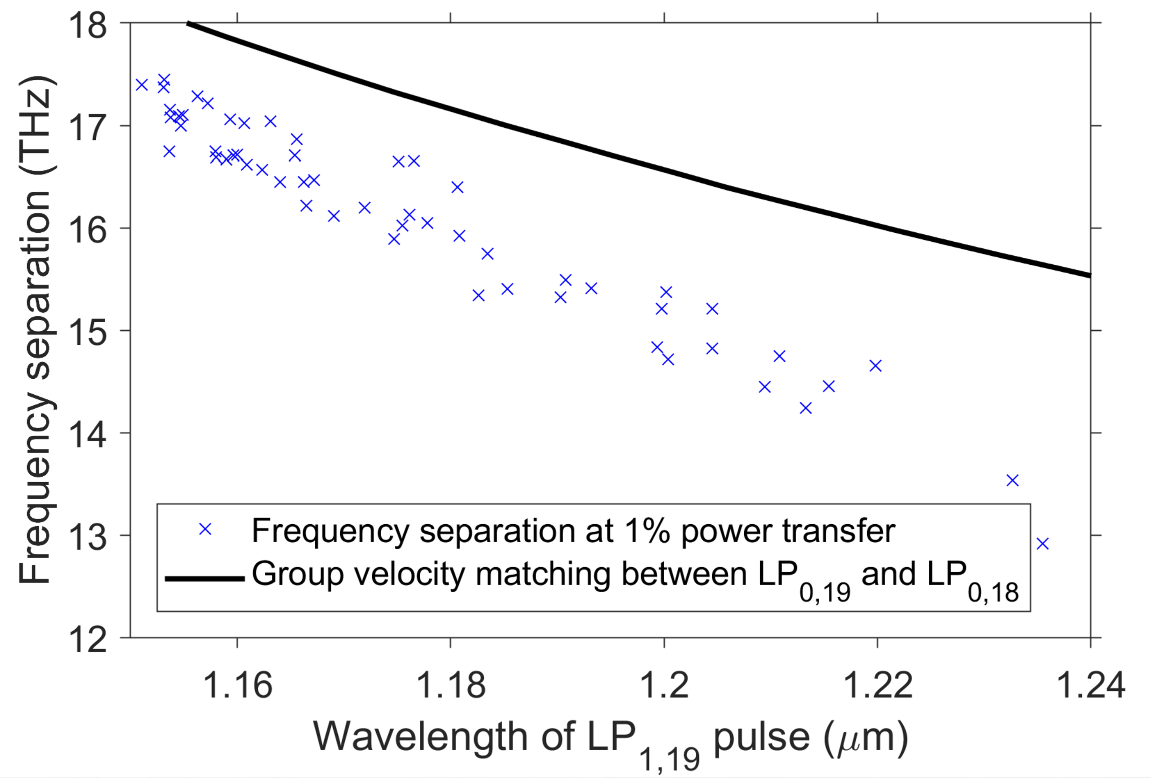
Group velocity matching and power transfer

Power transfer happens when the initial pulse has red shifted to satisfy group velocity matching for a frequency separation near the Raman gain peak

Spectral FWHM > 3 THz



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Conclusions

Intermodal Raman scattering transfers close to 100 % of the total power to a lower-order spatial mode

Power transfer between two modes requires group velocity matching and a non-negligible nonlinear overlap integral

The shorter the pulse, the shorter the distance during which power is transferred

A strong dispersive wave can be generated at the pump mode upon intermodal power transfer, further study needed

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