New model for fiberoptic Raman gain spectrum and response function

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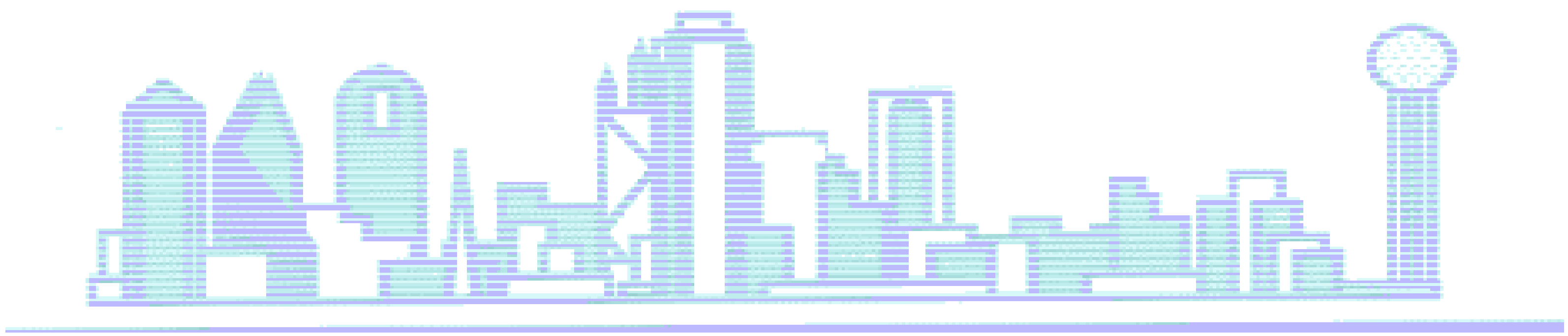

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BACKGROUND

- The FPWE for the Stokes or signal field $\mathcal{E}_S(z,t)$ in the SVEA:

$$\left(\frac{\partial}{\partial z}+\beta_{,1}\frac{\partial}{\partial t}+i\frac{1}{2}\beta_{,2}\frac{\partial^2}{\partial t^2}-\frac{1}{6}\beta_{,3}\frac{\partial^3}{\partial t^3}\right)\mathcal{E}_S(z,t)=-\frac{\alpha}{2}\mathcal{E}_S(z,t)+\frac{2\pi i\omega_0^2}{\beta_0 c^2}\mathcal{P}_S(z,t)$$

  ▷ where

$$\beta_{,j}=\left.\frac{d^j\beta}{d\omega^j}\right|_{\omega=\omega_0}$$

  ▷ Nonlinear polarization

$$\mathcal{P}_S=\mathcal{P}_{S,i}+\mathcal{P}_{S,R}$$

  ∘ Instantaneous (electronic) term:

$$\mathcal{P}_{S,i}\propto(1-f_R)\mathcal{E}_S\left[|\mathcal{E}_S|^2+2|\mathcal{E}_L|^2\right]$$

  where f_R is the Raman fraction

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TIME-DELAYED POLARIZATION

- Time-delayed (vibrational) term:

$$\mathcal{P}_{S,R}(t) \propto i f_R \mathcal{E}_S(z,t) \int_{-\infty}^{\infty} h(t-t''', 0) e^{-i(\omega_L-\omega_S)(t-t''')} \mathcal{E}_L^*(z,t''') \mathcal{E}_S(z,t''')\, dt'''$$

where $\mathcal{E}_L$ is the laser or pump field envelope

  - ▷ Convolution of the Raman response function h with the force that drives the vibrational oscillator
  - ▷ Provides for non-instantaneous (transient) buildup of Raman gain
  - ▷ Can compute integral in time domain (signal space)
  - ▷ Can also compute integral in transform space as product of transfer function and convolution of $\mathcal{E}_L^*$ and $\mathcal{E}_S$

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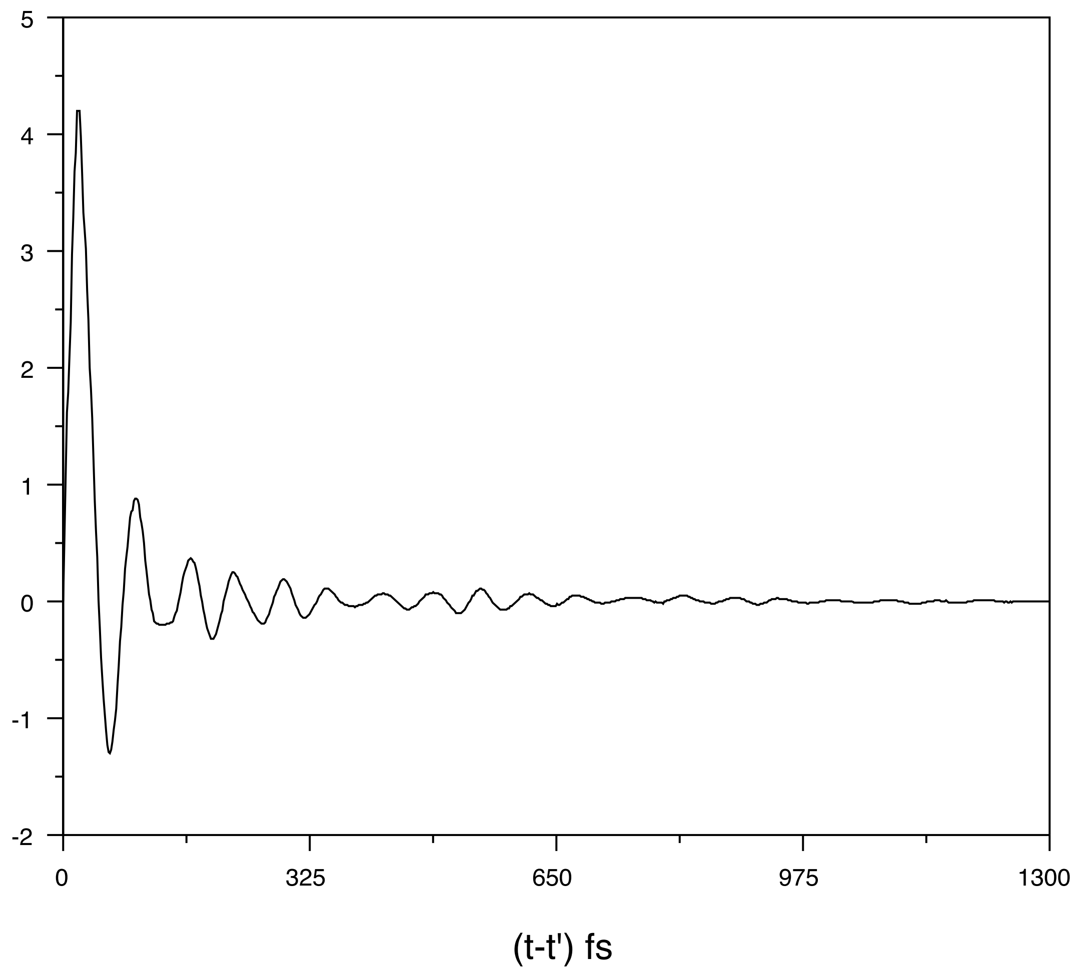
EXPERIMENTAL RAMAN RESPONSE FUNCTION



Scanned and digitized from Stolen, et al, "Raman response function of silica-core fibers", JOSA B **6**, 1159–1166 (1989)

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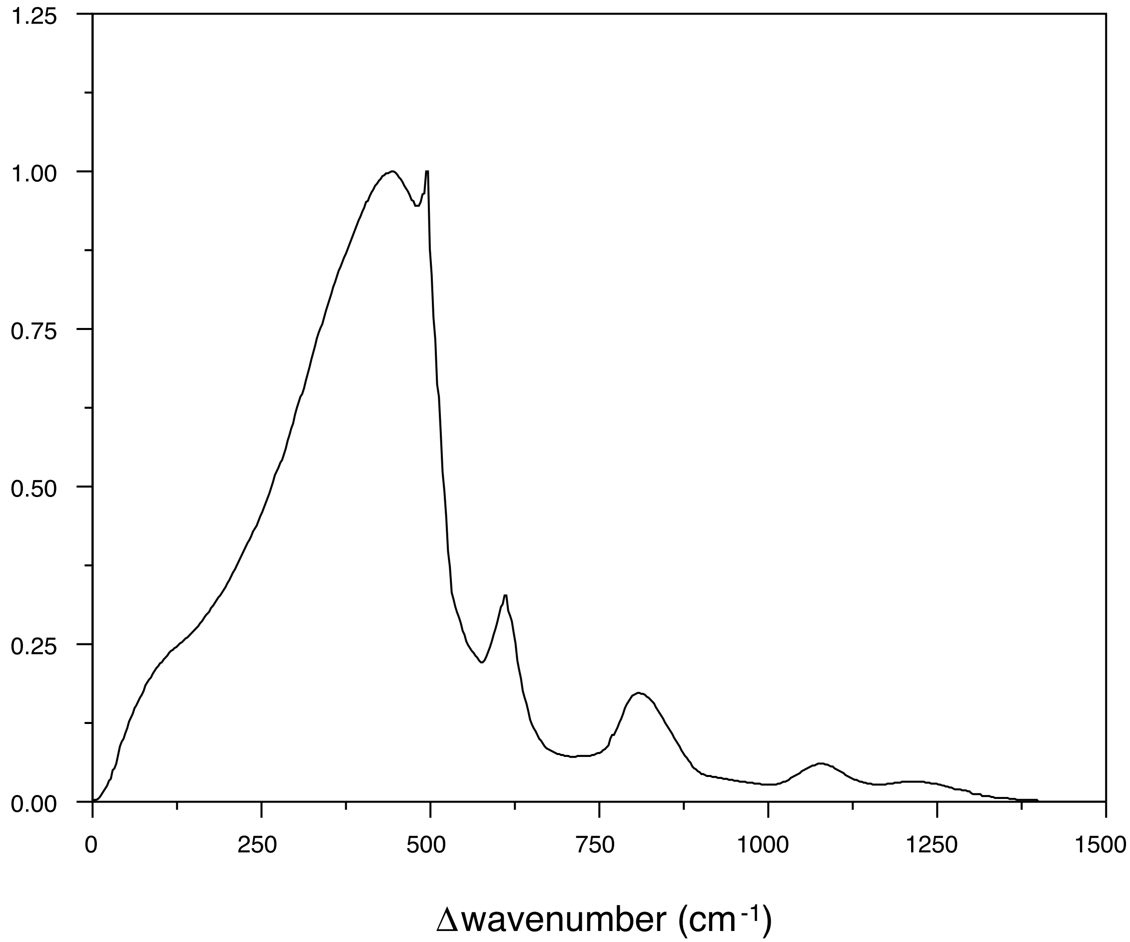
EXPERIMENTAL RAMAN GAIN SPECTRUM



Scanned and digitized from Stolen, et al, "Raman response function of silica-core fibers", JOSA B **6**, 1159–1166 (1989)

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RAMAN RESPONSE FUNCTION (1)

- Blow and Wood ("Theoretical description of transient stimulated Raman scattering in optical fibers", JQE 25, 2665–2673 (1989)) used a simple harmonic oscillator approach
  - ▷ Single damped oscillator

$$h_R(t) \propto e^{-t/\tau_2} \sin(t/\tau_1)$$

    where
    - ○ $\tau_1 = 1/\omega_v = 12.2\,\mathrm{fs}$
    - ○ $\tau_2 = 1/\gamma = 32\,\mathrm{fs}$

- Raman gain spectrum can be obtained from the Raman response function via

$$g_R(\Delta\omega) = \frac{\omega_0}{cn_0} f_R \chi^{(3)} \operatorname{Im}\left[\tilde{h}_R(\Delta\omega)\right]$$

  - ▷ yielding a Lorentzian

$$g_R(\Delta\omega) \propto \frac{2\omega\gamma}{(\omega^2 - \omega_v^2)^2 + (2\omega\gamma)^2}$$

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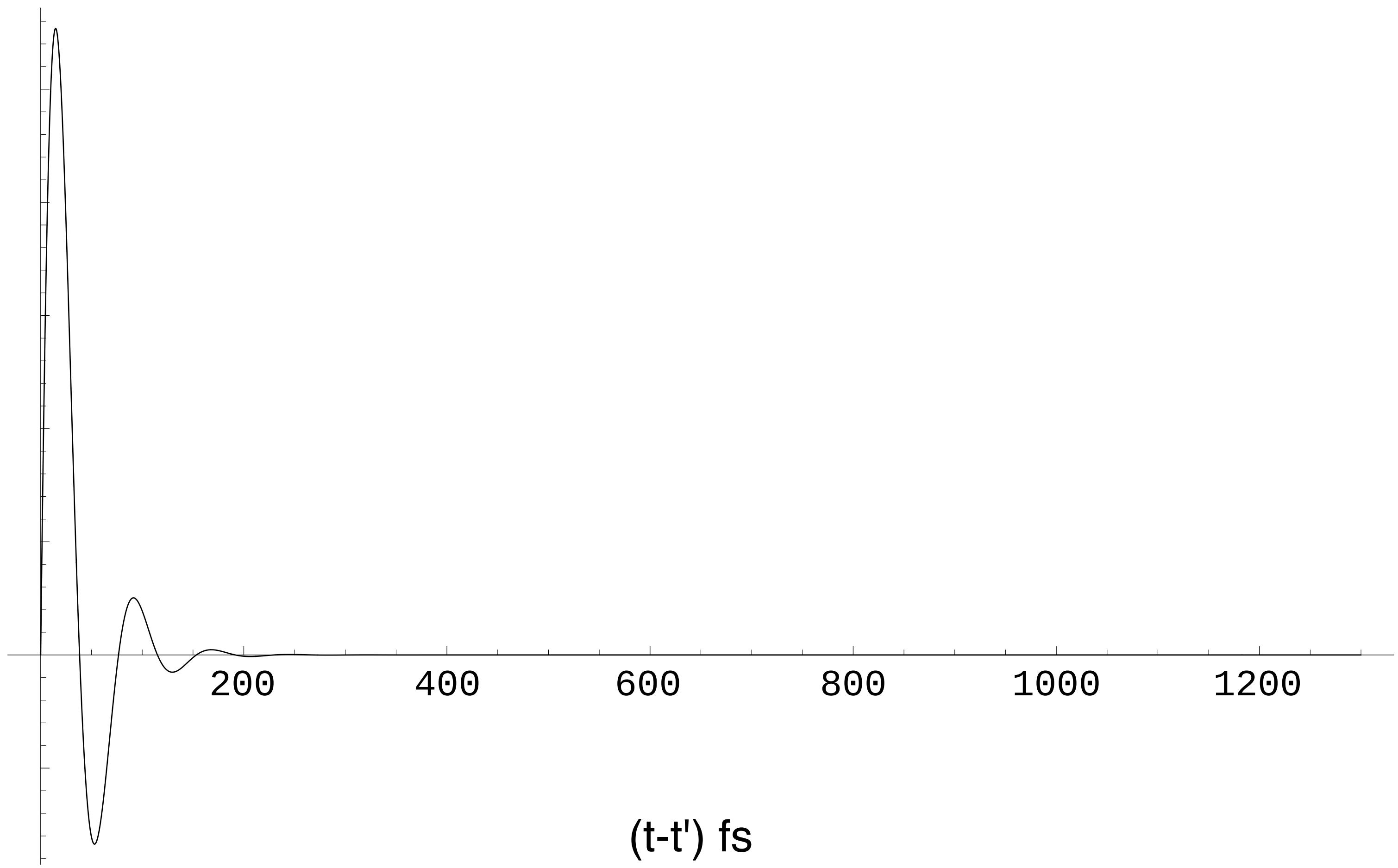
RAMAN RESPONSE FUNCTION (2)



$$h_R(t) \propto e^{-t/\tau_2} \sin(t/\tau_1)$$

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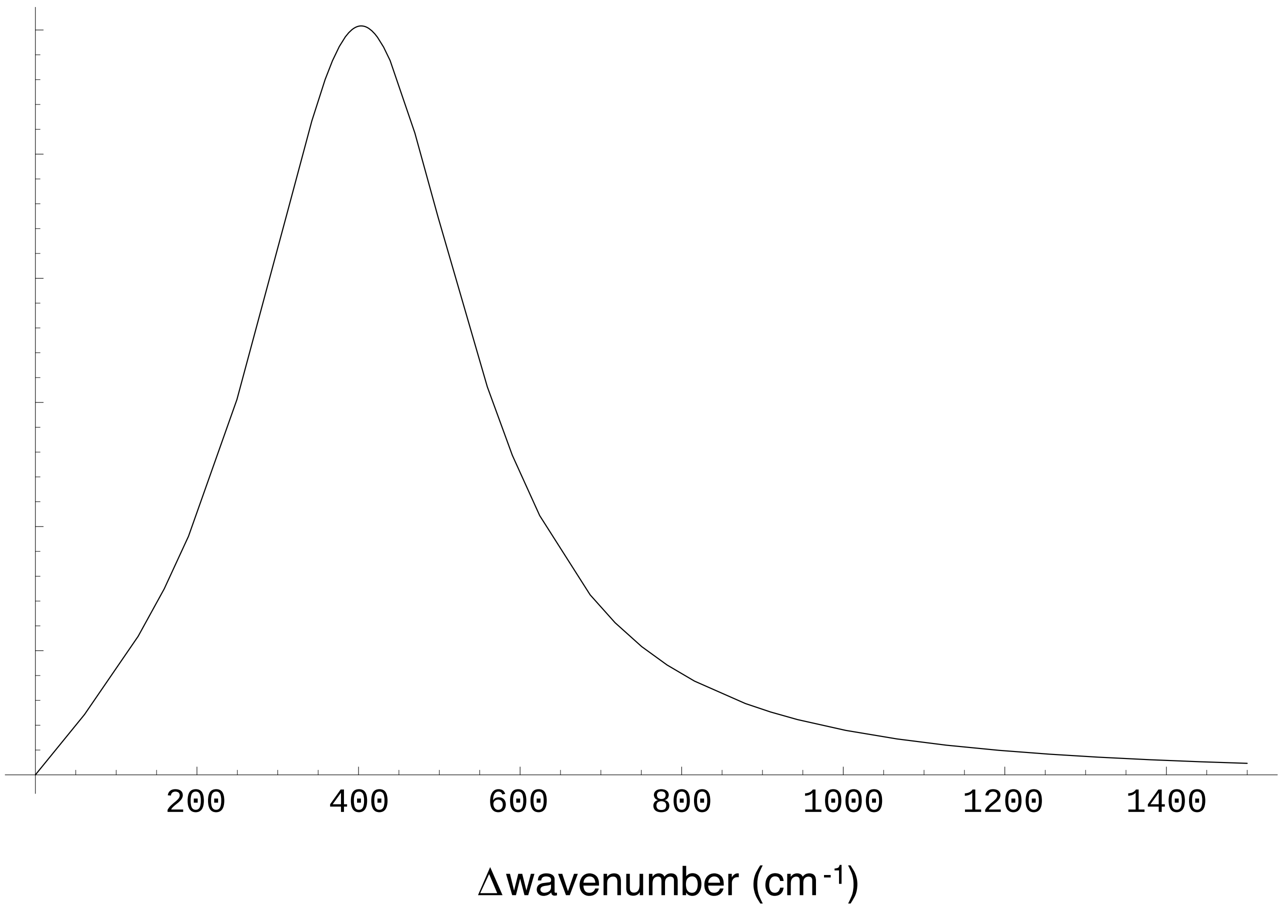
RAMAN GAIN SPECTRUM (1)



$$g_R(\Delta\omega) \propto \frac{2\omega\gamma}{(\omega^2 - \omega_v^2)^2 + (2\omega\gamma)^2}$$

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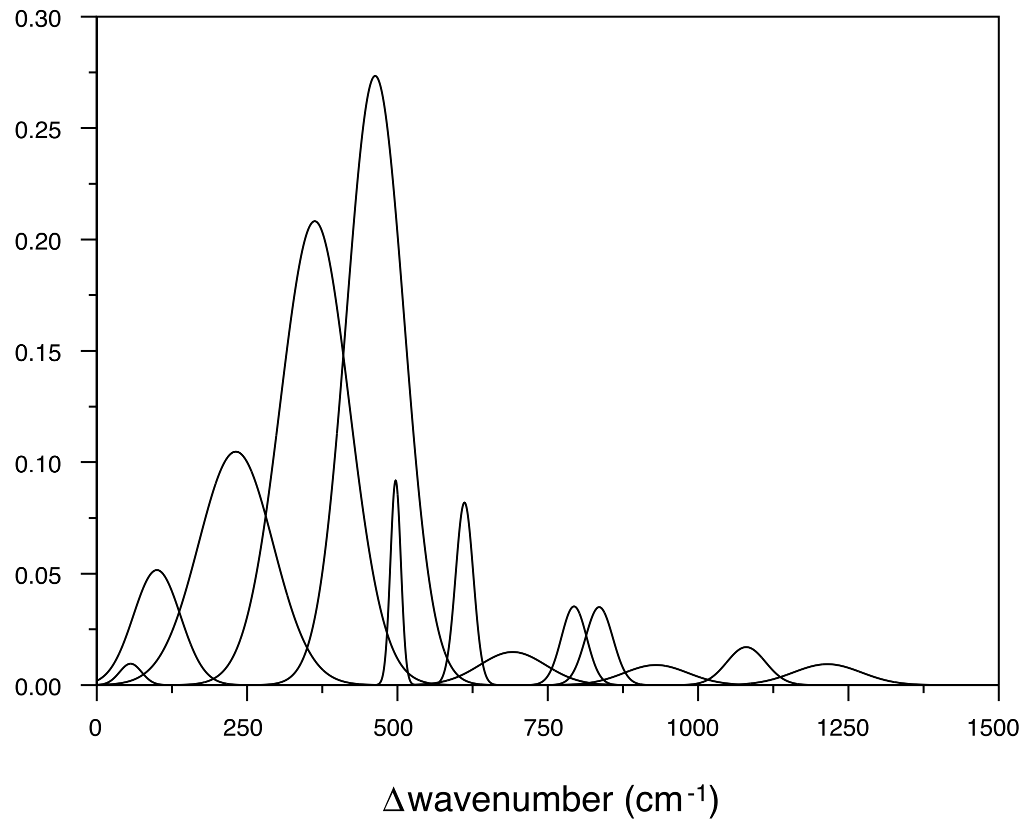
RAMAN GAIN SPECTRUM ANALYSIS

- Decomposition of the Raman gain spectrum into a superposition of 13 Gaussians by Walrafen, et al, "Model analysis of the Raman spectrum from fused silica optical fibers", Applied Optics **21**, 359–360 (1982)



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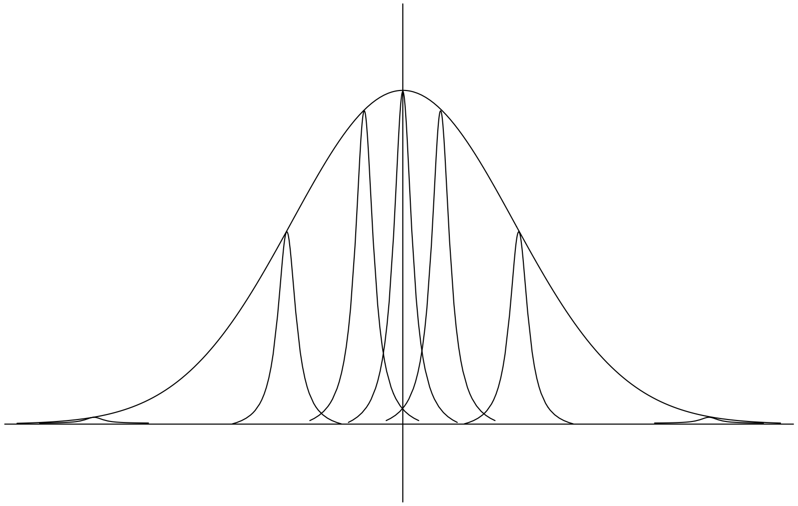
BROADENING

- Inhomogeneous
  - ▷ Random perturbations of vibrational frequencies
  - ▷ Gaussian via central limit theorem
- Homogeneous
  - ▷ Single vibrational frequency
  - ▷ Lorentzian
- Combined inhomogeneous and homogeneous



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13–MODE MODEL

- Response function:

$$h(t,0) = \sum_{i=1}^{13} \frac{A'_i}{\omega_{v,i}} e^{-\gamma_i t} e^{-\Gamma_i^2 t^2/4} \sin(\omega_{v,i} t)\theta(t)$$

- Spectrum:

$$s(\omega) = \sum_{\ell=1}^{13} \frac{A'_\ell}{2\omega_{v,\ell}} \int_0^\infty \left\{ \cos\left[(\omega_{v,\ell} - \omega)t\right] - \cos\left[(\omega_{v,\ell} + \omega)t\right] \right\} e^{-\gamma_\ell t} e^{-\Gamma_\ell^2 t^2/4}\, dt$$

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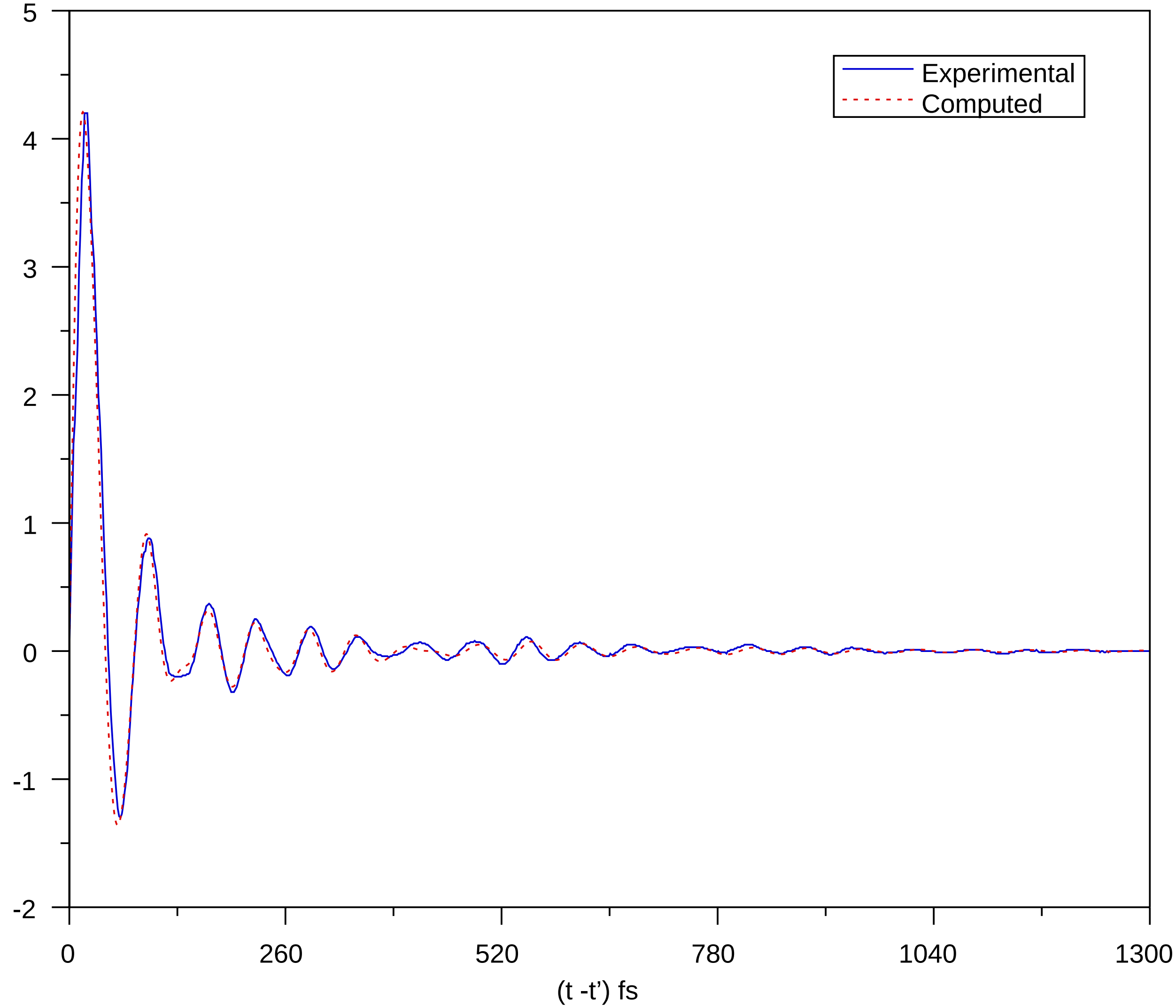
RAMAN RESPONSE FUNCTION (3)



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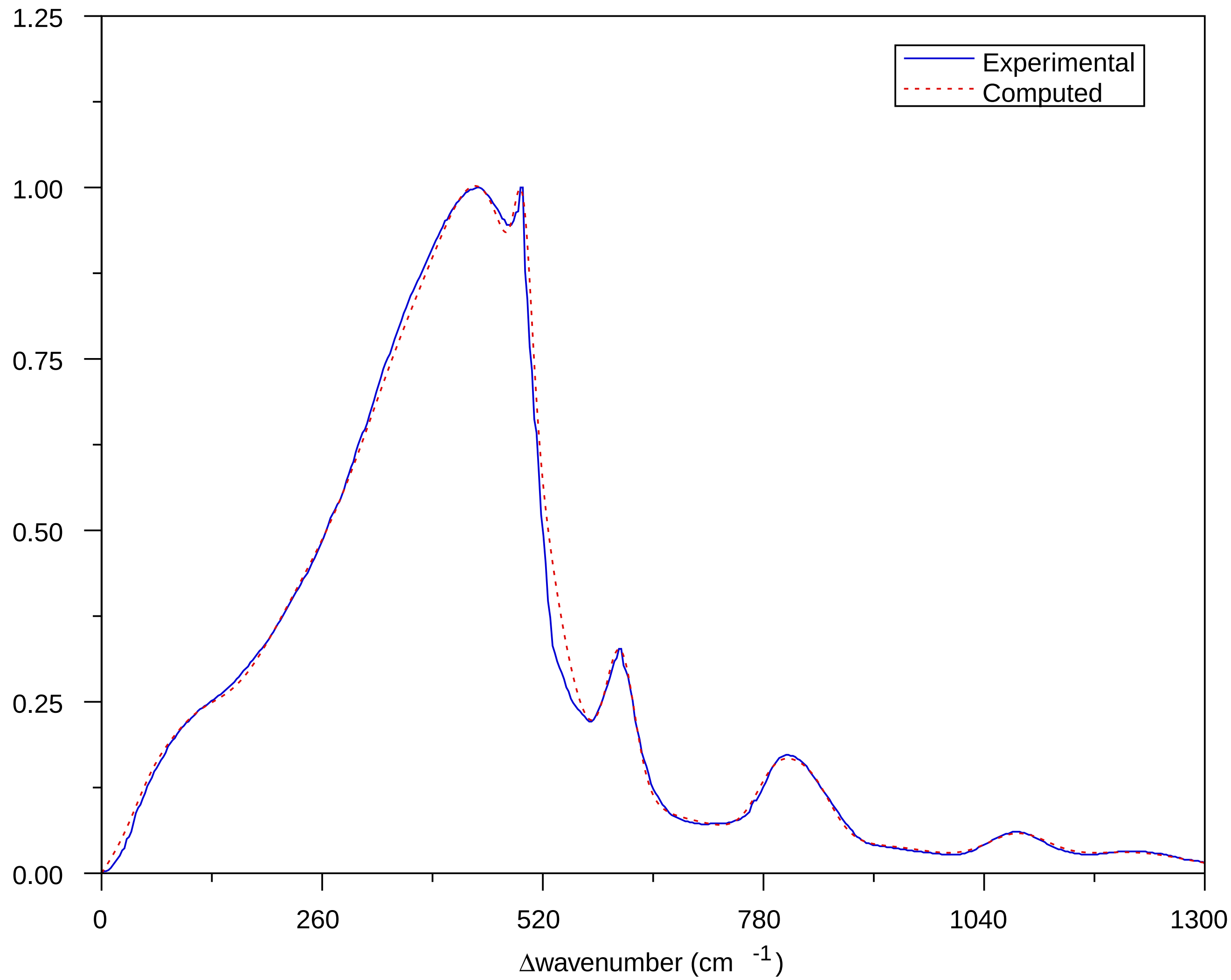
RAMAN GAIN SPECTRUM (2)



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CONCLUSIONS

- Detailed, spectroscopically accurate model of Raman gain and response function in silica fibers
- Different mode amplitudes for each fiber segment
  - ▷ Low-frequency (bending) modes are most likely to vary from fiber to fiber
  - ▷ Dopants may create extra modes or modify existing ones

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