Optimal pulse propagation in an inhomogeneously gas-filled hollow-core fiber

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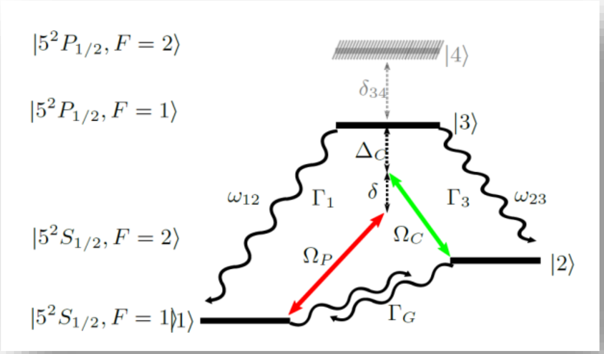
Tight 2D transverse confinement of atoms & light



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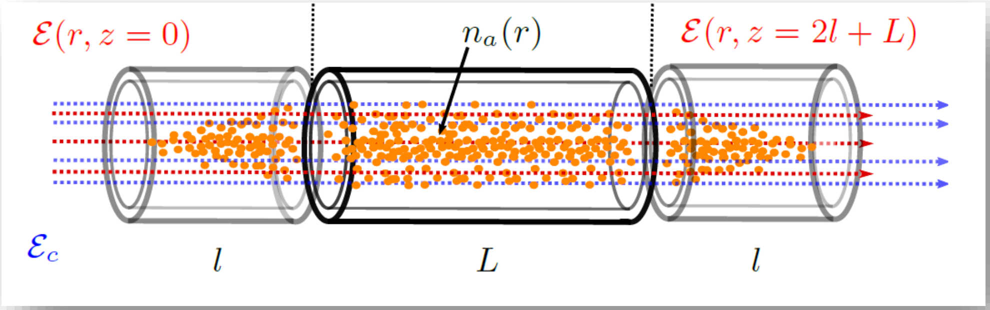

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Content

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1. Experimental setup
2. Electromagnetically induced transparency
3. Light propagation in a HCF
4. Pulse characterisation in frequency and time
5. Mitigation of lensing effects

Experiment: Tight 2D transverse confinement of atoms & light

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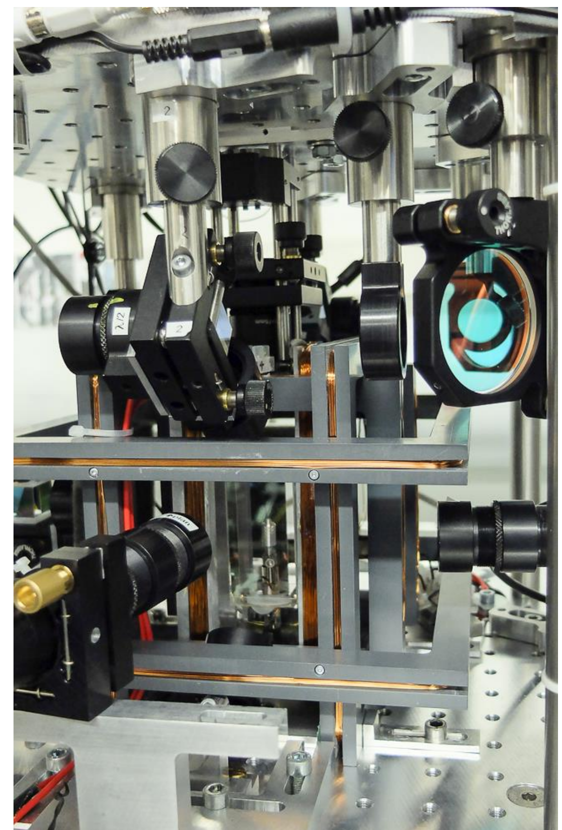

Hollow-core photonic bandgap fiber

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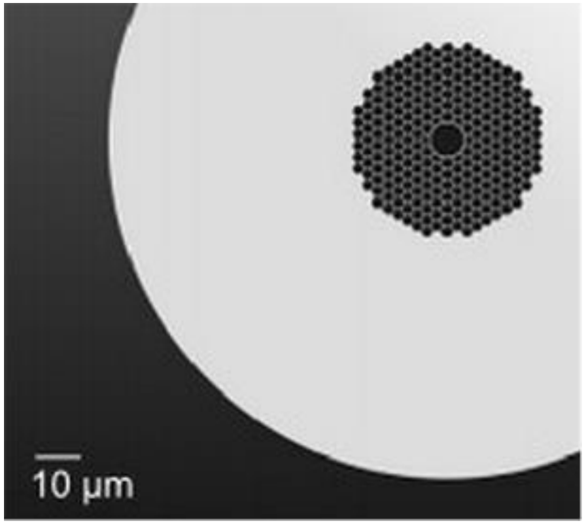
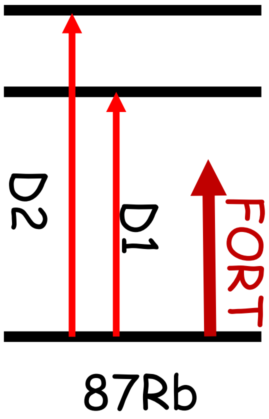
NKT Photonics HC-800-02

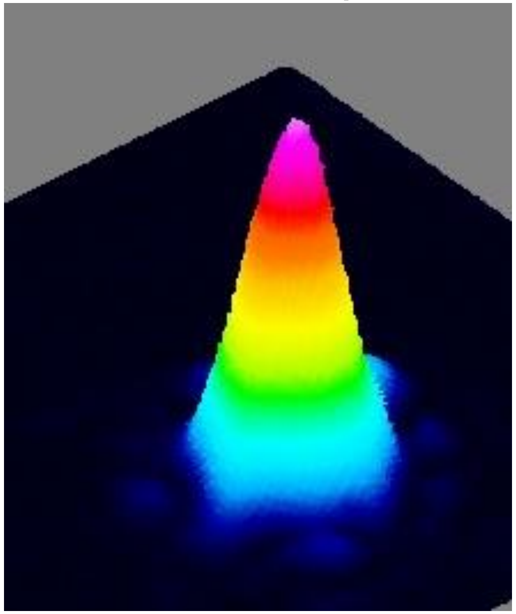


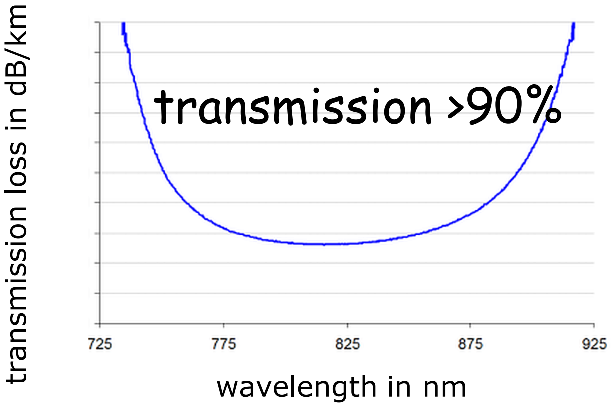
Physical properties	
Core diameter(1)	7.5 µm ± 1 µm
Pitch	2.3 µm

NA = 0.1

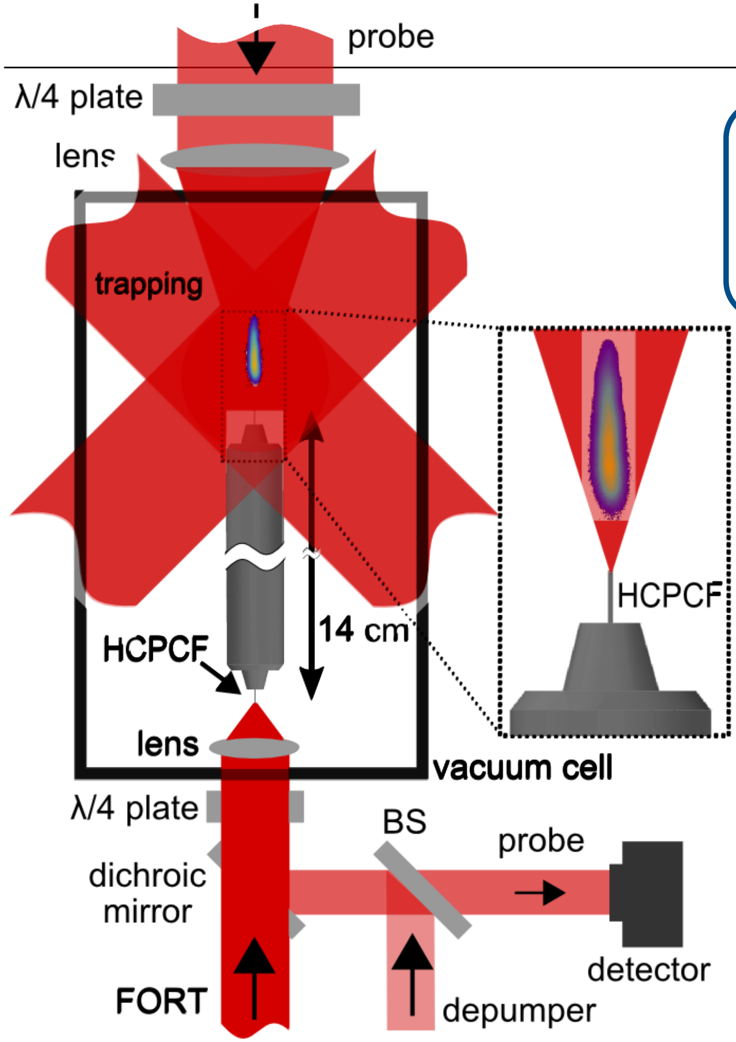


near Gaussian profile





Putting atoms into a tube



2 ECDLs @ 780 nm
each 100 mW
I ~Isat

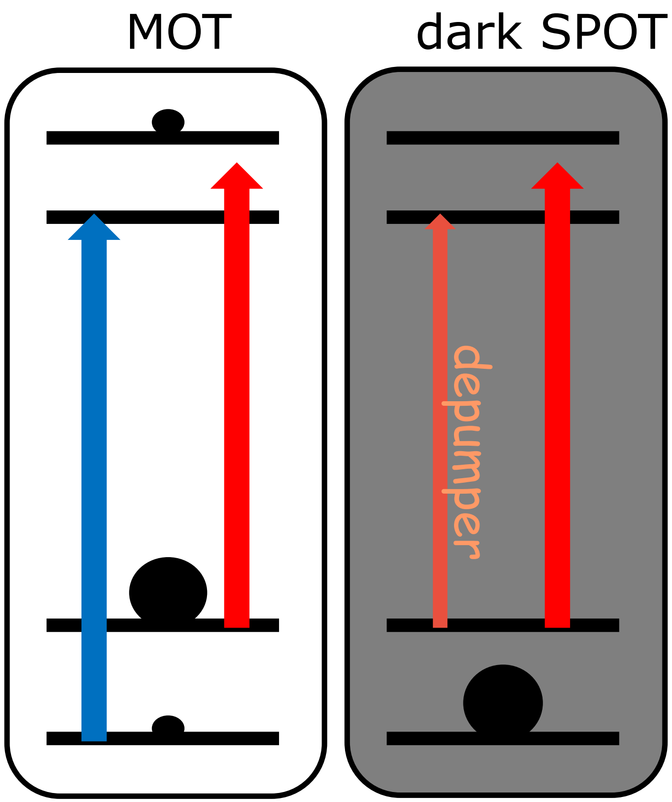
N ~ 1E7

T ~ 120 μK

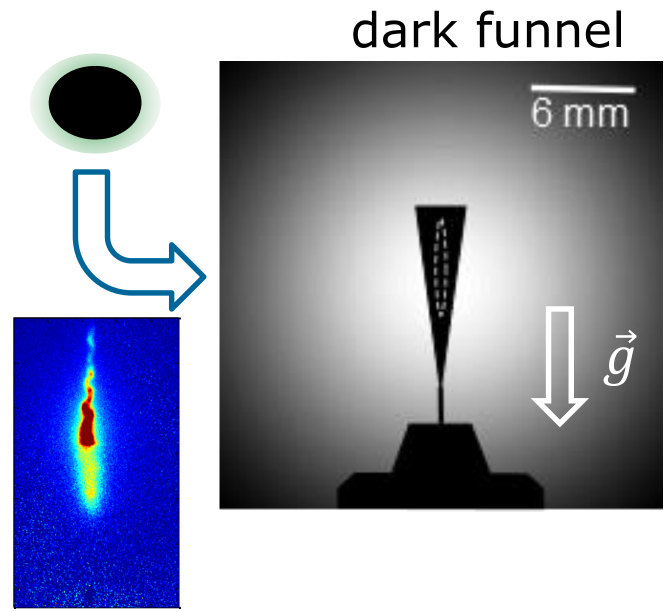
V ~ $5x0.8^2\ mm^3$

FORT:
1 W TA system @ 855 nm,
270 mW in fiber

Guiding atoms to the fiber

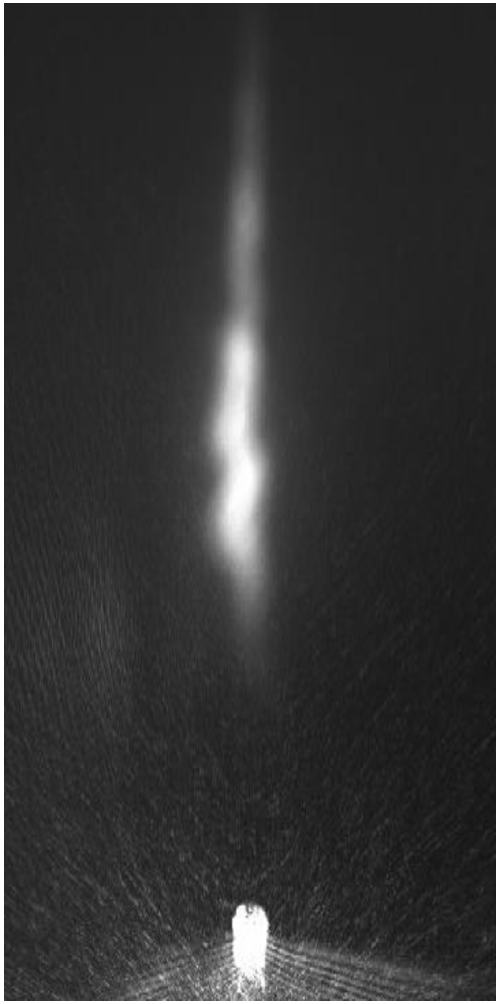


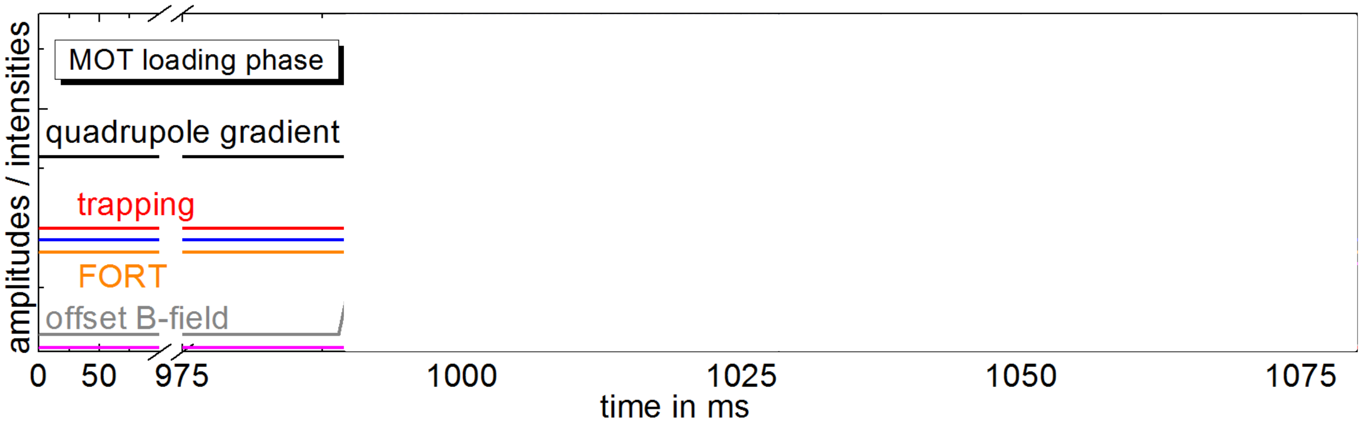
Ketterle et al., Phys. Rev. Lett. **70**, 2253-2256 (1993).



slowest atoms gather in shadow
no light-assisted collisions
► density increases

HCF loading sequence

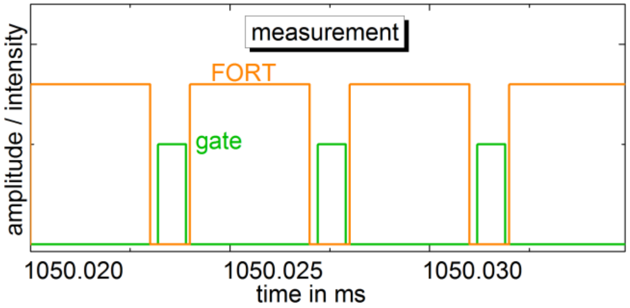




„purge“ repumper: pump atoms above fiber to F=2

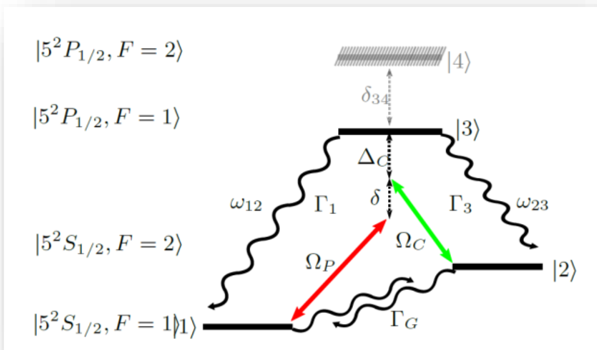
detect atoms in F=1

measurement sequence



F. Blatt, Th. Halfmann, and Th. Peters, "One-dimensional ultracold medium of extreme optical depth," Opt. Lett. **39**, 446-449 (2014)

Theory: Tight 2D transverse confinement of atoms & light



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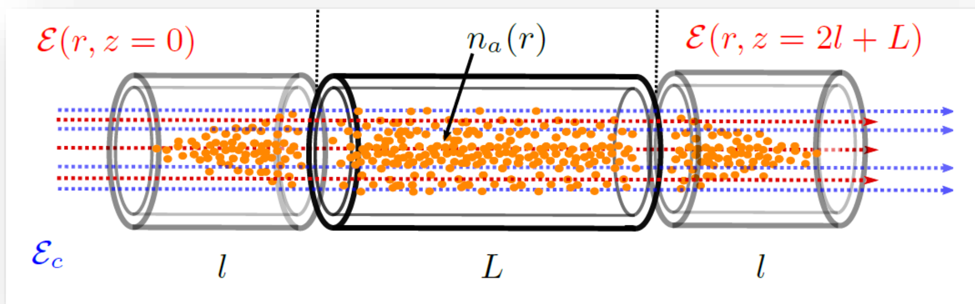
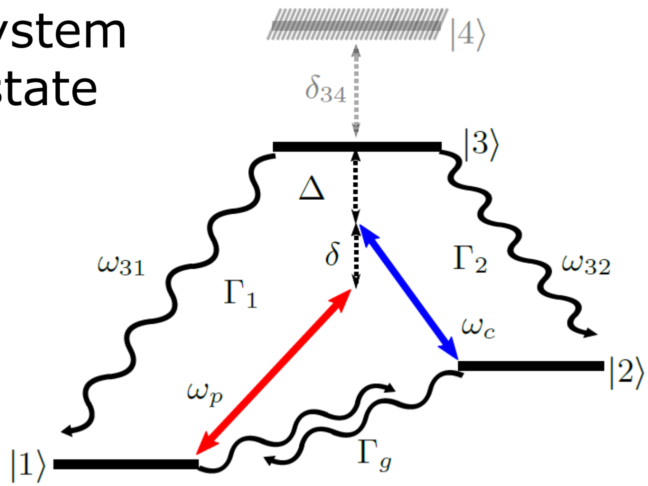


Crystallization of strongly interacting photons in a nonlinear optical fibre
D. Chang, V. Gritsev, G. Morigi, V. Vuletic, M. Lukin, E. Demler, Nature Physics 4, 884 (2008)
Quantum transport of strongly interacting photons in a one-dimensional nonlinear waveguide
M. Hafezi, D. Chang, V. Gritsev, E. Demler, M. Lukin Phys. Rev. A 85, 013822 (2012)
Quantum nonlinear optics — photon by photon
D. Chang, V. Vuletić, M. Lukin, Nature Photonic 8, 685 (2014)

Atomic Raman transitions

Three level system with ground state dephasing



Rotating wave Hamilton matrix:

$$H' = \hbar \begin{pmatrix} \Delta + \delta & 0 & \frac{\Omega_p^*}{2} \\ 0 & \Delta & \frac{\Omega_c^*}{2} \\ \frac{\Omega_p}{2} & \frac{\Omega_c}{2} & 0 \end{pmatrix}$$

Two-photon detuning: $\delta = \omega_p - \omega_c - \omega_{21}$

One-photon detuning: $\Delta = \omega_c - \omega_{32}$

Dark state: decouples from interaction

$|D\rangle = \cos\theta\,|1\rangle - \sin\theta\,|2\rangle$ at mixing angle: $\tan\theta = \Omega_p/\Omega_c$.

M. Jain, A. Merriam, A. Kasapi, G. Yin, and S. E. Harris Phys. Rev. Lett. 75, 4385 (1995)
M. Fleischhauer, A. Imamoglu, J. Marangos, Rev. Mod. Phys. 77, 633 (2005)

Dynamics with dissipation

Master equation

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[H', \hat{\rho}] + \sum_{i=1}^{2} \Gamma_i (\hat{\sigma}_{i3}\hat{\rho}\hat{\sigma}_{i3}^\dagger - \tfrac{1}{2}\hat{\sigma}_{i3}^\dagger\hat{\sigma}_{i3}\hat{\rho} - \tfrac{1}{2}\hat{\rho}\hat{\sigma}_{i3}^\dagger\hat{\sigma}_{i3})$$

$$+ \Gamma_g \left(\hat{\sigma}_{ii}\hat{\rho}\hat{\sigma}_{ii} - \tfrac{1}{2}\hat{\sigma}_{ii}\hat{\rho} - \tfrac{1}{2}\hat{\rho}\hat{\sigma}_{ii}\right)$$

Rearranging the 9 matrixelements

$$\boldsymbol{\varrho} = (\rho_{11}, \rho_{12}, \rho_{13}, \rho_{21}, \rho_{22}, \rho_{23}, \rho_{31}, \rho_{32}, \rho_{33})$$

$$\partial_t \boldsymbol{\varrho} = iL\boldsymbol{\varrho},$$

Stationary state

$$0 = L\boldsymbol{\varrho}^s$$

$$L = \begin{pmatrix}
0 & 0 & \frac{\Omega_p}{2} & 0 & 0 & 0 & -\frac{\Omega_p^*}{2} & 0 & -i\Gamma_1 \\
0 & i\Gamma_g - \delta & \frac{\Omega_c}{2} & 0 & 0 & 0 & 0 & -\frac{\Omega_p^*}{2} & 0 \\
\frac{\Omega_p^*}{2} & \frac{\Omega_c^*}{2} & i\frac{\Gamma_t}{2} - \delta - \Delta & 0 & 0 & 0 & 0 & 0 & -\frac{\Omega_p^*}{2} \\
0 & 0 & 0 & \delta + 2i\Gamma_g & 0 & \frac{\Omega_p}{2} & -\frac{\Omega_c^*}{2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{\Omega_c}{2} & 0 & -\frac{\Omega_c^*}{2} & -i\Gamma_2 \\
0 & 0 & 0 & \frac{\Omega_p^*}{2} & \frac{\Omega_c^*}{2} & i\frac{\Gamma}{2} - \Delta & 0 & 0 & -\frac{\Omega_c^*}{2} \\
-\frac{\Omega_p}{2} & 0 & 0 & -\frac{\Omega_c}{2} & 0 & 0 & \delta + \Delta + i\frac{\Gamma}{2} & 0 & \frac{\Omega_p}{2} \\
0 & -\frac{\Omega_p}{2} & 0 & 0 & -\frac{\Omega_c}{2} & 0 & 0 & \Delta + i\frac{\Gamma}{2} & \frac{\Omega_c}{2} \\
0 & 0 & -\frac{\Omega_p}{2} & 0 & 0 & -\frac{\Omega_c}{2} & \frac{\Omega_p^*}{2} & \frac{\Omega_c^*}{2} & i(\Gamma_1 + \Gamma_2)
\end{pmatrix}$$

Electromag. induced transparency

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Atomic polarization:

$$\mathbf{P}_p(\omega) = n_a \mathbf{d}_{13}\rho_{31}^s = \epsilon_0\ \chi^{(1)}(\omega)\mathbf{E}_p(\omega) + \dots$$

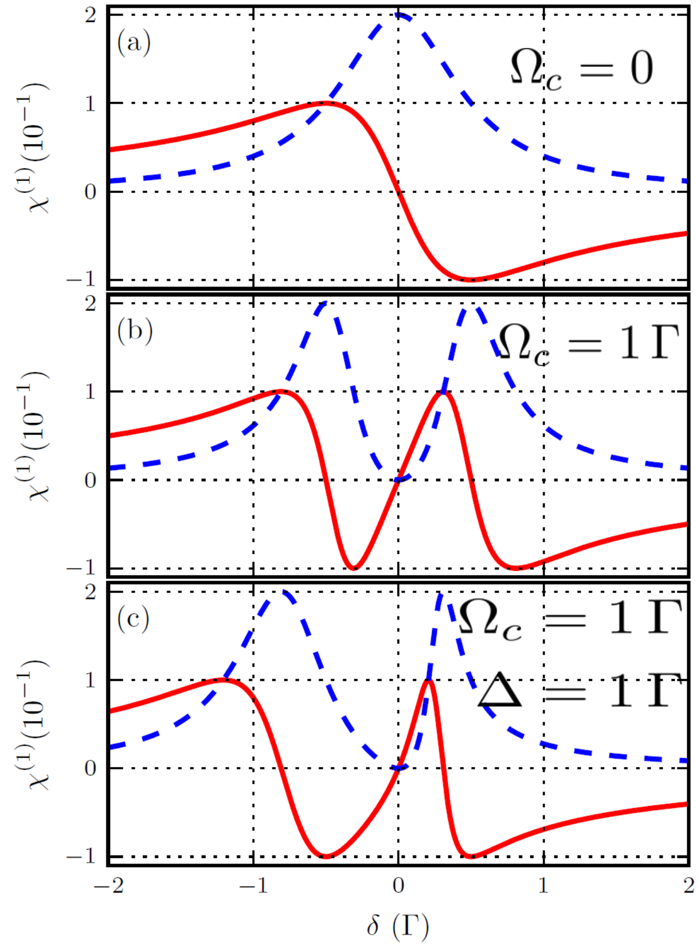
Probe pulse susceptibility:

$$\chi^{(1)} = \chi_0^{(1)} f,\ \chi_0^{(1)} = n_a\alpha_0,\ \alpha_0 = \frac{|d_{13}|^2 S_{FF'}}{2\epsilon_0\hbar\Gamma}$$

$$f = \delta\Gamma \frac{\frac{|\Omega_c^2|}{4} - \delta(\delta+\Delta) + i\delta\frac{\Gamma}{2}}{\left[\frac{|\Omega_c^2|}{4} - \delta(\delta+\Delta)\right]^2 + \delta^2(\frac{\Gamma}{2})^2}$$

$$= \underline{\delta}\left(1 + \frac{\Delta}{\Gamma}\underline{\delta}\right) + i\frac{\underline{\delta}^2}{2}\left(1 + \frac{2\Delta}{\Gamma}\underline{\delta}\right) + \dots$$

$$\underline{\delta} = \delta/\delta_{\mathrm{EIT}}, \quad \delta_{\mathrm{EIT}} = \frac{|\Omega_c|^2}{4\Gamma}$$



Light propagation in a HCF

inhomogeneous Helmholtz equation: $\varepsilon_r = 1 + \chi$

$$\left(\nabla^2 + k^2 \varepsilon_r(\mathbf{x},\omega)\right)\mathbf{E}_p(\mathbf{x},\omega) = -\cancel{\nabla(\mathbf{E}_p \cdot \nabla \log \varepsilon_r)},$$

Fiber parameter: $3.5\,\mu\text{m} < a_0 < 25\,\mu\text{m}$

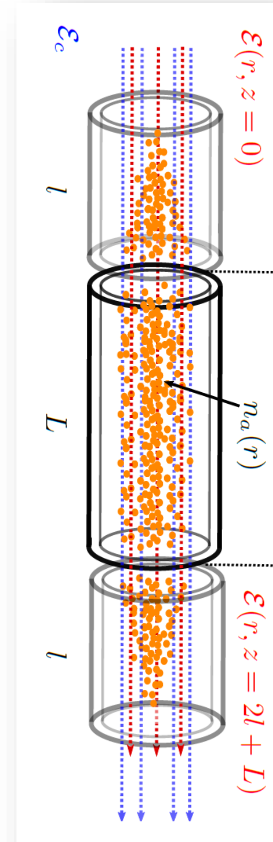
$$v = \frac{a_0}{\lambda\!\!\!^{-}_p} \approx 25 > 1$$

Slowly varying enevelope:

$$\mathbf{E}_p(\mathbf{x},\omega) = \mathbf{e}_p e^{ik_p z}\mathcal{E}_p(\mathbf{x},\omega),$$

optical Schrödinger equation $\lambda\!\!\!^{-} \leftrightarrow \hbar$, $z \leftrightarrow t$:

$$i\lambda\!\!\!^{-}_p \partial_z \mathcal{E}_p(\mathbf{x},\omega) = \left[-\frac{\lambda\!\!\!^{-2}}{2a_0^2}\Delta_\perp - \frac{1}{2}\chi^{(1)}(\mathbf{x},\omega)\right]\mathcal{E}_p$$



M. Born and E. Wolf, Principles of Optics (Cambridge Univ. Press)
M. Lax, Phys. Rev. A 11, 1365 (1975).

2D modes & complex spectrum

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Adiabatic eigenmode

$$\mathcal{E}_p(r,\varphi,z;\delta) = e^{-i\phi(z)} u(r,\varphi,z;\delta)\mathcal{E}_p(\delta),$$

$$\phi(z) = \int_0^z \mathrm{d}\zeta\, q_p \varepsilon(\zeta;\delta)$$

with $q_p = k_p/2v^2$

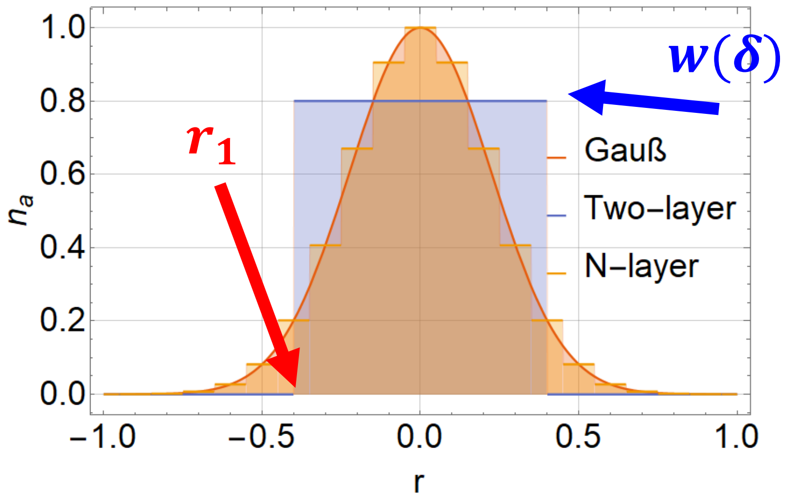
2D Eigen-modes and complex dispersion

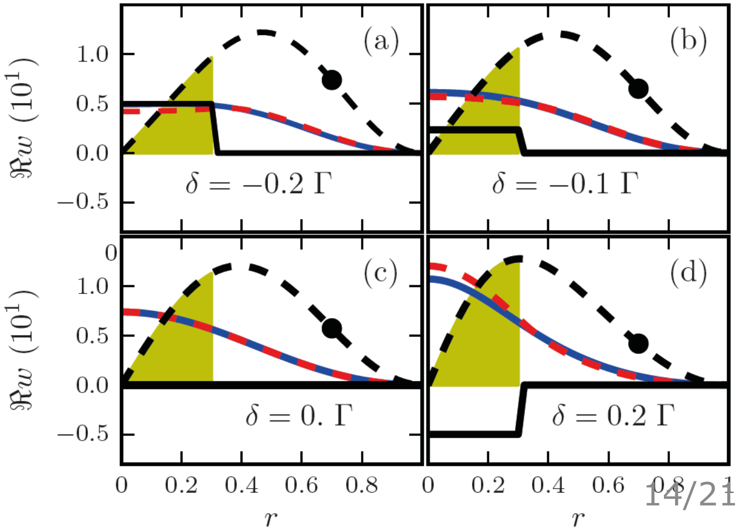
$$\varepsilon(z;\delta) u(r,z,\varphi;\delta) = \left[-\Delta_\perp + w(r,z;\delta)\right] u,$$

Optical potential

$$w(r,z;\delta) = -v^2 n_a(r,z)\alpha_0 f(\delta,\Delta,|\Omega_c(r)|),$$

Atomic density: $n_a(r,z) = n_0(z) e^{-\frac{r^2}{\sigma_a^2}}$





Complex dispersion $\varepsilon(\delta)$

Complex transfer function:

$$\mathcal{E}_p^{(\text{out})}(\delta) = \mathcal{T}(\delta)\mathcal{E}_p^{(\text{in})}(\delta),$$

$$\mathcal{T}(\delta) = e^{i\eta + ik(\delta)L}, \quad k(\delta) = k_p - q_p\varepsilon(\delta)$$

Finding the complex dispersion

- Numerically: Gauß density
- Analytically: two-layer density

Homogeneous potential:

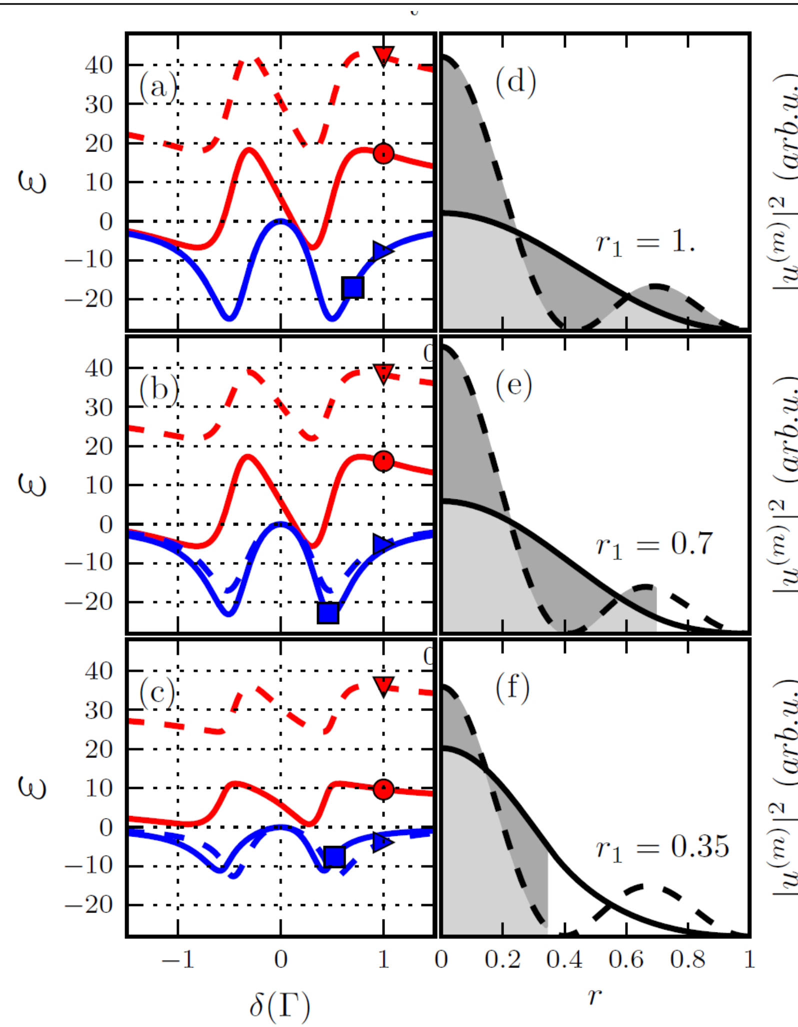
$$u(r) = aJ_0(\kappa r) + bY_0(\kappa r)$$

$$\kappa^2 = \varepsilon - w \in \mathbb{C}$$

Homogeneously filled HCF & BC

$$u^{(m)}(r;\delta) = J_0(j_m r),$$

$$\varepsilon^{(m)}(\delta) = j_m^2 + w(\delta)$$



Implicit function theorem

Implicit function

$H(w(\delta), \varepsilon(\delta)) = 0$

Implicit function theorem

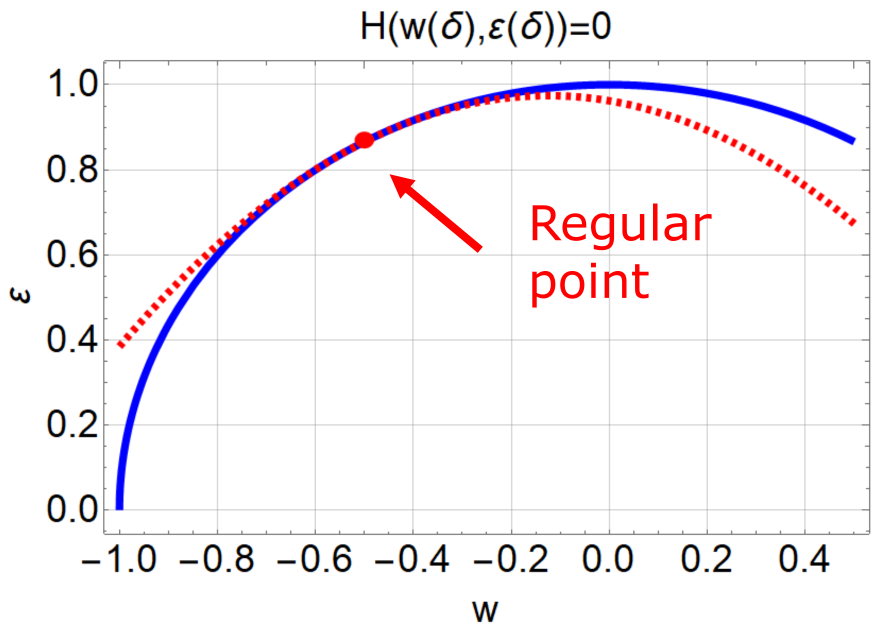
$\partial_\delta^n H(w(\delta), \varepsilon(\delta)) = 0$

Explicit expressions for

$\partial_\delta^n \varepsilon(\delta = 0)$

Taylor series for complex dispersion

$$\varepsilon(\delta) = \epsilon + \epsilon' \delta + \frac{\epsilon''}{2}\delta^2 + \mathcal{O}(\delta^3),$$



Two-layer model: quantization condition from boundary condition

$$H = \frac{J_0(\kappa_1 r_1) J_1(\kappa_2 r_1)\kappa_2}{J_0(\kappa_2 r_1) J_1(\kappa_1 r_1)\kappa_1} - \frac{G_0(\kappa_2 r_1) - G_0(\kappa_2)}{G_1(\kappa_2 r_1) - G_0(\kappa_2)}, \quad (w(0) = 0, \varepsilon(0) = j_m^2)$$

Spectral response for pulses

Intensity transmission: $I(\delta) = |\mathcal{E}(\delta)|^2$:

$$I_p^{(\text{out})}(\delta) = |\mathcal{T}(\delta)|^2 I_p^{(\text{in})}(\delta), \quad T(\delta) = e^{-d_{\text{opt}}(\delta)},$$

Optical density (Beer' law) $\theta = q_p L$

$d_{\text{opt}}(\delta) = -2\theta\Im\varepsilon(\delta) > 0$, $d_{\text{opt}}(0) = 0$?

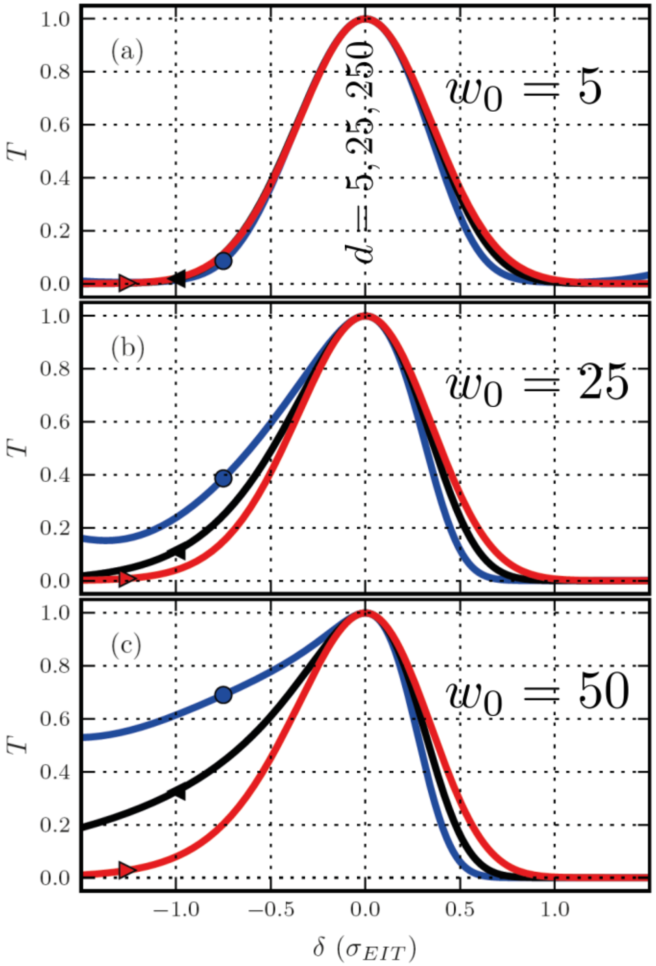
EIT optical density and 1/e full width

$$d_{\text{opt}}(\delta) = \left(\frac{2\delta}{\sigma_{\text{EIT}}}\right)^2 + \dots \qquad \sigma_{\text{EIT}} = \frac{2}{\sqrt{-\theta\Im\epsilon''}}$$

Universal result as homogeneous system

$$d_{\text{EIT}} = \frac{|\Omega_c|^2 L}{\Gamma v_g} \gg 1, \quad \sigma_{\text{EIT}} = \frac{|\Omega_c|^2}{\Gamma\sqrt{d_{\text{EIT}}}}$$

Group velocity: $v_g = \dfrac{1}{\partial_\delta \Re k(0)} = -\dfrac{1}{q_p \Re\varepsilon'(0)}$



Real time pulses: delay, distortion

Output power:

$$P_p^{(\mathrm{out})}(t) = 2c\epsilon_0|\mathcal{E}_p^{(\mathrm{out})}(t)|^2.$$

OUT field for Gaussian IN field

$$\mathcal{E}_p^{(\mathrm{out})}(t) = e^{-i[\omega_p t - k_p L - \eta]}\Phi(t)\mathcal{E}_p,$$

$$\Phi(t) = \int_{-\infty}^{\infty} \mathrm{d}\delta \, \frac{e^{-i\theta\varepsilon(\delta) - it\delta - \frac{\delta^2}{\Delta\omega^2}}}{2\sqrt{\pi}\Delta\omega}.$$

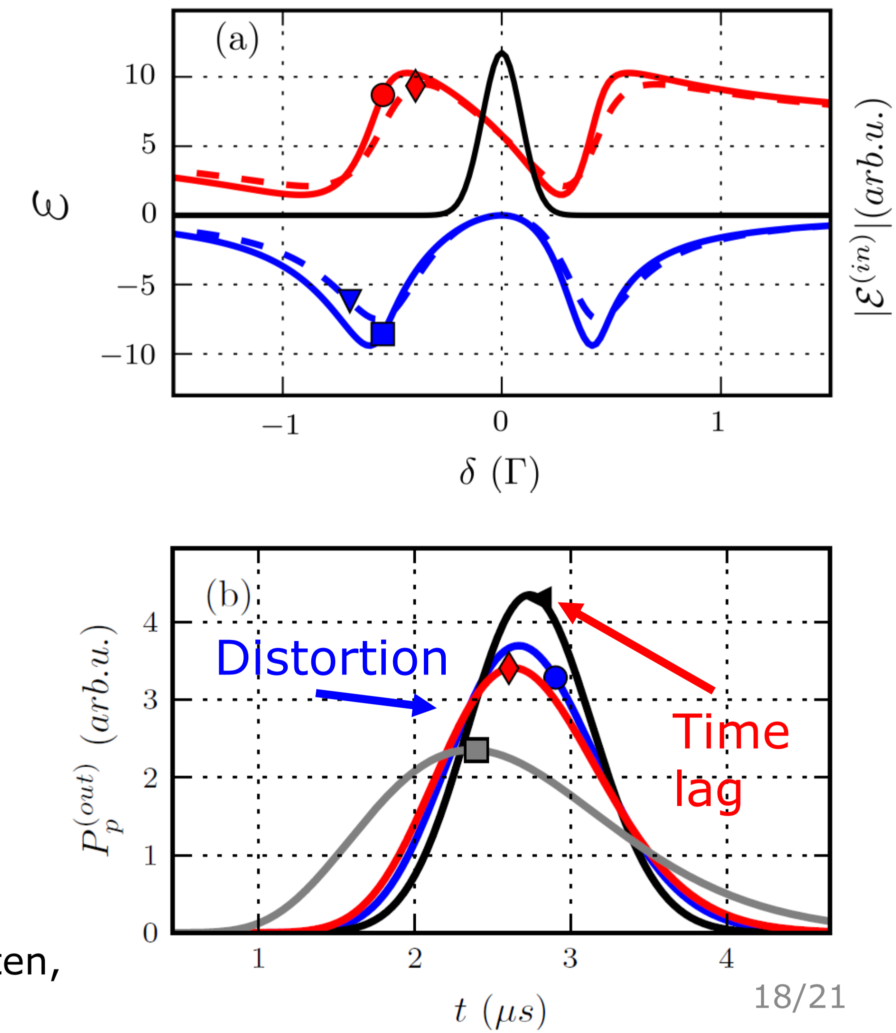
Parameter

$(a)\, r_1 = 0.301, w_0 = 12.5, \Omega_c = \Gamma, \Delta = 0$

$(b)\, \tau_p = 150\,\mathrm{ns}, w_0 = 25.0, d_{opt} = 100$

one-photon detuning:

$\Delta/\Gamma = -1$ (●), -0.5 (◀), 0 (♦), 0.5 (■)



M. Noaman, M. Langbecker, P. Windpassinger, Opt. Lett. 43, 3925 (2018);
A.Hilton, C. Perrella, F. Benabid, B. Sparkes, A. Luiten, P. Light, Phys. Rev. Applied 10, 044034 (2018)

Gaussian approximation

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Real time resonse

$$\Phi(t) = \frac{e^{-i\theta\epsilon - \frac{(t-\tau_{\text{lag}})^2}{\tau_p^2(1+i\xi)}}}{2\sqrt{1+i\xi}}, \xi = \frac{2\theta}{\tau_p^2}\epsilon'' \in \mathbb{C}$$

Time lag

$$\tau_{\text{lag}} = -\theta\epsilon' = \frac{L}{v_g} > 0,$$

Pulse width can be minimized

$$(\tau_p^{\text{out}})^2 \equiv \frac{(1-\Im\xi)^2 + (\Re\xi)^2}{1-\Im\xi}\tau_p^2 \geq \tau_p^2,$$

Group velocity two-layer model

$$v_g(r_1) = \frac{1}{\mu(r_1)} \frac{|\Omega_c|^2 \lambda\!\!\!^{-}}{2\Gamma n_a \alpha_0}$$

Light speed reduction to 17 metres per second, L. Hau, S. E. Harris, Z. Dutton, C. Behroozi, Nature 397, 594 (1999)

Mitigation of lensing effects

Minimal pulse width

$$\Re\varepsilon''(\delta = 0, \Delta, r_1, n_a, \ldots) = 0$$

E. g., optimal one-photon detuning

$$\Delta^{(m)}_{\text{opt}}(r_1) = \Gamma\alpha_0 v^2 n_a \mathcal{C}^{(m)}(r_1),$$

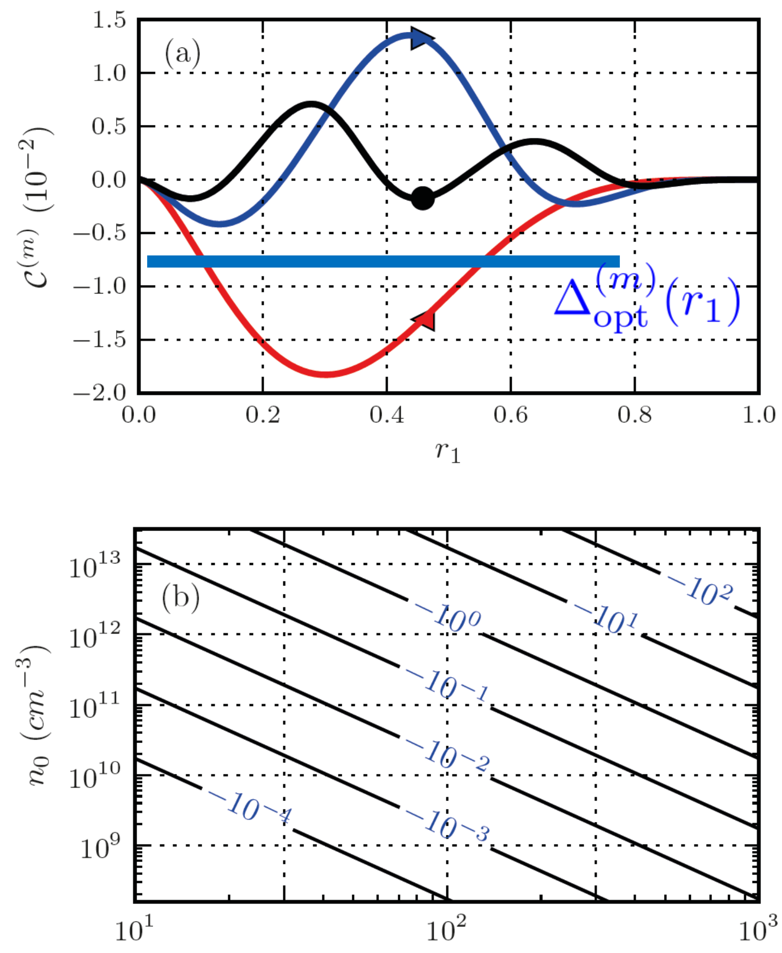
$$\mathcal{C}^{(m)}(r_1) = \frac{H_{\varepsilon\varepsilon}H_w}{2H_\varepsilon^2} - \frac{H_{w\varepsilon}}{H_\varepsilon} + \frac{H_{ww}}{2H_w}$$

Or, minimize deviation

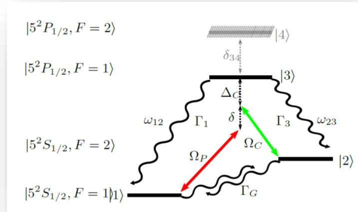
$$|\Delta^{(m)}_{\text{opt}}(r_1) - \Gamma\alpha_0 v^2 n_a \mathcal{C}^{(m)}(r_1)|$$

by modifying density

$$\Delta^{(1)}_{\text{opt}}(r_1)\Big|_{N_a=const} = \Gamma\alpha_0 v^2 \frac{N_a}{\pi L}\frac{\mathcal{C}^{(1)}(r_1)}{r_1^2}$$



Conclusion



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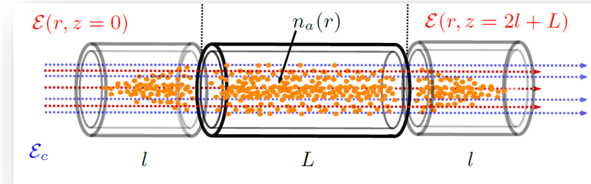
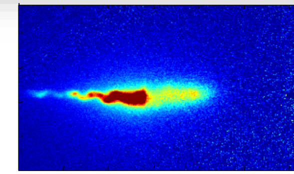
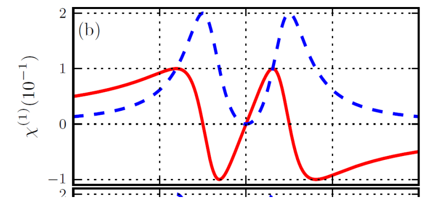
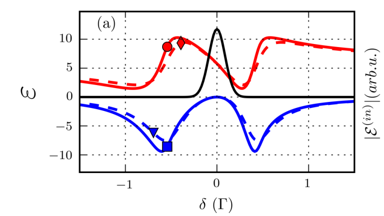




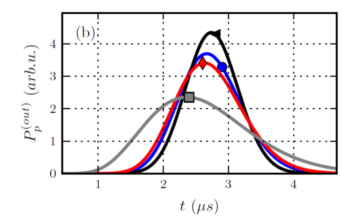
1. Experimental setup



2. Electromagnetically induced transparency



3. Light propagation in a HCF
4. Pulse characterisation in frequency and time
5. Mitigation of lensing effects



6. https://arxiv.org/abs/1905.02807

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