Spectroscopy of materials can be enhanced by the quantum coherent effects. It is the quantum coherence effects such as electromagnetically induced transparency and coherent population trapping that attract attention due to the increasing development of new applications such as high-precision spectroscopy, and large Kerr nonlinearities. Localized plasmon interaction in quantum confined structures strongly modify the optical and electronic properties with potential for manipulating light on the nanoscale. Another approach to demonstrate quantum coherent and cooperative effects is to study the Bi-exponential decay of dye fluorescence near the surface of plasmonic metamaterials and core-shell nanoparticles that has been shown to be an intrinsic property of the coupled system.

We have demonstrated the new sensing mechanism based on an adiabatically changing electric field interacting with the rotational structure of the molecules with dipole moments. We have theoretically demonstrated a single low frequency gas detector that can be used for sensing of gas mixtures with high selectivity, accuracy, and sensitivity. The enhancement of the population difference between corresponding molecular levels and reached the theoretical maximum of absorption have been shown. Such a gas sensor can be used for a huge range of applications -- stretching from technology, sciences, control of environment, biology, and medicine.

Optica Laser Systems Technical Group, November 14, 2023
Motivation – what is quantum coherence? And why is it important?

Manipulation of population under interactions with adiabatically changing fields

Reduced graphene oxide and nanoparticles
  Electromagnetically induced transparency

Coherent effects in gases
  Gas sensing and masers at room temperature

Second harmonic generation in MoS2

Applications
  Generation of entanglement states,
  Application to quantum information and quantum processing and quantum sensing

Conclusion
A two-level atomic system

\[ \hat{H} = \hbar \Delta |a\rangle \langle a| + \hbar \Omega (|a\rangle \langle b| + |b\rangle \langle a|) \]
A two-level atomic system

\[ \hat{H} = \hbar \Delta |a\rangle \langle a| + \hbar \Omega (|a\rangle \langle b| + |b\rangle \langle a|) \]

\[ \lambda_{\pm} = \omega_{\pm} = \frac{\Delta}{2} \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + \Omega^2} \]
A two-level atomic system

$$\hat{H} = \hbar \Delta |a\rangle \langle a| + \hbar \Omega (|a\rangle \langle b| + |b\rangle \langle a|)$$

$$\lambda_{\pm} = \omega_{\pm} = \frac{\Delta}{2} \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + \Omega^2}$$

$$|\pm\rangle = \frac{\omega_{\pm}|a\rangle + \Omega |b\rangle}{\sqrt{\omega_{\pm}^2 + \Omega^2}}$$
CHIRAP in a two-level atomic system

\[ \hat{H} = \hbar \Delta |a\rangle \langle a| + \hbar \Omega (|a\rangle \langle b| + |b\rangle \langle a|) \]

\[ \lambda_{\pm} = \omega_{\pm} = \frac{\Delta}{2} \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + \Omega^2} \]


\[ \hat{H} = \hbar \Omega_p |b\rangle \langle a| + \text{adj} \]

\[ \Delta = \Delta_0 - \alpha t \]
$$\hat{H} = \hbar \Omega_p |b\rangle \langle a| + \text{adj}$$

Diagram:

- State $|a\rangle$ with energy $\Delta$
- State $|b\rangle$ with energy $\Omega_p$
- Graphs $\chi'$ and $\chi''$ with $\Omega = 0$
\[ \hat{H} = \hbar \Omega_p |b\rangle \langle a| + \text{adj} \]

\[ \hat{H} = \hbar (\Omega_p |b\rangle \langle a| + \Omega |c\rangle \langle a|) + \text{adj} \]

\[ |B\rangle = \frac{\Omega_p |b\rangle + \Omega |c\rangle}{\sqrt{|\Omega|^2 + |\Omega_p|^2}} \]

\[ |D\rangle = \frac{\Omega |b\rangle - \Omega_p |c\rangle}{\sqrt{|\Omega|^2 + |\Omega_p|^2}} \]
\[ \hat{H} = \hbar (\Omega_p |b\rangle \langle a| + \Omega |c\rangle \langle a|) + \text{adj} \]

\[ |B\rangle = \frac{\Omega_p |b\rangle + \Omega |c\rangle}{\sqrt{\Omega^2 + \Omega_p^2}} \]

\[ |D\rangle = \frac{\Omega |b\rangle - \Omega_p |c\rangle}{\sqrt{\Omega^2 + \Omega_p^2}} \]

\[ \Omega_{eff} = \sqrt{\Omega^2 + \Omega_p^2} \]
\[
\hat{H} = \hbar (\Omega_p |b\rangle \langle a| + \Omega |c\rangle \langle a|) + \text{adj}
\]

\[
|B\rangle = \frac{\Omega_p |b\rangle + \Omega |c\rangle)}{\sqrt{|\Omega|^2 + |\Omega_p|^2}}
\]

\[
|D\rangle = \frac{\Omega |b\rangle - \Omega_p |c\rangle)}{\sqrt{|\Omega|^2 + |\Omega_p|^2}}
\]
Electromagnetically Induced Transparency in gases


Electromagnetically Induced Transparency in gases: applications

Electromagnetically Induced Transparency in gases: applications

Reduced graphene oxide and nanoparticles

Meg Mahat, Yuri Rostovtsev, Sanjay Karna, Gary N Lim, Francis D'Souza, Arup Neogi, Plasmonically induced transparency in graphene oxide quantum dots with dressed phonon states, ACS Photonics, 2017, 5, 614-62
Coherent effects for sensing and detecting

(A) Not coherent

\[ P_{|b\rangle \rightarrow |a\rangle} \leq 50\% \]

(B) Coherent

\[ P_{|b\rangle \rightarrow |a\rangle} = 100\% \]

\[ \rho_{aa} = \frac{2|\Omega_p|^2}{\gamma^2 + \Delta^2 + 2|\Omega_p|^2} \rho_{bb} \]

Z Branković, Y Rostovtsev, A resonant single frequency molecular detector with high sensitivity and selectivity for gas mixtures. Scientific Reports 10, 1537 (2020)
Sensing molecules with electric dipole


Molecular alignment

\[ \hbar \omega_E \gg k_B T \]

\[ \varphi \mathcal{E}_0 \gg \left( \frac{k_B T}{\hbar B} \right)^2 \hbar B \]

Weak alignment

\[ \varphi \mathcal{E}_0 \approx \hbar B, \]
Cavity

$$\dot{\Omega}_s = -i(\omega_0 - \omega_s)\Omega_s + i\Omega_a^2 \rho_{ab}$$

$$\Omega_a^2 = \frac{2\pi \omega_0 \phi^2 N}{\hbar}$$

$$i\hbar \dot{\rho} = [\hat{H}, \rho].$$
Cavity

\[
\frac{2I(E_2 - E_1)}{\hbar^2} = F \left( \frac{2\varphi I \varepsilon_0}{\hbar^2} \right)
\]

\[
\delta \Theta \simeq \frac{\delta P_s}{P_s} = \frac{P_{\text{noise}}}{P_s}
\]

\[
\delta N_{\text{min}} = \frac{\hbar \alpha}{2\pi \omega_0 \varphi^2} \frac{P_{\text{noise}}}{P_s}
\]
\[
\begin{array}{cccc}
\text{Molecules} & \varphi & \text{Rotational Constant} & \text{dc Electric field} \\
\text{CO} & \varphi_{CO} = 0.122 \text{ D} & B = 1.93 \text{ cm}^{-1} & 45 \times 10^3 \text{ V/cm}, 2 \times 10^{10} \text{ cm}^{-3} \\
\text{HCN} & \varphi_{HCN} = 2.98 \text{ D} & B = 1.47 \text{ cm}^{-1} & 1600 \text{ V/cm}, 3 \times 10^{10} \text{ cm}^{-3} \\
\text{N}_2\text{O} & \varphi_{N_2O} = 0.17 \text{ D} & B = 0.42 \text{ cm}^{-1} & 15 \times 10^3 \text{ V/cm}, 9 \times 10^{10} \text{ cm}^{-3} \\
\text{NO} & \varphi_{NO} = 0.16 \text{ D} & B = 1.67 \text{ cm}^{-1} & 30 \times 10^3 \text{ V/cm}, 2 \times 10^{10} \text{ cm}^{-3} \\
\text{SO} & \varphi_{SO} = 1.55 \text{ D} & B = 0.72 \text{ cm}^{-1} & 2200 \text{ V/cm}, 5 \times 10^{10} \text{ cm}^{-3} \\
\text{KBr} & \varphi_{KBr} = 10.6 \text{ D} & B = 0.08 \text{ cm}^{-1} & 106 \text{ V/cm}, 5 \times 10^9 \text{ cm}^{-3} \\
\text{NO}_2 & \varphi_{NO_2} = 0.316 \text{ D} & A = 8.0 \text{ cm}^{-1}, B = 0.43 \text{ cm}^{-1}, C = 0.41 \text{ cm}^{-1} & 8300 \text{ V/cm}, 9 \times 10^{10} \text{ cm}^{-3} \\
\text{H}_2\text{O} & \varphi_{H_2O} = 1.85 \text{ D} & A = 27.88 \text{ cm}^{-1}, B = 14.512 \text{ cm}^{-1}, C = 9.29 \text{ cm}^{-1} & 6500 \text{ V/cm}, 4 \times 10^9 \text{ cm}^{-3} \\
\text{O}_3 & \varphi_{O_3} = 0.53 \text{ D} & A = 3.550 \text{ cm}^{-1}, B = 0.44 \text{ cm}^{-1}, C = 0.39 \text{ cm}^{-1} & 4800 \text{ V/cm}, 1 \times 10^{11} \text{ cm}^{-3} \\
\text{CCl}_2\text{O} & \varphi_{CCl_2O} = 1.17 \text{ D} & A = 0.26 \text{ cm}^{-1}, B = 0.16 \text{ cm}^{-1}, C = 0.08 \text{ cm}^{-1} & 1080 \text{ V/cm}, 4 \times 10^{11} \text{ cm}^{-3} \\
\text{NH}_3 & \varphi_{NH_3} = 1.47 \text{ D} & A = 9.44 \text{ cm}^{-1}, B = 9.44 \text{ cm}^{-1}, C = 6.19 \text{ cm}^{-1} & 6600 \text{ V/cm}, 6 \times 10^9 \text{ cm}^{-3} \\
\end{array}
\]
Goran Branković, and et al. New technique for gas sensing: Experiment results, University of Belgrade, Institute for Multidisciplinary Research, and Center for Nonlinear Sciences and Department of Physics, University of North Texas, USA (in progress);

Z Branković, Y Rostovtsev, A resonant single frequency molecular detector with high sensitivity and selectivity for gas mixtures, Scientific Reports 10, 1537 (2020)
To build Maser (motivation)


To build Maser

\[ \dot{\Omega}_s = -i(\omega_0 - \omega_s)\Omega_s + i\Omega_a^2 \rho_{ab} \]

\[ \Omega_a^2 = \frac{2\pi \omega_0 \phi^2 N}{\hbar} \]

\[ i\hbar \dot{\rho} = [\hat{H}, \rho]. \]
Maser pumping (at room temperature)

\[
\hat{H} = -B \frac{\partial^2}{\partial \phi^2} - B \frac{\partial^2}{\partial \phi^2} - \phi E_0 \cos \phi,
\]

\[
E_n = \frac{\hbar^2 m^2}{2l} = B m^2
\]

- (A)
- (B) \( B \gg \phi E_0 \)
- (C) \( B \ll \phi E_0 \)
- Metropolitan networks via fiber
- Inter-city networks connected by quantum repeaters
- Long-distance quantum communication between satellite and ground
Barium borate (BBO)

\[ g \sim \chi_2 \]

\[ V_I = \hbar g (\hat{a}_1^+ \hat{a}_2^+ \hat{b} + \hat{b}^+ \hat{a}_1 \hat{a}_2) \]

\[ |\Psi\rangle = \sum_n B_{n,\alpha} |n, \alpha, \alpha\rangle \]

\[ B_{n,\alpha} = \frac{(-ig\alpha^2 t)^n}{\sqrt{n!}} B_{0,\alpha} \]

\[ |\Psi\rangle = \sum_n B_{\beta,n} |\beta, n, n\rangle \]

\[ B_{\beta,n} = (-ig\beta t)^n B_{\beta,0} \]

\[ |\Psi\rangle = (-ig\beta t) |1_1, 1_2\rangle + (-ig\beta t)^2 |1_1, 1_2\rangle + ... \]
Quantum control and coherence in MoS$_2$ (2D) materials

Figure 1: The experimental setup is shown.
Figure 4: (a) MoS$_2$ structure (b) Simplified view of just one lattice site (blue circles) and an exciton (red circle). (c) The polarization dependence with respect to the orientation of the laser field. (1) response of lattice, exciton response is much smaller; (2) lattice and exciton responses are comparable and (3) the exciton response is much larger than lattice.
Figure 2: The dependence of the SHG signal and its width on the power of the pump laser for different wavelengths of the pump laser (upper panel). The polarization dependence of the SHG signal on the polarization of the pump laser for different wavelengths of the pump laser (lower panel).
Figure 3: The inset represents the schematics of the density matrix model. We assume $a$ is electronic excited state, and $c_A$ and $c_B$ represent the ground states that correspond to transitions $|a\rangle \rightarrow |c_A\rangle$ and $|a\rangle \rightarrow |c_B\rangle$ related to A-exciton and B-exciton correspondingly. We show also the states $b_A$ and $b_B$ representing the vibrational states related to the phonon excitation in the system. The energy of vibration is 40 meV that is larger than the energy corresponds to the thermal energy at the room temperature 25 meV, we assume that initially the vibrational states are empty. We show the pump and delayed probe fields.
Angular dispersion

Prisms:

\[ \frac{d\theta}{d\lambda} = 10^{-4} \text{ nm}^{-1} \]

Diffraction gratings

Interferometers

\[ \frac{d\theta}{d\lambda} = 10^{-3} \text{ nm}^{-1} \]

What is angular dispersion of media with excited quantum coherence?
Angular dispersion

Prisms:

\[ \frac{d\theta}{d\lambda} = 10^{-4} \text{ nm}^{-1} \]

Diffraction gratings

Interferometers

\[ \frac{d\theta}{d\lambda} = 10^{-3} \text{ nm}^{-1} \]

The medium with excited quantum coherence

\[ \frac{d\theta}{d\lambda} = 10^3 \text{ nm}^{-1} \]

Quantum fields

\[ |\psi\rangle = \sum_k \alpha_k |1_k\rangle \]

\[ \hat{E} = \sum_k (\hat{a}_k \exp[ikz - i\omega t] + \hat{a}_k^\dagger \exp[-ikz + i\omega t]) = \hat{E}^{(+)} + \hat{E}^{(-)} \]

\[ \langle E^2 \rangle = \langle \psi | \hat{E}^{(-)} \hat{E}^{(+)} |\psi\rangle = \langle \psi | \hat{E}^{(-)} \left( \sum_n |n\rangle \langle n| \right) \hat{E}^{(+)} |\psi\rangle = \left| \langle 0 | \hat{E}^{(+)} |\psi\rangle \right|^2 \]

\[ \alpha_k = \exp\left[-\frac{k^2 L^2}{2}\right] \]

\[ \langle E^2 \rangle = \left| \langle 0 | \hat{E}^{(+)} |\psi\rangle \right|^2 = \exp \left[ -\frac{(z - ct)^2}{L^2} \right] \]
One Mode of the Quantum field

\[ v(z, t) = \sum \alpha_k e^{ikz - i\omega_k t} = \exp \left[ ik_0 z - i\omega_0 t - \frac{(z - ct)^2}{2L^2} \right] \]

\[ \hat{E} = E_0 (v(z, t) \hat{b} + v(z, t)^* \hat{b}^+) = \hat{E}^{(+)} + \hat{E}^{(-)} \]

\[ E_0 = \sqrt{2\pi \hbar \omega_0 / V}. \]
A two-level atom

\[
\hat{V}_I = -\hat{\phi} \cdot \hat{E} = \varphi_{ab} E_0 \left( v(z, t) e^{i \omega_{ab} t} |a\rangle \langle b| + \hat{b}^+ v^*(z, t) e^{-i \omega_{ab} t} |b\rangle \langle a| \right)
\]

\[
\omega_{ab} = \frac{(E_a - E_b)}{\hbar} \text{ is}
\]
A two-level atom interacting with quantum field

\[ |\Psi\rangle = A|a, 0\rangle + B|b, 1\rangle \]

\[ i\hbar \frac{\partial}{\partial t} |\Psi\rangle = \hat{V}_I |\Psi\rangle \]

\[ \dot{\hat{A}} = -i\Omega_0 e^{ik_0 z + i\delta_0 t} V \hat{B} \]
\[ \dot{\hat{B}} = -i\Omega_0 e^{-ik_0 z - i\delta_0 t} V^* \hat{A} \]
A two-level atom interacting with quantum field

\[ E_0 \exp \left[ i k_0 z - i \left( \omega_0 + \frac{\Omega_0^2}{\delta_0} |V|^2 \right) t \right] B_0 V \left[ z - \left( c + c \frac{\Omega_0^2}{\delta_0^2} |V|^2 \right) t \right] \]

\[ \mathcal{E} = \langle 0 | \hat{E}^{(+)} | \Psi \rangle \approx \]

\[ V_{ph} = \frac{\omega_0 + \frac{\Omega_0^2 |V|^2}{\delta_0}}{k} \]

\[ V_g = \frac{\partial}{\partial k} \left( \omega_0 + \frac{\Omega_0^2 |V|^2}{\delta_0} \right) = c + c \frac{\Omega_0^2}{\delta_0^2} |V|^2 \]
\[
\begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} = \begin{pmatrix}
\cos \zeta & -i \sin \zeta \\
-i \sin \zeta & \cos \zeta
\end{pmatrix} \begin{pmatrix}
\hat{a}_1 \\
\hat{a}_2
\end{pmatrix} = S \begin{pmatrix}
\hat{a}_1 \\
\hat{a}_2
\end{pmatrix} S^+
\]

\[
S = \exp \left[ i \zeta \left( \hat{a}_1^\dagger \hat{a}_2 + \hat{a}_1 \hat{a}_2^\dagger \right) \right],
\]
\[
\begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} = S_1 \begin{pmatrix}
\hat{a}_1 \\
\hat{a}_2
\end{pmatrix} S_1^+ \\
\begin{pmatrix}
\hat{c}_1 \\
\hat{c}_2
\end{pmatrix} = S_2 \begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} S_2^+
\]
\[
\begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} = S_1 \begin{pmatrix}
\hat{a}_1 \\
\hat{a}_2
\end{pmatrix} S_1^+ \\
\begin{pmatrix}
\hat{c}_1 \\
\hat{c}_2
\end{pmatrix} = S_2 \begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} S_2^+
\]

\[
\begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} \rightarrow \begin{pmatrix}
1 & 0 \\
0 & \exp[i\phi]
\end{pmatrix} \begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} = U \begin{pmatrix}
\hat{b}_1 \\
\hat{b}_2
\end{pmatrix} U^+
\]

\[
|\text{out}\rangle = MZ|1, 0\rangle = S_2US_1|1, 0\rangle = \frac{e^{i\phi} - 1}{2}|1, 0\rangle + \frac{e^{i\phi} + 1}{2}|0, 1\rangle
\]
\[ \hat{E}(z, t) = E_0 \begin{cases} 
  v_{1a} \hat{a}_1 + v_{1a}^* \hat{a}_1^+ & z_1 < z_{BS_1} \\
  v_{2a} \hat{a}_2 + v_{2a}^* \hat{a}_2^+ & z_2 < z_{BS_1} \\
  v_{1b} \hat{b}_1 + v_{1b}^* \hat{b}_1^+ & z_{BS_1} < z_1 < z_{BS_2} \\
  v_{2b} \hat{b}_2 + v_{2b}^* \hat{b}_2^+ & z_{BS_1} < z_2 < z_{BS_2} \\
  v_{1c} \hat{c}_1 + v_{1c}^* \hat{c}_1^+ & z_1 > z_{BS_2} \\
  v_{2c} \hat{c}_2 + v_{2c}^* \hat{c}_2^+ & z_2 > z_{BS_2} 
\end{cases} \]

\[ \begin{align*}
  v_{1,2a}(z_{1,2}, t) &= \exp \left[ ik_0 z_{1,2} - i\omega_0 t - \frac{(z_{1,2} - ct)^2}{2L^2} \right] \\
  v_{1,2b}(z_{1,2}, t) &= \exp \left[ ik_0 z_{1,2} - i\omega_0 t - \frac{(z_{1,2} - ct)^2}{2L^2} \right] \\
  v_{1,2c}(z_{1,2}, t) &= \exp \left[ ik_0 z_{1,2} - i\omega_0 t - \frac{(z_{1,2} - ct)^2}{2L^2} \right].
\end{align*} \]

\[ \frac{B - B_0}{2} = \frac{e^{i\phi_A} - 1}{2} B_0 \simeq i \frac{\phi_A}{2} \]

\[ \hat{E} = E_0 (v(z, t) \hat{b} + v(z, t)^* \hat{b}^+) = \hat{E}^{(+)} + \hat{E}^{(-)} \]

\[ |\Psi\rangle = \hat{T} \exp \left[ -\frac{i}{\hbar} \int_0^t dt' V_I(t') \right] |\Psi_0\rangle \simeq \exp[-i\phi_A] |\Psi_0\rangle, \]
Figure 3. Mach-Zehnder interferometer signal imaginary and real parts.
\[ |\Psi\rangle = B_0 |B, 1_0\rangle + \sum_{k_{\perp}} B_{\perp} |B, 1_{\perp}\rangle + \sum_j A_j |a_j, 0\rangle \]

\[ |B, 1_0\rangle = |b_1 b_2 \ldots b_N, 1_0\rangle, \quad |a_j, 0\rangle = |b_1 b_2 \ldots a_j \ldots b_N, 0\rangle \]

\[ \hat{E} = E_0 (v_0(r, t) \hat{b}_0 + v_0(r, t)^* \hat{b}_0^+) + \sum_{k_{\perp}} E_{k_{\perp}} (v_{k_{\perp}}(z, t) \hat{b}_{k_{\perp}} + v_{k_{\perp}}(z, t)^* \hat{b}_{k_{\perp}}^+) \]

\[ v(r, t) = e^{ik_0 r - i\omega_0 t} \tilde{V}_0(r, t) \]

\[ v_{k_{\perp}}(r, t) = e^{ik_{\perp} r - i\omega_0 t} \tilde{V}_{k_{\perp}}(r, t) \]

\[ E_0 = \sqrt{2\pi \hbar \omega_0 / V}, \quad E_{k_{\perp}} = \sqrt{2\pi \hbar \omega_{k_{\perp}} / V} \]
(A)

Quantum Source

Quantum channel

Classical channel

Quantum Detector 1

Quantum Detector 2
CHIRAP in a two-level atomic system

\[
\hat{H} = \hbar \Delta |a\rangle \langle a| + \hbar \Omega (|a\rangle \langle b| + |b\rangle \langle a|)
\]

\[
\lambda_{\pm} = \omega_{\pm} = \frac{\Delta}{2} \pm \sqrt{\left(\frac{\Delta}{2}\right)^2 + \Omega^2}
\]

\[
\omega_+(\Delta) = \begin{cases} 
0, & \Delta \to -\infty \\
\Delta, & \Delta \to +\infty 
\end{cases}
\]

and \[|+\rangle(\Delta) = \begin{cases} 
|b\rangle, & \Delta \to -\infty \\
|a\rangle, & \Delta \to +\infty 
\end{cases}\]

\[
\omega_-(\Delta) = \begin{cases} 
\Delta, & \Delta \to -\infty \\
0, & \Delta \to +\infty 
\end{cases}
\]

and \[|\rangle(\Delta) = \begin{cases} 
|a\rangle, & \Delta \to -\infty \\
|b\rangle, & \Delta \to +\infty 
\end{cases}\]
Vacuum field

Laser field

Laser field

Vacuum field

Laser and vacuum Fields

Populations in b and c
Cooperative effects in metamaterials

Fig. M2. A core-shell particle: diagram, scheme of deposition on a glass substrate.

Fig. M1. A grating with SU-8 epoxy spacer 28nm, followed by Rh800 embedded in thinner epoxy 18 nm layer; gratings strips substructure: Ti 5nm, 30 nm Ag, 40 nm alumina, 5 nm Ti, 30 nm Ag, and 10 nm alumina. The periodicity of the gratings is ~310 nm. The e-beam writing parameters were as follows: dose was 650, 725, 750, and 800 μC/cm² for A, B, C, and D, respectively; 1.2 nA; and 100 kV accelerating voltage.

David P Lyvers, Mojtaba Moazzezi, Vashista C de Silva, Dean P Brown, Augustine M Urbas, Yuri Rostovtsev, Vladimir P Drachev, Cooperative bi-exponential decay of dye emission coupled via plasmons, Journal Scientific Reports, 2018, 8. 9508.
Figure 5: The models of the experimental and theoretical samples. Left - gratings with Rh800 molecules on top, grating strips substructure: Ti 5 nm (blue), 30 nm Ag (purple), 40 nm alumina (brown), 5 nm Ti (blue), 30 nm Ag (purple), and 10 nm alumina (brown). The periodicity of the gratings is 310 nm. Right Core shell nanoparticles Au/silica/ATTO655.
Figure 2. Bi-exponential fitting of theoretical results versus the effective coupling to the plasmonic structure. (a) The superradiance and subradiance decay times $\tau_1$ and $\tau_2$ normalized by the decay time without metamaterial $\tau_0$. Dashed lines show average of $A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}$ over $0 < G < 14$ (b) the amplitudes at the exponents $A_1$ and $A_2$, dashed lines are average. (c) A ratio of the amplitudes, and a ratio of the decay times, (d) a ratio of the total number of photons (a product of the amplitude and life time).
Figure 6. The scheme of energy level for the case of a single two-level atom (Left); the scheme of energy level for the case of three two-level atoms: (Middle) bare state basis and (Right) the Dicke state basis. The dipole-allowed transitions are shown by blue lines. The mixing between Dicke states are shown by the dashed red lines.
Blackbody radiation

\[ J_\lambda = \frac{8\pi^2}{\lambda^4} \Delta \lambda \exp\left(\frac{hc}{k_B T \lambda}\right) - 1 \]
Biophotons vs blackbody radiation

A living cell

A rock
Biophotons, firefly

![Image of a firefly emitting light]

**Diagram:**

- **A:**
  - AkaLumine-HCl
  - d-luciferin
  - CycLuc1

- **B:**
  - Plot showing normalized BL intensity vs. BL wavelength (nm)
  - d-luciferin, CycLuc1, Aka-HCl
Figure 4: Comparison between the logistic equation prediction and experimental results of Ref. [42].
Figure 4: Comparison between the logistic equation prediction and experimental results of Ref. [42].
Biophotons

\[ |B⟩ = \sum_{i=1}^{N} \frac{|bb...a_i...b⟩}{\sqrt{N}} \]

\[ |D_j⟩ = \sum_{i=2}^{j} \frac{|bb...a_i...b⟩ - (j - 1)|bb...a_j...b⟩}{\sqrt{j(j-1)}} \]

\[ |B⟩ = \frac{|abbb⟩ + |babb⟩ + |bbab⟩ + |bbba⟩}{\sqrt{4}} \quad |D_3⟩ = \frac{|abbb⟩ + |babb⟩ - 2|bbab⟩}{\sqrt{6}} \]

\[ |D_2⟩ = \frac{|abbb⟩ - |babb⟩}{\sqrt{2}} \]

\[ |D_4⟩ = \frac{|abbb⟩ + |babb⟩ + |bbab⟩ - 3|bbba⟩}{\sqrt{12}} \]

\[ \Gamma_{eff} \approx \frac{1}{2} \left( \frac{\langle \delta \omega ⟩}{\Gamma_{col}} \right)^2 \gamma_{rad} \]
Conclusion

Properties of materials can be enhanced by the quantum coherent effects. We have shown that localized plasmon interaction in quantum confined structures strongly modify the optical and electronic properties with potential for manipulating light on the nanoscale.

- Transparency was observed in reduced graphene oxide near nanoparticles
- The molecular gas sensors based on adiabatic manipulation of the electric field have been experimentally demonstrated
- Manipulation of the absorption has been demonstrated in MoS2
- Ultra strong second harmonic generation has been shown in MoS2 promising the bright source of entanglement photons
- Control of the propagation of quantum fields using “quantum prisms”
- New area for quantum optics applications – quantum biology, biophotons, radiation produced by living tissues

We have demonstrated the quantum coherent effects are able to have an all-optical control, on ultrafast time scales, over the photonic topological transition, for applications as varied as quantum sensing, quantum information processing, and quantum simulations.

Thank you for your attention!
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Dr. Kamesh Namuduri, Department of Electrical Engineering
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PhD Students, Current
Colin Roy
MS. Mikaila Lapinski
MS. Steven Lanier
Erin Thornton
Trever Harborth
Brian Squires (together with Dr. Jingbiao Cui)
Cap Billi DeLuca (AFIT)
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Conclusion

Properties of materials can be enhanced by the quantum coherent effects. We have shown that localized plasmon interaction in quantum confined structures strongly modify the optical and electronic properties with potential for manipulating light on the nanoscale.

- Transparency was observed in reduced graphene oxide near nanoparticles
- The molecular gas sensors based on adiabatic manipulation of the electric field have been experimentally demonstrated
- Manipulation of the absorption has been demonstrated in MoS2
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