# Modulation Instability in Semiconductor Quantum Dots

Y-type Excitation Scheme

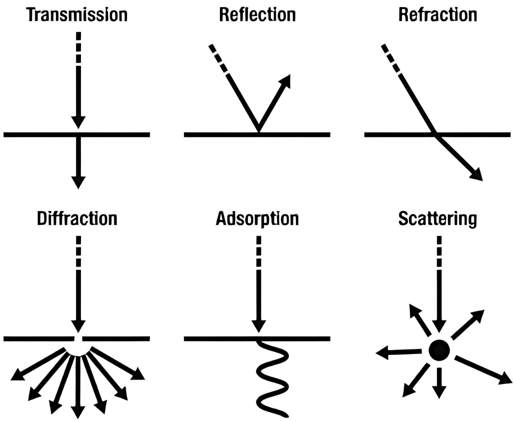
Shaon Samanta
Department of Physics (MSc.)
Sem-IV

*Supervised by,*
Dr. Rohit Mukherjee
Assistant Professor of Dept. of Physics (MSc.)
Sarala Birla University

# Overview

- Motivation: Understanding Modulation Instability (MI) in SQDs (Y-type excitation).
- Tools: Density matrix formalism, NLSE.
- Focus: Interpretation of numerical plots & physical insights.

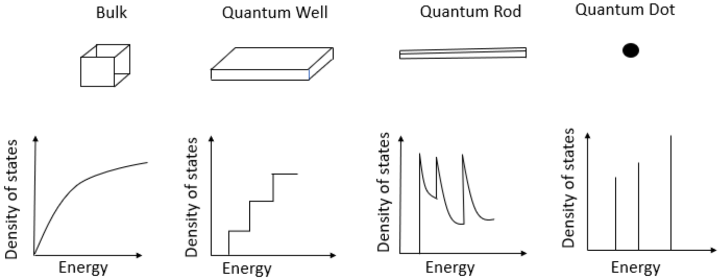
# Light Matter Interaction



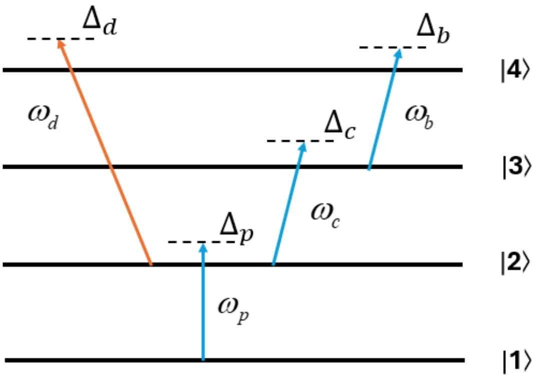

- Quantum dots confine charge carriers in all three dimensions.
- Enhanced interaction with electromagnetic fields due to confinement.
- Leads to strong nonlinear effects: Kerr nonlinearity, EIT, and MI.

# What are Semiconductor Quantum Dots

- Tiny semiconductor nanocrystals (2–10 nm in size).
- Exhibit size-dependent fluorescence, unique electronic properties, enhanced optical properties.
- Intermediate properties between bulk semiconductors and discrete molecules.



# Y-type Excitation Scheme in SQDs

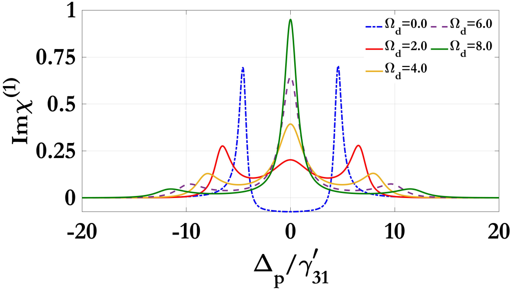



- Probe field couples levels $|1\rangle \to |2\rangle$.
- Control fields modulate transitions $|2\rangle \to |3\rangle$, $|3\rangle \to |4\rangle$.
- The interacting electric field inside QD is: $\vec{E} = \sum_{j=p,c,b} \hat{e}_j E_j e^{i(k_j z - \omega_j t)}$

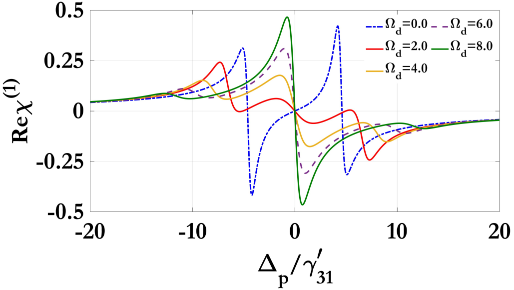
# Modulation Instability

- It is a process where a small perturbation on a Continuous Wave grows exponentially as it propagates through dispersive media.
- It happens due to interplay between nonlinear effects and dispersion.
- It produces the periodic wave train whose amplitude is high.
- It is a wave breaking process where stable wave become unstable and cause modulation instability

# Absorption & Dispersion Spectra



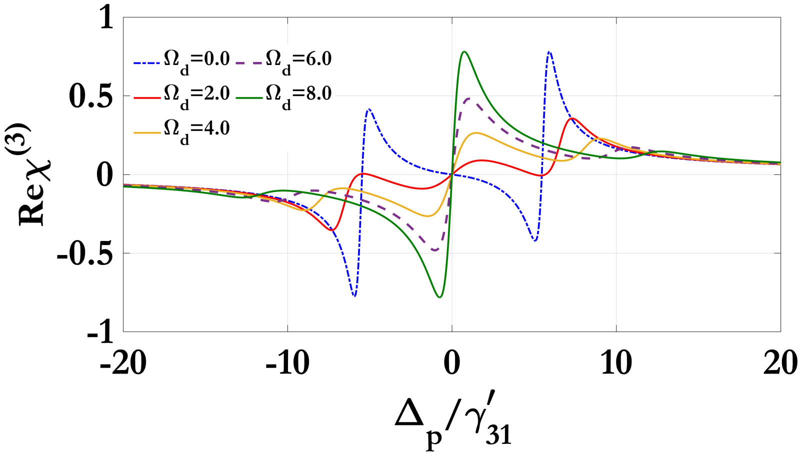

(a)




(b)

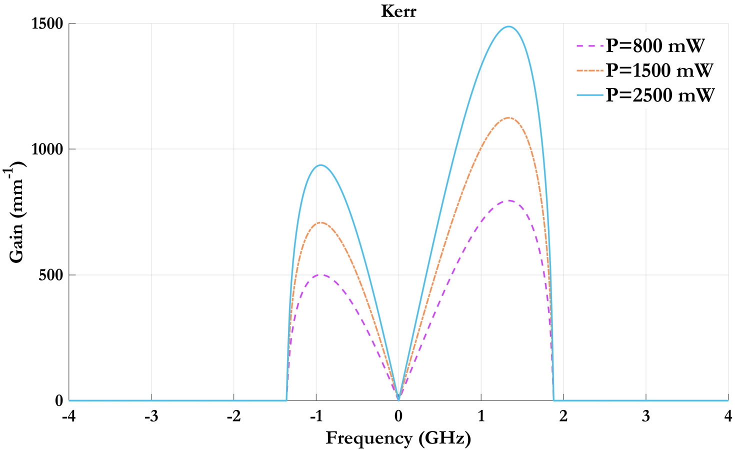
- $\Omega_d$ modifies absorption: transparency windows form.
- Side peaks grow $\Rightarrow$ indicative of coherent interference.
- Re $\chi^{(1)}$ slope changes $\Rightarrow$ group velocity control.

# Kerr Nonlinearity: Re $\chi^{(3)}$



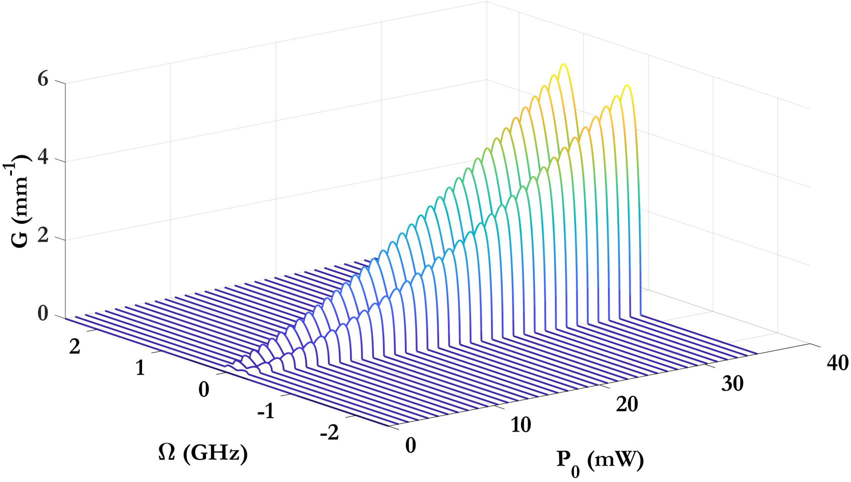

- $\Omega_c$, $\Omega_d$ enhance Kerr nonlinearity.
- Enables efficient four-wave mixing and phase modulation.
- $\chi^{(3)}$ control $\Rightarrow$ quantum gates, optical switches.

# Modulation Instability Gain




- MI gain shows symmetric sidebands $\Rightarrow$ phase matching.
- Gain increases with laser power.
- Peaks shift outward with higher nonlinear refractive index.

# MI Gain




- Fourth-order dispersion ($\beta_4$) broadens bandwidth.

# Conclusion & Applications

- SQDs exhibit tunable nonlinearity through coherent control.
- Applications:
- Quantum memory and communication
- Slow light and optical buffers
- Frequency combs and all-optical logic