Quantum
Photonics
Laboratory

Coherent Dynamics in Quantum Emitters under Dichromatic Excitation

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Summary

Available on arXiv:2009.02121 (2020)

- Resonant driving of solid-state quantum emitters generate on-demand, near perfect single photons.
- A major challenge is the limited (< 50%) collection efficiency due to the polarization filtering, typically used to suppress scattered laser.
- Dichromatic excitation, where a pair of phase-locked, equally-detuned (from the fundamental transition) laser pulses excites a two-level system, can mitigate this limitation, and enable background-free photon extraction from the emitter.
- We find that while dichromatic driving using symmetrically-weighted pulses is highly inefficient, excitation using asymmetric-weighted pulses enables efficient, coherent population control and complete population inversion.
- We verify this experimentally on a solid-state two-level system and show that while decoherence from the solid-state environment reduces the inversion fidelity, we demonstrate coherent control and much larger inversion efficiency in the asymmetric case, compared to the symmetric case.
- Our measured results, supported by simulations using a real-time path-integral method, offer a new perspective towards realizing efficient, background-free photon generation and extraction.

Dichromatic symmetric excitation

- Population occupation n_e

$$n_e(t) = \frac{1}{2}\left[1 - \cos\left(\int_{-\infty}^{t} 2\epsilon(t')\cos(\Delta\omega\, t')dt'\right)\right]$$

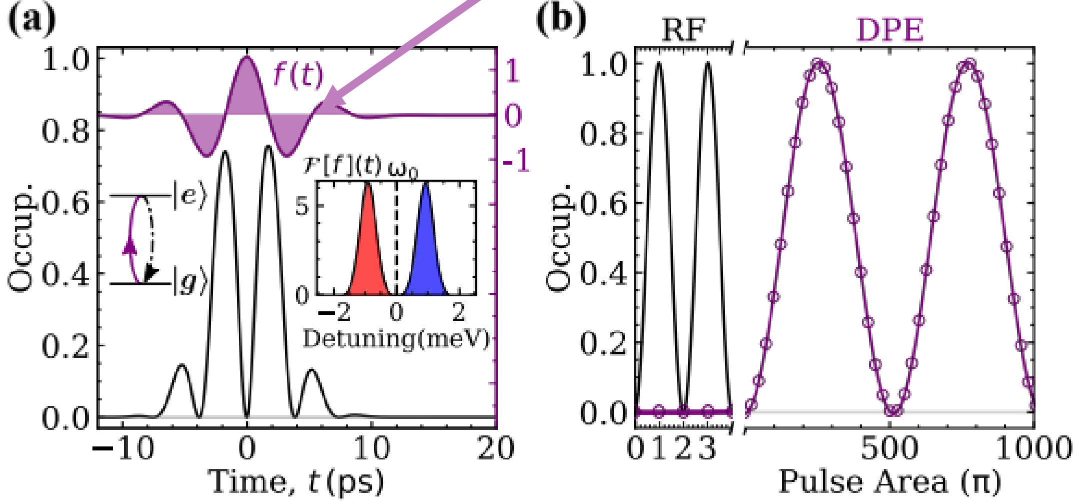
- at the long time limit (steady state):

$$n_e(t \to \infty) = \frac{1}{2}[1 - F[f](\omega = \omega_0)]$$

Fourier transform

- State occupation depends on spectral overlap of the laser and the atomic transition.

$$\boxed{f(t) = \epsilon(t)\cos(\Delta\omega\, t)\cos(\omega_0\, t) = \epsilon'(t)\cos(\omega_0\, t)}$$



(a) No spectral overlap means no population inversion at the long time limit. (b) Huge pulse areas needed for population inversion results in highly inefficient excitation.

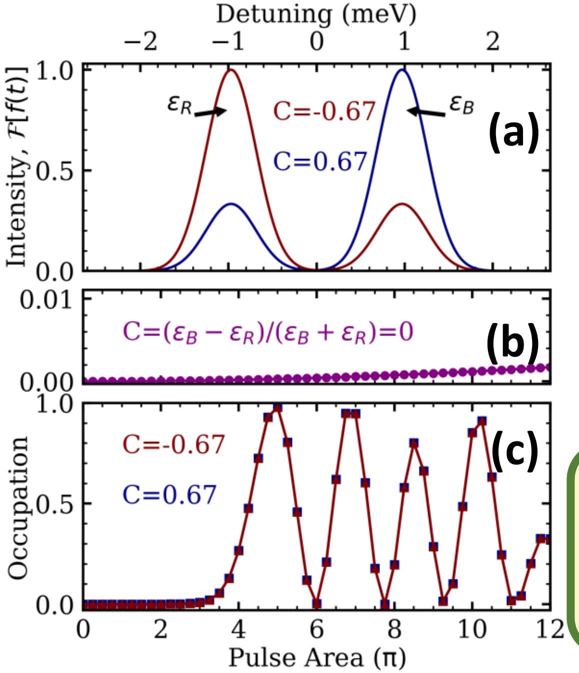
Dichromatic asymmetric excitation

- Excitation laser, $f(t)$ and the Hamiltonian, $\boldsymbol{H}$ of a two-level system can be written as

$$f(t) = \epsilon_R(t)e^{-i\Delta\omega\, t} + \epsilon_B(t)e^{i\Delta\omega\, t}$$
$$\boldsymbol{H} = \hbar/2(f(t)|g\rangle\langle e| + cc.) = \boldsymbol{\Omega}(t)\ \cdot \boldsymbol{s}$$

Where we express the two-level state as pseudo-spin Bloch vector $\boldsymbol{s}$ precessing about the time-dependent precession axis $\boldsymbol{\Omega}(t)$

$$\Omega(t) = \begin{pmatrix} Re[f(t)] \\ Im[f(t)] \\ 0 \end{pmatrix} = \begin{pmatrix} (\epsilon_R(t) + \epsilon_B(t))\cos(\Delta\omega\, t) \\ -(\epsilon_R(t) - \epsilon_B(t))\sin(\Delta\omega\, t) \\ 0 \end{pmatrix}$$

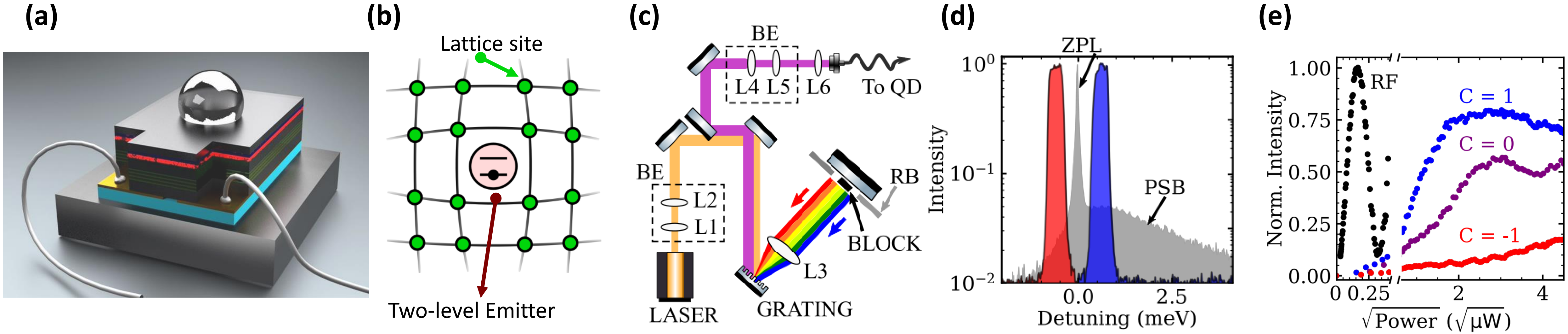


(a) Spectra of asymmetric pulses $\epsilon_R \neq \epsilon_B$ leads to $\Omega_y(t) \neq 0$. (b, c) Excited state occupation as a function of pulse area for symmetric (b) and asymmetric (c) (C= ± 0.67) pulses.

Asymmetric dichromatic driving enables **coherent control** and **efficient** population inversion.

Experimental realization of dichromatic excitation on a solid-state quantum emitter.

Pulse contrast, $C = (I_B - I_R)/(I_B + I_R)$



(a) Schematic of our solid-state device, consisting of semiconductor quantum dots sandwiched in Schottky-diode, which enables electric field control to deterministically load charges into the emitter.

(b) Artistic interpretation of the semiconductor quantum dot as a two-level emitter embedded in a lattice.

(c) Schematic of the dichromatic pulse generation using a folded 4f setup, with beam block removing the frequency component resonant to ZPL. The scattered photons from ZPL (zero-phonon line) are spectrally filtered from the PSB (phonon sideband) and excitation laser. L: Lenses, BE: Beam expander, RB: Razor blades

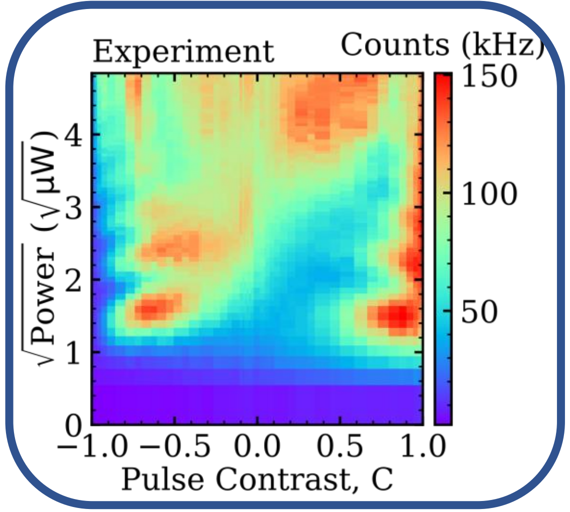
(d) Spectra of the excitation laser (red and blue) and the QD absorption (mirrored from the emission spectra, grey), as measured on a spectrometer.

(e) Emission count rate as a function of excitation power using excitation from monochromatic resonance fluorescence (RF), the red sideband (C=-1), blue sideband (C=1) and an equally weighted combination of the two (C=0), normalized to maximum intensity obtained via monochromatic resonant excitation.

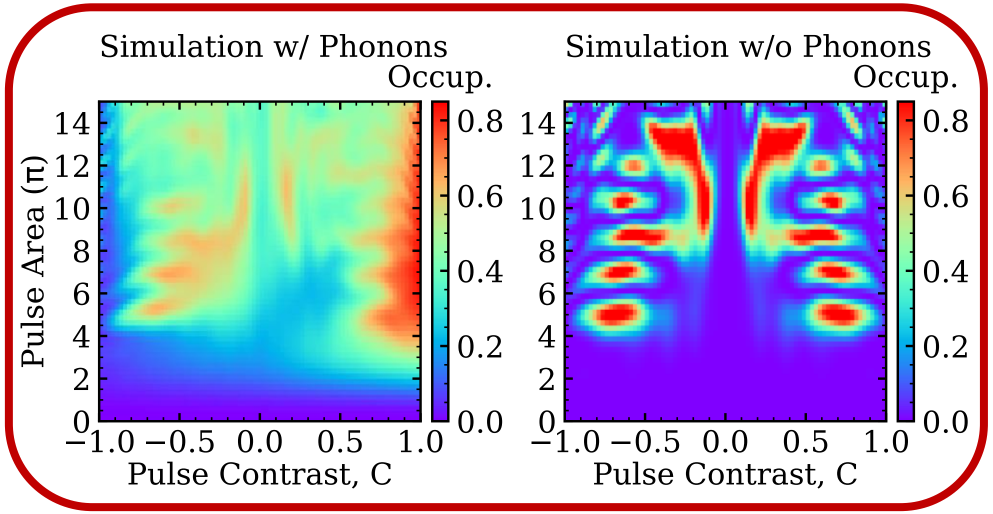
Coherent Dynamics and Single Photon Quality of a two-level system under asymmetric dichromatic excitation.

Coherent Dynamics

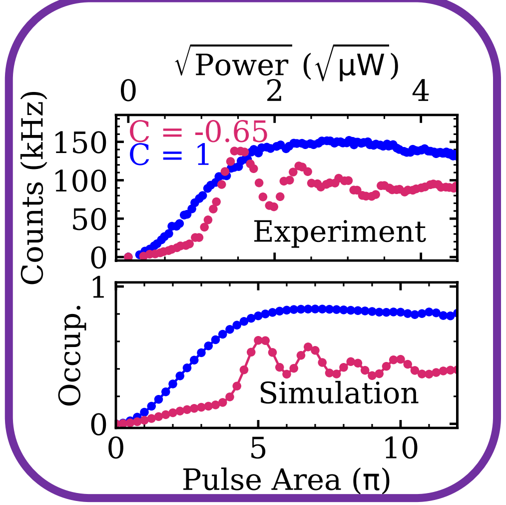
Experiment



Simulation

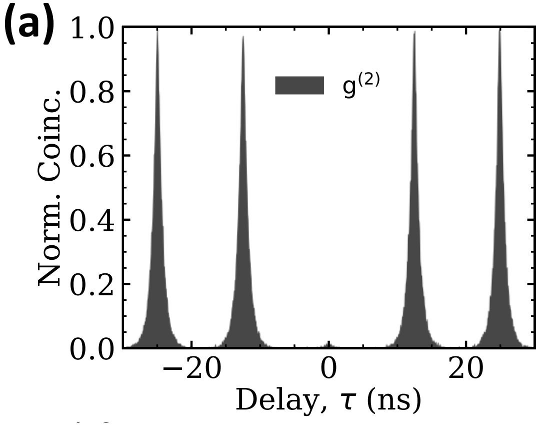


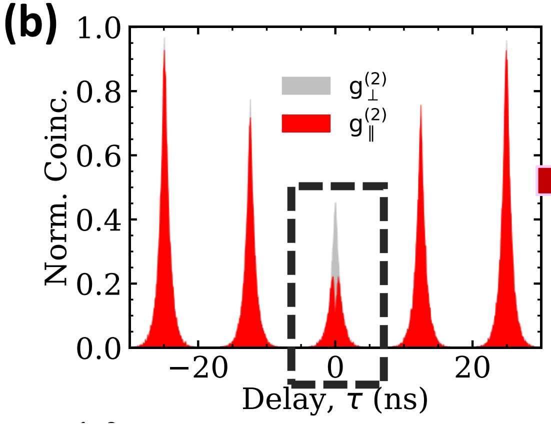
Comparison

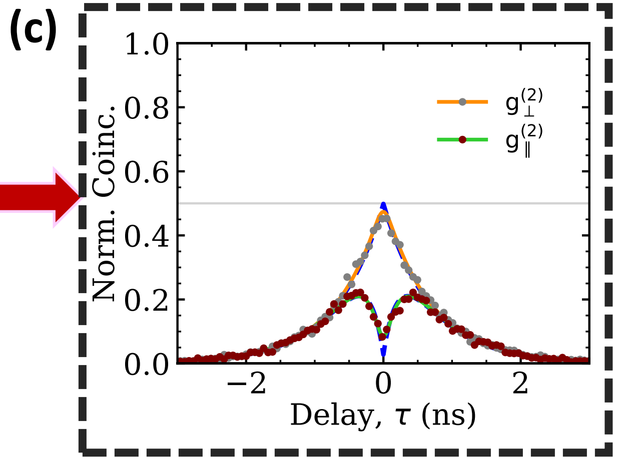


Good agreement between experimental and simulated data! This verifies our theoretical work.

Single photon Quality







Asymmetry dichromatic excitation leads to background free single photon emission (a) $(g^{(2)}(0) < 0.02)$ and non-classical photon indistinguishability (b, c) $(V_{HOM}^{0.1\,ns} > 0.8)$