Off-resonant excitation swing up of a quantum emitter

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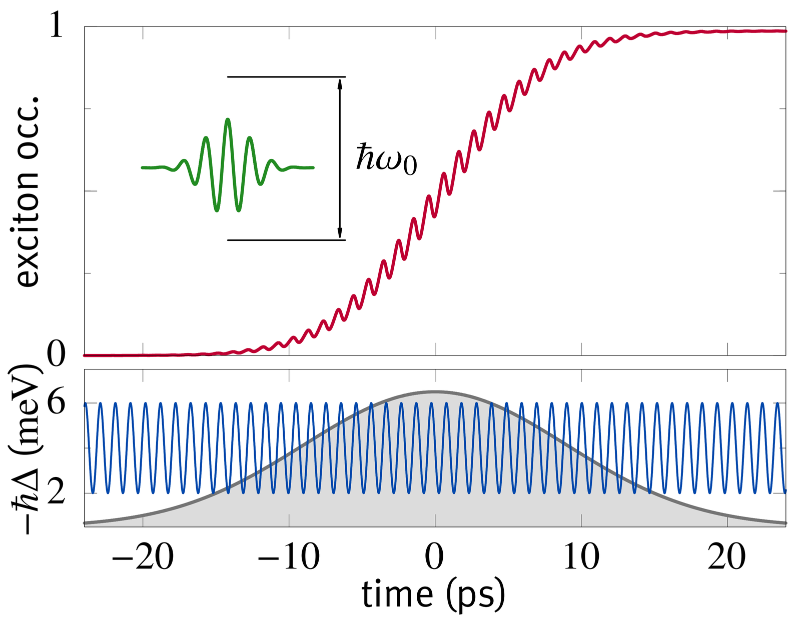
Introduction

Two level system (eg. Quantum dot):

- determinsitc preparation of the excited state needed for usage as single photon source
- existing scheme like Rabi rotations or phonon-assisted preparation with different advantages and disadvantages
- New proposal: TLS excited by modulated laser pulse

⇒ Modulation leads to a swing up of the excited state occupation



Two level dynamics

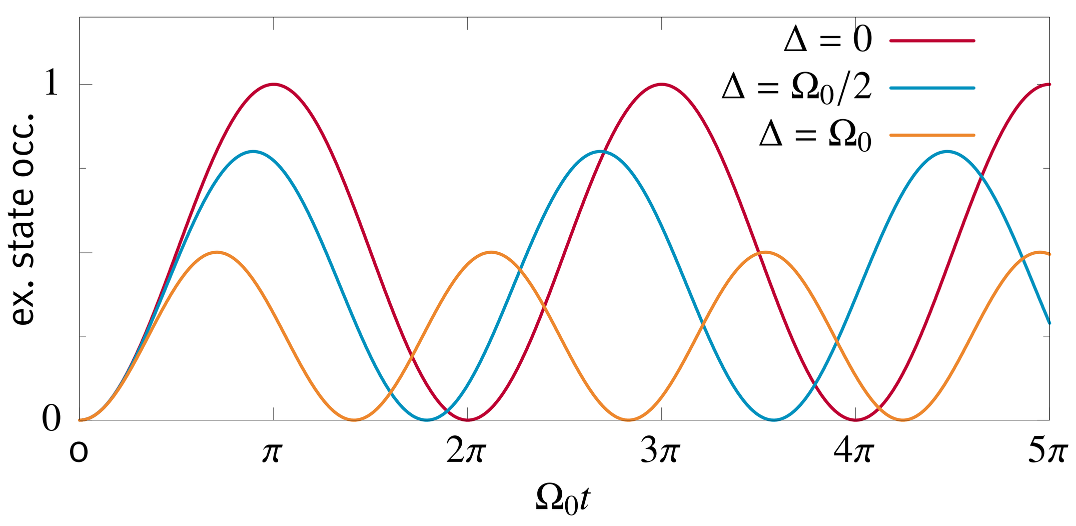
- Simple model: general TLS consisting of ground state $|g\rangle$ and excited state $|x\rangle$ with time-dependent driving term

$$H = \hbar\omega_0 |x\rangle\langle x| - \frac{\hbar}{2}\Omega^*(t)|g\rangle\langle x| - \frac{\hbar}{2}\Omega(t)|x\rangle\langle g|$$

- For constant driving, this system performs Rabi oscillations. If excited with frequency ω_L, the detuning is $\Delta = \omega_L - \omega_0$. For laser envelope Ω_0, the frequency Ω_R and amplitude a of the Rabi oscillations then reads

$$\Omega_R = \sqrt{\Omega_0^2 + \Delta^2}, \quad a = (\Omega_0/\Omega_R)^2$$

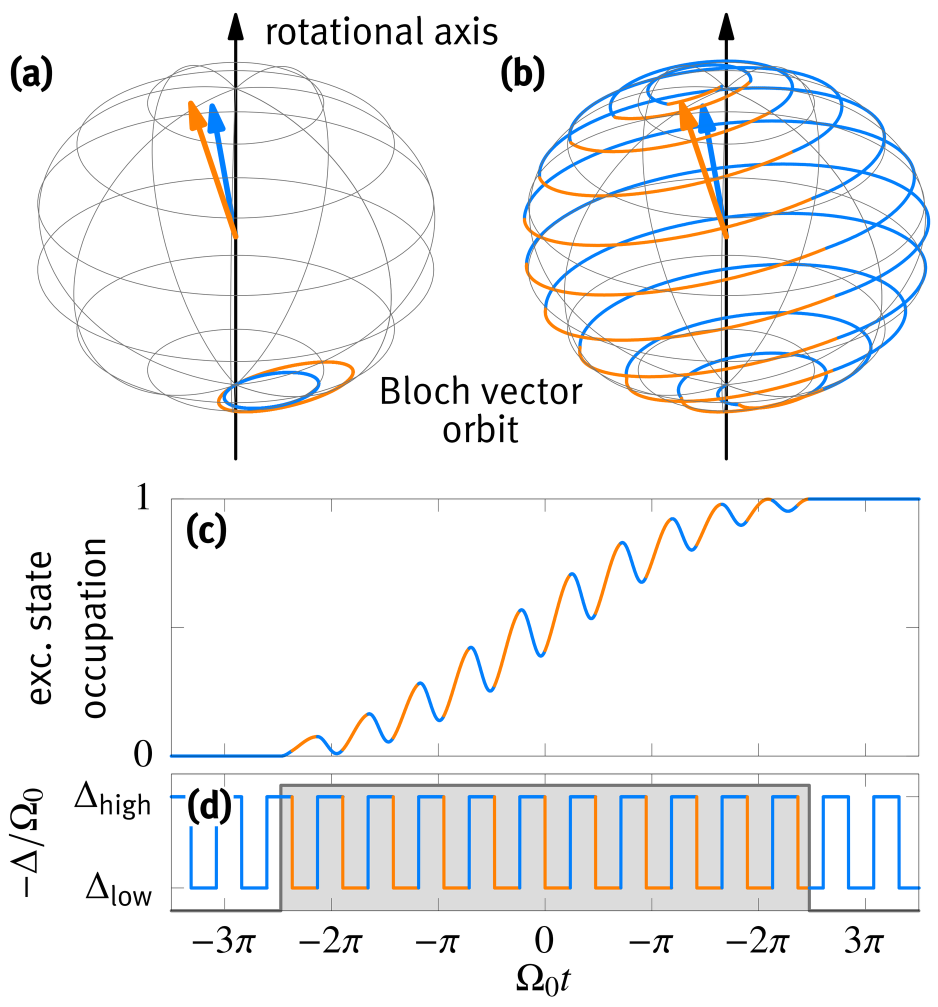
- For larger detuning, the oscillations are faster and the maximum occupation is decreased



⇒ **We want to combine different detunings to use the different amplitudes and Rabi frequencies to increase the occupation**

Swing-up using frequency modulation

- (a) detuned lasers do not lead to inversion
- (b) combination of both detunings: swing-up effect occurs
- for this, the frequency of the pulse is modulated, it switches between the two detunings
- (c) occupation dynamics for the bloch sphere in (b)
- (d) pulse shape and rectangular frequency modulation of the pulse



- The swing-up dynamics occur because of the different Rabi frequencies
- during the lower detuning (slow but higher amplitude Rabi oscillation) the occupation rises (orange color)
- during the higher detuning (fast but lower amplitude Rabi oscillation) the occupation falls (blue color)
- the switching occurs with the rabi frequency $\Omega_R = \sqrt{\Omega_0^2 + \Delta^2}$ induced by a constant pulse with mean detuning $\Delta = (\Delta_{high} + \Delta_{low})/2$

The same effect can be used with Gaussian pulses!

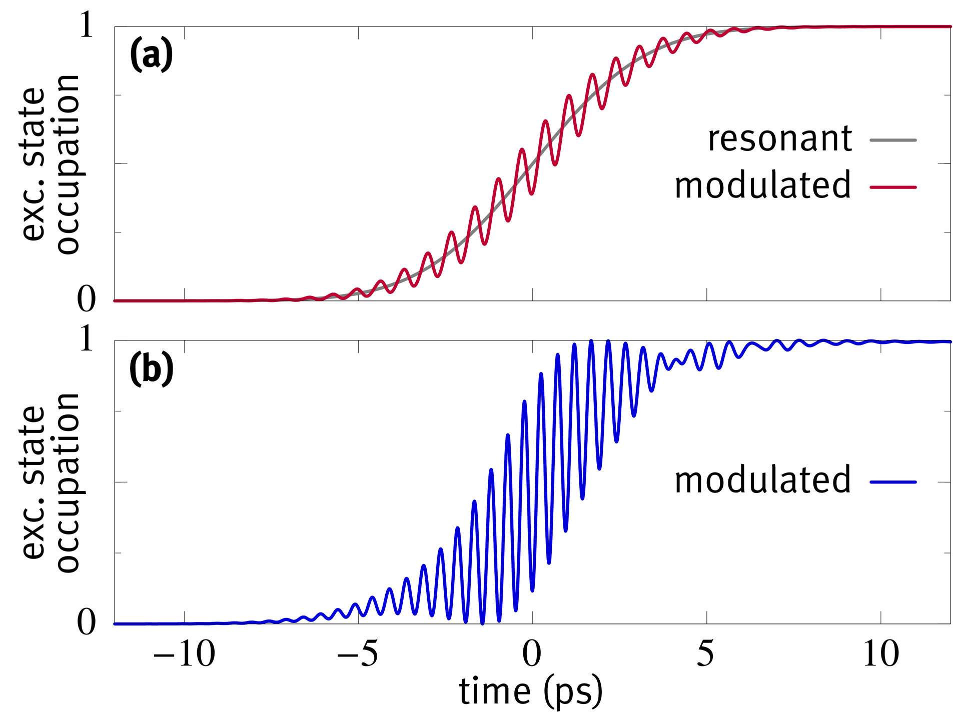
$$\Omega(t) = \Omega_0(t)e^{-i\phi(t)}, \quad \Omega_0(t) = \frac{\alpha}{\sqrt{2\pi\sigma^2}}e^{-t^2/(2\sigma^2)}$$

We choose a smooth modulation with a frequency ω_M close to the Rabi frequency at the pulse maximum

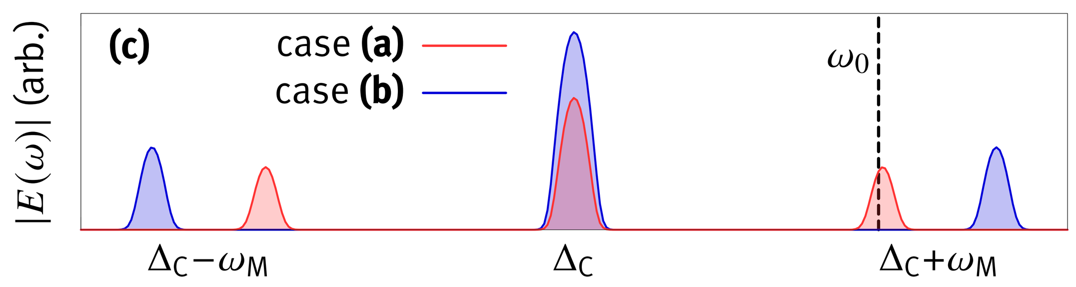
$$\Delta(t) = \Delta_C + \Delta_M \sin(\omega_M t), \quad \omega_M \approx \sqrt{\Omega_0^2 + \Delta_C^2} \qquad (1)$$

Frequency modulation: side bands and performance

- We now use specific parameters: $\hbar\Delta_C = -6\,\text{meV}$ and $\sigma = 4\,\text{ps}$
- (a) $\hbar\Delta_M = 2\,\text{meV}$, $\alpha = 6.2\pi$ which leads to $\hbar\omega_M = 6.08\,\text{meV}$
  → in this case, $|\omega_M| \approx \Delta_C$
- (b) $\hbar\Delta_M = 1\,\text{meV}$, $\alpha = 30.3\pi$, $\hbar\omega_M = 8.32\,\text{meV}$
  → here, $\hbar\Delta_C - \hbar|\omega_M| > 2\,\text{meV}$



- (a) has a shape very similar to that of a resonant excitation, overlayed with small oscillations
- (b) looks distinct from (a) in that it shows high-amplitude oscillations and an irregularity towards the end of the pulse
- In all cases, the frequency modulation leads to side-bands in the spectrum, depending on the amplitude and frequency of the modulation term in Eq. 1
- (c) shows the spectrum of the laser pulses used in (a) and (b). For (a), a resonant side band exists while **in (b) no spectral components are resonant**



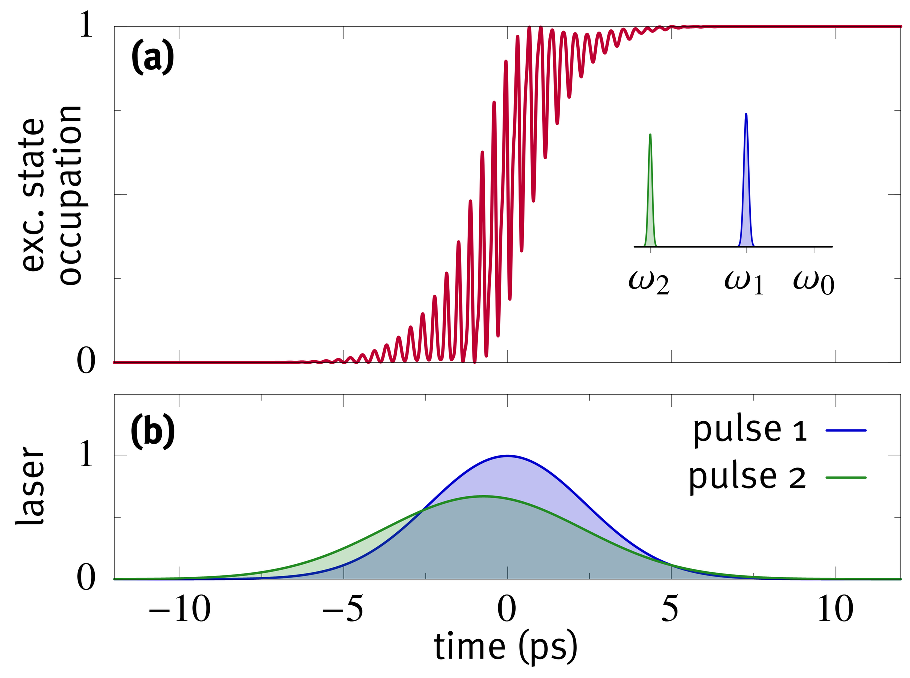
Two color approach

- In the scheme using frequency modulation, multiple spectral components of the pulse exist, spaced by the modulation frequency corresponding to the Rabi frequency at the pulse maximum

→ **Use two pulses, with the second pulsed spectrally displaced by the Rabi frequency corresponding to the first one**

- this can also be understood as an amplitude modulation due to the beat effect of the two lasers

- (a) time evolution of exciton occupation for pulse sequence in (b)
- pulse 1: $\sigma = 2.4\,\text{ps}$, $\alpha = 22.65\,\pi$, $\Delta = -8\,\text{meV}$
- pulse 2: $\sigma = 3.04\,\text{ps}$, $\alpha = 19.29\,\pi$, $\Delta = -19.163\,\text{meV}$
- pulse separation: $0.73\,\text{ps}$



- for the two color scheme, the driving laser is

$$\Omega(t) = \Omega_1(t)e^{-i\omega_1 t} + \Omega_2(t-\tau)e^{-i\omega_2 t}$$

→ the two pulses now have a constant frequency!

- We choose the detuning of the first pulse and then calculate that of the second:

$$\Delta_2 = \Delta_1 - \sqrt{\Omega_1^2(t=0) + \Delta_1^2} \qquad (2)$$

→ this is always less than Δ_1. If Δ_1 is below the transition energy, so is Δ_2

If we choose $\Delta_1 < 0$, both pulses are below the transition energy. The excitation then happens in the transparent region of the material

Conclusions

- Modulation of the pulses opens up a class of interesting excitation schemes
- Using these schemes, true off-resonant excitation can be achieved, relying only on the carrier-light interaction
- This is universal for all driven two-level systems!

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