BEAM DENSITY MODULATION DURING EMISSION USING RF AND LASER FIELDS

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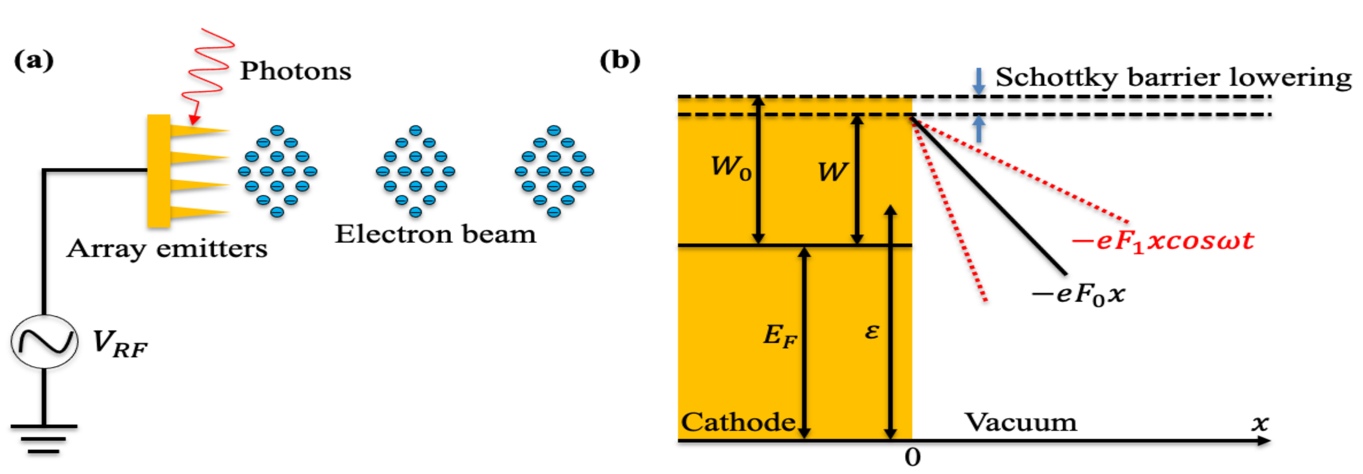
I. Abstract

We analyze the emission of density modulated electron beams of different temporal shapes under the excitation of combined radio frequency (RF) field and a continuous wave (CW) or pulsed laser field, using an exact quantum model for photo-/field-emission [1- 4].

II. Motivation

- **Electron beam sources** are critical to many applications such as accelerators, X-ray sources, and microwave sources and **amplifiers**.
- Traveling wave tubes (TWTs) rely on electron beam **bunching** or **density modulation** to achieve signal amplification.
- If we can generate an electron beam with **direct density modulation during its emission**, rather than modifying a continuous beam in an RF interaction region to achieve density modulation, the operation performance of the TWT can be greatly enhanced.
- Combining RF electric field and a laser field is expected to achieve the same current level with significantly reduced RF field strength, as compared to RF field emission alone. Thus, it can prevent instability induced by poor vacuum conditions when pressed local electric field at the nanotip is close to the field emission threshold. The occurrence of arcs may also be diminished as the relevant heating effect during emission is restrained to short temporal pulses with density modulation [5].

III. Quantum model



$E_F = 5.53$ eV: Fermi energy

ε: the initial energy

$W_0 = 5.1$ **eV**: work function of the gold cathode

W: effective work function

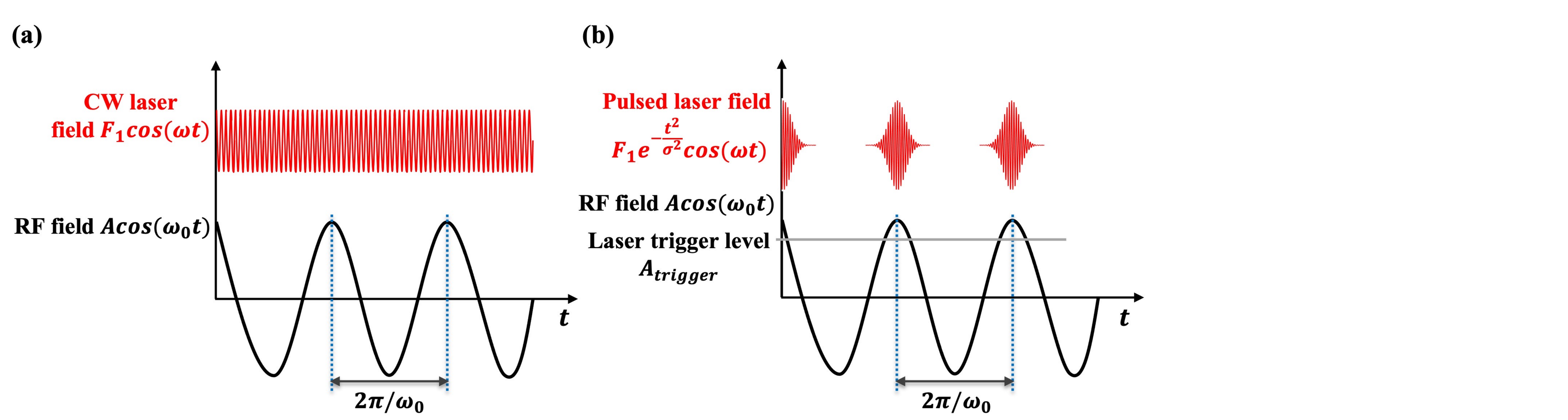
$F_0 = A\cos\omega_0 t$: **RF field,** with A and ω_0 being the amplitude and angular frequency.

$F_1\cos\omega t$: **laser field**

Consider the combination of **RF field** with **photon/laser field**, we solve time-dependent Schrödinger equation:

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial t^2} + \Phi(x,t)\psi(x,t)$$

where $\Phi(x,t) = \begin{cases} 0, & x < 0 \\ E_F + W - eF_0x - eF_1\cos\omega t x, & x \geq 0 \end{cases}$



F_1 being **continuous wave** (CW)

F_1 being **Gaussian profile** as $F_1e^{-t^2/\sigma^2}$, with $\sigma = \frac{\tau_p}{2\sqrt{\ln 2}}$, and τ_p being the **pulsed laser duration**

The time-averaged electron transmission probability from the energy level of ε,

$$D(\varepsilon) = \sum_{n=-\infty}^{\infty} w_n(\varepsilon),$$

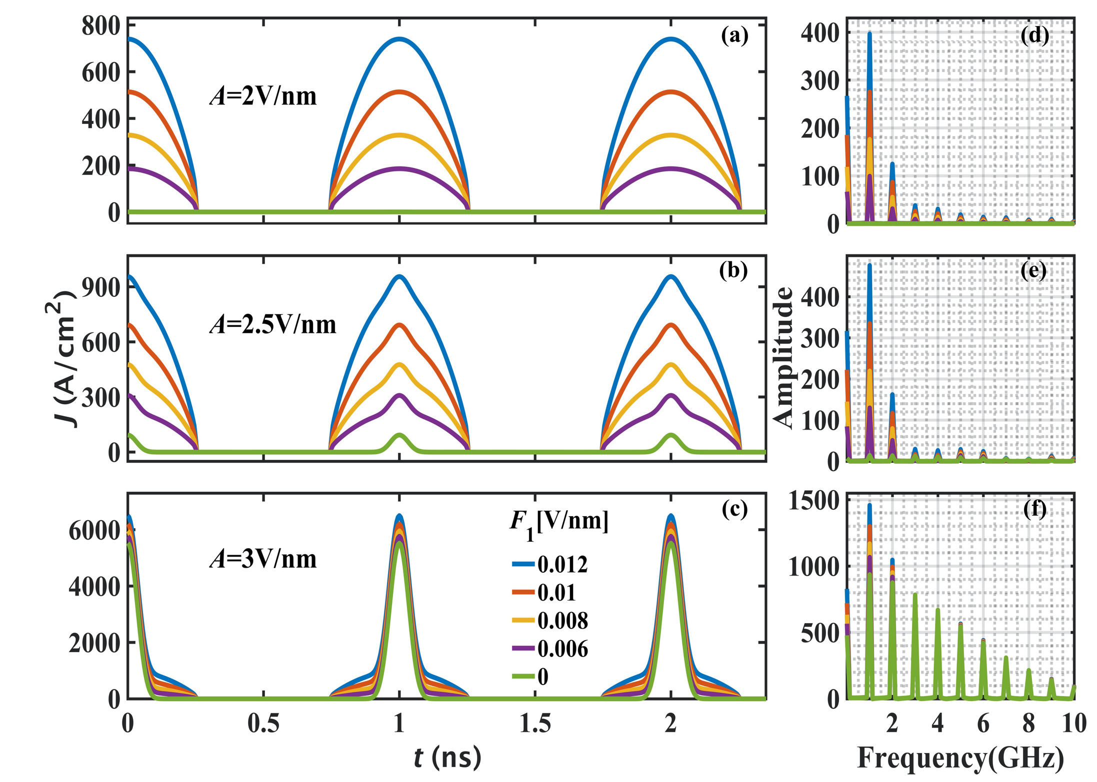
where $w_n(\varepsilon)$ denotes the electron transmission probability through the n-photon process.

Thus, the **total emission current density**:

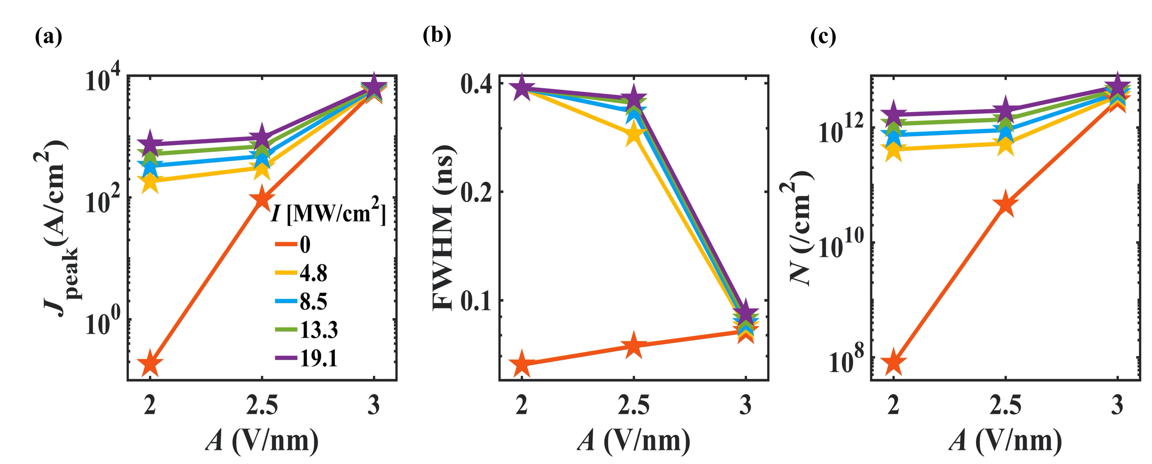
$$J = e\int_0^\infty D(\varepsilon)N(\varepsilon)d\varepsilon,$$

where $N(\varepsilon) = \frac{mk_BT}{2\pi^2\hbar^3}\ln\left[1+\exp\left(\frac{E_F-\varepsilon}{k_BT}\right)\right]$ is the supply function derived from the free electron model for metal.

IV. Emission under RF and CW optical fields



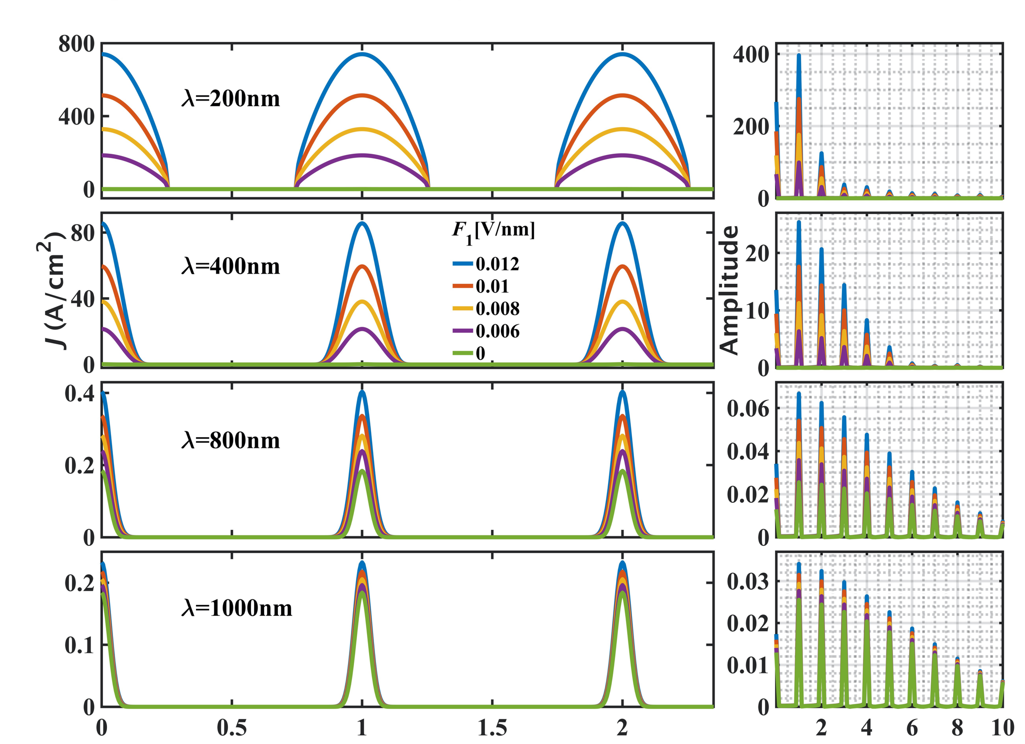
- When the RF field dominates the emission process, the shape of the temporal emission current density is in **Gaussian profile**.
- When the laser field dominates the emission process, the current density profiles change towards a **sinusoidal shape.**



- (a) shows that the peak emission current density increases with the RF field.
- (b) shows the full width at half maximum (FWHM) under different RF fields.
- (c) shows the number of emitted electron flux per RF cycle, N, which is calculated by,

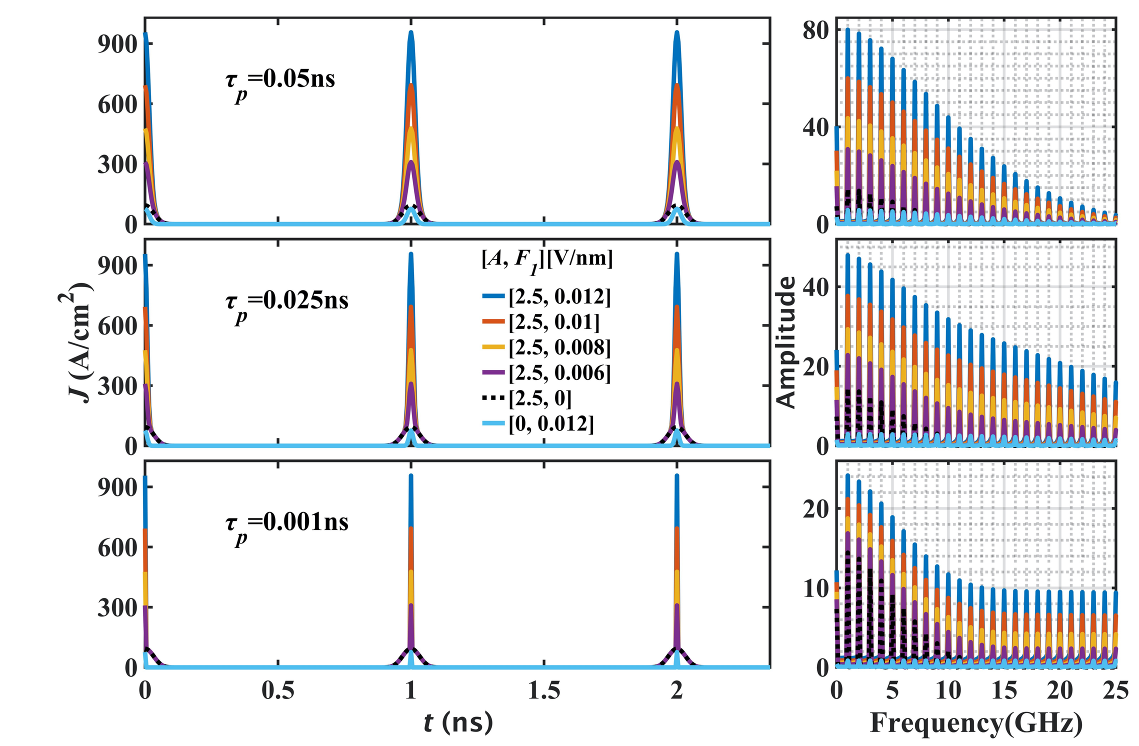
$$N = \frac{1}{e}\int_0^{2\pi/\omega_0} J(t)dt,$$

where $J(t)$ is the temporal emission current density.

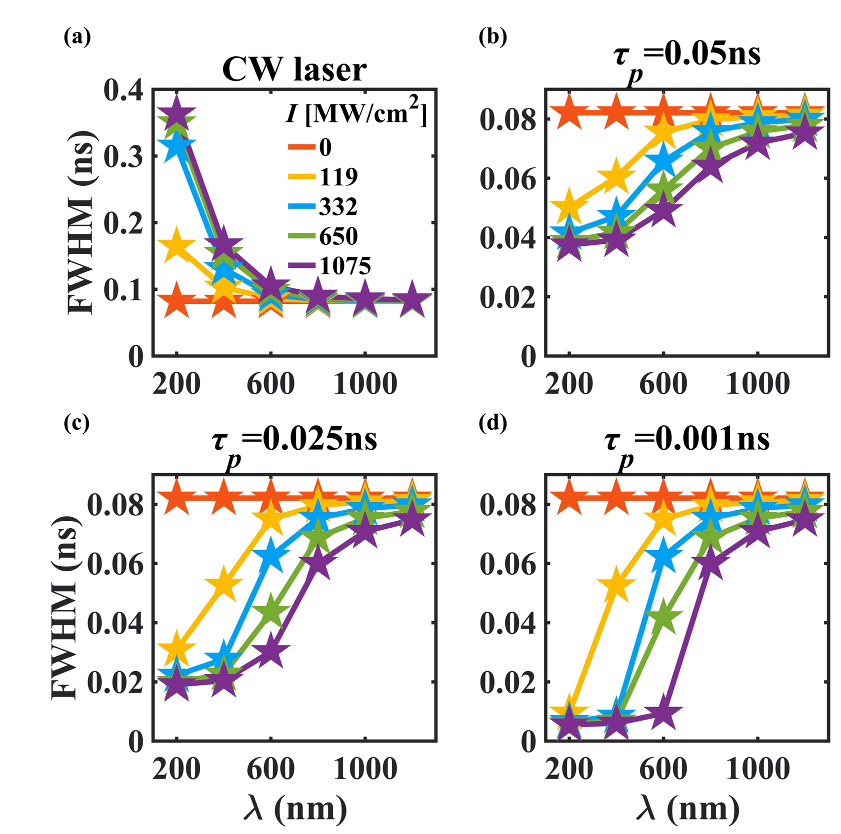


- Emission current density **decreases** rapidly as laser wavelength increases.
- There appears more **higher-harmonic** contents in the density-modulated electron beam as laser wavelength increases.

V. Emission under RF and pulsed laser fields



- The width of the electron beam can be controlled by the **laser pulse duration** τ_p.
- As τ_p decreases, the reduction of higher harmonics becomes slower.



- For a pulsed laser, the **pulse width of the emission current density** increases with laser wavelength for a given **laser intensity**, while it decreases with the laser intensity for a given **laser wavelength**. The emitted current pulse width is more sensitive to laser intensity for shorter laser wavelengths.

VI. Conclusion

- We explore **direct density modulation** of high current electron beam during its emission from an RF cold cathode using optical excitation.
- The **shape** of the temporal emission current density varies in different combinations of the RF field and laser field.
- The presence of photons provides significant flexibility in controlling the emission current by varying **intensity**, **wavelength**, and **pulse length** of the optical field.
- **Pulsed photon/optical sources together with an RF field** can produce sharp, high-current electron bunches with pulse duration comparable with or even less than that of the optical pulse.
- The emission current pulse amplitude, beam width (i.e., FWHM of the current pulse), and electron numbers per pulse, as well as the harmonic spectrum, are investigated in detail under various combinations of RF and optical fields.

References

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