Two-Color Laser Induced Electron Emission from Biased Metal Surface

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Abstract: *By solving the time-dependent Schrödinger equation, we construct an exact analytical solution for nonlinear ultrafast electron emission from a dc-biased metal surface illuminated by two-color laser fields. Our results show a large dc bias can significantly increase the photoemission current, while maintaining a strong current modulation with respect to the phase delay of the two-color lasers. Application of our model to time-resolved photoelectron spectroscopy shows the dynamics of n-photon exited states depends strongly on the dc field.*

Keywords: ultrafast photoemission; field emission; two-color lasers; analytical solution; current modulation depth.

Introduction

Electron emission from nanostructures, as driven by high-intensity lasers, is a robust method to control electron dynamics in ultrafast scales. It is important to the development of time-resolved electron microscopes, tabletop particle accelerators, free electron lasers, and nanoscale vacuum electronics [1-3]. Recently, photoelectron emission from nanotips driven by two-color lasers has aroused intense interests [4-6], because of the relatively straightforward manipulation of two-color waveform and the substantial emission current modulation depth. However, the role of dc bias on two-color photoemission processes is not well studied. In this work, we present an exact analytical solution for nonlinear ultrafast photoemission from a dc-biased metal surface driven by two-color laser fields, by the solving time-dependent Schrödinger equation (TDSE) exactly [6-8]. Combined effects of a dc electric field and two-color laser fields are systematically analyzed.

Our one-dimensional (1D) model (see Fig. 1) considers electrons with initial energy ε emitted from a metal surface at x = 0 under a dc electric field F_0 and the illumination of two-color laser fields $F_1\cos(\omega t)$ and $F_2\cos(\beta\omega t+\theta)$, where F_1 and F_2 are the amplitudes of laser fields, ω is the fundamental laser frequency, β is a positive integer, and θ is the relative phase [8]. The potential energy can be written as $\Phi(x,t)$ = 0 for $x<0$ inside the metal, and $\Phi(x,t)=W+E_F-exF_0-exF_1\cos(\omega t)-exF_2\cos(\beta\omega t+\theta)$ for $x>0$ in the vaccum, where E_F and W are the metal Fermi energy and work function respectively. By solving TDSE,

$$i\hbar\frac{\partial\psi(x,t)}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2}+\Phi(x,t)\psi(x,t), \qquad (1)$$

the exact solution of electron wave function $\psi(x,t)$ for $x<0$ and $x>0$ is obtained [8], which denotes the superposition of a set of electron waves with eigenenergies $\varepsilon+n\hbar\omega$. By applying boundary conditions that both $\psi(x,t)$ and $\partial\psi(x,t)/\partial x$ are continuous at x = 0, the amplitude of wave function at each state can be determined. Following the probability current density $J(x,t)=(i\hbar/2m)(\psi\nabla\psi^*-\psi^*\nabla\psi)$, the normalized emission current density, defined as the ratio of the transmitted current density over the incident current density, $w(\varepsilon,x,t)=J_t(\varepsilon,x,t)/J_i(\varepsilon,x,t)$, is calculated.

Photoelectron energy spectra for different in-phase (θ=0) two-color ω-laser F_1 and 2ω-laser F_2, and dc fields F_0 are shown in Fig. 2 [8]. The default values for the calculations are E_F= 5.53 eV, W=5.1 eV (gold); $\hbar\omega$=1.55 eV (λ=800 nm). When F_0 is turned off (Fig. 2(a)), the dominant emission process is four-photon absorption (n = 4) for the ω-laser F_1, indicating electrons at the Fermi level need to absorb at least four photons to overcome the potential barrier ($W/\hbar\omega=3.29$). Applying a strong dc field F_0 opens more tunneling emission channels ($n<$ 4) as shown in Fig. 2(b). For a fixed F_0, the energy spectra become broader as F_1 increases, because higher order n-photon processes contribute to the photoemission.

Figure 3 shows the combined effects of the dc field F_0 and the interference between two-color lasers on the total emission current density $\langle w\rangle$ and modulation depth Γ. As shown in Fig. 3(a), $\langle w\rangle$ oscillates as a function of θ with a period of 2π, and the maximum (minimum) values of $\langle w\rangle$ occur around θ=0 (π) for a given F_0. The modulation depth, $\Gamma=(\langle w\rangle_{max}-\langle w\rangle_{min})/(\langle w\rangle_{max}+\langle w\rangle_{min})$, as a function of F_0 is shown in Fig. 3(b). As F_0 increases, Γ decreases. However, for F_0 up to 3 V/nm (>> the laser fields $F_1=1.6$ V/nm and $F_2=0.22$ V/nm), strong emission current modulation still persists ($\Gamma\geq 70\%$), with significantly increased total photoemission current. This suggests a practical way to maintain an intense modulation to high-current photoemission, by simply adding a strong dc bias and a weak harmonic laser [8].

Application of our model to the time-resolved photoelectron spectroscopy of a tungsten nanotip is shown in Fig. 4. When the dc field is small, $F_0=0.01$ V/nm, n-photon excited states are modulated in the same way as a function of the phase delay θ. However, when F_0 = 0.09 V/nm, the excited states behave differently with respect to θ. This demonstrates the dynamics of n-photon exited states due to two-color lasers depends strongly on the dc bias.

Acknowledgements

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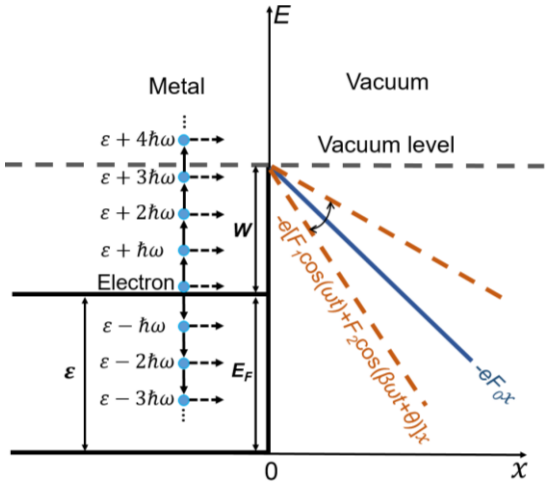

Figure 1. Energy diagram for electron emission under two-color laser fields and a dc bias. Electrons with initial energy of ε are emitted by absorbing photon energy $n\hbar\omega$, with n being an integer [8].

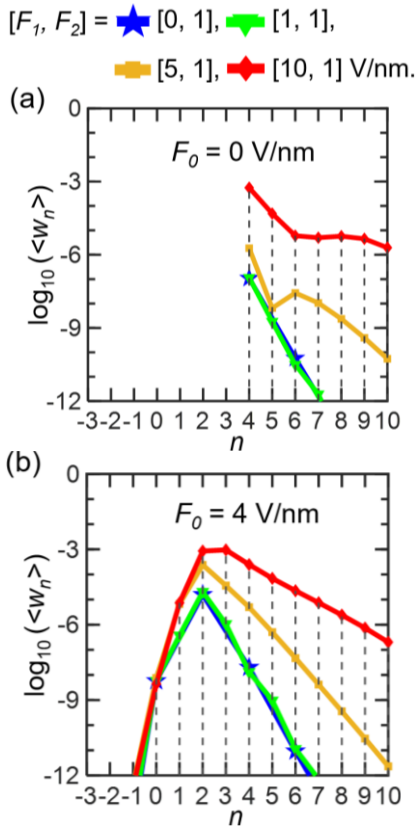

Figure 2. Photoelectron energy spectra under different in-phase (i.e. θ=0) laser fields and dc fields.

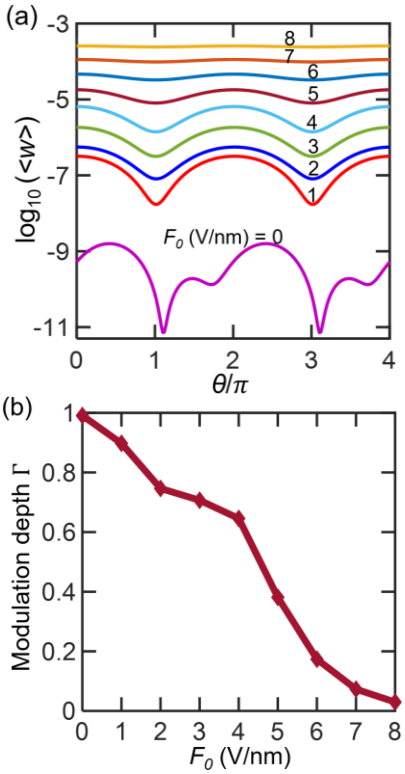

Figure 3. Emission current modulation depth $\Gamma = (\langle w\rangle_{max} - \langle w\rangle_{min})/(\langle w\rangle_{max} + \langle w\rangle_{min})$. Here, ω-laser field F_1 and 2ω-laser field F_2 are 1.6 and 0.22 V/nm respectively.

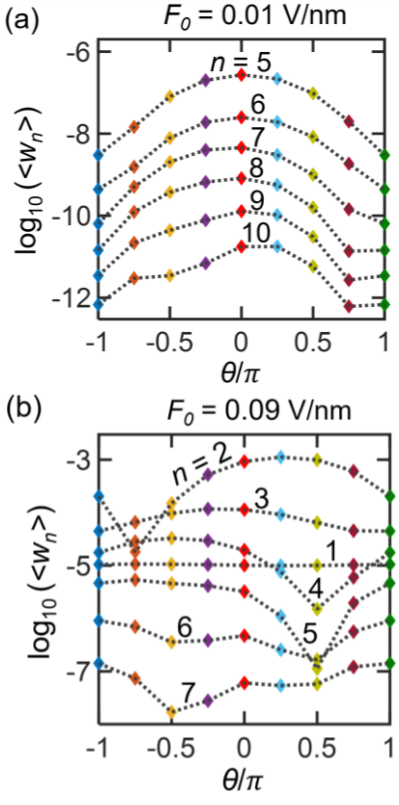

Figure 4. Time-resolved photoelectron energy spectra for the tungsten nanotip. Here, the fundamental (1560 nm) laser field F_1=1.8 V/nm and the second harmonic laser field F_2=0.3 V/nm.