Plasmon-assisted double-gate field emitter arrays

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Abstract— **Electron pulses down to the femtoseconds duration can be generated by exciting metallic nanotips by ultrafast laser pulses. Using an array of metal nanotips, one can generate high-bunch charge pulses with ~10^7 electrons. Double-gate field emitter arrays with sub-micron pitch nano-tips combined with the surface plasmon polariton resonance of the gate electrode and the beam collimation performance of the stacked-double-gate structure have been proposed recently to further enhance the electron yield and reduce the beam emittance aiming at realizing a ultrabright cathode for the X-ray free-electron lasers and THz vacuum electronic amplifiers, In this work, we present the detailed numerical studies of the proposed structure to elucidate the physical process that enables the efficient tip-laser couplings.**

Keywords—field emission; free-electron laser; extraordinary transmission; surface plasmon; vacuum electronic

I. INTRODUCTION

Generation of electron beam from metal nanotips excited by femtosecond near infrared lasers because of the high beam brightness of the field emission beam combined with possibility to create ultrafast electron pulses. To create an extremely low emittance, ultrafast electron pulses with and high charge, recent study proposed to assemble the metal nanotips as an array and combine with the stacked-double-gate structure that is also in resonant with the excitation near infrared laser pulses via the surface plasmon polariton of the gate layers [1,2]. Such nano-tip emitters are of interesting for applications e.g. the THz vacuum electronic oscillators and amplifiers, cathodes for x-ray free electron lasers (FELs), as well as time-resolved microscopy. X-ray FELs such as the Swiss FEL demand a cathode with a most stringent specification: 200 pC, 10 ps electron pulses with an intrinsic transverse emittance below 0.2 mm-mrad [3]. To achieve this, the electron yield of the field emitter array (FEA) per near infrared laser photons has to be enhanced to minimize the array size for the low beam emittance requirement. A recently suggested promising method involves reducing the period of tips to increase the emitter density and tuning the modulated surface plasmon polariton (SPP) resonance on the gate electrode to the photon energy of the illuminating laser pulses. Via the extraordinary transmission (EOT) effect through the gate apertures and the coupling of the light to the metal tip apex, the electron excitation efficiency by near infrared laser pulses can be significantly enhanced at the metal tip apex. Together with the experimentally obtained electron yield from individual molybdenum by near infrared laser pulses and the particle tracking simulation of the transverse velocity spread of the beam, we proposed that 0.1 mJ near infrared laser pulses can generate 200-pC electron pulses from 10^6 tip FEAs with stacked-double-gate structure with an array diameter of 1 mm [2].

The resonance frequency of the resonant enhancement of the tip-field coupling is closely related to the EOT of sub-wavelength nano-aperture array defined on a metal film. In Ref. [1], this was shown in the case of the single-gate FEA. However, precise physical mechanism and the quantitative relation between the SPP resonance and the tip-light coupling in double-gate layer structures are yet to be elucidated. In this work, we therefore analyzed these phenomena numerically.

II. NUMERICAL METHOD

We studied the electromagnetic distribution and the expected electron beam performance using the 3-dimensional double-gate emitter model, Fig. 1: cone-shaped molybdenum nanotip arrays with the apex radius of curvature of 5 nm aligned with the array period of 750 nm. We assumed copper as the material of the electron extraction gate G_{ex} and the collimation gate G_{col} layers. The tip/aperture period corresponds to the SPP resonance wavelength near 800 nm. The aperture diameters are equal to 200 nm and 600 nm, respectively for G_{ex} and G_{col}. To have a finite tip-field enhancement, the tip position x_{tip} is shifted [1,2] by 30 nm from

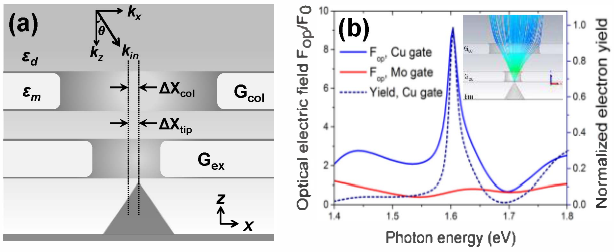

Fig. 1. Cross-sectional view of the model along the *x–z* plane, from the side. The thickness of the copper gate layer is 50 nm, and the separations between G_{col} and G_{ex} and between G_{ex} and the Mo emitter are both 120 nm. (b) Relation between yield of electrons generated by laser illumination and photon energy, normalized by the peak value of 1.6 eV. The ratio of the optical electric field F_{op} at the tip apex center to the field of the incident field (F_0) is also shown. In set presents trajectories of electrons calculated at V_{ext} = 70 V, V_{col} = 76 V, F_{acc} of 100 MV/m. The figure shows the tranjectories along *x-z* plane.

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the G_{ex} center. The center of G_{col} was shifted by Δx_{col} equal to 30 nm to minimize the beam divergence. For comparison, we also calculated the optical transmission through nano-aperture arrays without emitters. The electro-magnetic field and the beam trajectories and emittance of the laser-induced field emission beam were calculated using an adaptive tetrahedral-mesh 3-dimensional finite-element code (Comsol Multiphysics) and an adaptive hexahedral-mesh 3-dimensional simulator (CST particle studio), respectively. Floquet boundary condition was used to simulate the electro-magnetic distribution of a large array with oblique incident wave.

III. RESULT

In Fig. 1(b), we display the calculated results of the optical electric field F_{op} at the emitter tip apex (F_0 is the electric field of the incident radiation) and the electron yield Y_{op} when the incidient angle of the light is normal to the FEA. The latter was obtained by integrating the electron flux over the emitter apex. Y_{op} and F_{op} are resonantly enhanced at the photon energy of 1.6 eV. As shown in the inset of Fig. 1(b), the generated electrons subsequently propagate through the double-gate apertures. At an optimum V_{col} value, the electron beam is highly collimated with the rms transverse velocity of 4×10^{-4} c (c is the speed of the light) with the corresponding intrinsic beam emittance for a 1-mm-diameter FEA less than 0.1 mm-mrad [2].

Fig. 2 compares the F_{op} distribution at the laser incident angle of 0 and 7 degrees. We found that the photon energy that gives the maximum F_{op} shifted by ~13 meV by the 7 degree increase of the incidence angle but the value of the maximum F_{op} are same within a few percent between the two angles. This characteristic is important for actual applications since a slight tilt of the laser path from the electron beam axis (normal to the FEA) is needed. Further, as shown in the inset, the distribution of the F_{op} at the emitter tip is symmetric around the emitter tip axis despite the structural asymmetry caused by the Δx_{col} and this is advantageous for the optimum collimation.

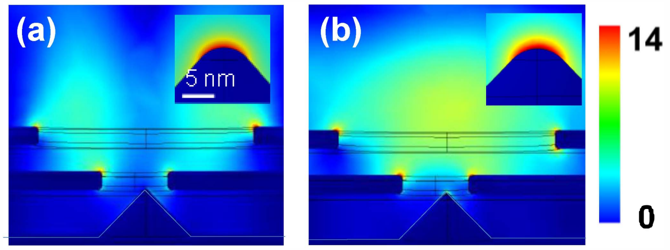

Fig. 2 Cross-sectional electric field distribution of a Mo tip array under laser irradiation with incident angle along the x–z plane, (a) θ=0° and (b) 7°.

To have an insight of the tip-light coupling mechanism, we calculated the transmission through copper nano-aperture array in 3 cases; single-layer with 200 nm-diameter aperture same as G_{ex} aperture, single-layer with 600 nm-diameter aperture same as G_{col} aperture, and double-layer with 200 and 600 nm-diameter apertures, with the same copper thickness and the same separation between the two layer case as the model nano-tip, Fig. 1, with the array pitch of 750 nm. The calculated transmission spectra are shown in Fig. 3. The 600 nm-diameter aperture array exhibits an order of magnitude higher transmission than the 200 nm-diameter aperture array, owing to the larger geometrical area. Interestingly, the transmission through the double-layer aperture array is larger than that of the single-layer array with 200 nm-diameter apertures. This enhanced transmission is ascribed to the coupling of the SPP excitation of the two layers. In fact, we found that the peak transmission of the double-layer array increases with the decrease of the layer separation. Further optimization of the tip-light coupling efficiency will be possible by engineering the SPP excitation and the near field distribution.

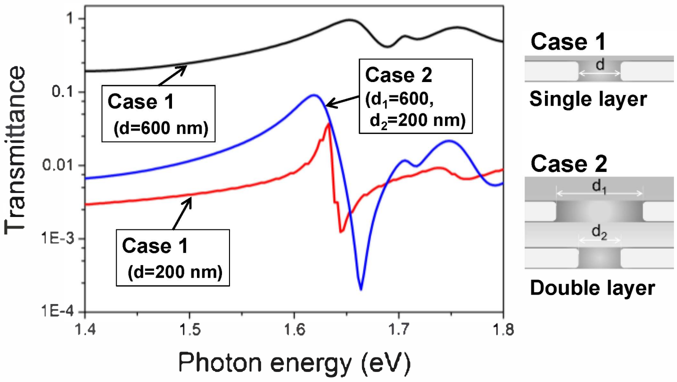

Fig. 3 Transmittance spectrum of single- and double-layer nano-aperture arrays with the same parameters as the model double-gate emitter, Fig. 1.

IV. CONCLUSION REMARKS

In this study, we present numerical studies of an SP-enhanced double-gate FEA structure. Our results indicate that SP-enhanced double-gate FEAs are highly promising as high current and high brightness cathodes for X-ray FELs.

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