

Experimental Verification of the Theory on Energy Modulation of an Electron Beam with an Optical Near-Field

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SUMMARY An exchange of energy between nonrelativistic electrons and evanescent waves in an optical near-field has been investigated in an infrared region. A metal microslit has been adopted as an optical near-field generator which produces a number of evanescent waves by illumination of a laser beam. The theory has predicted that electrons interact selectively with the evanescent wave whose phase velocity is equal to the velocity of the electrons. In order to verify the theory, two types of precise microslits with different shapes, a slot and a V-shaped groove, have been fabricated. Experiments performed using these slits at the wavelength of 10.6 μm have shown that the energy change of the electrons has varied from 2 eV to 13 eV with their initial energy between 25–95 keV for a 3.2 kW CO_2 laser pulse. The measured results have given experimental verifications to the theory.

key words: optical near-field, evanescent wave, free electron, microslit, electron energy modulation

1. Introduction

Many kinds of electron beam devices including klystrons, traveling wave tubes, and backward wave oscillators, have been developed and widely used to generate intense coherent waves in electromagnetic wave spectra from microwave through ultraviolet ray[1]. Only free electron lasers among them can operate in the visible light region by utilizing relativistic electron beams[2]. On the other hand, a nonrelativistic electron beam with energy of less than 100 keV is more desirable than a relativistic one to develop convenient compact beam devices operating in an optical region[3]. However, there are few reports on the theoretical and experimental studies for the interaction between lower energy electrons and light. In 1969, Schwarz and Hora reported that a 50 keV electron beam passing through a thin dielectric film was modulated with an argon laser beam at the wavelength of 488 nm [4]. This effect, however, has not yet been reproduced by other experimental groups.

In order to investigate electron-light energy-exchanges in nonrelativistic regime, a metal microslit whose width is less than an operation wavelength has been proposed as an interaction circuit [5]. In Fig. 1, an optical near-field is generated in the proximity of the slit by illumination of a laser beam. The near field contains a number of evanescent waves with different wave numbers k_{ev} and phase velocities $v_p = \omega/k_{ev}$, where ω is the angular frequency of the laser. An electron beam with a velocity v_i interacts selectively with an evanescent wave when $v_p = v_i$. This is so called the phase matching condition or the synchronous condition in the interaction [6]. Since the optical near-field comprises an evanescent wave having a phase velocity much smaller than the light speed, low energy electrons can be used for the interaction in the microslit circuit. The slit structure is so simple that can be easily fabricated even with a submicron width which is required for experiments in the visible light region.

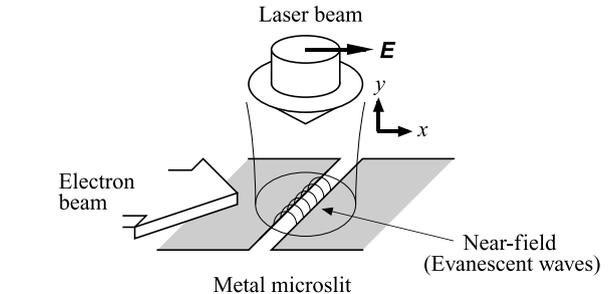


Fig. 1 Conceptual drawing of energy modulation of an electron beam with an optical near-field using a metal microslit.

Experimental demonstration of the metal microslit interaction circuit was successfully done using a CO_2 laser in the infrared region [7], [8]. In the experiments, the metal microslit which was formed by two polished copper blocks and had a width of 8 μm with the accuracy of $\pm 2\mu\text{m}$, were used. The experimental results indicated that the 10 kW laser pulse can modulate electron energy more than ± 5 eV for an 80 keV electron beam at the wavelength of 10.6 μm . The theory on the interaction including the phase matching, however, has not been fully verified through the experiments due to the inaccurate microslit.

In order to confirm the theoretical predictions with high accuracy, two types of precise silicon microslits with different shapes, a slot and a V-groove, has been fabricated and used for measurements. In this paper, the experimental verifications of the theory in the infrared region are presented.

2. Fabrication of Metal Microslits

Metal microslits with precise dimensions have been fabricated using an anisotropic wet chemical etching technique for silicon (Si) [9]. The fabrication process is shown in Fig. 2. Two types of the slits with different shapes, (a) V-shaped groove and (b) slot, were fabricated by using 380 μm and 630 μm thick Si-wafers with (110) and (100) orientations,

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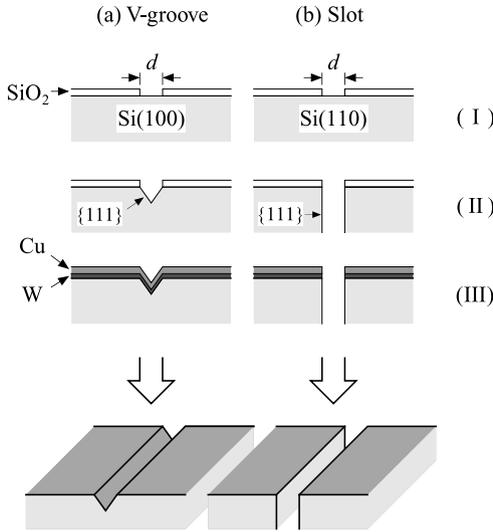


Fig. 2 Process sequence for fabrication of microslits on silicon substrates using an anisotropic wet chemical etching method, (a) the V-shaped groove on (100) orientation silicon, (b) the slot on (110) orientation silicon; (I) after wet thermal oxidation, patterning photoresist, and etching a window in silicon dioxide, (II) after anisotropic etching silicon in KOH (30 wt%) solution, (III) after depositing tungsten and copper metal layers.

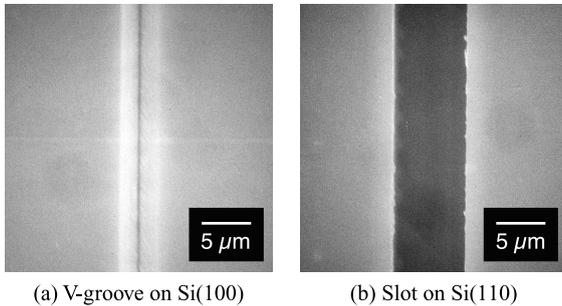


Fig. 3 SEM images of the fabricated (a) V-groove ($d = 4 \mu\text{m}$) and (b) slot ($d = 7.5 \mu\text{m}$) on the silicon substrates.

respectively. In Fig. 2 (a), the depth of the slot was chosen to be more than 4 times of the laser wavelength of $10.6 \mu\text{m}$. The deep slot of about $50 \mu\text{m}$ makes propagation waves in the slot negligible due to a large rf-loss. In Fig. 2 (b), the V-shaped corner at the bottom of the groove has a fixed angle of 70.5 degrees which is determined by the (100) Si orientation. In Fig. 2, the gap widths d , i.e., the slit widths were adjusted from $4 \mu\text{m}$ to $12 \mu\text{m}$ by changing a size of a photo-mask pattern used in photolithography. In the final process (III), the Si-microslits were coated with 20 nm tungsten and 100 nm copper metal layers. The tungsten layer increases tolerance for the input laser beam intensity. Test results for the fabricated microslits have shown that the laser power density of more than $14 \text{ MW}/\text{cm}^2$ can be used for both the microslits without any damage at $\lambda = 10.6 \mu\text{m}$. This power density was 1.5 times higher than that for the slits without the tungsten layer.

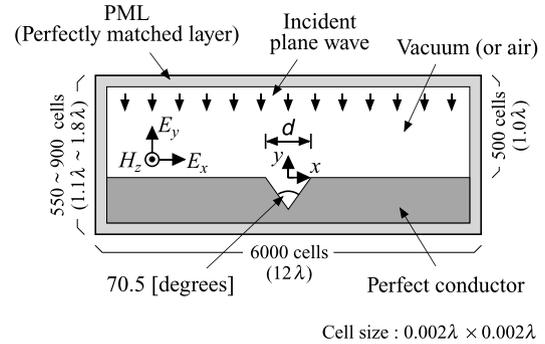


Fig. 4 Calculation model of near-field distributions on the metal microslits with the V-groove using a two-dimensional FDTD method. In the calculation for the metal slit, the V-groove was simply replaced with the metal slit having a thickness of single cell size.

Figure 3 shows the SEM images of the fabricated microslits with (a) a V-groove and (b) a slot. The slit widths d are $4 \mu\text{m}$ and $7.5 \mu\text{m}$ for the V-groove and the slot, respectively. It is seen from Fig. 3 that the microslits have optically smooth surfaces and clear edges of the slot and the groove.

3. Theoretical Analyses

3.1 Near-Field Distributions

Near-field distributions on the microslits with the shapes, the V-groove and the slot, have been estimated theoretically using the finite-difference time-domain method (FDTD method) [10]. In the calculation, the microslit with the slot has been treated as a metal slit with a perfect conductance and a thickness of nearly zero, because it is expected that the slot with the large depth does not affect the near-field distribution as described in Sect. 2.

The calculation model used in the FDTD analyses is shown in Fig. 4. The calculation cell size and numbers are also indicated in Fig. 4. For ease of calculation, it has been assumed that a normally incident plane wave is polarized perpendicularly to the groove with an infinite length. In the case of the V-groove, the depth of the groove varies with the width d . The height of the calculation area, thus, was adjusted from 1.1λ to 1.8λ for different d between 0.01λ and λ . The width of the calculation area is 12λ . Those dimensions of the calculation area have been chosen to fully cover the near-field region on the microslits. The calculation area was bounded by the Berenger perfect matched layer (PML) [11]. In the calculation for the metal slit, the thickness of the slit was set to be one cell size, i.e., 0.002λ .

In the FDTD field analyses, all wave components including an incident wave, scattered waves from the microslit, and waves reflected at the conducting plane excepting the part of the microslit structure, have been taken into account for calculation. The calculated fields, thus, contain fields of a strong standing wave formed by the incident and reflected waves. It is known from theoretical consideration on the electron-light interaction that the standing wave does not contribute to the interaction with electrons [12]. In order to re-

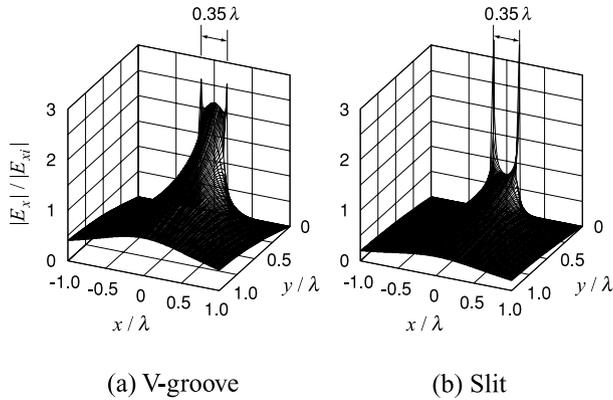


Fig. 5 Calculated field intensity distributions of $|E_x|$ on (a) the V-groove and (b) the slit. The widths are same and 0.35λ . The field intensities were normalized to the field of incident wave, $|E_{xi}|$.

move the standing wave and to see clearly the near-field distributions in the proximity of the microslits, electromagnetic fields calculated for a simple conducting screen have been subtracted from the fields calculated for the microslits.

Figure 5 shows the near-field distributions calculated for the two microslits, (a) the V-groove and (b) the metal slit. The widths of the two microslits are same and 0.35λ . The electric field intensities $|E_x|$ in the x -direction and the x and y positions have been normalized to the one of the incident wave, $|E_{xi}|$, and the wavelength λ , respectively.

The near-field distribution shown in Fig. 5 (b) has agreed with that previously calculated for the metal slit using the method of moments [8], [13]. The field intensity is approximately 0.9 at $x = y = 0$. This intensity is raised by 2.3 times using the microslit with the V-groove. The enhancement of the near field results from a resonant effect in the groove.

3.2 Electron-Energy Changes

Using the theoretical near-field distributions, energy changes of electrons passing close to the microslit surface were estimated through computer simulation. Referring to Fig. 1, the electrons with a velocity v_i move in the x -direction at the distance y_i from the surface of the slit. The total energy changes of the electrons were estimated by integrating small energy changes with the near field in a small distance along the electron trajectory. The detailed description on the calculation method is given in Ref. [8].

Figure 6 shows the calculated maximum energy changes ΔW in the microslits with and without the V-groove for the electrons with a velocity of $\beta (= v_i/c, c: \text{light speed}) = 0.5$ as a function of d at $y_i = 0.01\lambda$. ΔW is normalized to the maximum value in the curve for the V-groove at $d/\lambda = 0.3$. As seen from Fig. 6, optimum slit widths giving large ΔW for both the microslits exist. The curve for the microslit without the V-groove, i.e., the metal slit has two peaks of 0.6 and 0.69 at $d = 0.125\lambda$ and 0.625λ , respectively. The spacing between the peaks is exactly a half the wavelength. From similar calculation results for different β , it is found that the optimum widths for the metal slit have a periodicity of $\beta\lambda$ [14]. This

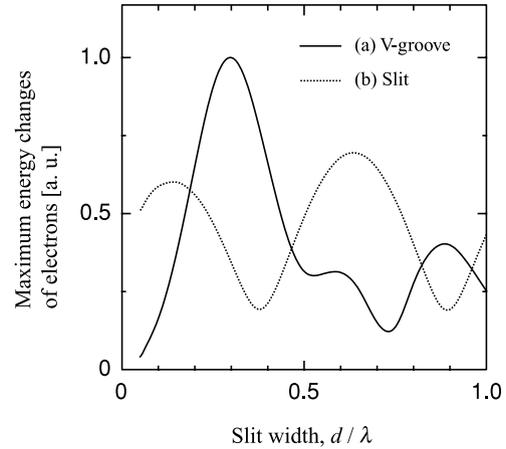


Fig. 6 Calculated maximum energy changes of electrons with $\beta = 0.5$ in the two microslit circuits, the V-groove and the slit, as a function of the width d at $y_i = 0.01\lambda$.

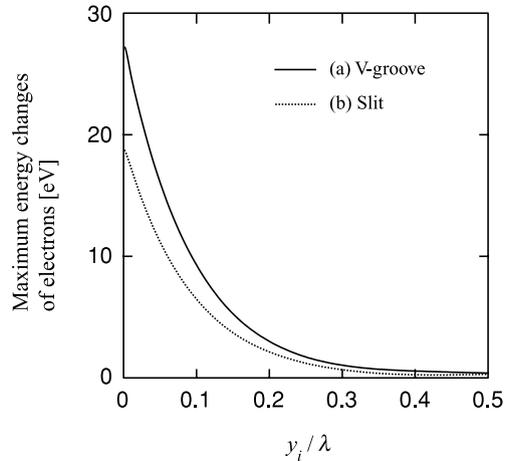


Fig. 7 Calculated maximum energy changes of electrons with $\beta = 0.5$ in the two microslit circuits, the V-groove and the slit, as a function of y_i/λ .

variation of the ΔW curve results from the periodicity of phase in the laser field. In contrast to the result for the metal slit, the curve for the V-groove has only single peak at $d = 0.3\lambda$, and the $\beta\lambda$ periodicity has disappeared, because the depth of the groove varies with d . The groove, however, acts as a resonator and increases ΔW by 1.45 times compared to the maximum ΔW at 0.625λ in the metal slit.

Figure 7 shows the calculated ΔW for the electrons with $\beta = 0.5$ in the two microslits as a function of the position y . The optimum widths of 0.3λ for the V-groove and 0.625λ for the slit were used for calculation. A CO_2 laser beam with $\lambda = 10.6 \mu\text{m}$ and a power density of 10 MW/cm^2 was assumed as the incident wave. This power density corresponds to a 3.2 kW output power focused onto a $200 \mu\text{m}$ diameter area.

In Fig. 7, when y increases from zero to $0.5l$, ΔW falls off exponentially to near zero. The exponential decay in both curves suggests that the electrons have exchanged energy with evanescent waves in the optical near-fields on the microslits. From the theory, the decay constant a of the evanescent wave

is given by $k_0(1-\beta^2)^{1/2}\beta^{-1}$ [5], where k_0 is the wave number of the laser beam in free space. Using this relation, for $\beta = 0.5$, $\alpha = 1.73k_0$ which has agreed with ones estimated from the *DW*-curves in Fig. 7.

From the results shown in Fig. 7, it is seen that the 3.2 kW laser beam gives ΔW of 25 eV in the V-groove and 17 eV in the metal slit to the electrons passing at $y_i = 0.01\lambda$, i.e., 0.1 μm . These ΔW decrease to a measurable energy change of 1 eV, at $y_i = 3.0 \mu\text{m}$ for the V-groove and at $y_i = 2.7 \mu\text{m}$ for the metal slit. The microslit with the V-groove is superior to the simple metal slit as the interaction circuit in the view points of both the interaction strength and space.

4. Experiments

Experiments have been done to verify the theory in the infrared region. Figure 8 shows the experimental set up which is almost the same as a previous one used in the first experiment [7], except for the microslit interaction circuit. The Simicroslit with the V-groove shown in Fig. 3 (a) was used for the measurements. The CO_2 laser has output pulses with a peak power of more than 4 kW and a width of 180 nsec at a repetition rate of 1 kpps [15]. The experimental wavelength was 10.6 μm . The focused laser beam at the surface of the microslit has a fundamental Gaussian intensity profile with a diameter of about 200 μm . The initial energy of the electron beam has been adjusted between 25–95 keV. The slot aperture with a height of 5 μm and a width of 100 μm confines the beam area on the microslit. The electron energy was measured by using a retarding field analyzer [16]. Our energy analyzer has resolution of better than 0.8 eV for an 80 keV electron beam [8]. This analyzer passes all the higher-energy electrons than the filter bias V_f which is a variable retarding-potential. The electrons passed through the energy analyzer were detected by a high speed secondary electron multiplier (collector) connected to a gated counter which is triggered by the laser pulses.

Figure 9(a) shows the measured energy spectra of the electrons A with and B without laser illumination, while (b) shows the difference between the two spectra A-B. The peak power of the laser was 4 kW and the initial electron energy W_i was 80 keV ($\beta \sim 0.5$) which is the center energy at $V_f = 0$ in Fig. 9. The ordinates are the output counts from the gated counter with a gate width of 2 μsec and an integration time of

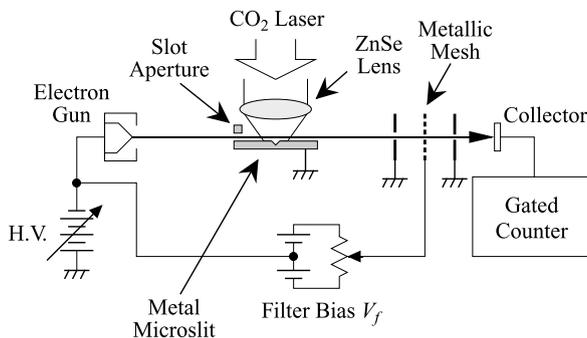


Fig. 8 Experimental setup.

5 sec. In Fig. 9(a), the decrease in the output counts at V_f above +0.5 V is due to the dispersion of the energy analyzer used in the experiment.

When the laser beam irradiates the electrons, the spectrum B is changed to the spectrum A with a wider energy spread. The spectrum A still contains a number of electrons that have not interacted with the light. Fig. 9(b) thus indicates the energy spectrum only for the electrons that were interacted with the light. The plus counts for $V_f < 0$ and the minus for $V_f > 0$ represent the numbers of electrons accelerated and decelerated by the laser field, respectively. The asymmetry in the energy spectrum would be due to the dispersion of the energy analyzer. From the energy distribution at $V_f < 0$ in Fig. 9(b), it is seen that the maximum energy change ΔW of the electrons is greater than 5 eV. The experimental results indicate that the microslit with the V-groove can be used to modulate the electron beam with the laser in the optical region as well as the metal slit.

From the measured spectra shown in Fig. 9, it is seen that 3700 electrons have passed through the slit, and 1900 electrons among them have interacted with the laser beam. Since the height of the electron beam on the slit is 5 μm , the ratio of the signal electrons to the total ones implies that the interaction space of the slit is about 2.6 μm which agrees with the theory.

Dependence of ΔW on the polarization of the laser field has been measured to confirm that the observed energy

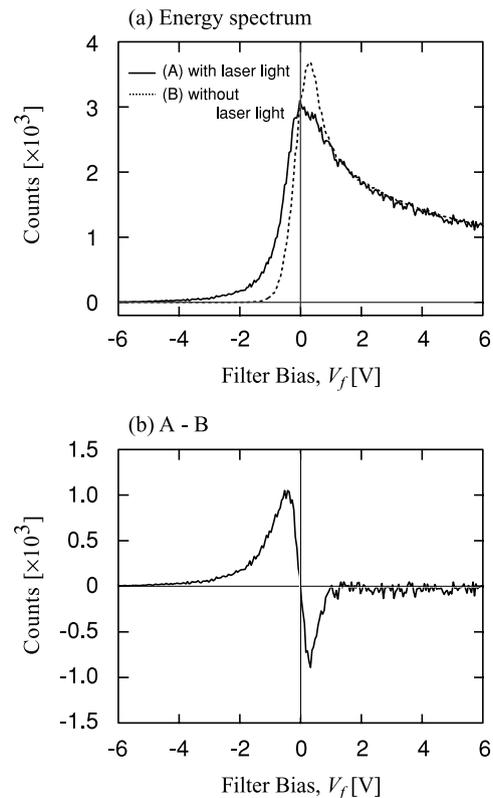


Fig. 9 (a) Measured electron-energy spectra A with and B without laser illumination, and (b) the difference between the two spectra A-B for an electron beam with an initial energy of 80 keV.

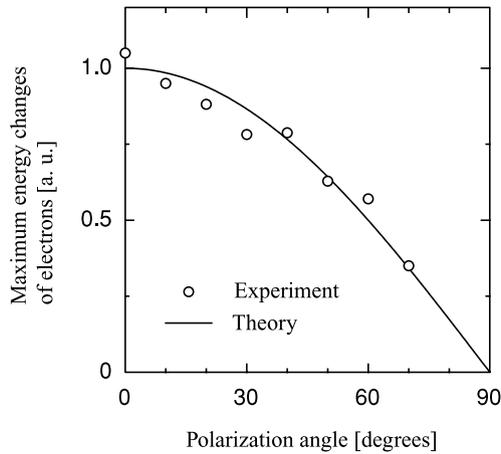


Fig. 10 Maximum energy changes of the electrons as a function of the polarization angle of the CO₂ laser field. The solid curve is the theoretical variation of the energy changes.

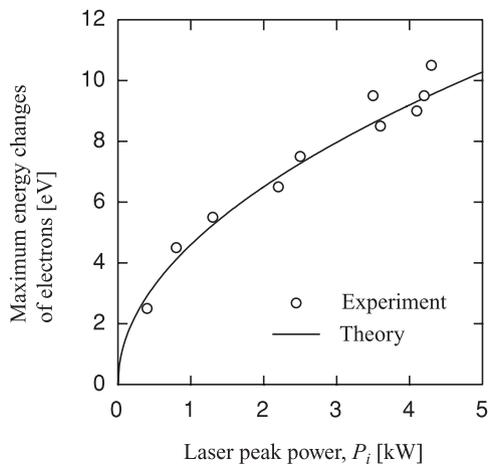


Fig. 11 Maximum energy changes of the electrons with $\beta = 0.5$ as a function of the laser peak power. The solid curve is a theoretical fit to the measurements.

changes of the electrons are due to the laser field. The measured result is shown in Fig. 10. The zero angle of the polarization is an angle at which the electric field of the laser beam is polarized in the direction of traveling of the electrons. The solid line is a cosine curve that is the theoretical change of ΔW . The results are a direct verification for the laser field modulation of the electron beam in the microslit.

Figure 11 show the measured variation of ΔW with the laser power P_i . The experimental parameters are the electron current of 30 pA, $W_i = 80$ keV, and $V_f < -2$ V. The solid curve indicates the theoretical variation of ΔW which is proportional to the field intensity of the incident wave, i.e., the square root of P_i . The theory has agreed well with the measurements. The measured ΔW is about 9 eV at $P_i = 4$ kW which is compared to 19 eV predicted through the computer simulation. The reduction of the energy change by 0.47 times would arise from differences of the actual microslit from the theoretical one. Since the actual slit surface has finite conductance, the amplitude of the evanescent wave may be small compared to

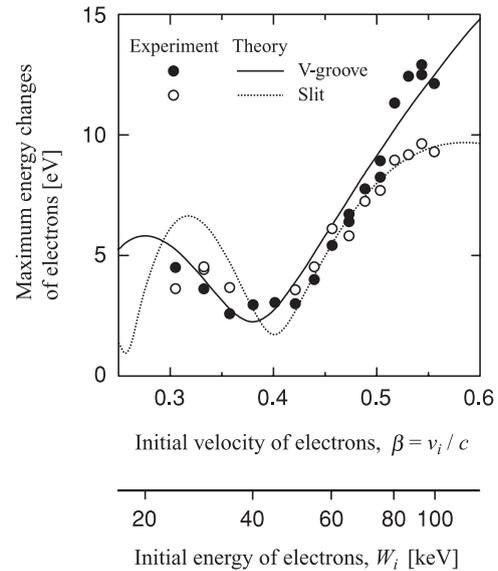


Fig. 12 Maximum energy changes of the electrons in the two microslit circuits, the V-groove and the slot, for the laser power of 3.2 kW as a function of the initial electron energy W_i . The solid and dotted curves are the theoretical variations. The electron velocity β corresponding to W_i is also indicated in the ordinate.

the theoretical one.

Figure 12 is the measured variation of ΔW for the microslits with the V-groove and the slot as a function of W_i . The two microslits used in the experiment are the same ones shown in Fig. 3. The solid and dotted curves represent the theoretical variations of ΔW for the microslits with the V-groove and the slot, respectively. As mentioned in Sect. 3.1, the theoretical curve for the microslit with the slot are the theoretical values calculated for a metal slit with the same width, a perfectly conducting screen, and a nearly zero thickness.

To obtain the best fit to the measurements, the theoretical energy changes have been decreased by 0.47 times, but any adjustment has not been made for the slit widths, i.e., 4 μm for the V-groove and 7.5 μm for the slot. The theory has well predicted the measured variations of ΔW for both the microslits. These results show that the theory on the microslit interaction circuits is valid.

The measured curves shown in Fig. 12 represent wave number spectra of the optical near-fields on the microslits, because the electron velocity β is converted to the wave number k_{ev} of the evanescent wave through the relation $\beta = k_0 / k_{ev}$. In this point of view, it is seen from Fig. 12 that the electrons with W_i between 25–95 keV have interacted with evanescent waves with k_{ev} between $1.8k_0$ and $3.3k_0$. The optical near-field on the V-groove has wave components with higher amplitudes at k_{ev} below about $2k_0$ ($W_i \sim 80$ keV) compared to the microslit with the slot. The reason for it would be due to the V-groove having the obtuse edges compared to the slot. The microslit with the V-groove thus has the smaller peaks of the near field at the edges as shown in Fig. 5. Therefore, the wave components of lower k_{ev} in the wave number spectrum for

the V-groove is more dominant than those for the slot. These results suggest that an electron beam can be used to measure an optical near-field on a small object in the optical region.

5. Conclusions

Energy modulation of a nonrelativistic electron beam with a CO₂ laser using a metal microslit as an interaction circuit has been analyzed theoretically and measured experimentally at the wavelength of 10.6 μm. The theory has predicted that an evanescent wave comprised in an optical near-field on the microslit modulates energy of electrons, when the phase velocity of the wave is equal to the velocity of the electrons. Careful experiments have been carried out using precise metal microslits with and without the V-shaped groove and have verified the theory. The experimental results have indicated the metal microslits can be used to modulate an electron beam even with low initial energy of 25 keV. It has been also confirmed from those results that the metal microslit with the V-shaped groove is a potential interaction circuit to achieve strong coupling between electrons and a light.

Acknowledgment

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References

- [1] R. G. E. Hutter, *Beam and Wave Electronics in Microwave Tubes*, ed. H. J. Reich, D. Van Nostrand, Tronto, 1960.
- [2] C. A. Brau, *Free-Electron Lasers*, ed. P. W. Hawkes, Academic Press, San Diego, 1990.
- [3] K. Mizuno and S. Ono, "Optical klystron," *Proc. IEEE*, vol.63, no.7, p.1075, 1975.
- [4] H. Schwartz and H. Hora, "Modulation of an electron wave by a light wave," *Appl. Phys. Lett.*, vol.15, no.11, pp.349–351, 1969.
- [5] J. Bae, S. Okuyama, T. Akizuki, and K. Mizuno, "Electron energy modulation with laser light using a small gap circuit — A theoretical consideration," *Nucl. Instrum. & Methods in Phys. Research A*, vol.331, pp.509–512, 1993.
- [6] J. Bae, H. Shirai, T. Nishida, T. Nozokido, K. Furuya, and K. Mizuno, "Experimental verification of the theory on the inverse Smith-Purcell effect at a submillimeter wavelength," *Appl. Phys. Lett.*, vol.61, no.7, pp.870–872, 1992.
- [7] J. Bae, R. Ishikawa, S. Okuyama, T. Miyajima, T. Akizuki, T. Okamoto, and K. Mizuno, "Energy modulation of nonrelativistic electrons with a CO₂ laser using a metal microslit," *Appl. Phys. Lett.*, vol.76, no.16, pp.2292–2294, 2000.
- [8] R. Ishikawa, J. Bae, and K. Mizuno, "Energy modulation of nonrelativistic electrons in an optical near-field on a metal microslit," *J. Appl. Phys.*, vol.89, no.7, pp.4065–4069, 2001.
- [9] K. E. Petersen, "Silicon as a mechanical material," *Proc. IEEE*, vol.70, no.5, pp.420–457, 1982.
- [10] A. Taflove, *Computational Electrodynamics, The Finite-Dif-*

ference Time-Domain Method, Artech House, Norwood, MA, 1995.

- [11] J. P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves," *J. Computational Phys.*, vol.114, no.1, pp.185–200, 1994.
- [12] J. Bae, K. Furuya, H. Shirai, T. Nozokido, and K. Mizuno, "The inverse Smith-Purcell effect in the submillimeter wave region — Theoretical analyses," *Jpn. J. Appl. Phys.*, vol.27, no.3, pp.408–412, 1988.
- [13] T. Y. Chou and A. T. Adams, "The coupling of electromagnetic waves through long slots," *IEEE Trans. Electromagn. Compat.*, vol.EMC-19, no.2, pp.65–73, 1977.
- [14] J. Bae and K. Mizuno, "Electron energy modulation with optical evanescent waves," in *Optical and Electronic Process of Nano-matters*, ed. M. Ohtsu, pp.95–122, Kluwer Academic Publishers, Tokyo, 2001.
- [15] J. Bae T. Nozokido, H. Shirai, H. Kondo, and K. Mizuno, "High peak power and high repetition rate characteristics in a current pulsed Q-switched CO₂ laser with a mechanical shutter," *IEEE J. Quantum Electron.*, vol.30, no.4, pp.887–892, 1994.
- [16] J. F. Graczyk and S. C. Moss, "Scanning electron diffraction attachment with electron energy filtering," *Rev. Sci. Instrum.*, vol.40, no.3, pp.424–433, 1969.



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