

Energy modulation of nonrelativistic electrons with a CO₂ laser using a metal microslit

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A metal microslit has been used as an interaction circuit between a CO₂ laser beam and nonrelativistic free electrons. Evanescent waves which are induced on the slit by illumination of the laser light modulate the energy of electrons passing close to the surface of the slit. The electron-energy change of more than ± 5 eV for the 80 keV electron beam has been observed using the 7 kW laser beam at the wavelength of 10.6 μm . © 2000 American Institute of Physics. [S0003-6951(00)03516-6]

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 at optical frequencies.¹ However, there are few reports on the experimental studies for the interaction between the lower energy electrons and a light. In 1969, Schwarz and Hora reported that the wave function of 50 keV electrons passing through a thin dielectric film was modulated with an argon laser beam.² However, this effect has not yet been reproduced by other experimental groups. Successful experiments on the (inverse) Smith–Purcell effect using the nonrelativistic electron beam have been reported, but the operation frequencies still remain in the far-infrared region.^{3,4} In this letter, the experimental results of the energy modulation of a 80 keV electron beam with an infrared laser are presented.

The metal microslit whose width is less than an operating wavelength has been proposed and used to provide significant coupling between visible or infrared waves and a nonrelativistic electron beam.⁵ In Fig. 1, an optical near-field is induced in the proximity of the slit with illumination of laser light. An electron beam with a velocity v_e passes through the near-field region in the direction perpendicular to the slit. The near-field contains an evanescent wave which has a wave number k_{ev} much greater than that of the light in the free space in the direction of traveling of the electrons.⁶ When the phase velocity $v_p = \omega/k_{ev}$, is equal to v_e , this is, the phase matching is achieved, the evanescent wave interacts with the electrons, consequently modulating their energy. This type of metal microslit is more suitable than the dielectric film for precise measurement of energy-exchange between free electron and light and for investigating quantum effects⁷ that will happen in the interaction, because there is no disturbance such as electron scattering in dielectric medium.

The modulation degree of an electron beam is determined by a field intensity of the evanescent wave and an effective slit width. Both of them are changed depending on the slit width. In order to find the optimum width, the computer simulation on energy-exchange of electrons interacted

with the evanescent wave has been performed.⁸ In the calculation, the near-field distribution was determined using the method of moments assuming a metal slit with perfect conductance and a zero thickness.⁹ The results for the 80 keV electron beam ($v_e \sim 0.5c$, c : light speed) is shown in Fig. 2. For comparison, the calculated result for a conventional parallel metal plate circuit⁵ as used in klystrons is also indicated in the figure. It is found that the optimum slit width is 0.64λ , corresponding to the transit angle of 2.55π rad for the electrons. This width is narrower than that of the parallel metal plates by about 0.11λ due to an inhomogeneous near-field distribution in the slit. The slit structure is quite simple so that we can easily fabricate it even with a submicron width, which is required for experiments in a visible light region.¹⁰

Experimental demonstration for energy modulation of an electron beam with the microslit has been carried out in the infrared region. Figure 3 shows the experimental setup. The slit consists of two polished copper blocks and a piezoelectric transducer (PZT). Using the PZT, the slit width can be adjusted, *in situ*, between 4 and 10 μm to give a maximum energy change to electrons. The electron beam has an initial energy of 80 keV and a diameter of 240 μm . The slot aperture confines the beam area on the slit to 20 μm in height and 100 μm in width. The electron energy is analyzed by using a retarding field analyzer.¹¹ Our energy analyzer has a resolution better than 1 eV (full width at half maximum) at an

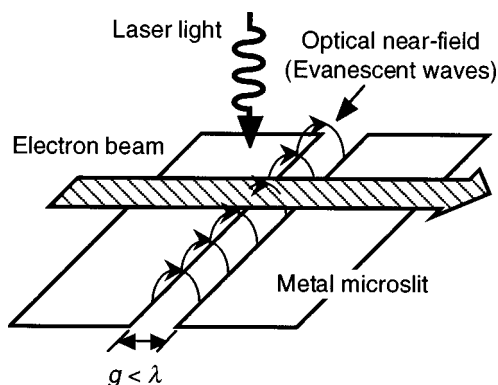


FIG. 1. Schematic diagram of interaction between an electron beam and a laser light in the metal microslit. g is the slit width and λ is the wavelength.

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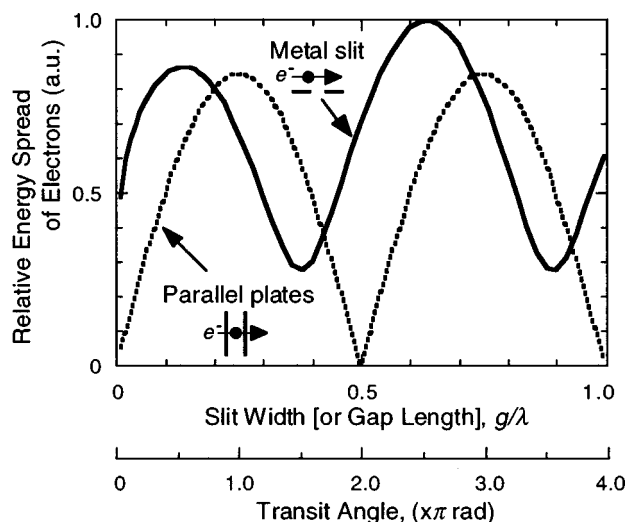


FIG. 2. Theoretical changes of the energy spreads of electrons in the metal slit and metal film gap circuits as a function of the slit width or the gap length (spacing between the metal plates). The slit widths g are normalized to the wavelength λ and the corresponding transition angles are indicated in the figure. The energy spreads are also normalized to the maximum value at $g/\lambda = 0.64$. In the calculation, it has been assumed that the electrons with an initial energy of 80 keV move at a distance of 0.01λ away from the slit surface.

electron-energy of 80 keV and a current of 10 nA.¹²

An electromechanical Q -switched (EMQ) CO₂ laser¹³ was developed and used for this experiment. The EMQ laser is oscillated in a TEM₀₀ mode at $\lambda = 10.6 \mu\text{m}$. The output pulses have a peak power of 7 kW and a width of 140 ns at a repetition rate of 1 kpps. The ZnSe lens is used to concentrate the laser beam on the slit surface. The measured beam diameter at the surface is $360 \mu\text{m}$. This laser beam irradiates the entire electron beam passing through the slit.

The pulsed laser output modulates the energy of the electron beam, so that the electron current through the analyzer changes during the pulse. The change in the collector current is measured by a boxcar averager which is triggered by the laser pulse. Figure 4 shows the measured electron-energy spectra with and without laser illumination. The slit width was $5.3 \mu\text{m}$ and the total collector current was 7 nA. The abscissa is a filter bias voltage V_f which is the retarding

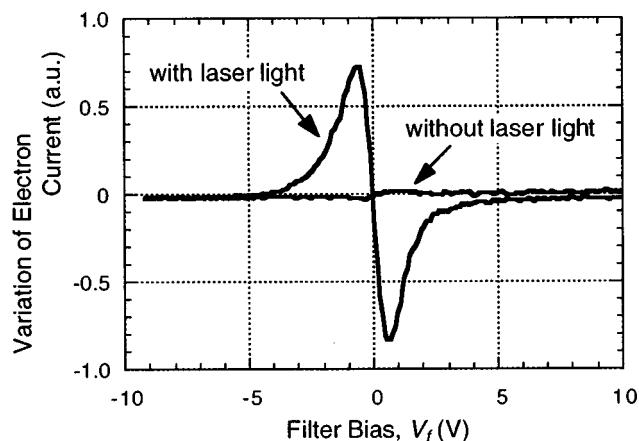


FIG. 4. Measured electron-energy spectra with and without laser illumination.

potential of the energy analyzer. The ordinate is the change in electron current by the laser. The measured maximum energy spread is about $\pm 6 \text{ eV}$ which is compared to the theoretical value of $\pm 13.6 \text{ eV}$ predicted through the computer simulation.

In this experiment, the maximum output voltages of the boxcar averager were -0.83 and $+0.73 \text{ V}$ at $V_f = \pm 0.6 \text{ V}$, respectively. Using these values, the number of electrons interacted with the laser light can be estimated, when the signal gain of the charge-sensitive amplifier has been taken into account. The estimated number of the signal electrons is 2200 particles/pulse, which is about one third of the total number of electrons passing through the slit during the pulse. Since the height of the electron beam on the slit is about $20 \mu\text{m}$, this high ratio of the signal electrons to the total ones implies that electrons passing at distances within about $5 \mu\text{m}$ of the slit have contributed to the signal output.

Since the energy analyzer passes all the higher-energy electrons, it is expected that, for large bias voltages the current change with laser illumination should be the same as the one without laser illumination. However as shown in Fig. 4, the current change with laser illumination is slightly smaller than the one without laser illumination when $V_f > +7 \text{ V}$. This would be due to deflection of the electron beam with the laser illumination. Consequently a part of the electron beam has been clipped by the aperture before the collector.

Figure 5 is the measured energy spread of the electrons as a function of the slit width. The slit widths g are normalized to the wavelength λ , and the corresponding transition angles are also indicated in the figure. From the results, it is found that the optimum slit width is about 0.5λ . This measured width is largely different from the theoretically predicted one of 0.64λ shown in Fig. 1. However, the variation of the energy spreads with g and is consistent with the theoretical one which has a $\lambda/2$ periodicity. In the fabricated slit, the accuracy of the slit width is sacrificed due to its movable structure and is about $\pm 2 \mu\text{m}$ ($\sim \pm 0.19\lambda$). Therefore, the main reason for the discrepancy would be due to this insufficient accuracy of the width. In addition, the amplitude of the evanescent wave may not be the same as the theoretical one because the actual slit has consisted of the two thick copper blocks with finite conductance.

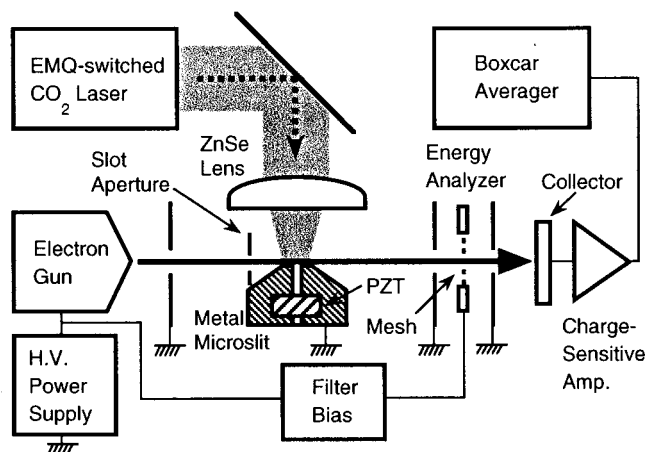


FIG. 3. Block diagram of experimental apparatus.

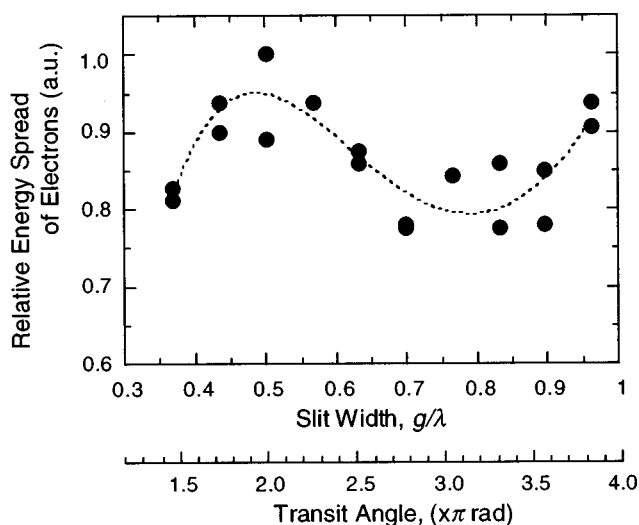


FIG. 5. Measured variation of electron-energy spreads as a function of the slit width. The energy spreads are normalized to the maximum value of 6 eV at $g/\lambda = 0.5$.

In conclusion, we have observed light–electron interaction in the metal microslit at the wavelength of $10.6 \mu\text{m}$. The 7 kW CO_2 laser output had given the energy spread of ± 6 eV to the 80 keV electron beam. The results indicate that the metal microslit can be used to modulate a nonrelativistic electron beam with the laser light. While this research is to investigate energy-exchange between low energy electron and light, the experimental results could be useful for developing an infrared-region grating linac (inverse Smith-Purcell type laser accelerator).^{14,15}

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