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Phys. Rev. E **97**, 023204 — Published 15 February 2018

DOI: 10.1103/PhysRevE.97.023204

For submission to *Physical Review E*

Induction of sub-terahertz surface wave on a metal-wire by intense laser interaction with a foil

Kensuke Teramoto[1,2,*], Shunsuke Inoue[1,2], Shigeki Tokita[3], Ryo Yasuhara[4], Yoshihide Nakamiya[1], Takeshi Nagashima[5], Kazuaki Mori[1,2], Masaki Hashida[1,2], and Shuji Sakabe[1,2]

[1]*Advanced Research Center for Beam Science, Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*
[2]*Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa, Sakyo, Kyoto 606-8502, Japan*
[3]*Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*
[4]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*
[5]*Faculty of Science and Engineering, Setsunan University, 17-8 Ikedanaka-machi, Neyagawa, Osaka 572-8508, Japan*

*Corresponding author, email address: kteramoto@laser.kuicr.kyoto-u.ac.jp

Abstract

We have demonstrated that a pulsed electromagnetic wave (Sommerfeld wave) of sub-terahertz frequency and 11-MV/m field strength can be induced on a metal wire by the interaction of an intense femtosecond laser pule with an adjacent metal foil at a laser intensity of 8.5×10^{18} W/cm^2. The polarity of the electric field of this surface wave is opposite to that obtained by the direct interaction of the laser with the wire. Numerical simulations suggest that an electromagnetic wave associated with electron emission from the foil induces the surface wave. A tungsten wire is placed normal to an aluminum foil with a gap so that the wire is not irradiated and damaged by the laser pulse, thus making it possible to generate surface waves on the wire repeatedly.

In recent years, the generation of terahertz-frequency electromagnetic waves (hereinafter, simply THz waves) has been made possible by advances in femtosecond laser technology. A THz wave with high peak power is required for many applications, such as studies of the nonlinear properties of materials [1], acceleration of charged particles [2], and studies of magnetization dynamics in the THz frequency region [3]. A THz wave can be generated by femtosecond laser sources such as photoconductive antennas [4], nonlinear optical crystals [5], and laser–plasma interaction [6]. In recent studies, an intense THz wave with sub-millijoule pulse energy was generated by using a nonlinear optical crystal [7], but the THz wave yield was limited by damage to the crystal. Because plasma is not damaged when used as a source element, even for intense laser pulses, laser–plasma interaction has been the subject of considerable study for generating intense THz waves. Moreover, many studies have investigated efficient THz wave generation by laser–solid interaction [8–11]. The generation of THz waves by laser–plasma interaction is often explained by a mechanism such as transient radiation due to electrons being emitted from the plasma [12], undulation of electrons due to a transient electric field induced by the intense laser [11], or a transient current due to electrons [10]. For example, intense THz wave generation has been demonstrated recently by irradiating a thin metal foil with a laser pulse at an intensity of 5×10^{19} W/cm^2. A transient current was generated on the rear side of the thin foil by the electrons accelerated by the laser. A pulse energy of at least 700 μJ was achieved by using a large ellipsoidal mirror to collect radiation emitted with a large divergence angle [8,9].

To irradiate a target with a THz wave for any application, it is necessary to transmit the wave from the source to the target and focus it on the target. For a free-space wave, there is transmission loss due to diffraction, and a large optical component such as a lens is necessary for focusing. Rather than allowing the THz wave to travel in free space, a waveguide is useful for long-distance transmission. In particular, a single metal wire is useful for guiding a THz wave with low dispersion and low attenuation [13]. The THz wave propagates along the wire as a surface (plasmon, polariton, or Sommerfeld) wave with radial polarization [14]. Because the wave is localized on the surface of the wire waveguide, it can be focused into a space smaller than the diffraction limit at the tip of a tapered metal wire [15]. Therefore, using a tapered-tip wire waveguide alleviates the need for focusing optics. The resulting combination of high transmission and focusability with a high-intensity source is expected to open the way to new applications such as THz near-field imaging [16], biological sensing [13], and the generation of high-electric-field pulses.

Even with both a high-power THz wave source and a low-loss waveguide, the issue remains of how to transfer the THz wave efficiently from the source to the waveguide [17]. In particular, linearly polarized THz waves propagating through free space cannot be transferred to the waveguide efficiently. However, it was demonstrated recently that a sub-THz surface wave could be generated by the interaction between an intense laser pulse (intensity: 10^{18} W/cm^2) and a metal wire [18]. The field strength of the surface wave was 200 MV/m and the pulse duration was 7 ps. It is thought that such a sub-THz surface wave is driven by the mass movement of laser-accelerated electrons along the wire. Using the wire waveguide itself as a THz wave source, an energy conversion efficiency as high as 1% from the laser to the surface wave has been demonstrated. However, with this generation method the wire waveguide is easily damaged, which makes it impossible to generate the surface wave repeatedly. Recently, another method for inducing a strong surface wave on a metal wire has been reported [19]. A THz surface wave can be induced by transient radiation by irradiating the wire with an electron bunch from a tabletop electron accelerator. However, the highest electric field achieved at the wire surface to date is only 0.4 MV/m.

In this letter, we report the induction of surface waves on a metal wire by electrons accelerated by the interaction of an intense femtosecond laser pulse with a thin foil adjacent to the wire, and we propose a new scheme to generate intense sub-THz surface waves repeatedly on a wire waveguide. The continuous supply of fresh foil surface using a rotating disk and the lack of damage to the wire guide make repeated surface wave generation possible. The peak electric field on the wire surface obtained by our method is estimated to be 11 MV/m when the distance between the foil and the wire is 0.5 mm and the intensity of laser pulses is 8.5×10^{18} W/cm^2. Numerical simulations suggest that the emission of laser-accelerated electrons generates an electromagnetic wave, some of which propagates along the wire as a surface wave.

The experiments were performed using the Ti:sapphire chirped-pulse amplification laser system at the Institute for Chemical Research, Kyoto University. The central wavelength is 810 nm, the pulse duration is 60 fs, and the pulse energy is 120 mJ. Laser pulses are focused with an *f*/3.5 off-axis parabolic mirror, resulting in a peak intensity of 8.5×10^{18} W/cm^2. Laser pulses with *p*-polarization are irradiated onto an aluminum foil target of 11 μm thickness at an incidence angle of 45°. A tungsten wire with a diameter of 300 μm and length of 250 mm is placed perpendicular to the foil with a gap of *d* mm (d = 0.5, 1, 2, 4 mm). The wire is held by it penetrating two black polypropylene films with a thickness of 60 μm. Figure 1 shows the experimental setup used to observe the surface wave traveling along the metal wire.

The field is measured by the method of electro-optic detection. A ZnTe <110> crystal of 0.5 mm thickness is placed 180 mm from the rear surface of the aluminum foil target and set near the wire. The [001] crystallographic axis of the crystal is aligned to be perpendicular to the wire. A linearly polarized probe laser pulse partially separated with a variable delay from the laser pulse for foil interaction is used for electro-optic detection. The probe pulse is guided parallel to the metal wire at a distance of 4 mm from the wire and focused on the <110> plane of the ZnTe crystal. When the surface wave and the probe laser are incident on the crystal simultaneously, the polarization of the probe laser changes to elliptical because of an electro-optic effect. The phase retardation is measured using a Wollaston prism and balanced photodiodes. Here, we define the outward radial direction from the wire to be the positive direction of the electric field. The experiments are performed in a vacuum of 0.1 Pa.

Figure 2(a) shows typical waveforms of the sub-THz surface wave induced by the irradiation of the foil target by the intense laser pulse for various foil–wire gaps (d = 0.5, 1, 2, and 4 mm) with a resolution of 500 fs. The electric field has a rapid (sub-picosecond) rise time for each distance. A half-cycle surface wave is observed over ~10 ps, and low-frequency fluctuations follow the peak for tens of picoseconds. Figure 2(b) shows waveforms near the peak for various foil–wire gaps (d = 0.1, 0.2, 0.3, 0.7, 1.5 mm). The electric field has almost the same sub-picosecond rise time for each distance. The polarity of the electric field of the surface wave is opposite to that obtained by irradiating the wire by the laser directly [18]. That is, the electric field is directed toward the wire center. The decay times for the gaps except d = 0.1mm are equal to each other. If the foil and the wire are sufficiently close, the influence of the discharge between the foil and the wire may appear on the surface wave. The peak electric field depends on the gap d, becoming stronger for smaller d. The peak electric field at the measurement position is calibrated to 4.2×10^2 kV/m when d = 0.5 mm. The field on the wire surface can be estimated as 11 MV/m assuming that the electric field is proportional to $1/r$ (where r is the distance from the center of the wire) [20]. When the energy of the surface wave is evaluated from the waveform, it is found to be around 1 μJ in the region within r = 10 mm when the distance between the thin film and the wire is 0.1 mm. The energy conversion efficiency from the laser to the surface wave is roughly 10^{-4}%.

To understand the process of surface wave induction, we performed three-dimensional numerical electromagnetic-field simulations. The mutual coupling between particles and the electromagnetic field is taken into account in this self-consistent particle-in-cell code. Hot electrons with a broad energy spectrum are generated on the surface of the foil by the intense laser pulse and emitted into vacuum. The hot-electron temperature T_{hot} scales as $k_{\mathrm{B}}T_{\mathrm{hot}} = 511\left[(1 + I_{18}\lambda^2/1.37)^{\frac{1}{2}} - 1\right]$ (keV), where k_{B} is the Boltzmann constant, I_{18} is the laser intensity in units of 10^{18} W/cm^2, and λ is the laser wavelength [21]. For the conditions of the present experiment, the hot-electron temperature is estimated to be about 640 keV. It is assumed that electrons in an energy range of 0–2,000 keV with a temperature of 640 keV are emitted from a region with a radius of 10 μm on an aluminum foil surface. In the experiment, the radiation distribution of electrons may be asymmetric with respect to the axis, and the propagating surface wave may have a non-axisymmetric electric field. This non-axisymmetric distribution converges to an axially symmetric mode in centimeter order, but in our simulations the electrons are distributed symmetrically to omit the non-axisymmetric component of the surface wave and to consider it simply. Electrons are emitted in an axially symmetric fashion at 65° to the normal of the foil with a spread angle of 40°, and the pulse width is 60 fs corresponding to the pulse width of the laser. A tungsten wire with a diameter of 300 μm is placed normal to the surface of the foil with a spatial gap. We calculate the dynamics of the electromagnetic field and emitted electrons in the space around the foil and wire, and we observe the electric field waveform on the wire surface at 6 mm from the foil. Electrons disappear if they collide with substances or reach the spatial boundary of the calculation; the electromagnetic wave is also absorbed at the spatial boundary of the calculation.

Figure 3(a) and (b) are snapshots of the time evolution of the calculated electric field distribution and Fig. 3(c) shows the corresponding electron distribution. Electrons are emitted spherically from the foil with a pulse width of 60 fs at t = 0, and the radiating THz electromagnetic wave has a hemispherical shape. The electromagnetic wave would diverge in the absence of the wire, but when the wire is present the electromagnetic wave propagates differently as follows. Most of the electromagnetic wave either radiates into free space or propagates on the foil surface. Part of the electromagnetic wave radiated in the direction of the wire is reflected at the end of the wire, but the remainder is coupled to the wire as a radially polarized surface wave. The total charge of electrons is assumed to 2 nC because the typical energy conversion efficiency from a laser to escaping hot electrons is roughly 1% for a laser intensity of 10^{18}–10^{19} W/cm^2 [22]. The peak electric field of the wave on the wire surface is calculated to be 13 MV/m. This agrees fairly well with the experimental value.

Figure 4 shows the waveforms of the surface wave near the peak when d = 0.5 mm. The solid line is the simulation result for an observation of the wire surface at 6 mm from the aluminum foil; the closed circles are experimental data. The simulation results reproduce well the steep rise of the surface wave obtained from the experiment. This suggests that the front of the peak can be explained by the electromagnetic wave generated by the emission of hot electrons. However, the present simulations cannot reproduce the waveform after the peak. This is probably because the calculation does not include phenomena related to high energy density plasma (e.g., ion acceleration on the rear of the foil and re-circulation of electrons between the front and rear of the foil).

Figure 5 shows the dependence of the peak electric field at the wire surface on the foil–wire gap d. The open and closed circles represent the experimental and calculated peak electric field, respectively, of the surface wave for various values of the foil–wire gap d. The experimental peak electric field is estimated by fitting the function $E(t) = \exp(-t/\tau_{\mathrm{decay}})/[1+\exp(-t/\tau_{\mathrm{rise}})]$ to the waveforms in Fig. 2. The peak electric field tends to become stronger as d becomes smaller, with the increase being more remarkable for d less than 1 mm. The experimental data are reproduced well by the simulations. The simulation results suggest that if the density of electrons passing near the wire tip is high, strong surface waves are induced. Therefore, the initial angular distribution of electron emission strongly influences the surface wave electric field. Thus, there is still room to improve the transfer efficiency from the laser to the surface wave if we could control the angular distribution of the electromagnetic wave emitted from the foil, for example by directing it closer to the wire.

In conclusion, we have demonstrated that a surface wave along a metal wire waveguide can be induced by the interaction of an intense femtosecond laser pulse with a foil adjacent to the wire. The peak electric field is estimated to be 11 MV/m on the wire surface at a laser intensity of 8.5×10^{18} W/cm^2. The wire is not damaged by laser irradiation; therefore, repeated operation is possible by supplying fresh foil surface as the target for each laser irradiation. This provides a good trade-off between peak field and repeated generation. Our simulation results suggest that the electric field associated with fast electron emission induces a sub-THz surface wave on the metal wire. Such intense surface waves arising from laser plasmas produced by intense femtosecond laser pulses are expected to be a powerful sub-THz wave source for studies in high-field physics, such as field evaporation in materials science.

This work was supported by a Grant-in-Aid for Scientific Research (grant no. 16H02127) from the Japan Society for the Promotion of Science (JSPS), the Japan Science and Technology Agency (JST)/Basic Research Programs “PRESTO”, and the Collaborative Research Program of the Institute for Chemical Research, Kyoto University (grant no. 2016-1).

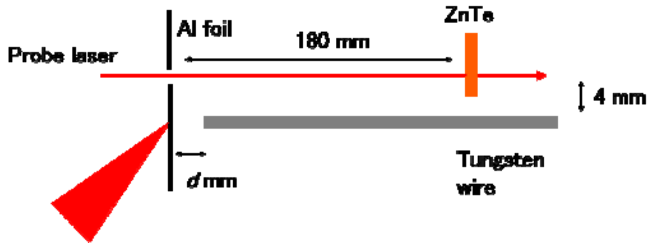

FIG. 1. Experimental setup for the generation and measurement of the surface wave. An Al foil target is irradiated with intense laser pulses at an incident angle of 45°. The surface wave is detected at a distance of 180 mm from the thin film and a distance of 4 mm from the wire using an electro-optical effect.

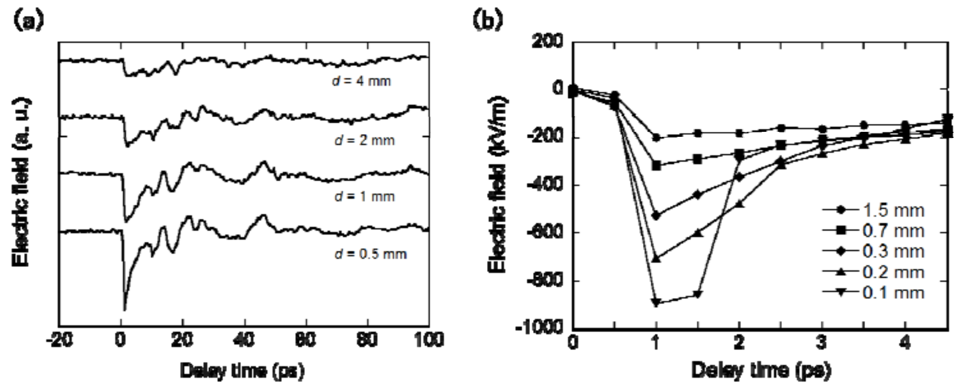

FIG. 2. (a) Typical waveform of the surface wave at various distances (d = 0.5, 1, 2, 4 mm) between the foil and the wire. (b) Waveforms near the peak for various values of d (0.1, 0.2, 0.3, 0.7, 1.5 mm).

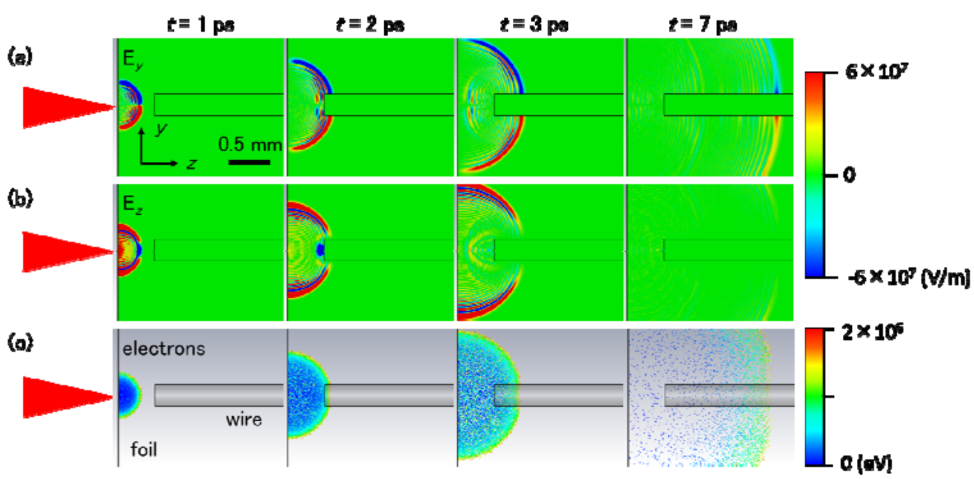

FIG. 3. Snapshots of the numerical simulation results. Electric field distributions along (a) the y axis and (b) the z axis, and (c) the electron distribution.

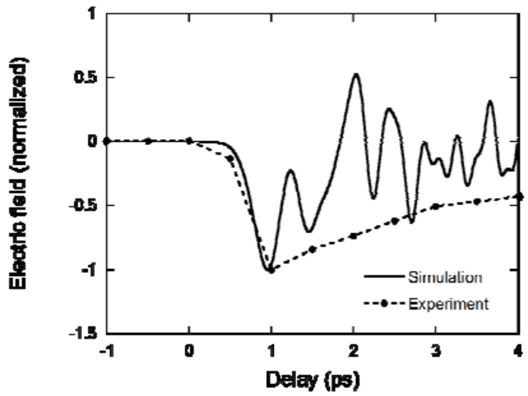

FIG. 4. Experimental and simulated waveforms of the surface wave near the peak (normalized by the peak). The solid line is the simulation result and closed circles are experimental data.

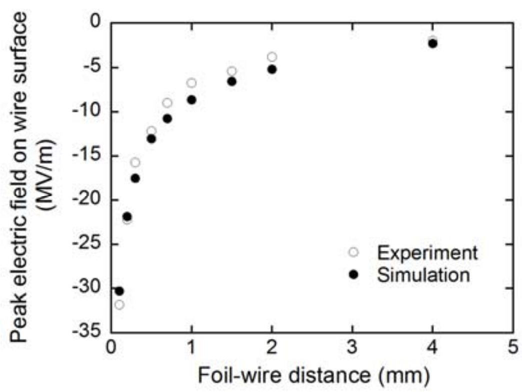

FIG. 5. Peak electric field of the surface wave on the wire for various distances between the foil and the wire. Assuming that the electric field is proportional to 1/r, the experimental peak values are obtained by fitting the function $E(t) = \exp(-t/\tau_{\mathrm{decay}})/[1+\exp(-t/\tau_{\mathrm{rise}})]$ to the waveforms in Fig. 2. Open and closed circles indicate experimental and numerical results, respectively.

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