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ABSTRACT
Transmission of intense laser light through a thin foil containing multiple near- or sub-wavelength holes is investigated using electromagnetic particle-in-cell simulation. It is found that the intensity of transmitted light neither increased with hole size nor decreased with the hole separation distance monotonically, but there are several maximum transmissivities with optimized parameters. Despite the nonlinear light-matter interaction that can accelerate and expel electrons and, eventually, also ions in the foil, the dependence of the transmitted light intensity on the foil and hole properties is similar to that of extraordinary optical transmission in the nondestructive interaction of weak light of the same profile with thin multiholed metal foils, provided that the ratio width:length:period of the hole dimensions is similar.

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I. INTRODUCTION
Propagation and diffraction of light through thin foils with subwavelength holes is of basic as well as practical interest, where novel properties such as wavelength filtering, extraordinary optical transmission, etc., can appear. Such properties have found applications in biophysics, chemical sensing, medicine, subwavelength optoelectronics, etc. Such properties can depend on the foil and hole configuration and have been attributed to interaction of light with the free electrons and the excited waves on the hole surfaces. Bethe showed that for light transmission through a hole of a subwavelength diameter in a thin metal foil, the transmitted light decreases as the fourth power of the ratio of the hole diameter to the incident-light wavelength and exponentially with the foil thickness. However, it was later found that when the multiholed foil is of a finite thickness, the transmitted light intensity can be higher than that predicted by Bethe, and this extraordinary transmission phenomenon has been attributed to resonant excitation on the metal surface of surface plasmon polaritons and/or quasicylindrical waves around the holes. In general, such phenomena are related to resonant or parametrically driven excitation of surface plasma waves from the response of the free electron on/near the surface of the foil to the incident light.

On the other hand, in view of potential applications of tabletop particle accelerators and X- and γ-ray generators for tumor therapy, high-energy density physics research, radio communication through plasma during reentry of space vehicles, fast ignition in inertial confinement fusion, etc., there has been much recent interest in the interaction of intense laser light with solid targets and with microstructures. Experiments and numerical simulations suggest that the latter can enhance light transmission as well as particle acceleration. In the interaction of intense laser with solid matter, the very front of the intense laser pulse (say, of Gaussian time-profile) can fully ionize the target so that the main part of the pulse actually interacts with a plasma, and the target can be strongly modified or even destroyed. However, for interactions involving very short laser pulses and very thin targets, the time of light transmission through the holes can be much less than that of the bulk plasma response so that the original foil structure can remain nearly unchanged during the light transmission, which only involves the nonlinear response of the affected electrons. It is, therefore, of interest to see, in more detail, if the
properties of light transmission during that stage, usually ignored in the existing studies of intense-laser interaction with matter, behave similarly as those of weaker light transmission through similar thin foils.

The transmission of intense short-pulse laser light with a solid-density plasma foil having a subwavelength hole array is highly non-linear and complex since several different processes can be involved and eventually the foil as well as the laser light can be modified by the interaction. Here, we consider the problem using the two-dimensional relativistic electromagnetic particle-in-cell simulation code OPIC. For convenience of comparing with existing experiments involving weak light and metal foils, we shall concentrate on the dependence of the intensity of the transmitted light on the spatial period, i.e., the distance between the holes and the laser frequency, as well as the relation between the amplitude of the waves excited in the holes and the transmitted light intensity. Our results show that intense laser-plasma interaction can also exhibit the characteristics of extraordinary optical transmission even though a large number of foil-surface electrons are accelerated and expelled by the laser during its passage through the foil. It is found that the intensity of transmitted light neither increased monotonically with hole size nor decreased monotonically with the hole separation distance. The dependence of the transmitted light intensity on the foil and hole properties is similar to that found in the experiments involving nondestructive transmission of much weaker light of the same wavelength and profile through thin multiholed metal foils if the ratio width:length:period of the hole dimensions is similar.

II. THE MULTHOLED FOIL

We consider a hydrogen plasma foil of thickness \( h \) and density \( n_c = 10n_c \), where \( n_c \) is the critical density. It is placed at \( x = 20 \) μm from the left boundary of the simulation box defined by \( 0 < x < 60 \) μm, and \( -100 \mu m < y < 100 \mu m \). The holes, or slits, of height \( d \) and separation distance, or spatial period, \( l \), between their centers are uniformly distributed across the height of the foil. The two-dimensional simulation box contains 6000 \( \times \) 20 000 cells (so that the cell size is \( 0.01 \times 0.01 \mu m^2 \) and 20 electrons and 20 ions each per cell. A \( p \) polarized Gaussian laser pulse of duration \( \tau = 33 \) fs centered on \( y = 0 \) and propagating along the \( x \) direction enters the simulation box at \( x = 0 \). Its transverse intensity profile is \( I(x) = I_0 \exp(-y^2/a_0^2) \), where \( a_0 = cE_0/m_0c = 1 \), unless otherwise stated, \( -e \) and \( m_0 \) are the electron charge and mass, respectively, \( c \) is the vacuum light speed, \( E_0 \) is the peak laser electric field, and \( a_0 \) is the laser spot size. The corresponding peak laser intensity is \( I_0 = 1.37 \times 10^{18} \) W/cm² so that the electron motion in the laser light is in the relativistic regime. Figure 1(a) shows a sketch of the interaction model.

III. SIMULATION RESULTS AND DISCUSSIONS

For the purpose of comparing with existing experimental and theoretical results, it is instructive to first consider the effect of the spatial period \( l \) of the holes. Figure 1(b) for \( 0.4 \mu m < l < 5.0 \mu m \), foil thickness \( h = 1.0 \mu m \), and hole width \( d = 1.6 \mu m \) shows the normalized transmitted light intensity \( \eta = E_t/E_i \), where \( E_t \) and \( E_i \) are, respectively, the total transmitted and incident light energies obtained from our PIC simulation (red curve), Fresnel light diffraction theory (blue curve), ray tracing (green curve), and the Bethe theory. Due to the limitation of our computing resource, here, \( E_t \) is the total transmitted light energy behind the foil in the region \( 21.2 \mu m < x < 60.0 \mu m \) and only up to \( t = 60 \) fs. That is, its value is somewhat underestimated. We see that, in general, the transmitted light intensity decreases with increase in the distance \( l \) between the holes as can be intuitively expected since for a fixed foil size, a larger \( l \) corresponds to less number of holes and less transmitted light. We can also see that the result of our simulation roughly follows that of the Fresnel light diffraction theory, except that it is somewhat higher for large \( l \); and, more distinctively, it contains two large dips at \( l \sim 0.8 \) and \( 2.4 \mu m \). This dependence is similar to that of extraordinary optical transmission and shall be discussed in more detail. It is higher than that from ray tracing, which treats light as straight lines and thus precludes electron-light interaction effects around the holes. As expected, all the curves are higher than \( (l/d)^-1 \) dependence from Bethe’s quasistatic analytical theory. On the other hand,
Figure 2 shows the dependence of the normalized transmitted light intensity \( \eta \) on the laser wavelength \( \lambda \) for the hole diameter \( d = 180 \text{ nm} \), foil thickness \( h = 300 \text{ nm} \), and \( l = 1, 2, 3, \) and \( 5 \times 1080 \text{ nm} \), respectively. One can see that \( \eta \) as well as the magnitudes of its humps and dips decrease as \( l \) becomes larger, i.e., less holes, which means there is a multiple hole effect, not only a single hole effect. In other words, there are interactions between holes when they are close with each other. The red curve for \( l = 1080 \text{ nm} \) is similar to that shown in Fig. 2, and the corresponding ratio \( d:h \) is \( 3:18:5 \) of this experiment is close to that of the latter. Moreover, as \( l \) increases, the part of the curve for \( \lambda \) larger (less) than \( 1 \mu \text{m} \) is red (blue) shifted. The behavior for \( \lambda < 1 \mu \text{m} \) is also in agreement with that of the experiment in this regime but involving much weaker light.

We have also investigated the effect of the hole separation distances on the excited wave fields inside a hole and the total transmitted light. Figure 4 shows the peak magnitude of the electric field fluctuations at the center of a hole near the center of the foil for different laser wavelengths and the total transmitted light intensity (normalized by that of the incident laser) for (a) \( l = 420 \text{ nm} \) and (b) \( l = 1.5 \mu \text{m} \). It may be of interest to note that in panel (a), there is a rough positive correlation relation between the (humps and dips of the) wave magnitude in the center hole and the total transmitted light intensity. In contrast, panel (b) shows a negative correlation. This difference in behavior can be attributed to interference effects of the waves since the total transmitted light intensity here includes the contributions, which strongly depend on \( l \), of the light from all holes.

For completeness, we now look at how the foil is eventually affected by the interaction. Figures 5(a) and (b) show the distribution of the foil electrons at \( t = 32 \text{ fs} \) for \( \lambda = 525 \text{ nm} \) and \( \lambda = 675 \text{ nm} \), respectively. One can see that unlike those in weak light transmission through multiholed metal foils, the affected electrons are also accelerated by the intense laser light and driven out from both the front and back sides of the foil, especially in the low transmission (\( \lambda = 675 \text{ nm} \) case). Electrons in the boundary regions of the hole channels are also driven by the intense light waves, making the boundary profile effectively time dependent for the latter. A quasicoherent electron wave structure can be observed inside the thin foil. One can consider such waves as laser driven nonlinear surface waves.
FIG. 5. Density of the foil electrons for laser wavelengths (a) $\lambda = 525$ nm and (b) $\lambda = 675$ nm at $t = 32$ fs when the laser pulse has almost passed the foil; (c) and (d) are density of the foil ions for $\lambda = 525$ nm and $\lambda = 675$ nm, respectively at $t = 52$ fs long after the laser pulse has passed the foil. One can see low-density ion waves appear on all foil surfaces, and a dense shock-like ion wave front is formed just inside the front foil surface, indicating that the excited ion wave therein is highly compressive.

IV. SUMMARY

We have studied the propagation of intense laser light through a plasma foil with near-wavelength and subwavelength holes using relativistic electromagnetic PIC simulation. An extraordinary transmission of intense laser light is found. The intensity of transmitted light neither increased monotonically with hole size nor decreased monotonically with the hole separation distance, but there are several maximum transmissivities with optimized parameters. The dependence of the transmitted light intensity, such as the locations of its humps and dips, on the hole size, and the hole period, is quite similar to that of nondestructive weaker light interaction with a thin metal foil if the ratio $d:lh$ of the hole properties is similar. Moreover, the relation between the magnitude of the excited waves in the center hole and the transmitted light intensity depends on the distance between the holes, which shows there are interference effects of the waves. Our result suggests that if the hole properties have the same width:length:period ratio, the transmission properties of an intense laser pulse through a thin foil with a hole array can be quite similar to those for weak light transmission with multiholed metal foils. Moreover, since theoretical understanding of the rather complex nonlinear interaction of intense-laser excited surface waves of the thin foil. Figures 5(c) and 5(d) show the distribution of the foil ions at $t = 52$ fs for $\lambda = 525$ nm and $\lambda = 675$ nm, respectively. These snapshots are taken at a larger $t$ since the heavy ions take a longer time to respond to the space-charge field created by the fast laser driven electrons. At this time, the laser pulse has already passed through the foil, (i.e., the electrons are no longer laser driven) and the plasma everywhere has become quasineutral. Inside the foil, the density perturbation of the excited ion waves is rather weak, except near the front surface where a relatively high density shock-like layer structure is formed from compression of the ion wave front. However, outside both the front and back sides of the foil, one finds coherent ion wave structures although at a very low density. Moreover, in the hole channels, one can see merging low-density ion wave fronts. To our knowledge, this interesting (but beyond the scope of the present work on the light transmission properties) scenario of the surface waves has not been reported earlier. Of interest here is that although both the front side of the foil is considerably modified by the interaction, the boundaries of the cylindrical hole channels remain almost unchanged. This could have contributed to the result that the properties of light transmission here can be similar to those of weak light propagation through multiholed metal foils.
around closely packed tiny hole channels is still lacking, the results here can also serve as a guide for more detailed analyses of the problem.

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