Femtosecond laser pulse propagation in a metallic nano-slit array

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The property of femtosecond laser pulse propagation in a metallic nano-slit lens, which is composed of nano-slits with variant widths, is investigated by using the finite-difference time-domain method. By appropriately setting the width profile of the arrayed nano-slits, we find that the femtosecond laser pulse can be focused on a nano-scale spot, while the pulse shape is well maintained beyond the spot location.

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In 1998, Ebbesen and his coworkers first observed transmission spectra with extraordinarily high transmission at certain wavelengths in metallic nanohole arrays[1,2]. Following this, Lezec *et al.* reported their experimental observation that the light emerging from a subwavelength aperture surrounded by periodic corrugations on the exit side of a metallic film displays extensive beam shaping[3,4]. This opens up a new avenue for new types of nano-optical devices with metallic films. As application examples, Sun and Kim reported the refractive transmission of light through a metallic nano-slits array and demonstrated that the convex-shaped metallic lenses possessed the capability of beam shaping in a way that resembled the refractive optics[5]. Shi *et al.* have designed a metallic nano-slits lens which can be utilized to modulate light spatially if the slit widths are appropriately designed[6].

To date, investigations into a subwavelength aperture or slit array transmission have primarily focused on continuous electromagnetic wave propagation. In this regime, surface plasmon polariton (SPP) excitation is in a state of constant generation[7]. Very recently, femtosecond optical pulse propagation in subwavelength metallic aperture arrays or a single aperture surrounded by periodical corrugations has received considerable attention[8,9]. When the exciting pulse has a duration shorter than or comparable to the plasmon lifetime, the coupling of femtosecond optical pulse with SPPs will be of particular interest. Since ultrashort pulse bandwidths cross a wider frequency range than that encompassed by the SPP resonance, ultrashort pulses will experience a remarkable temporal shaping. Shi *et al.* have investigated a metallic array of nano-slits with variant widths illuminated by continuous-wave laser pulse[6]. In this paper, we investigate the similar metallic nano-slit lens structure illuminated by ultrashort femtosecond laser pulses. We find that the ultrashort pulse can be focused on a nano-scale dimension while its shape is almost not changed but with a higher amplitude at and beyond the focus spot.

The propagation of pulses in the metallic nano-slits array is described by Maxwell's equations that are coupled to an equation for the light-induced oscillations of quasi-free electrons in the metal (Drude model), which can be expressed as

$$\begin{aligned} \bigtriangledown \times \mathbf{E} &= -\mu_0 \frac{\partial \mathbf{H}}{\partial t}, \\ \bigtriangledown \times \mathbf{H} &= \varepsilon\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}, \\ \frac{\partial \mathbf{J}}{\partial t} &+ \gamma \mathbf{J} = \varepsilon_0 \omega_{\rm p}^2 \mathbf{E}, \end{aligned} \tag{1}$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field vectors, respectively, $\mathbf{J}$ is a current density (A/cm^2) and $\mathbf{J} = \partial \mathbf{P}/\partial t$. The parameter ε is the relative dielectric constant. $\omega_{\rm p}$ is the plasma frequency of the metal and γ is the damping frequency characterizing ohmic absorption losses. The frequency-dependent dielectric function of metal is given by the Drude model[10]:

$$\varepsilon_{\rm m}(\omega) = 1 - \frac{\omega_{\rm p}^2}{\omega^2 + i\gamma\omega}. \tag{2}$$

In our analysis, $\omega_{\rm p}$ and γ are taken to be 1.35×10^{16} and 9.617×10^{13} rad/s, respectively. By solving Eq. (1) with the finite-difference time-domain (FDTD) method[11], the dynamical field distribution and temporal evolution of ultrashort pulse can be obtained.

We study light propagation through a structure composed of subwavelength nano-slits with variant widths perforated on a silver film with thickness of $h = 500$ nm, as shown in Ref. [5]. A y-polarized Gaussian pulse of 2-fs full width at half maximum (FWHM) is propagating in the z-direction and illuminates the metallic nano-slits array at normal incidence, as shown in Fig. 1. The magnetic and electric field strengths of the input pulse, linearly polarized along y, are given by

$$H_{y,\rm in}(z,t) = A_{\rm in} \cos\left[\omega_{\rm in} t - \frac{2\pi n_{\rm s}}{\lambda_{\rm m}} z\right], \tag{3}$$

and

$$E_{x,\rm in}(z,t) = n_{\rm s}\sqrt{\mu_0/\varepsilon_0} H_{y,\rm in}(z,t). \tag{4}$$

Here, c is the light speed in vacuum, $n_{\rm s}$ is the refractivity at the substrate, and $A_{\rm in}$ is taken as a Gaussian shaped function

$$A_{\rm in} = A_0 \exp\left[-2\ln 2 \left(\frac{t - t_0 - z n_{\rm s}/c}{\tau_0}\right)^2\right], \tag{5}$$

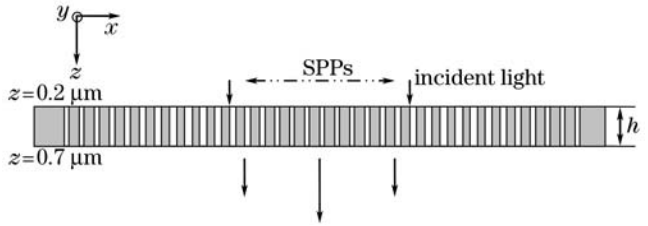

Fig. 1. Physical picture of femtosecond pulse transmission through a metallic nano-slit lens. The incident light is a TM-polarized 2-fs Gaussian shape pulse located at $z = 0$ μm.

where A_0 is the field amplitude. The parameters t_0, τ_0 are arbitrarily chosen delay time and pulse width, respectively.

Figure 1 schematically shows the FDTD simulation model in which a metallic film is perforated with a great number of nano-slits with specially designed widths. The two sides of the metal film are in air. The different slit width is to introduce phase retardation among the re-radiation waves at the exit surface of metal. Narrower slits provide larger propagation constant, and hence greater phase retardation. In our simulation, the slit width ranges from 10 to 70 nm with slit depth of 500 nm and the total slit number is 65.

The FDTD simulation is performed with a uniform grad spacing of 2 nm. The time step used is 0.004 fs. Perfect matched layer (PML) absorbing boundary conditions are applied on all boundaries. The wavelength of incident TM-polarized Gaussian modulated continuous wave is 650 nm. The simulation result shows that a focus spot appears about 0.75 μm away from the exit surface. The cross section of Poynting vector $\vec{S}_z$ in x direction at $z = 1.35$ μm is shown in Fig. 2. Figure 2 shows a focus spot with a FWHM of 260 nm, which is similar with the result of Ref. [6], but in our case, the side peaks at

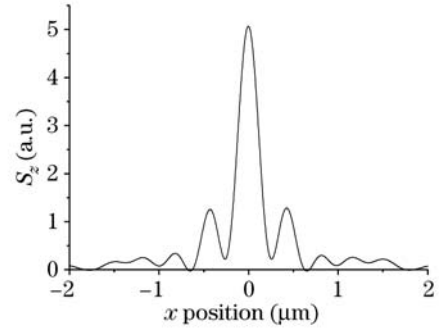

Fig. 2. Poynting vector S_z along the array direction on the focal plane at $z = 1.5$ μm.

$z = \pm 1.2$ μm are smaller and only 3 main peaks appear.

Figure 3 depicts the temporal evolution of the transmitted 2-fs pulse at four representative locations $z = 0.7$, 1.0, 1.5 and 1.99 μm, respectively. These figures show that the femtosecond pulse experiences a remarkable pulse shaping at the exit surface of the metal, which is given in Fig. 3(a). The 2-fs femtosecond pulse breaks into a pulse train composed of a high-amplitude pulse followed by a group of low-amplitude pulses, and the pulses are temporally coupled. At a farther location $z = 1.0$ μm the following oscillations are suppressed, as given in Fig. 3(b). The transmitted pulse evolves to a distorted pulse with a damping tail but the amplitude increases and becomes higher than that of the incident light. The nature of these oscillations is due to the re-radiation interference between the impulsively excited SPP waves originated from different locations along the array. At the focus spot, the oscillation tail of the transmitted pulse is nearly eliminated while the amplitude is enlarged which is about 2.7 times of the incident pulse, shown in Fig. 3(c).

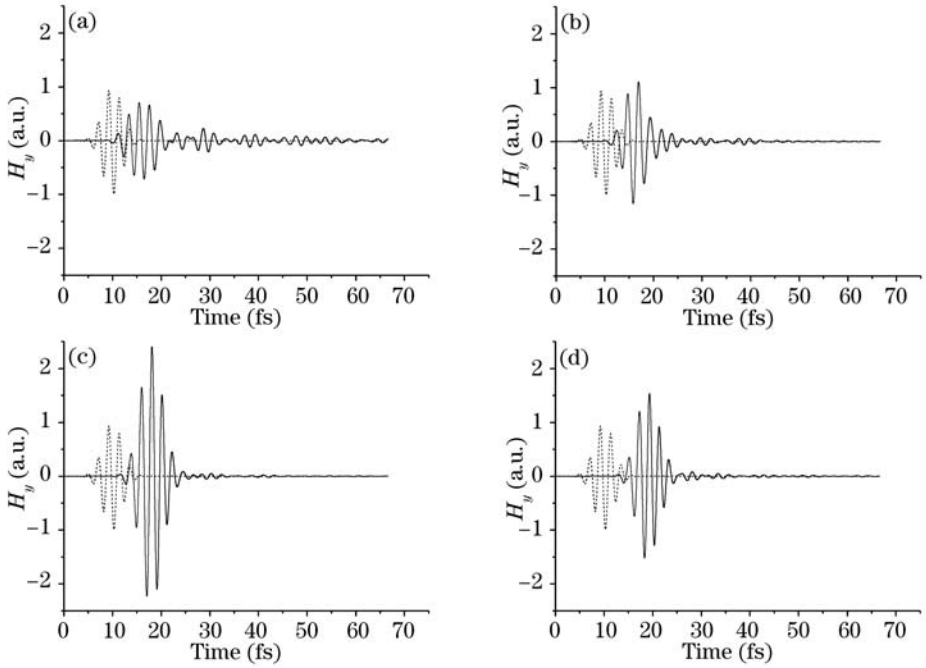

Fig. 3. Temporal evolution of 2-fs transmitted pulse (a) at the exit surface $z = 0.7$ μm, (b) $z = 1.0$ μm, (c) at focus spot $z = 1.5$ μm and (d) $z = 1.99$ μm. The dashed lines are the incident pulse envelopes.

The envelope of the transmitted pulse light is well maintained but the absolute phase is changed by $\pi/2$. The pulse shape is well maintained at a location beyond the focus spot, but with a smaller amplitude than that of the focus location, shown in Fig. 3(d). Another point worth to note is that the peak of the 2-fs pulse shows a transit time of 8 fs to traverse the slit on the 500-nm film, corresponding to an effective group velocity of $\sim c/5$. Similar pulse delay has previously been reported for metallic aperture arrays[12].

In this paper, the FDTD simulation of 2-fs optical pulse propagation in a specially designed metallic nano-slits lens shows that the ultrashort pulse can be focused on a nano-scale dimension. Meanwhile, the 2-fs pulse experiences large oscillations before the pulse transits to the focal plane. At the focus spot the transmitted pulse has a similar envelope as the incident pulse while the amplitude is enlarged and the absolute phase is changed. Beyond the focus spot, the shape of the transmitted pulse is maintained but the amplitude decreases. Once we understand the phenomenon of coupling mechanism of the incident light with impulsively excited SPPs, we can control the shaping of pulses in the ultrashort and nano-scale domains. Various nano-optical research fields such as the field of optical switches, optical sensors, optical lithography, optical storage, and optical microscopy, can be facilitated and amplified.

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