All-optical switching of the transmission of electromagnetic radiation through subwavelength apertures

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Unprecedented optical control of the surface plasmon polariton assisted transmission of terahertz radiation through subwavelength apertures is rendered possible by carrier-induced changes to the dielectric properties of a semiconductor grating. Although the study presented is static, the extension of our approach to dynamic switching and tuning is deemed straightforward, opening the way for the realization of ultrafast surface plasmon based devices. © 2005 Optical Society of America

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Surface plasmon polaritons (SPPs) are electromagnetic waves coupled to the collective oscillation of free carriers on a metal–dielectric interface.[1] SPPs propagate along the metal surface and decay evanescently away from it, having proved to be extremely useful for the investigation of thin films deposited onto metal surfaces, for chemical sensing and biomolecular analysis.[2] Moreover, SPPs allows the concentration and control of electromagnetic waves on length scales smaller than the radiation wavelength. The recent discovery of extraordinary transmission of light through gratings of subwavelength holes[3,4] has significantly contributed to a renewed interest in SPPs from both a scientific and an applied point of view.[5] This extraordinary transmission has been explained in terms of the grating-assisted excitation of surface waves such as SPPs.[6–10]

One of the greatest challenges in the field of plasmonics is the realization of active devices. At a metal–air interface the SPP's characteristics are governed by the permittivity of the metal. The permittivity in turn is mainly determined by the number of free charge carriers and their mobility. Due to the large number of free carriers in metals, the modification of their permittivity is not trivial. An appealing alternative to metals for the excitation and propagation of low-frequency SPPs is semiconductors,[11,12] since their permittivity is easily modified by a change of temperature, by carrier injection, or by optical generation of carriers. The use of semiconductor gratings renders possible unprecedented control of the SPP transmission characteristics.[13,14]

In this Letter we demonstrate optical switching and tuning of the SPP-enhanced transmission of terahertz (THz) radiation through gratings of subwavelength apertures structured in indium antimonide (InSb). By illuminating one of the faces of the grating with a laser beam, we generate additional charge carriers in the semiconductor material. The resulting increase of the free carrier density modifies the permittivity and, thereby, the enhanced transmission characteristics of the grating structure. This phenomenon is interpreted in terms of a change of the SPP decay length into the semiconductor material.

The sample used in this study is a 130 μm thick InSb grating with square apertures of side length $d = 65\ \mu$m and lattice constant $a_0 = 300\ \mu$m.[14] As a high-mobility semiconductor ($\mu_e \approx 7.7 \times 10^4\ \mathrm{Vs/cm^2}$) with an intrinsic carrier concentration of $\simeq 10^{16}\ \mathrm{cm^{-3}}$ at room temperature, undoped InSb is well suited for the generation of THz SPPs. Optically induced changes of the carrier density are easily facilitated by use of moderate pump powers delivered from a non-amplified laser system.

To investigate the response of the SPP resonance to optical excitation we have performed time-resolved optical pump–THz probe transmission measurements.[15] A mode-locked Ti:sapphire laser delivering 100 fs pulses centered at a wavelength of 780 nm and with a pulse repetition rate of 76 MHz is used to generate and detect pulsed coherent THz radiation by use of a modified InGaAs surface-field emitter[16] and a photoconductive antenna as a receiver. The THz radiation impinges on the sample at normal incidence, collinearly with the optical pump beam derived from the same laser system. When the grating is illuminated an electron–hole plasma is created in a thin layer ($\simeq 100$ nm), with a thickness determined by the absorption length of InSb at the chosen optical wavelength of 780 nm. Since the pulse repetition rate is larger than the inverse of the carrier recombination time in InSb ($\tau_{\mathrm{rec}} \simeq 50$ ns; Ref. 17), the optical excitation can be considered continuous wave. Average optical pump powers ranged from 5 to ~ 200 mW, which corresponds to excitation densities of $\simeq 0.8 \times 10^{16}$ to $3.4 \times 10^{17}\ \mathrm{cm^{-3}}$ at a spot size of $\simeq 1$ mm. Although the generated carriers diffuse a few micrometers before they recombine, it is reasonable to assume an inhomogeneous carrier distribution as a function of the depth into the semiconductor.

Figure 1 illustrates the effect of the optical excitation as measured in the time domain. As the pump power increases, the transmitted THz amplitude de-

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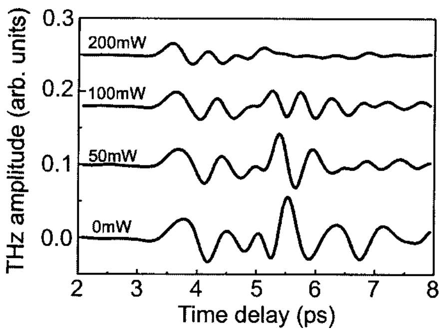

Fig. 1. THz time domain transmission through a grating of subwavelength apertures structured in InSb and under optical illumination with a laser beam on one face. The temperature of the grating is 240 K. The different curves correspond to different optical pump powers. The transients are offset vertically for clarity.

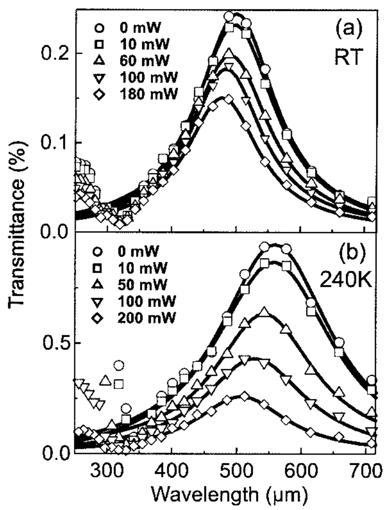

Fig. 2. Transmittance through a grating of subwavelength apertures structured in InSb for five different optical pump powers at (a) room temperature and (b) 240 K. The solid curves are Lorentzian fits.

creases. This decrease is more pronounced for higher-frequency components appearing at a time delay of $\simeq 5.5$ ps. The longer time delay signifies transmission through the grating material rather than through the apertures. This behavior reveals the optically induced shift of the plasma reflectivity edge: At frequencies higher than the plasma frequency the semiconductor behaves as a dielectric and is transparent. The plasma frequency is proportional to the square root of the carrier density. As the number of carriers increases with pump power, the grating material becomes proportionally opaque at higher frequencies, i.e., longer wavelengths. Throughout this study the grating material remains opaque in the wavelength range of interest, i.e., around the SPP resonance that occurs at comparatively long wavelengths.[14]

For further analysis, the power spectra are calculated by Fourier transforming the transients. To define the transmittance through the grating the power spectra are normalized to a reference measurement taken without a sample. In Figs. 2(a) and 2(b) the resulting spectral transmittances are plotted as a function of wavelength for pump powers ranging from 0 to 200 mW, at room temperature and 240 K, respectively. A maximum transmittance of $\simeq 1\%$ at a wavelength of 560 μm (240 K, no pumping), i.e., nine times the aperture side length, signifies the subwavelength transmission enhancement. With increasing pump powers the maximum transmittance decreases and the position of the SPP resonance is blueshifted for both temperatures. The solid curves in Figs. 2(a) and 2(b) are Lorentzian fits from which the maximum transmittance and the central wavelength of the SPP resonance are extracted. The corresponding values are depicted separately in Figs. 3(a) and 3(b). The reduction in transmittance as well as the wavelength shift is more pronounced at 240 K. The maximum transmittance is switched by a factor of 3.5 (240 K) and 1.5 (room temperature). The central wavelength exhibits a tuning range of $\simeq 50$ μm at 240 K and $\simeq 25$ μm at room temperature. By fitting the measurements in Fig. 3(a) phenomenologically with an exponentially decaying function (solid curves), we obtain a transmittance switching coefficient of $(-10.9\pm1.2)\times10^{-3}$ at 240 K and $(-8.8\pm2.2)\times10^{-3}$ at room temperature. The central wavelength is tuned linearly by (-0.28 ± 0.01) μm/mW (240 K) and $(-0.14\pm0.01)\mu$m/mW (room temperature).

Similar to the qualitative explanation of the thermal transmission switching presented in Ref. 14, the main mechanism responsible for the optical switching is a variation of the SPP decay length into the semiconductor material or the semiconductor skin depth, δ_{InSb}. Since the semiconductor surrounding the apertures is a nonperfect conductor, δ_{InSb} is finite and increases the effective size of the apertures to $d+2\delta_{\mathrm{InSb}}$, where d is the nominal aperture width.[18] A larger skin depth thus leads to a larger effective aperture size through which more radiation is transmitted. The dependence of the skin depth on the

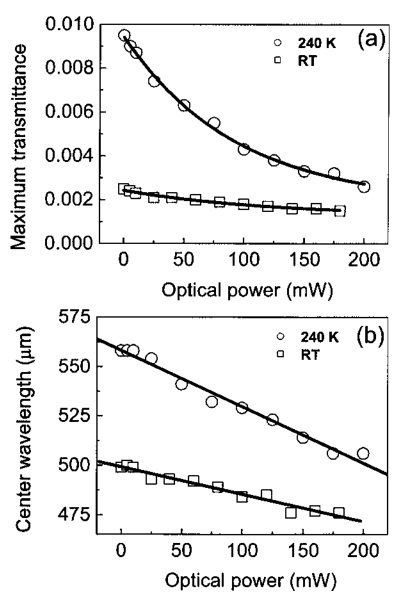

Fig. 3. (a) Maximum transmittance and (b) center wavelength of the SPP resonance as a function of optical power for room temperature (open squares) and 240 K (open circles). The solid curves and lines are fits to the measurements.

permittivity can be approximated by $\delta_{\mathrm{InSb}} \propto |\sqrt{(\epsilon'+1)/\epsilon'^2}|$, where ϵ' denotes the real part of the complex permittivity with $\epsilon'<0$. This expression of the skin depth is valid for good conductors and accurate to within 5% for InSb. The absolute value of ϵ' increases with an increasing density of free carriers. At room temperature the carrier density of InSb is $\simeq 10^{16}$ cm^{-3} and $\delta_{\mathrm{InSb}} \simeq 7$ μm at $\lambda = 500$ μm. At 240 K the number of thermally excited carriers is reduced to $N \simeq 0.3 \times 10^{16}$ cm^{-3} and $\delta_{\mathrm{InSb}} \simeq 16$ μm. After illumination the number of free carriers and the absolute value of ϵ' are increased on the illuminated face, giving rise to a shorter δ_{InSb} and a smaller effective aperture size at the aperture entrance. The changes in the SPPs' decay length into air, the SPPs' propagation length, and the losses in the apertures may play a role in transmission, although the variation of δ_{InSb} is dominant.[14]

It is apparent from Figs. 2 and 3(a) that the change of the maximum transmittance with optical pump power is much less pronounced at room temperature. This may be attributed to the larger background of thermally activated carriers: at low temperatures the number of optically generated carriers relative to the number of thermally activated carriers increases and optical switching becomes more efficient. As can be appreciated from Fig. 3(a), the maximum transmittance converges for both temperatures for increasing optical pump powers. This suggests that at high pump power the optically excited carriers determine the transmission through the grating.

The spectral position of the first SPP resonance has been reported to be approximately given by[1,4] $\lambda_{\mathrm{SPP}} \simeq a_0[\epsilon'/(\epsilon'+1)]^{1/2}$, where a_0 denotes the lattice constant. At THz frequencies the resonant wavelength occurs at much lower values than predicted by this expression. However, the qualitative dependence of λ_{SPP} on ϵ' has been shown to be correct[14]; i.e., as the absolute value of the permittivity increases, the resonance shifts to lower wavelengths. This behavior is observed in Fig. 3(b), where a shift of the center wavelength toward shorter wavelengths occurs at high optical pump powers because of an increase of optically generated carriers. In accordance with the change of the maximum transmittance this shift is more pronounced at lower temperatures.

In summary, by optically exciting an InSb semiconductor grating structure, switching and tuning of the SPP-assisted transmission at THz wavelengths are demonstrated. The qualitative change of the transmission as a function of the incident optical pump power can be understood in terms of a modification of the finite semiconductor skin depth that gives rise to an effective aperture size. Furthermore, the extension to dynamic ultrafast switching and tuning by use of suitable materials with short carrier lifetimes is deemed straightforward.

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