Extraordinary Interaction of Terahertz and Optical Waves through Metallic Nano-Slits

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Abstract

The unique property of periodic arrays of subwavelength metallic slits to allow extraordinary electromagnetic wave interaction at multiple frequency bands is described. Diffraction limit in periodic arrays of subwavelength metallic slits is mitigated by excitation of surface waves which assist efficient coupling of a TM-polarized incident electromagnetic wave into the TEM waveguide modes of the subwavelength slab waveguides formed by metallic slits. By investigating the geometry dependence of the electromagnetic guided modes supported by periodic arrays of subwavelength metallic slits, we present the design of an array of metallic nano-slits which enables efficient interaction of terahertz and optical waves at nano-scale dimensions. Such unique capability would significantly improve the performance of existing photoconductive terahertz detectors and mixers and enable fundamental studies on light-matter interaction at a very fundamental level.

1. Introduction

Efficient interaction of terahertz and optical waves is crucial to high sensitivity operation of photoconductive terahertz detectors and mixers. Conventional photoconductive terahertz detectors and mixers consist of a terahertz antenna (such as spiral or dipole antenna) coupling the incident terahertz wave to a photo-absorbing semiconductor gap of a few micrometers. A photocurrent is generated and sensed as a result of terahertz field interaction with photo-generated electron-hole pairs. The micrometer-scale of photo-absorbing semiconductor gap-size is to prevent diffraction limited optical absorption and the *RC* roll-off of terahertz antenna efficiency [1]. Therefore, in order to maintain ultrafast device operation, conventional photoconductive terahertz detectors employ low carrier lifetime semiconductors [2], which offer significantly low responsivities due to the low carrier mobility, thermal conductivity and quantum efficiency of low carrier lifetime semiconductors [3]. To solve the limitations introduced by low carrier lifetime semiconductors, photoconductive terahertz detectors and mixers with nanometer-scale gap-sizes filled with a high-quality crystalline photo-absorbing semiconductor are required. In this work, we present the design of a periodic array of subwavelength metallic slits which enables extraordinary interaction of terahertz and optical waves at nano-scale dimensions, and thus, significant sensitivity enhancement of photoconductive terahertz detectors and mixers. Such unique capability would also enable fundamental studies on light-matter interaction at a very fundamental level such as single molecule spectroscopy

2. Principles of Design and Operation

Figure 1 illustrates the cross-sectional view of a periodic array of subwavelength metallic slits supporting multiple subwavelength guided modes. Because of the two-dimensional geometry of the metallic slits, their interaction with electromagnetic waves is strongly polarization dependent. For a TE polarized electromagnetic excitation (electric field in *y* direction), the metallic slits only support evanescent modes. For a TM polarized electromagnetic excitation (magnetic field in *y* direction), in addition to evanescent modes, the subwavelength slab waveguides formed by the metallic slits also support TEM electromagnetic guided modes at wavelengths larger than the slit periodicity, *d*. Therefore, efficient electromagnetic power transmission through the metallic slits can be achieved [4, 5].

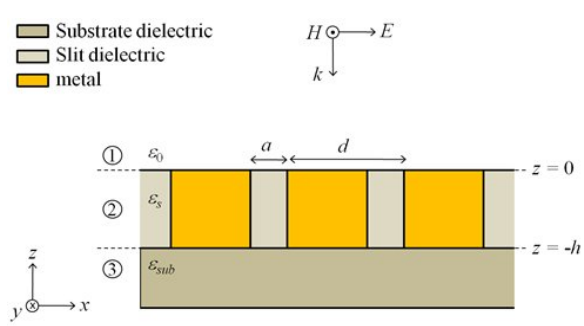

Fig. 1. Schematic view of the subwavelength metallic slits supporting multiple subwavelength guided modes

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In this section, the power transmissivity of a TM-polarized incident electromagnetic wave through the metallic slits into a dielectric substrate, as a function of slit geometry (*a, h, d*) and electromagnetic wavelength is analytically derived. For a normally incident TM-polarized electromagnetic excitation, the magnetic field in regions 1 ($z \geq 0$) and 3 ($z \leq -h$) are calculated as:

$$\widetilde{H}_y^{(1)} = -\sum_{p=-\infty}^{\infty}\left[u_{1,p}e^{i\alpha_p z}e^{iG_p x} + r_{1,p}e^{-i\alpha_p z}e^{iG_p x}\right] \tag{1}$$

$$\widetilde{H}_y^{(3)} = -\sum_{p=-\infty}^{\infty} t_p e^{i\alpha_{psub}(z+h)}e^{iG_p x} \tag{2}$$

where, $u_{1,p}$ is the amplitude of the forward-propagating p^{th} diffraction mode on the periodic subwavelength metallic slits, $r_{1,p}$ is the amplitude of the backward-propagating p^{th} diffraction mode from the top of the periodic subwavelength metallic slits, t_p is the amplitude of the transmitted p^{th} diffraction mode into the dielectric substrate. $G_p = 2\pi p/d$ is the parallel momentum along metal surface, k is the momentum of the incident wave, $\alpha_p = \sqrt{(k^2 - G_p^2)}$ is the momentum of electromagnetic wave in the z direction, ε_{sub} is the substrate permittivity, k_{sub} is the electromagnetic momentum in the dielectric substrate, $\alpha_{psub} = \sqrt{(k_{sub}^2 - G_p^2)}$ is the z component of electromagnetic momentum in the dielectric substrate. The electric field in regions 1 and 3 has components in x and z direction which are calculated using Maxwell's equation $\nabla \times \widetilde{H} = \varepsilon \frac{\partial \widetilde{E}}{\partial t}$ ($\widetilde{E}_x = \frac{1}{j\omega\varepsilon}\frac{\partial \widetilde{H}_y}{\partial z}, \widetilde{E}_z = \frac{1}{j\omega\varepsilon}\frac{\partial \widetilde{H}_y}{\partial x}$):

$$\widetilde{E}_x^{(1)} = \sum_{p=-\infty}^{\infty}\left[\frac{\alpha_p}{\omega\varepsilon_0}u_{1,p}e^{i\alpha_p z}e^{iG_p x} - \frac{\alpha_p}{\omega\varepsilon_0}r_{1,p}e^{-i\alpha_p z}e^{iG_p x}\right] \tag{3}$$

$$\widetilde{E}_x^{(3)} = \sum_{p=-\infty}^{\infty}\frac{\alpha_{psub}}{\omega\varepsilon_{sub}}t_p e^{i\alpha_{psub}(z+h)}e^{iG_p x} \tag{4}$$

The magnetic field in region 2 ($0 \geq z \geq -h$) is calculated as:

$$\widetilde{H}_y^{(2)} = -u_2 e^{ik_s z} - r_2 e^{-ik_s(z+h)} \tag{5}$$

where u_2 and r_2 are the magnetic field amplitudes of the forward and backward propagating TEM modes in the slits with permittivity of ε_s, and k_s is the electromagnetic momentum in the metallic slits. The corresponding x component of the electric field in region 2 is calculated using Maxwell's equation:

$$\widetilde{E}_x^{(2)} = \frac{k_s}{\omega\varepsilon_s}u_2 e^{ik_s z} - \frac{k_s}{\omega\varepsilon_s}r_2 e^{-ik_s(z+h)} \tag{6}$$

Boundary condition (continuity of the tangential field components) at $z = 0$ and $z = -h$ is used to find the transmissivity of an incident TM-polarized electromagnetic wave into the dielectric substrate. Except for the zeroth order diffraction mode, other excited surface diffraction modes are evanescent. Therefore, the amplitude of guided modes through the metallic slits into the dielectric substrate is calculated as

$$t_0 = \frac{4\frac{a}{d}\frac{k_s}{\omega\varepsilon_s}}{\left(\frac{k_{sub}}{\omega\varepsilon_{sub}} - \eta\right)\left(1 + \eta\frac{\omega\varepsilon_0}{k}\right)}\frac{e^{-jk_s h}}{(1+\Phi_1)(1+\Phi_2) - e^{-j2k_s h}(1-\Phi_1)(1-\Phi_2)} \tag{7}$$

where,

$$\Phi_1 = \sum_{p=-\infty}^{\infty}\frac{a}{d}g_p^2\frac{\frac{k_s}{\omega\varepsilon_s}}{\frac{\alpha_p}{\omega\varepsilon_s} + \eta}, \quad \Phi_2 = \sum_{p=-\infty}^{\infty}\frac{a}{d}g_p^2\frac{\frac{k_s}{\omega\varepsilon_s}}{\frac{\alpha_{psub}}{\omega\varepsilon_{sub}} - \eta}$$

3. Results and Discussion

Figure 2 illustrates predictions of the presented model (Eq. 7) to estimate the power transmission spectrum of a TM-polarized electromagnetic wave through a periodic array of subwavelength metallic slits as a function of slit geometry. For this analysis, silicon and silicon dioxide are used as the slit and substrate dielectrics. Slit geometric parameters are set to h = 1.2d and a = 0.1d, 0.5d (d: slit periodicity). Also, perfect metals with infinite permittivity are used to keep the generality of our theoretical model at an arbitrary wavelength. Our calculations indicate several guided modes at wavelengths much larger than the slit periodicity, d, with a cutoff wavelength of $\lambda_{cutoff} \cong d\sqrt{\varepsilon_{sub}/\varepsilon_0}$. The first guided mode is at the wavelength range much larger than the slit height ($\lambda >> h$), and the rest of guided modes are at the resonant wavelengths of the subwavelength slab waveguides formed by the metallic slits, $\lambda_{guided}^{(n)} \cong 2h\sqrt{\varepsilon_s/\varepsilon_0}/n$ (n = 1, 2, ...). Because of the non-resonant nature of the first guided mode, the maximum power transmission of the first guided mode into the dielectric substrate is limited by the reflection at the substrate-air interface. In the meantime, depending on the metallic slit geometry, the maximum power transmission of the resonant TEM guided modes into the dielectric substrate can be as high as 100%.

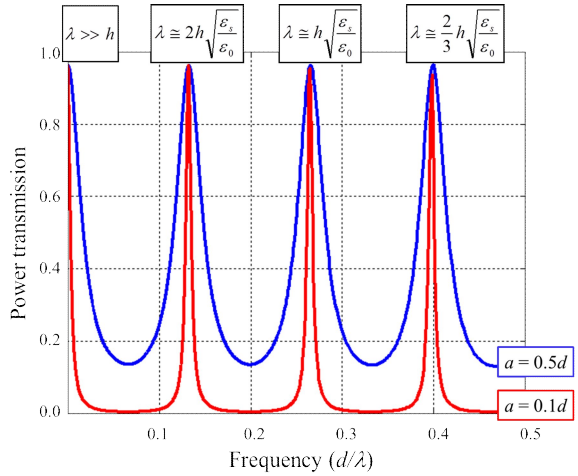

Fig. 2. Transmission spectrum of a TM-polarized electromagnetic wave through a periodic array of subwavelength metallic slits (h = 1.2d and a = 0.1d, 0.5d) on a dielectric substrate, showing multiple guided modes. Silicon and silicon dioxide are used as the slit and substrate dielectrics. Perfect metals with infinite permittivity are used in this analysis to keep the generality of our theoretical model at an arbitrary wavelength.

As the results predict, the subwavelength metallic slit geometry can be specifically designed to support guided modes at wavelength ranges that are orders of magnitude far from each other. We have used this unique capability to design subwavelength metallic slit geometries that support guided modes at terahertz and optical wavelength ranges. In order to allow the first and second guided modes to fall in the terahertz and optical wavelength ranges, the selected slit height should be much smaller than the terahertz wavelength ($h << \lambda_{THz}$) and satisfy $h \cong 0.5\lambda_{opt}\sqrt{\varepsilon_0/\varepsilon_s}$. Additionally, the supported optical and terahertz guided modes should be at wavelengths larger than the cutoff wavelength ($d < \lambda_{opt}\sqrt{\varepsilon_0/\varepsilon_{sub}}$). These requirements necessitate the use of nano-scale metallic slits in order to support guided modes at terahertz and optical wavelengths simultaneously. The inherent tradeoff between the bandwidth and field intensity enhancement of guided modes inside the subwavelength metallic slits should be taken into account to select a proper slit aspect ratio, d/a. While the transmission bandwidth of each guided mode is inversely proportional to the slit aspect ratio, d/a, the intensity enhancement of the transmitted electric field inside the subwavelength metallic slits has a quadratic dependence on the slit aspect ratio d/a. Figure 3a shows a periodic array of Au nano-slits designed for coupling TM-polarized terahertz and optical waves into the nano-scale $In_{0.53}Ga_{0.47}As$ semiconductor regions inside the nano-slits. Metallic slits can be employed as the interdigitated anode and cathode electrodes of a photoconductive terahertz detector. In spite of two orders of magnitude difference between the terahertz and optical wavelengths, the presented theoretical model predicts more than 70% of terahertz (λ > 300μm) and optical (1500nm > λ > 1600nm) power to couple into the nano-scale $In_{0.53}Ga_{0.47}As$ semiconductor regions. Figure 3a also shows the calculated power transmission spectrum of a normally incident TM-polarized electromagnetic wave into the nano-scale $In_{0.53}Ga_{0.47}As$ semiconductor regions inside the nano-slits using a finite element method solver (COMSOL). The experimental complex permittivity of Au from literature is used for the finite element method simulation [6]. Predictions of the presented theoretical analysis and the finite element method solver perfectly match at the terahertz wavelength range. Slight differences between the wavelength and power transmissivity of the optical guided mode are associated with the extension of optical guided mode into the air, substrate, and metal regions compared to the boundary conditions considered in the presented theoretical model. This leads to a longer effective resonance length and higher attenuation for the optical TEM guided mode. Figures 3b and c show the color map of the calculated electric field density through the finite element method solver at the 2nd (optical) and 1st (terahertz) guided mode wavelengths supported by the metallic slits. The electric field distribution profiles confirm that the guided modes through the array of metallic slits correspond to the TEM resonance modes supported by the subwavelength slab waveguides formed by the slits.

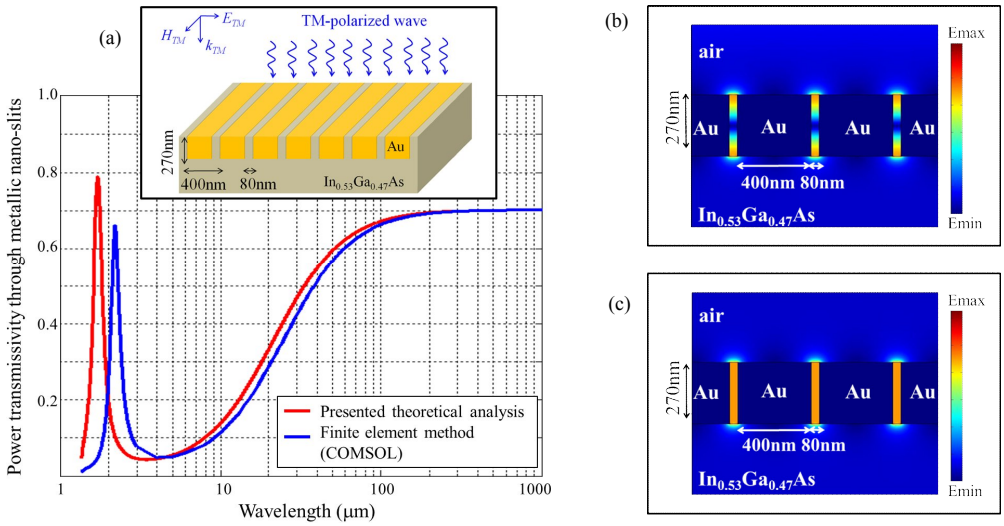

Fig. 3. a) Periodic arrays of Au nano-slits designed to efficiently couple terahertz and optical electromagnetic waves into the nano-scale $In_{0.53}Ga_{0.47}As$ semiconductor regions and the transmitted power into the nano-scale semiconductor regions calculated by the presented theoretical analysis (red curve) and the finite element method (blue curve). b and c) Color map of the electric field density of a TM-polarized electromagnetic wave interacting with the periodic array of Au nano-slits at the 2nd (optical) and 1st (terahertz) guided mode wavelengths supported by the metallic slits and calculated through the finite element method solver.

4. Conclusion

Theoretical analysis on electromagnetic interaction with periodic arrays of subwavelength metallic slits indicates the existence of several electromagnetic guided modes at wavelengths much higher than metallic slit periodicity, which are strongly geometry dependent. Based on this analysis, we have designed a periodic array of metallic nano-slits that supports subwavelength TEM guided modes at terahertz and optical frequencies, enabling efficient interaction of terahertz and optical waves at nano-scale dimensions. Additional advantages of the designed array of nano-slits are the efficient interaction of optical and terahertz waves at deep subwavelength device active regions (less than $\lambda_{THz}/1000$), over a broad terahertz wavelength range ($h << \lambda_{THz}$) and a large device active area. Utilizing the presented periodic array of metallic nano-slits can significantly increase responsivity and sensitivity of photoconductive terahertz detectors and mixers. The Nano-scale gap-size between metallic slits enables ultrafast collection of photo-generated carriers accelerated by the incident terahertz field. Due to direct coupling of terahertz electric field into the metallic nano-slits, the capacitance between metallic nano-slits does not degrade ultrafast response of the device. Therefore, large area arrays of metallic nano-slits can be used. The advantage of large area photoconductive terahertz detectors is enabling device operation under high optical power levels without being restricted by the carrier screening effect and thermal breakdown. Quantum-limited terahertz detection sensitivity at room temperature is envisioned through this unique capability.

5. References

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