A hybrid analysis method for plasmonic enhanced terahertz photomixer sources

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Abstract: A hybrid analysis of a continuous-wave terahertz photomixer source structure with plasmonic nano-grating electrodes is presented. Using the hybrid analysis, the enhancement of the optical power absorption due to the presence of the one-dimensional metallic nano-grating is investigated by defining an absorption enhancement factor. We show that the proposed absorption enhancement factor can be used as a design tool, whose maximization provides the optimum geometrical parameters of the nano-grating. Based on drift-diffusion model, the photocurrent enhancement due to the nano-grating electrodes is studied under three different bias configurations. Moreover, the dependence of the photocurrent on the physical parameters of the photomixer is analyzed.

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References and links


1. Introduction

Optical properties of one-dimensional (1-D) nanoscale metallic grating and some interesting phenomena, such as the extraordinary optical transmission (EOT) introduced by Ebbesen et al. [1] have been studied in numerous works over the last decade. Considerable amount of research efforts have been dedicated to develop theories underlying EOT, in which, this phenomena is described by the excitation of transverse resonance modes of the grating that occur at certain frequencies depending on the geometry. On the other hand, optical field enhancement at the vicinity of grating has stimulated the exploration and the usage of 1-D metallic grating in optical devices such as metal-semiconductor-metal (MSM) photodetectors [2, 3] and optical waveguides [4, 5].

Very recently, there has been an increasing interest in applying such grating to enhance the efficiency of the terahertz photocductive switches for continuous-wave and pulse emission [6–8]. These works report the measurement results for two configurations of photoconductive sources. In [9] and [10], nano-antenna is employed to enhance optical absorption in terahertz emitters by surface plasmonic localization of light. In a previous work [11], the authors have analyzed terahertz radiation due to a current source in the presence of a nano-grating.

Despite considerable number of experimental efforts that have been made to incorporate metallic nano-gratings in photomixers, accurate analytical model of such photomixers that incorporate all the physical phenomena involved are far less developed. Different aspects such as
optical grating and current manipulation by bias electrodes need to be considered in an accurate modeling. Up until now, to the best of our knowledge, a comprehensive analysis, including optical scattering and carrier transport simultaneously, has not been reported in the literature for such THz photomixer sources. It has to be mentioned that, scattering of electromagnetic wave by a 1-D subwavelength metallic grating on absorbing substrate has been well treated in the literature for different applications. Moreover, various theoretical models, such as nonequilibrium Boltzmann equations [12], Drude-Lorentz models [13] and standard drift-diffusion equations [14], have been used to describe carrier dynamics in photomixers.

The purpose of this paper is to apply a hybrid numerical approach for designing a metallic nano-grating using it as the bias electrodes of a THz photomixer source to enhance photocurrent generation. The applied numerical approach, similar to those described in [15, 16], consists of two main steps. In the first step, scattering of two laser beams, with difference frequency at terahertz range, from the metallic nano-grating on the photo-conductor substrate is analyzed. Since the two lasers are slightly detuned, the spatial distribution of the optical absorbed power remains identical to that for one of the beams, and it is modulated in time with the difference frequency. Therefore, in the first step, a photonic solver is used to determine scattered field of a single wavelength laser beam. The resonance modes of the metallic grating can be used to enhance optical power transmission and absorption in the photoconductor, and therefore play an important role in the optimal design of grating. In the second step, the photo-carrier generation rate, which is proportional to optical absorbed power in the photoconductor, is used to solve drift-diffusion equations. The drift-diffusion equations and the Poissons equation are solved simultaneously to determine the distribution of generated terahertz current.

In Section 2, the optical field analysis and the optimal design of nano-grating to maximize the optical power transmission and electromagnetic field enhancement are described. An overview of the resonance modes of the metallic grating is also presented and the results of different analysis methods are compared in Section 2. Optical absorbed power enhancement in the photoconductor substrate for different grating geometries is studied in Section 3. In Section 4, the photocurrent created under three bias configurations is obtained from the drift-diffusion carrier transport analysis. Section 5 concludes the paper.

2. Optical design

Shown in Fig. 1(a) is the one-dimensional metallic grating, which is used in photomixer source structure. It consists of a periodic array of gold strips with thickness $h$, periodicity $d$, and width $w$ on a substrate made of a photoconductive material with a thickness, sufficiently larger than its absorption length. One of the common photoconductive materials in THz photomixers is Low temperature grown GaAs (LTG-GaAs) due to its short carrier lifetime. We define the height ratio and the filling factor as $h/d$ and $w/d$, respectively. In this paper, we restrict our study to TM polarized (magnetic field parallel to the grating) laser beam impinging on the grating plane in perpendicular direction. In addition, the incident laser beams are modeled as plane waves.

In this Section, we compare the results of different optical transmittance analysis methods for 1-D metallic grating illuminated by a single frequency plane wave. A discussion on transmission resonance modes has been provided in [17] which is obtained from the transfer matrix method [18]. In this method, a surface impedance boundary condition is used to model the horizontal metal surfaces and perfect conductor boundary condition is used to model slit vertical walls, and a single-mode propagation inside the slit is assumed.

The analytical expression for denominator of the zero-order transmission coefficient, $T_0$, defined as the ratio of power of transmitted zero diffraction order to that of incident planewave, allows one to identify the modes that play important roles in the optical transmission [17]. Surface plasmon polariton (SPP) resonances are due to the coupling of the Floquet modes of the
grating with the surface plasmons of the top and bottom metal-dielectric interfaces. Surface plasmon polaritons wavelengths are given by $\lambda_{j}^{SPP} = \frac{d}{j} \sqrt{\epsilon_m \epsilon_i / (\epsilon_m + \epsilon_i)}$, where $j = 1, 2, \cdots$ and $\epsilon_i = 1, \epsilon_s$ for top and bottom surface plasmons, respectively, and $\epsilon_m$ is electrical permittivity of metal. Also shown on transmission plots, shown in 1(b), are Fabry-Perot-like (FP) resonances within the slit which lead to channeling of the light through the grating. FP resonances are calculated from the analysis presented in [19], which is a semi-analytical approach based on the method of moment and the expansion of the field inside the slit. This approach carefully takes the channeling properties of the slit into account, and all metallic characteristics of the grating are included in the calculation of the effective index ($n_{eff}$) of the fundamental waveguide mode of the slit. We have used a simple approximate model for $n_{eff}$ with acceptable accuracy presented in [20]. In addition to these resonances, Wood-Rayleigh (WR) anomalies occurs at $\lambda_{j}^{WR} = d \sqrt{\epsilon_i / j}$, where $j = 1, 2, \cdots$. These anomalies correspond to the abrupt changes in transmittance due to the emergence and vanishing of the diffraction orders from a metallic grating.

Figure 1(b) shows the denominator of the zero-order transmission, $T_0$, from the analytical expression in [17] which is derived for a non-absorbing substrate with constant electrical permittivity, $\epsilon_s = 12.25$. The location of SPP and FP resonances are found from the aforementioned discussion. In addition to analytical method, which is useful to find the resonances, to simulate more realistic model, we use a finite difference time domain (FDTD) solver, provided by EMW module of Synopsys TCAD [21], in order to solve the optical scattering problem. In the FDTD solver, Lorentz-Drude model [22] is used for gold, and optical parameters for LTG-GaAs are obtained from [23]. It can be observed that the transmittance drops rapidly to zero at wavelengths shorter than 950nm which corresponds to the GaAs energy band-gap.

Total transmission coefficient, $T_{tot}$, defined as the ratio of transmitted power into the substrate to the incident power (see Fig. 1(a)), for the LTG-GaAs is also plotted in Fig. 1(b) obtained from FDTD solver. It shows that resonances in nano-grating provides total optical power transmission into the substrate in non-absorbing range which cannot be achieved by bare substrate surface. The nano-grating can be designed to shift this resonance to the absorbing frequency range of LTG-GaAs; therefore, all transmitted power will be eventually absorbed into the substrate. However, interaction of absorbed optical power distribution with DC bias field deter-
mines the efficiency of the photomixer, i.e., the maximum absorption is desired in the region with strongest bias field. In the following Section, the effect of absorbed power distribution is studied.

3. Optical absorption

In a terahertz photomixer, the average absorbed power for two optical beams with equal powers is modulated by the difference frequency of $f_{\text{THz}}$ as

$$ P_{\text{ave}}^{I}(t, \vec{r}) = P_{\text{ave}}^{I}(\vec{r})(1 + \cos(2\pi f_{\text{THz}} t)) $$

where $P_{\text{ave}}^{I}$ is time-averaged absorbed optical power distribution in the photoconductive substrate for a single beam and $\vec{r} = (y, z)$ is the position vector in $yz$ plane (see Fig. 1(a)). In this Section, we study the absorbed optical power due to a single beam at 800nm wavelength for different grating dimensions.

![Diagram](image)

**Fig. 2.** (a) Optical absorption density, $P_{\text{ave}}^{I}$, profile for resonance modes occurs in different grating periods, $d$, with $h/d = 0.7$ and $w/d = 0.67$ illuminated by a laser beam at 800nm wavelength with intensity of 0.5 $W/cm^2$, (b) three configurations for applying voltage to the nano-grating to act as bias electrodes.

Figure 2(a) illustrates the $P_{\text{ave}}^{I}$ distribution for various grating periods for which the transmission resonance occurs. It can be observed that in FP resonances most of the power is absorbed under the slit, whereas for SPPs the absorption occurs within some lobes under the metals, and the number of these lobes determines the order of the SPPs. Absorption within these lobes is only significant in the first resonance (SPP1). Thus, a quantitative measure is required to compare between various grating dimensions and a reference conventional photomixer, considering the effect of DC bias field. In this paper, the reference photomixer is a photomixer with sufficiently large electrode distance, e.g. $d = 4 \mu$m, that the resonance modes, discussed in previous Section, cannot be observed [16]. The reference photomixer consist of electrodes with $w = 200$ nm and $h = 50$ nm, and is under the identical illumination and bias voltage ratio, $V/d$, to non-grating photomixers. We define the absorption enhancement factor, $\nu$, by the following expression,

$$ \nu = \frac{\bar{P}}{\bar{P}_0} = \frac{\int \int P_{\text{ave}}^{I}(\vec{r}) |E_b(z)| \, dy \, dz}{\int \int P_0(\vec{r}) |E_{20}(z)| \, dy \, dz} $$

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where $P_b(\vec{r})$ is the absorbed power distribution for the reference photomixer and $|E_b(z)|$ is the bias electric field. $P_b(\vec{r})$ can often be approximated by its value for a bare LTG-GaAs surface. The surface integrations are calculated on a window with width of one period and depth of $L$, which is sufficiently larger than absorption length of LTG-GaAs. This choice for absorption enhancement, $\nu$, can be justified by noting that the drift component of the photocurrent is proportional to the charge density and the bias electrical field at each point. $\vec{P}$, as defined by Eq. (2), is a good approximation of the generated photocurrent that is obtained without going through the time-consuming carrier transport analysis. This choice of $\nu$ will be verified in the next Section. Bias electric field of alternating configuration in Fig. 2(b) is approximated by $E_b = \frac{V_0}{d} e^{-\pi |z|/d}$, which is the dominant term in the exact solution of the bias electric field in [24]. For horizontal bias type in Fig. 2(b), applying incremental voltages to the strips with step of $V_0$ the bias field can be approximated by $E_b = \frac{V_0}{d}$. Similarly for the vertical bias configuration $E_b = V_1/H$, where $H$ is the substrate thickness. $E_{b0}(z)$ is the bias electric field for the reference photomixer. In all of the following calculations, we keep the ratio $V_0/d$ constant, therefore $\nu$ for vertical bias is identical to that for horizontal bias, which is presented in Fig. 2.

Fig. 3. Contours of absorption enhancement factor, $\nu$, for horizontal (a,c) and alternating (b,d) bias configurations (see Fig. 2(b)) with respect to the grating period $d$ and (a,b) height ratio when $w/d = 0.67$, (c,d) filling factor when $h/d = 0.7$. The locations of FP resonances are also shown by black dots. The white doted represents the common data points between the corresponding figures.

The absorption enhancement factor, $\nu$, obtained from FDTD simulation as a function of the grating dimensions is shown in Fig. 3. $\nu$ is calculated for alternating and horizontal bias types as a function of the grating period and height ratio when filling factor is kept constant, $w/d = 0.70$, in Fig. 3(a,b). WR anomalies and SPP resonance modes obtained from the theoretical model...
are also shown by vertical dashed lines. As expected, high absorption occurs along the FP resonances which are represented by black dots [3]. As shown in Fig. 3(a,b), FP resonances follow a hyperbolic curve suggesting that they mostly depend on the grating height, \( h \). Besides, in Fig. 3(a,b) there are discontinuities at WR anomalies due to the transition between the resonance of surface plasmons at vertical (inside the slit) and horizontal metal-dielectric interfaces by introducing a new diffraction order [25]. These transitions provide a high concentration of the field around the grating which result in high optical absorption close to the grating. Moreover, the absorption has a dip at SPP\(_{\text{top}}\) resonances, which prevents optical power to penetrate into the substrate. Figure 3(c,d) show the absorption enhancement factor with respect to the grating period and filling factor when height ratio is constant, \( h/d = 0.67 \). As shown in Fig. 3(c), for small values of the filling factor the enhancement is close to one due to the fact that the absorption is identical to the bare photoconductor substrate without any grating. As the filling factor increases the emergence of FP resonances causes the absorption to have maximum value at these resonances. The absorption enhancement factor for the vertical and horizontal biases reaches to 1.4 showing that all the incident power is absorbed in the substrate as compared to the bare photoconductor surface with around 30% reflection of power. In Fig. 3, the plots for alternating bias configuration shows smaller absorption enhancement for shorter grating periods as compared to horizontal bias configuration. This is due to the fact that for the former plots the weighting function of \( E_\phi(z) \) for alternating bias type decays much faster than that of horizontal bias along the z direction inside the photoconductor.

4. Carrier transport analysis

The optical generation rate given by \( G = \eta P_{\text{ave}}^\text{THz}(t)/E_{\text{ph}} \), where \( E_{\text{ph}} \) is the energy of optical photons and \( \eta \) is the quantum efficiency, is used in solving the coupled electrostatic and carrier transport equations governed by the drift-diffusion processes [15], and are expressed as

\[
\begin{align*}
\nabla \cdot (\varepsilon \nabla \phi) &= q(\rho_n - \rho_p) \quad (3a) \\
\pm \nabla \cdot \vec{J}_{n,p} &= q(G_{\text{opt}} - R) + q \frac{\partial \rho_{n,p}}{\partial t} \quad (3b) \\
\vec{J}_{n,p} &= -q \mu_{n,p} \rho_{n,p} \nabla \phi \pm q D_{n,p} \nabla \rho_{n,p} \quad (3c)
\end{align*}
\]

where subscripts \( n \) and \( p \) designate electron and hole, respectively, \( \phi \) is the electrostatic potential, \( \varepsilon \) is the electrical permittivity, \( \rho \) is the carrier density, \( q \) is the electron charge, \( D \) is the diffusion coefficient, \( \mu \) is the carrier mobility and \( R \) is the carrier recombination rate. The set of differential equations in Eq. (3) are solved in SDevice module of Synopsys TCAD self-consistently in an iterative manner [21]. In the simulations, gold-GaAs interface is assumed as an ohmic contact implying infinite surface recombination velocity [26]. Shockley-Read-Hall (SRH) and Auger carrier recombination [27] are considered in the simulations. Zero-field life time and mobility for electron and hole are assumed \( \tau_e = 0.2 \) ps, \( \tau_h = 0.9 \) ps, \( \mu_e = 3000 \ \text{cm}^2/\text{Vs} \) and \( \mu_h = 1000 \ \text{cm}^2/\text{Vs} \) [28,29].

The time-dependent photocurrent, \( J_{\text{ph}}(t) = J_n + J_p \), at an arbitrary point in the substrate is given by

\[
J_{\text{ph}}(t) = J_{\text{DC}} + J_{\text{AC}} \cos(2\pi f_{\text{THz}} t) \quad (4)
\]

where \( J_{\text{AC}} \) and \( J_{\text{DC}} \) are AC and DC components of the photocurrent at that point. The desired component is \( J_{\text{AC}} \) which oscillates with \( f_{\text{THz}} \). The generated carriers can be manipulated by applied bias to flow in the desired direction. Therefore, proper choice of the bias configuration for each resonance mode is of great importance. The photocurrent distribution inside the structure with three bias configurations are presented in Fig. 4. Alternating bias, that can be realized by
Fig. 4. Distribution of AC component of the photocurrent, $J_{\text{ph}}$, for three configuration of biased voltage for $d = 430\,\text{nm}$, $w/d = 0.8$ and $h/d = 0.4$, and definition of photocurrent, $I_{\text{ph}}$, for each case. The structure is illuminated by two laser beams with power density of 0.5 $W/cm^2$ each, and the bias voltage are chosen in such a way that $V_0/d = V_1/H = 5 \times 10^4\,V/cm$.

interdigitated fingers, is consecutive toggling of voltage of electrodes to $\pm V_0$. In this case, the current is mainly between neighbor electrodes, thus $I_{\text{ph}}$ is defined as the current collected by one electrode [8]. In vertical bias, top electrodes are all biased at the same voltage of $V_0$ with respect to a ground plane located at the $H$ distance underneath, in such a way that $V_1/H$ equals to $V_0/d$ for other bias configurations. For this case, the photocurrent is along vertical direction and the $I_{\text{ph}}$ is the current of one top electrodes. The vertical bias configuration is realized by a two far apart comb electrodes as in [6]. We define $I = I_{\text{ph}}/d$ as an indication of acquired photocurrent per grating period, in vertical and alternating bias configuration. In horizontal bias, electrodes are biased by incrementally increasing voltage which cause an overall horizontal electric field. In this case, not only photocurrent can be conducted from electrodes to a terahertz antenna, but also the photocurrent itself radiates and propagate through grating for sufficiently large grating area [11]. Thus, $I$ for horizontal bias is considered the total photocurrent flow passing through an arbitrary vertical cross-section.

In addition to photocurrent values, the capacitance of the electrodes provides an RC roll-off term in the frequency response of the terahertz photomixer [30]. The total capacitance of interdigitated electrodes consist of a parallel set of capacitors between two electrode combs, therefore, there is a trade-off between the number of fingers and the operation speed of the device. In the horizontal bias configuration, the capacitance between electrodes are in series, which leads to a lower capacitor by a factor of $1/N^2$, where $N$ is number of electrodes, as compared to alternating bias configuration.

The normalized photocurrent values for different grating dimensions is presented in Fig. 5(a), for alternating bias configuration. The normalized photocurrent is obtained by dividing the calculated photocurrent by a reference value $I_0$ which is the photocurrent of a reference photomixer described in previous Section. It is interesting to note that the photocurrent per period increased by a factor of 4 as compared to that of the reference photomixers because of two reasons. First, the total absorption of the incident optical power which is enhanced by around 40% as illustrated in Fig. 3, and the second reason is the enhancement of the bias electric field in the same location where carriers are generated. Furthermore, very short gaps between the electrodes causes the carriers to be collected before they recombine in the photoconductor. Comparing Fig. 5(a) with Fig. 3(b), reveals that both plots have very similar behavior. This justifies the use of the absorption enhancement factor defined in Eq. (2), as a legitimate objective function to be maximized for determination of optimal geometric parameters of the nanograting.

Figure 5(b) shows the weighted average of optical absorption, $P$, and the photocurrent per period, $I$, for three bias configurations with respect to the grating period for a constant filling factor and $h = 160\,\text{nm}$ at FP$_1$ resonance. Good agreement can be observed between the $P$ and

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corresponding $I$ as a function of grating period for three bias configurations.

![Graph of photocurrent enhancement](image)

Fig. 5. (a) Contour of photocurrent enhancement, $I_{Alt}/I_0$, for alternating bias with respect to $d$ and $h/d$. (b) Absorption and photocurrent enhancements for all bias types with respect to $d$ for $w/d = 0.7$ and $h = 160$ nm.

![Graph of AC and DC components](image)

Fig. 6. $I_{AC}$ (solid lines) and $I_{DC}$ (dashed lines) as a function of (a) carrier lifetime of LTG-GaAs [28] for alternating bias type under the same condition described for Fig. 4, (b) $V_0/d$ for alternating and horizontal bias types, and $V_1/H$ for vertical bias configuration under the same illumination.

We have also investigated the dependency of the photocurrent on the physical parameters of the photomixer as shown in Fig. 6. Figure 6(a) shows that $I_{DC}$, which is mainly due to non-modulated portion of optical generation rate, increases with carrier lifetime of photoconductor, almost independent of the terahertz modulation frequency. However, AC component of the photocurrent drops for higher frequencies, and grows slightly with carrier lifetime of photoconductor [30]. Photocurrent variation with respect to bias voltage, $V_0$, is also presented in Fig. 6(b) for three bias types. Both AC and DC components of photocurrent increases with bias voltage, which is limited by the break down field (around $5 \times 10^5 \text{V/cm}$ for LTG-GaAs) of the substrate.
5. Conclusion

The power conversion efficiency of the conventional CW photomixers are considerably lower than the quantum efficiency limit. Our analysis in this paper shows that by using nano-grating electrodes the optical absorption can be enhanced by a factor of around 1.4 at the optical resonances that eliminate the light reflection from the substrate. Moreover, our study shows that the nano-grating electrodes have a two-fold impact on the enhancement of the photocurrent; the increase in the optical absorption, and the bias field enhancement in the locations where the carriers are generated. Our proposed absorption enhancement factor defined in Eq. (2) provides a design tool to obtain optimum geometrical parameters for the nano-grating.

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