Spectral Response Tuning of Photoconductive Terahertz Emitters With Binary Phase Masks

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Abstract—In this work, binary phase masks are designed and implemented for use with a photoconductive terahertz (THz) emitter in order to shape the frequency response of the emitted THz waveforms. Theoretical and experimental results are applied to study the system. The theoretical results are presented in the form of both numerical simulations (to characterize and uniquely identify the underlying time-delayed photogeneration and resulting charge-carrier dynamics) and a simplified model (to conceptualize the system). The theoretical and experimental results are found to agree. It is ultimately shown that the phase delay through the binary phase mask can be used to preferentially allocate power into bands within the THz spectrum. Such results can lay the groundwork for future studies needing precise control of power within the THz spectrum.

Index Terms—frequency response, optical beams, photoconductivity, terahertz radiation.

I. INTRODUCTION

OVER the past decades, ultrafast pulsed lasers have enabled numerous advances in pure and applied studies—many of which rely upon the effective emission and detection of terahertz (THz) radiation [1], [2]. This THz radiation, spanning 0.1-10 THz, has traditionally been difficult to emit and detect [3]–[6], due to the low photon energy, but the advent of sub-picosecond pulse durations with modern ultrafast pulsed lasers has enabled access to the THz spectrum. We now see THz radiation applied to communications, given its high carrier frequencies [7]–[9], biomedical imaging, given its low (and typically safer) photon energies [10], [11], and spectroscopy, given its extreme sensitivity to molecular absorption lines [12], [13].

Given the myriad of THz applications, the incorporated systems are often required to possess suitable characteristics in terms of (ideally high) emission power [14] and (ideally tunable) spectral response [15]. Photoconductive (PC) THz emitters, i.e., Auston switches [1], [16], have been successful in these regards. In terms of high emission powers, Berry *et al.* [16] and Jooshesh *et al.* [17] investigated nanoplasmonic enhancements to improve the optical-to-THz-radiation conversion efficiency in PC THz emitters, while Ropagnol *et al.* [18] and Mittendorf *et al.* [19] developed materials and structures for high-power large-area PC THz emitters. In terms of tunable spectral responses, there has also been a great deal of work. Such work has been motivated by applications in communications, for which there is a desire to transmit in low-loss communication bands, such as the 0.8-0.9 THz band [8], [9], and in spectroscopy, for which there is a desire to preferentially excite molecular absorption lines, such as the known 1.36 and 1.82 THz lines for lactose [20]. The THz techniques needed to enable tunable spectral responses have not developed to the extent of the techniques seen for high emission powers, but there is now a greater focus on establishing the underlying techniques needed to control THz frequency responses.

In response to the need for a tunable spectral response in PC THz emitters, techniques such as chirped pulse difference frequency generation [15] and temporal delay of optical pulses [21] have been introduced. The temporal delay of optical pulses, in particular, is a very simple but promising approach. The temporal delay has been achieved in PC THz emitters by oblique illumination with ultrafast pulsed lasers [22] and by incorporating binary phase masks [21], whereby portions of the cross-sectional area of the illuminating ultrafast pulsed laser beam experience differing optical paths, via differing refractive indices. The PC THz emitters with binary phase masks allow for orthogonal illumination by the ultrafast pulsed laser beam, which offers practical advantages in terms of compactness and ease of alignment. However, the design, implementation, and analyses of such tunable PC THz emitters have not been explored to a great extent. The proposed work carries out such an exploration.

The proposed work provides an investigation into the

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design, implementation, and analysis of PC THz emitters with binary phase masks being used for spectral response tuning. The binary phase mask covers half of the PC gap—to delay half of the illuminating ultrafast pulsed laser beam—and the thickness of this mask is found to influence the spectral response of the PC THz emitter. The far-field THz emission of the PC THz emitter is analysed via simulations, characterizing the coupled semiconductor and electromagnetic dynamics, and the simulated results are compared to experimental results in the time- and frequency-domains. It is shown that the thickness of the binary phase mask can achieve effective tuning of the spectral response from the PC THz emitter. It is interesting to note that the proposed technique, which applies a time-domain offset to prescribe the desired frequency-domain response, has a duality to the existing continuous-wave THz generation technique, which applies a frequency-domain offset to prescribe the desired continuous-wave time-domain response. (Further details on continuous-wave THz generation are seen in Naftaly *et al.* [23], which applies two-colour continuous-wave photo-mixing for THz generation, and the references therein.) Ultimately, the proposed technique can support future THz studies needing power preferentially allocated to specific frequency bands.

II. ANALYSES

The overall goal of this work is to design, implement, and analyse PC THz emitters that can enable effective control of their spectral responses. The THz system shown in Figure 1 is implemented to do this. Figure 1(a) shows the full system with the PC THz emitter, while Figure 1(b) shows a close-up of the PC THz emitter. The emitter is comprised of a semi-insulating GaAs substrate, on which there are patterned two electrodes, being 50/150 nm thick Cr/Au metal layers. A voltage is applied to the electrodes to establish a bias field across the PC

gap, being defined here by the region between the electrodes. The x and y axes shown in Figure 1(b) have an origin at the centre of the PC gap. For such a configuration, the radiated THz radiation will be polarized along the x axis, and it will be emitted preferentially along the z axis, as defined by the cross-product of the x and y axes in the figure. The PC THz emitter also incorporates a binary phase mask. The binary phase mask is a glass layer with a refractive index of n and a thickness of d . It covers the upper (positive y) region of the PC gap, while leaving the lower (negative y) region of the PC gap uncovered. Upon illuminating the PC THz emitter with an ultrashort optical pulse, as shown in the figure, the lower portion of the PC gap is photoexcited before the upper portion of the PC gap. The primary and secondary THz pulses are separated temporally by the time delay of $\Delta t = (n - 1) \cdot d/c$, where c is the speed of light in free space. The PC THz emitter and binary phase mask are shown in Figure 2. Figure 2(a) shows the structure as viewed from above, parallel to the y axis, and Figure 2(b) shows the structure as viewed along the optical axis of the propagating beams, parallel to the z axis. By carefully selecting the time delay of the binary phase mask, the frequency response of the far-field THz emission is tuned.

To rigorously define the relationship between the applied glass layer and the resulting THz frequency response, the PC THz emitter is first analysed via numerical simulations. The simulations describe the charge-carrier photogeneration and transport processes within the PC gap and the electromagnetic radiation that forms from these processes. The work closely follows that of Rodriguez and Taylor [24], [25]. The simulation parameters are defined according to the PC THz emitter and binary phase mask in Figure 1. The PC gap has dimensions in the x and y directions of $L_x = 300 \mu\text{m}$ and $L_y = 300 \mu\text{m}$, respectively. A bias voltage of $V_b = 50 \text{ V}$ forms a bias electric field of $E_b \approx V_b/L_x = 1.7 \text{ kV/cm}$ in the PC gap.

Figure 1. A three-dimensional schematic is shown of (a) the complete THz setup with the PC THz emitter having a binary phase mask and (b) a close-up image of the PC THz emitter. The x and y axes for the simulations are shown in (b) with the z axis defined by the cross-product of the x and y axes. The PC THz emitter is comprised of a GaAs PC gap between two metal electrodes and a binary phase mask having a tunable thickness. The mask covers the top half of the illuminated PC gap. The THz emission takes the form of primary and secondary THz pulses, being separated by the time delay set by the binary phase mask.

a PC THz emitter viewed from above **b** PC THz emitter viewed along the optical axis

Figure 2. A cross-sectional schematic of the PC THz emitter is shown (a) as viewed from above, being parallel to the y axis, and (b) as viewed along the optical axis of the propagating beams, being parallel to the z axis. The schematic shows the incident optical pulse, with an intensity profile of $I(x, y, t)$, and the resulting THz pulse, with an emitted electric field of $E_{THz}(z, t)$. The semi-insulating GaAs substrate has two metal electrodes on it, with a bias voltage of V_b establishing the electric field of $E(x, y, t)$ in the PC gap. The binary phase mask has a thickness of d .

The PC THz emitter is illuminated by an optical pulse having a Gaussian spatial profile and a Gaussian temporal profile. The optical pulse in the region for $y > 0$ (mask) experiences a time delay of $n \cdot d/c$, and the optical pulse in the region for $y < 0$ (air) experiences a time delay of d/c . This leads to a piece-wise expression for the illuminating intensity on the PC gap, according to

$$I(x, y, t) = \begin{cases} \frac{\Phi}{\tau_p} \exp\left[-\frac{4 \ln 2 t^2}{\tau_p^2}\right] \exp\left[-\frac{4 \ln 2 x^2}{x_p^2}\right], & y < 0 \\ \frac{\Phi}{\tau_p} \exp\left[-\frac{4 \ln 2 (t-\Delta t)^2}{\tau_p^2}\right] \exp\left[-\frac{4 \ln 2 x^2}{x_p^2}\right], & y > 0 \end{cases}, \quad (1)$$

where $x = y = z = 0$ defines the centre of the PC gap. In this expression, $\tau_p = 1.3$ ps is the temporal full-width-at-half-maximum (FWHM) of the incident optical pulse and semiconductor response time, $x_p = 100$ μm is the spatial FWHM of the illuminating beam, and $\Phi = 5$ $\mu\text{J}/\text{cm}^2$ is the fluence of the illuminating pulse. Note that the illumination intensity is identical in the covered ($y > 0$) and uncovered ($y < 0$) regions, for all but the time delay of $\Delta t = (n - 1) \cdot d/c$.

The illuminating intensity is linked to the response of the PC gap by way of semiconductor photogeneration and transport equations. These equations define the surface electron current as

$$\frac{\partial n_s(x, y, t)}{\partial t} = \frac{(1-R)}{h\nu} I(x, y, t) + \frac{1}{q} \frac{\partial k_n(x, y, t)}{\partial x}, \quad (2)$$

and the surface hole current as

$$\frac{\partial p_s(x, y, t)}{\partial t} = \frac{(1-R)}{h\nu} I(x, y, t) - \frac{1}{q} \frac{\partial k_p(x, y, t)}{\partial x}, \quad (3)$$

where $n_s(x, y, t)$ and $p_s(x, y, t)$ are the respective surface electron and hole densities, $k_n(x, y, t)$ and $k_p(x, y, t)$ are the

respective surface electron and hole currents, q is the elementary charge, h is Planck's constant, $\nu = 375$ THz is the optical frequency of the ultrafast pulsed laser, and $R \approx 0.3$ is the reflectivity of the GaAs surface at the 780 nm wavelength. For this work, the assumption of $k_p(x, y, t) \approx 0$ is made, as the GaAs hole mobility, $\mu_p = 400$ $\text{cm}^2/\text{V/s}$, is much less than the GaAs electron mobility, $\mu_n = 3000$ $\text{cm}^2/\text{V/s}$. This simplifies Equation (3) and allows for an explicit expression for the surface hole density distribution, according to

$$p_s(x, y, t) = \begin{cases} \sqrt{\frac{\pi}{16 \ln 2}} \frac{(1-R)}{h\nu} \Phi \left\{ 1 + \text{erf} \left[\frac{2\sqrt{\ln 2} t}{\tau_p} \right] \right\} \\ \quad \cdot \exp \left[-\frac{4 \ln 2 x^2}{x_p^2} \right], & y < 0 \\ \sqrt{\frac{\pi}{16 \ln 2}} \frac{(1-R)}{h\nu} \Phi \left\{ 1 + \text{erf} \left[\frac{2\sqrt{\ln 2} (t-\Delta t)}{\tau_p} \right] \right\} \\ \quad \cdot \exp \left[-\frac{4 \ln 2 x^2}{x_p^2} \right], & y > 0 \end{cases}, \quad (4)$$

The surface electron current, $k_n(x, y, t)$, can be coupled to the electric field within the PC gap, $E(x, y, t)$, by matching boundary conditions [24]. The result is

$$k_n(x, y, t) = \frac{\mu_n q n_s(x, y, t) E(x, y, t)}{(1 + \sqrt{\epsilon_r})^{-1} \mu_n q c \mu_0 n_s(x, y, t) + 1}, \quad (5)$$

where $\epsilon_r = 13$ is the dielectric constant of GaAs, and μ_0 is the permeability of free space. An important result is seen here, in that the THz radiation can be saturated if the illuminating intensity is too high, i.e., the first term in the denominator becomes large. Such saturation is referred to as near-field THz screening, because it results from the THz electric field's opposition to the bias electric field.

To create explicit solutions for surface electron density,

$n_s(x, y, t)$ and electric field within the PC gap, $E(x, y, t)$, Equations (2), (4) and (5) are solved in conjunction with Poisson's Equation,

$$\frac{\partial E(x, y, t)}{\partial x} = \frac{q}{\delta \epsilon_r \epsilon_0} [p_s(x, y, t) - n_s(x, y, t)], \quad (6)$$

where $\delta = 700$ nm is the penetration depth of the illuminating optical beam, and ϵ_0 is the permittivity of free space. This result provides insight into another saturation mechanism for PC THz emitters, being charge-carrier screening. For charge-carrier screening, excessively high charge-carrier densities lead to substantial space-charge fields, from the separating charge-carriers, and these space-charge fields oppose the bias electric field and introduce saturation of the THz emission.

The solutions for the surface electron and hole densities, surface electron and hole currents, and electric field within the PC gap are solved by way of Equations (1)-(6), and the resulting surface electron current, $k_n(x, y, t)$, is used to define the far-field THz emission, $E_{THz}(z, t)$. A Hertzian dipole approximation is used for this. The far-field THz emission is due to the summation of current contributions across the area of the PC emitter, according to

$$\begin{aligned} E_{THz}(z, t) &= \frac{1}{4\pi\epsilon_0 c^2 z} \frac{d}{dt} \int_{-L_y/2}^{L_y/2} \int_0^{L_x} k_n(x, y, t) dx dy \\ &= \frac{L_y}{8\pi\epsilon_0 c^2 z} \frac{d}{dt} \int_0^{L_x} k_n(x, y > 0, t) dx \\ &\quad + \frac{L_y}{8\pi\epsilon_0 c^2 z} \frac{d}{dt} \int_0^{L_x} k_n(x, y < 0, t) dx \end{aligned} \quad (7)$$

This expression forms the basis for the simulated results of this work.

III. RESULTS

The simulation is used to compute time-domain waveforms for the far-field THz radiation from PC THz emitters with a binary phase mask having a refractive index of $n = 1.5$ and thicknesses of $d = 0, 225, 450, 675, 900$, and 1125 μm . These thicknesses correspond to time delays of $\Delta t = 0.39, 0.78, 1.17, 1.56$, and 1.95 ps, respectively. The results are shown in Figure 3(a). At a thickness of $d = 0$, there is no delay due to the binary phase mask, and we see a nominal waveform for the far-field THz radiation. The unipolar nature of the waveform that one might naïvely expect, given the step-like response of the charge-carrier density, is not present here. A bipolar waveform is formed. The bipolar form is due to the

Figure 3. Time-domain results of the far-field THz electric field, $E_{THz}(t)$, versus time, t , for the PC THz emitters. The figure shows (a) simulated and (b) experimental results. The PC THz emitters have binary phase masks with time delays of $\Delta t = 0.39, 0.78, 1.17, 1.56$, and 1.95 ps.

field, due to the separating charge-carriers. (Simulations independently applying near-field THz screening and charge-carrier screening reveal that the shape of the waveform is defined predominantly by the effects of charge-carrier screening.) As the thickness d , and thus the time delay Δt , is increased, however, varying levels of constructive and destructive interference occur and the shape of the far-field THz waveform changes. For example, two complete THz cycles are formed at $\Delta t = 1.95$ ps. It should be noted that the glass-air interfaces of the binary phase mask would introduce internal reflections, in general, but such reflections are negligible (approximately 0.2%) for this study. If future implementations of the proposed technique use higher-index materials, however, it may be necessary to consider such reflections and incorporate anti-reflection coatings. To substantiate these theoretical assertions, experiments are carried out with conditions corresponding to those of the above simulations. The experimental results are shown in Figure 3(b). The agreement between the simulated and experimental results is good—in that the experimental waveforms all exhibit the bipolar responses and time delays seen in the simulations.

The frequency-domain responses for the far-field THz radiation are computed, via Fourier transforms, and are shown in Figure 4. Figures 4(a) and 4(b) show the simulated and

experimental results, respectively. As one would expect, there remains good agreement between the simulated and experimental results in the frequency-domain. Moreover, the effects of spectral response tuning become evident. The application of binary phase masks with increasing time delays form an over-modulation, with peaks and nulls in the spectrum.

The over-modulation in the frequency-domain responses of the far-field THz radiation can be understood by constructing and analysing a simplified model. We construct such a model by characterizing the frequency-domain responses of Figure 4 by damped sinusoids. The damped sinusoids are each the product of a decaying exponential (for which the Fourier transform is a Lorentzian pulse) and a sinusoid with a periodicity in the frequency-domain of $\Delta f = 2/\Delta t$ (for which the Fourier transform is two delta functions separated by Δt). The corresponding time-domain waveforms of the far-field THz radiation are then found, via convolution, to be two Lorentzian pulses separated by Δt . Ultimately, this simplified model suggests that two pulses in the time-domain, separated a delay of Δt , yield periodicity in the frequency-domain of $\Delta f = 2/\Delta t$. Thus, the simulated and experimental results, having two pulses in the time-domain separated by a delay of Δt , exhibit periodicity (i.e., peaks and nulls) in the frequency-domain.

Figure 4. Frequency results of the far-field THz electric field, $E_{\text{THz}}(f)$, versus frequency, f , for the PC THz emitters. The figure shows (a) simulated and (b) experimental results. The PC THz emitters have binary phase masks with time delays of $\Delta t = 0.39, 0.78, 1.17, 1.56$, and 1.95 ps.

The understanding brought about through the simplified model can be linked to the simulated and experimental results. Figure 5 does this by showing discrete data points for the delay times predicted by the simulated and experimental results, as a function of the true time delays, Δt . The figure also shows the simple linear trendline that is predicted by the simplified model. The frequency-domain responses for the simulated and experimental results are curve fit to the damped sinusoid of the model, and the optimal curve fits are used to generate Δt_{fit} values for each of the six simulated/experimental conditions, i.e., the six d and Δt values. The fit values for the simulated and experimental time delays are plotted in the figure as a function of the true time delay and are seen to be in good agreement, i.e., $\Delta t_{\text{fit}} \approx \Delta t$. Moreover, the simulated and experimental results are in close proximity to the linear trendline that would be expected via the simplified model. The simulated and experimental results agree with the results of the simplified model, with R-squared values of $R^2 = 0.995$ and 0.996 , respectively.

Ultimately, this simplified model lets us see the underlying effects of the binary phase mask. The mask creates a phase shift in half the THz emission, with respect to the other half, with the two portions of the THz emission exhibiting beating in the far-field. The extent to which the phase shift is applied, i.e., the value of the time delay, can be used to form an over-modulation in the frequency response—and thus can be used to preferentially allocate power in THz bands.

IV. CONCLUSION

In this work, binary phase masks were designed and implemented for use with a PC THz emitter. The system was analysed by way of simulations and experiments. The

Figure 5. Time delay for fitting with the model, $\Delta t_{\text{fit}} = 2/\Delta f$, versus the true time delay, $\Delta t = \Delta n \cdot d/c$. The figure shows results of the simplified model (black solid line), simulated results (blue diamonds), and experimental results (red circles) for PC THz emitters with varying thicknesses for the binary phase masks. The simulated and experimental results for each time delay, Δt , are fit with damped sinusoids to define Δt_{fit} . The linear trendline of $\Delta t_{\text{fit}} = \Delta t$ depicts the predictions of the simplified model.

simulated and experimental results were in strong agreement, and were interpreted in terms of a simplified model. It was shown that the binary phase mask can preferentially tune the phase response of the emitted THz radiation—and thus preferentially allocate power into bands within the THz spectrum. These findings can be applied in future THz systems needing precise control of power within the THz spectrum.

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