Tunable GaAs metasurfaces for ultrafast image processing

Viacheslav Iushkov, Alexander Shorokhov, Andrey Fedyanin
Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
E-mail: iushkov@physics.msu.ru

Abstract. The design and construction of optical semiconductor metasurfaces for various applications have become an important topic in the last decade. However, most metasurfaces are static; they are optimized for only one exact purpose and typically realize only one operation. In this work, we discuss the basic methods for creating dynamic metasurfaces giving special attention to ultrafast optical switching and provide numerical modeling of metasurfaces made of GaAs material realizing different amplitude-phase profiles under asymmetrical optical pumping. The metasurfaces are composed of semiconductor discs immersed in a fused silica medium. We demonstrate that based on Fourier transform and spatial filtering methods, these structures can be used for image processing and optical computing. Ultrafast switching is achieved by using an optical pump-probe scheme. The characteristic relaxation times between the pumped state and the relaxed state are on the order of several picoseconds.

1. Introduction

Vision is a sense by which we receive most of the information about the world around us. One of humanity's most desirable goals is the creation of devices that will independently watch, analyze, and draw conclusions from what they see. Thus, image processing is an essential task both for technology and science.

One of the first breakthroughs in this area was the creating of "electronic eyes" - CCD cameras around the 70s by Willard Boyle and George Smith. It opened the way for a new important field – machine vision. At the moment, with the help of computer processing, many tools have been implemented that allow to transform an image, making it more convenient for analysis: finding boundaries and edges, specific patterns, faces, etc. Currently, machine vision is a successfully developing area of IT. However, it requires significant computational power, which, besides producing drastic heat losses, also consumes an incredible amount of energy. It raises the question of searching for new devices for effective image processing.

One of the solutions can be analog methods instead of the digital-based ones [1]. Such approaches have been used earlier, but with the use of bulk optical elements. Contrary, optical metasurfaces – flat optical devices that can form an arbitrary amplitude-phase profile on demand – can provide a large number of lightweight and compact elements for different operations. These include lenses [2, 3], holograms [4, 5, 6], and phase plates [7]. In some recent studies, various mathematical operations have also been implemented on an optical signal, such as integration, differentiation, and convolution [8, 9, 10]. It has been shown that such metasurfaces are useful for applications in real-time image processing. This area includes such methods as edge detection [11] and image recognition [12, 13]. There are also the first neural networks based on a cascade of metasurfaces [14, 15] for image recognition tasks. The advantages of metasurfaces usually include CMOS compatibility and low optical
losses. However, the latter advantage also sets some limitations on these dielectric and semiconductor nanostructures [16, 17, 18].

One of the most important limitations of metasurfaces is that they are generally static structures with a defined optical response. To fix this problem, one can use different mechanisms, some of which are mentioned below. Firstly, the use of silicon thermo-optical properties makes it possible to create a device with a noticeable reconfiguration of its response in a relatively small temperature range. However, it is difficult to produce it locally at the scale of individual supercells. The second method is the application of an external voltage [19, 20]. This method is faster than the first one, but it still has significant limitations on the speed of operation and difficulties in addressing individual nanoantennas. Finally, the third method is an optical injection of carriers by a femtosecond laser pulse [21], the fastest of all mentioned above.

In this work, we focus on the optical pumping mechanism under a uniform laser field irradiation to demonstrate tunable metasurface operation. Reconfiguration of the amplitude-phase profile is the result of the non-uniform absorption of the metasurface elements. Using such asymmetric optical pumping, one can switch between different amplitude-phase masks in the Fourier optical plane, providing different operations. The achieved results can be used to create reconfigurable compact imaging devices with remarkable processing time.

2. Ultrafast switching in gallium arsenide

Gallium arsenide was chosen as a material for tunable metasurfaces due to its widespread usage in semiconductor industry, well-known techniques for fabrication of micro- and nanodevices and a large number of scientific works devoted to studies of its opto-electronic properties [22]. Using the analytical description, we estimated the change in the optical response (refractive index $\Delta n$ and absorption coefficient $\Delta k$), taking into account the Burstein-Moss effect, bandgap shrinkage effect, and free-carrier absorption under ultrafast optical pumping of GaAs (fig. 1).

![Figure 1: Change of refractive index and extinction near the band gap of GaAs ($N = 10^{19} cm^{-3}$).](image)

The Burstein-Moss effect can be explained as following: the density of states of the conduction band is relatively small, and a small number of electrons will quickly fill it. In this case, other electrons will need to absorb more energy than the bandgap of the material. This leads to a decrease in absorption of the material. Using Kramers–Kronig relations one can obtain:
\[ \Delta n_{BM}(E) = \frac{2\epsilon h^2}{c^2} V_{p} \int_{0}^{\infty} \frac{\Delta \alpha(N, P, E')}{E'^2 - E^2} dE' \]

where \( \Delta \alpha(N, E, T) \) is the modulation of absorption for photon energies \( E \) lying above the band gap. To pass to the absorption coefficient, a simple relationship formula \( k = \frac{\alpha \lambda}{4\pi} \) is used.

The bandgap shrinkage effect appears due to the accumulation of many electrons near the edge of the conduction band. Due to the overlapping of their wave function and, consequently, screening, their energy decreases, and the zone edge shrinks. A similar effect occurs at the edge of the valence band. As a result, the bandgap becomes narrower. Unlike bandfilling, \( \Delta n \) is positive for energies below the bandgap.

Free carrier absorption is the last effect included in this discussion. In contrast to those considered above, this effect is intraband: an electron can absorb a photon for transition within the boundaries of one zone. An analytical expression for the results of such an effect:

\[ \Delta n_{FC} = -\frac{e^2 \lambda^2}{8\pi^2 c^2 \epsilon_0 \hbar} \left( \frac{N}{m_e} + P \left( \frac{m_{l_{sh}}^0 + m_{l_{h}}^0}{m_{l_{sh}} + m_{l_{h}}} \right) \right) \]

\[ \Delta k_{FC} = \frac{1}{k^2 + n^2} \frac{4\pi e^2 \tau}{1 + \omega^2 \tau^2 \frac{N}{\omega}} + k\tau \]

It should be noted that the relaxation of excited carriers occurs on a very short time scale (\( \tau \approx 1 \text{ ps} \)), which means that devices based on the described concept can be used for ultrafast processing.

One of the essential characteristics in choosing the mechanism for tuning the optical signal was the ultra-short relaxation time. It has already been demonstrated that upon optical pumping by a picosecond laser pulse the character of relaxation of excited carriers ranges from picoseconds to several tens of picoseconds[21, 23, 24]. This phenomenon may be the basis for the creation of all-optical devices for ultrafast light control.

3. The basic concept of Fourier filtering

Image processing using Fourier filtering is a widespread practice due to the simplicity of its realisation. In general, the idea of Fourier image processing has been described previously [8, 9, 10]. The Fourier transform is implemented using a lens (fig. 2).

Assume that the image propagate along the Oz axis, the distribution of the incident electric field in the \((x, y)\) plane is described by the function \( f(x, y) \), the transmitted one is \( g(x, y) \). The correspond fields in the focal plane of the lens are \( F(u, v) \) and \( G(u, v) \). Obviously, they are related by the dependence \( f(x, y) = FT[F(u, v)] \), \( G(x, y) = FT[G(u, v)] \). Placing a plate with a complex distribution of the transmission coefficient \( H(u, v) \) in the focal plane, we come to the following equations:

\[ F(u, v) = H(u, v) \cdot G(u, v) \]

\[ f = h \ast g = \iint h(x-x', y-y')g(x', y')dx'dy' \]

A confocal lens is used to perform the inverse Fourier transform. Taking into account the expression \( FT(FT(f(x,y))) \approx f(-x, -y) \), the post-processing of the final image is expressed in its reflection relative to the center of coordinates.

In this work we implement two different transformations: convolution and derivative. Convolution is required if you want to trace a given image \( h(x, y) \) on the analyzed one \( f(x, y) \). In this case, the role of the transmission function \( H(u, v) \) is played by the amplitude-normalized Fourier transform of the function
Figure 2: Schematic representation of the proposed idea. Laser radiation propagates through an amplitude mask creating an object image, which is focused by the lens on the metasurface forming the reference amplitude and phase profile. The metasurface is optically pumped from its backside. The transmitted radiation is detected by the camera.

$h(x,y)$. If you need to find the derivative along the Ox axis, then $H(u,v) \propto iu$. Since the metasurface is a bounded structure, it is necessary to take into account its longitudinal size $D$. As a result, $H(u,v) = \frac{2iu}{D}$.

The main difference between the approach proposed in this work and the one, which has been used previously, is that the metasurface can be quickly reconfigurated by optical pumping, which switches it between different transmission functions, for example, between a unity function and a function that implements a derivative.

4. Gradient metasurface with the tunable transmission function
We performed calculations to design metasurfaces that realize tunable analog operations. We chose a semiconductor disk immersed in a dielectric layer as a unit cell due to its polarization insensitivity and fabrication simplicity. Moreover, this geometry makes possible the excitation of electric and magnetic Mie-type resonances simultaneously for the same spectral region. It was shown that it is possible to obtain structures with reflection from 0 to 1 and a phase shift by $2\pi$ [25].

Previously, based on silicon [26], a metasurface was modeled [27] for tracing the given image on the analyzed one. However, as been already mentioned, the static nature does not allow for flexibility in such devices. A similar scheme was proposed, operating for transmission and utilizing the pump-probe method. Also, the material for nanoantennas was changed to GaAs [28]. In the proposed experiment, radiation passes through a beam splitter, part of the radiation propagates as the pump, which excites the metasurface from the backside. The probe passes through the spatial light modulator, which forms
Figure 3: The dependences of reflection, transmission, phase shift, and absorption at a wavelength of 800 nm for GaAs metasurfaces without pump (top row) and under pumping (bottom row).

The analysed image, and then focuses on the metasurface. Passing through the structure is similar to multiplying the Fourier transform by the transmission function of interest. The second Fourier transform produces the output image detected by the camera.

The function of transmission without pumping equals to the function $H(u, v) = \frac{2\mu D}{D}$, where $D$ is the longitudinal size of the metasurface corresponding to the derivative, which allows to find the edges on the image. The second function is $H(u, v) = 1$, corresponding to the uniform transmission. In this study the metasurface with a slowly varying period and diameter of the disks along the metasurface is proposed instead of the previously used division by pixels with defined reflection and phase.

We used Ansys Lumerical FDTD to perform numerical simulations. The dependencies of reflection, transmission, phase shift and absorption at the wavelength of 800 nm were obtained (fig. 3). Using this results, a design of the tunable metasurface was proposed (fig. 4).

Two amplitude-phase profiles were numerically demonstrated in the case of static and pumped

(a) Amplitude profile of the metasurface realizing $H(u, v)$ function without pumping
(b) Amplitude profile of the metasurface realizing $H(u, v)$ function with pumping

Figure 4: GRIN metasurface layout.
systems. They are shown in fig. 4 for initial (a) and pumped (b) cases. The spatial amplitude profile change is associated with non-uniform absorption of the metasurface elements.

5. Conclusion
A method of ultrafast spatial reconfiguration of semiconductor metasurfaces for tunable image processing is proposed. Metasurface based on GaAs material was numerically designed using the FDTD method, the approximate solution of the wave equation in the far-field, and Fourier analysis. To optimize the structure, algorithms were developed to smooth the profile of the transmission coefficient and phase shift. Tunable metasurface transmission functions are numerically demonstrated.

Acknowledgments
The authors acknowledge financial support from Russian Foundation for Basic Research (no. 20-02-00897, no. 21-52-12036). This research was performed according to the Development program of the Interdisciplinary Scientific and Educational School of Lomonosov Moscow State University "Photonic and Quantum technologies. Digital medicine". Part of the research is performed under the support of MSU Quantum Technology Center.

References
[1] Silva A, Monticone F, Castaldi G, Galdi V, Alù A and Engheta N 2014 Science 343 160–163
[2] Khorasaninejad M and Capasso F 2017 Science 358
[3] Lee D, Gwak J, Badloe T, Palomba S and Rho J 2020 Nanoscale Adv. 2 605–625
[4] Chong K E, Wang L, Staude I, James A R, Dominguez J, Liu S, Subramania G S, Decker M, Neshev D N, Brener I and Kivshar Y S 2016 ACS Photonics 3 514–519
[5] Wang B, Dong F, Li Q T, Yang D, Sun C, Chen J, Song Z, Xu L, Chu W, Xiao Y F, Gong Q and Li Y 2016 Nano Lett. 16 5235–5240
[6] Genevet P, Capasso F, Aïeta F, Khorasaninejad M and Devlin R 2017 Optica 4 139 ISSN 2334-2536
[7] Chong K E, Staude I, James A, Dominguez J, Liu S, Campione S, Subramania G S, Luk T S, Decker M, Neshev D N, Brener I and Kivshar Y S 2015 Nano Lett. 15 5369–5374
[8] Chizari A, Abdollahramezani S, Jamali M V and Salehi J A 2016 Opt. Lett. 41 3451–3454
[9] Cordaro A, Kwon H, Souzas D, Koenderink A F, Alù A and Polman A 2019 Nano Lett. 19 8418–8423
[10] Zhou Y, Zheng H, Kravchenko I and Valentine J 2020 Nat. Photonics 1–8
[11] Zhou J, Qian H, Chen C F, Zhao J, Li G, Wu Q, Luo H, Wen S and Liu Z 2019 Proc. Natl. Acad. Sci. U.S.A. 116 11137–11140
[12] Manzur T, Zeller J and Serati S 2012 Appl. Opt 51 4976–83
[13] Monjur M S, Tseng S, Tripathi R, Donoghue J J and Shahriar M S 2014 Journal of the Optical Society of America A 31 41
[14] Shen Y, Harris N C, Skirlo S, Prabhu M, Baehr-Jones T, Hochberg M, Sun X, Zhao S, Larochelle H, Englund D and Soljic M 2017 Nature Photonics 11 441–446
[15] Feldmann J, Youngblood N, Wright C D, Bhaskaran H and Pernice W H 2019 Nature 569 208–214
[16] Staude I and Schilling J 2017 Nat. Photonics 11 274–284
[17] Kuznetsov A I, Miroshnichenko A E, Brongersma M L, Kivshar Y S and Lukyanchuk B 2016 Science 354
[18] Yu N and Capasso F 2014 Nat. Mater. 13 139–150
[19] Komar A, Fang Z, Bohn J, Sautter J, Decker M, Miroshnichenko A, Pertsch T, Brener I, Kivshar Y S, Staude I and Neshev D N 2017 Applied Physics Letters 110
[20] Li S Q, Xu X, Veelit R M, Valuckas V, Paniagua-Dominguez R and Kuznetsov A I 2019 Science 364 1087–1090
[21] Shecherbakov M R, Liu S, Zubyuk V V, Vaskin A, Vabishechevich P P, Keeler G, Pertsch T, Dologova T V, Staude I, Brener I and Fedyanin A 2017 Nature Communications 8 17
[22] Bennett B R, Soref R A and Del Alamo J A 1990 IEEE Journal of Quantum Electronics 26 113–122
[23] Vabishechevich P P, Vaskin A, Karl N, Ren J L, Sinclair M B, Staude I and Brener I 2021 Applied Physics Letters 118 211105
[24] Della Valle G, Hopkins B, Ganzler L, Stoll T, Rahmani M, Longhi S, Kivshar Y S, De Angelis C, Neshev D N and Cerullo G 2017 ACS Photonics 4 2129–2136
[25] Staude I, Miroshnichenko A E, Decker M, Fofang N T, Liu S, Gonzales E, Dominguez J, Luk T S, Neshev D N, Brener I and Kivshar Y 2013 ACS Nano 7 7824–7832
[26] Palik E D 2012 Handbook of optical constants of solids ISBN 9780080547213
[27] Iushkov V V, Shorokhov A S and Fedyanin A A 2020 AIP Conference Proceedings 2300 020048
[28] Adachi S 1989 Journal of Applied Physics 66 6030–6040