Optimized 3D metasurface for maximum light deflection at visible range

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Abstract

In this contribution, we use two different efficient global optimization techniques in order to optimize 3D real life gradient metasurface based on GaN semiconductor. Our results show that we can achieve more than 87% of diffraction efficiency at the visible regime using only 150 solver calls for optimizing 12 parameters. Our methods seem to be more efficient than other optimization techniques that require costly simulations, especially for 3D structures. The optimized structure will be fabricated and characterized experimentally.

1. Introduction

The field of metasurface has drawn a lot of attention in the last few years, because of the offered degrees of freedom that provide nearly a full control of the light properties in a very short propagation distance with high resolution [1, 2, 3]. The complexity of the problem, the wide parameter space, and the new fabrication capabilities, make the direct modelling problem insufficient and the use of inverse design is mandatory to achieve the maximum desired performance [4]. Several optimization methodologies have been used in the field of metasurfaces, including local and global search methods. The former, require fewer iterations, however, they can be stuck in local maxima/minima, the later is more general and is suitable for optimizing large parameter space. Nevertheless, most of the global techniques used in the metasurface designs require large number of solver calls, which make them inapplicable for modelling 3D real-life designs that require 3D solvers. The main target of this contribution is to find an optimal geometry for 3D gradient metasurface made of GaN nano-ridges (see the inset in Fig. 1) in order to achieve a maximum light deflection (in the same plane of incidence) with a specific angle at $\lambda = 600\ nm$. We choose GaN semiconductor due to its negligible losses and due to its high refractive index in the visible regime, which make it ideal nanoresonator (phase-shifters) for metasurface designs [1, 3].

Here, we use two different efficient global optimization techniques based respectively on advanced evolution strategies and statistical learning. The first one is the covariance matrix adaptation evolution strategy (CMA-ES) [5]. The CMA-ES has been gaining a lot of attention since it requires fewer cost function evaluations compared to the other evolutionary algorithms like genetic algorithms (GA) [4, 6] especially for 3D designs that require expensive simulations. The second method is the Efficient Global Optimization (EGO) algorithm [7]. The EGO algorithm is based on the surrogate modelling, that is to say, replacing the complex or costly evaluation process by a simpler and cheaper model [7] to reduce dramatically the computational cost (number of calls for the electromagnetic solver). We use our rigorous Discontinuous Galerkin Time Domain (DGTD) solver from the DIOGENES software suite dedicated to computational nanophotonics [8] together with the optimization algorithms, in order to achieve a maximum diffraction efficiency ($\eta(n,m)$, where n, m are the mode indices) at $\lambda = 600\ nm$. We consider a normal incident

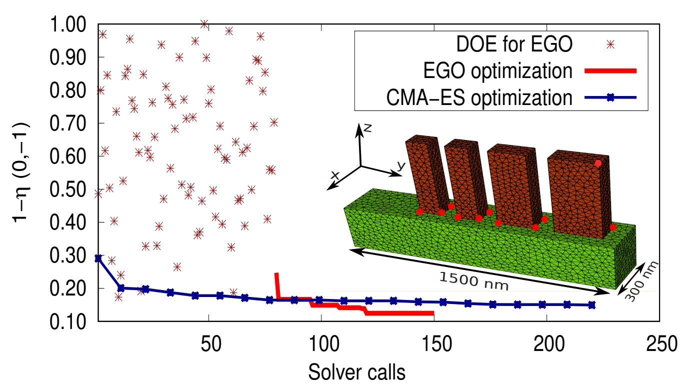

Figure 1: Optimization process using the EGO (red curve) and the CMA-ES (dark blue curve) methods as a function of the solver calls. The dark red points represent the DOE for the EGO. The inset shows the geometry under consideration, green region for the substrate (Al_2O_3), GaN ridges are shown in red. The 12 red circles represent the optimization parameters.

plane-wave with electric field polarized in the y-direction, and we aim to maximize the diffraction efficiency of the first order mode $\eta(0,-1)$ (deflect light in the same plane of incidence y-z plane). Thus, we consider a sub-wavelength period in the x-direction (300 nm), and we consider a period of 1500 nm in the y-direction, as it can be seen in the inset shown in Fig. 1. We restrict ourselves to rectangular shapes made of GaN semiconductor, in which the position and x and y thicknesses together with the height of the ridges need to be optimized. The 12 optimized parameters

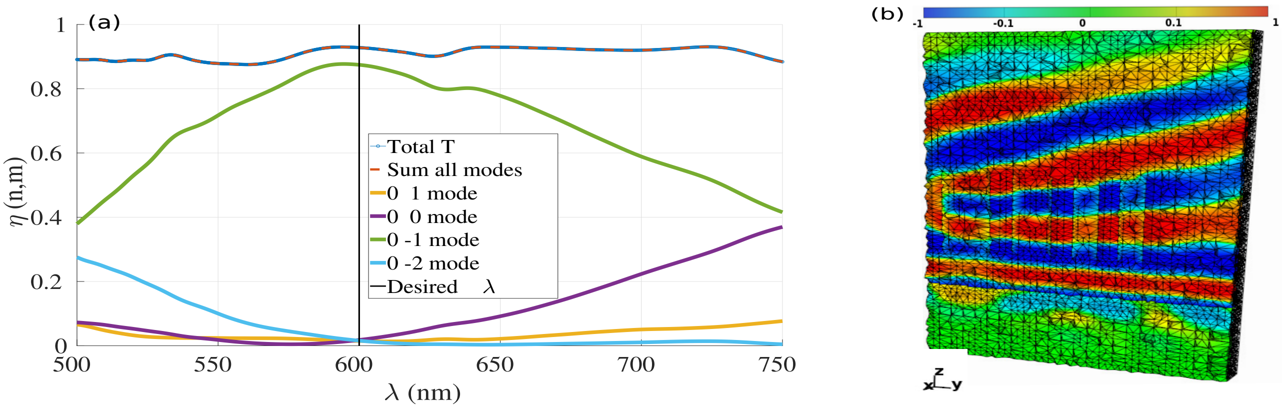

Figure 2: (a): Diffraction efficiency $\eta(n, m)$ for the main modes as a function of the wavelength, the total transmission is shown in blue. (b); $\Re e(E_y)$ obtained from our DGTD solver [8] at $\lambda = \ 600nm$.

are represented by the red circles in the inset of Fig. 1.

In Fig. 1, we show the results obtained using our optimization techniques. First, for the EGO model, the dark red points represent the design of experiment (DOE) obtained before the optimization process in the EGO model. Based on these points, a surrogate model is constructed and will be used during the optimization process to find a global minimum below the best point found in the DOE process. More precisely, after only 150 iterations (solver calls), we optimized 12 parameters and obtained a diffraction efficiency around 87% at $\lambda = 600\ nm$, which is sufficient for us at least at this moment, since we need to make a compromise between the number of iterations and the maximum diffraction efficiency obtained. The diffraction efficiency of the main modes, and total transmission as a function of the wavelength can be obtained in Fig. 2(a). As it can be seen, at $\lambda = 600\ nm$, nearly all the light is concentrated at the first order mode which is inferred in Fig. 2(b). Second, in Fig. 1, we show the results obtained from CMA-ES (dark blue curve). We have found that after 200 iterations, we obtain a point in which the diffraction efficiency is above 85%, but still the EGO provides a better point than the CMA-ES, at least below 200 iterations.

In conclusion, we used our global optimization techniques to optimize 3D gradient metasurface. Our results reveal that we can get up to 87% of diffraction efficiency by optimizing 12 different parameters using only 150 iterations. Our techniques seem to be more efficient than the usual global optimization methods [6] available in the literature in which numerous simulations are required for achieving optimized geometries. Based on the above results, the optimized geometry will be fabricated and characterized experimentally using our modern and efficient fabrication techniques.

References

[1] P. Genevet, F. Capasso, F. Aieta, M. Khorasaninejad, and R. Devlin, "Recent advances in planar optics: from plasmonic to dielectric metasurfaces," *Optica*, vol. 4, no. 1, pp. 139–152, 2017.

[2] S. Sun, K.-Y. Yang, C.-M. Wang, T.-K. Juan, W. T. Chen, C. Y. Liao, Q. He, S. Xiao, W.-T. Kung, G.-Y. Guo, *et al.*, "High-efficiency broadband anomalous reflection by gradient meta-surfaces," *Nano letters*, vol. 12, no. 12, pp. 6223–6229, 2012.

[3] N. Schmitt, N. Georg, G. Brière, D. Loukrezis, S. Héron, S. Lanteri, C. Klitis, M. Sorel, U. Römer, and P. Genevet, "Optimization and uncertainty quantification of gradient index metasurfaces," *Optical material express* vol. 9, pp. 892–910 (2019)

[4] S. Molesky, Z. Lin, A. Y. Piggott, W. Jin, J. Vuckovic, and A. W. Rodriguez, "Outlook for inverse design in nanophotonics," *arXiv preprint arXiv:1801.06715*, 2018.

[5] N. Hansen, S. Muller, and P. Koumoutsakos, "Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (CMA-ES)," *Evolutionary Computation*, vol. 11, no. 1, pp. 1–18, 2003.

[6] V. Egorov, M. Eitan, and J. Scheuer, "Genetically optimized all-dielectric metasurfaces," *Optics express*, vol. 25, no. 3, pp. 2583–2593, 2017.

[7] D. Jones, "A taxonomy of global optimization methods based on response surfaces," *Journal of Global Optimization*, vol. 21, pp. 345–383, 2001.

[8] *DIOGENES: A Discontinuous-Galerkin based software suite for nano-optics*. https://diogenes.inria.fr/.

[9] Zhenpeng Zhou, Juntao Li, Rongbin Su, Beimeng Yao, Hanlin Fang, Kezheng Li, Lidan Zhou, Jin Liu, Daan Stellinga, Christopher P Reardon, et al. Efficient silicon metasurfaces for visible light. *ACS Photonics*, 4(3):544–551, 2017.

[10] David Sell, Jianji Yang, Evan W Wang, Thaibao Phan, Sage Doshay, and Jonathan A Fan. Ultra-high-efficiency anomalous refraction with dielectric metasurfaces. *ACS Photonics*, 5(6):2402–2407, 2018.