Nanostructures for patterning phase: a review

Q. Lévesque, P. Bouchon, F. Pardo, J.L. Pelouard, R. Haïdar

NANOSTRUCTURES FOR PATTERNING PHASE: A REVIEW

Q. Lévesque[1,2], P. Bouchon[1], F. Pardo[2], J.-L. Pelouard[2] and R. Haïdar[1]

[1] *ONERA – The French Aerospace Lab, F-91761 Palaiseau, France.*
[2] *Laboratoire de Photonique et de Nanostructures (LPN-CNRS), F-91460 Marcoussis, France.*

KEYWORDS: metamaterial, nanophotonic, plasmonics, diffraction, sub-wavelength grating.

ABSTRACT:

Classical optical components, as they are miniaturized, are getting increasingly closer of the limit of diffraction while their fabrication is more and more challenging. Here, we review various nanostructures designs that, in contrast, are based on their ability to interact with the light at a deep subwavelength scale. They have promising properties such as the ability to reach artificial refractive index, to induce subwavelength phase pattern or to have a simpler fabrication.

1. CONTEXT

The development of optical systems in cameras and image post-treatments now permit to get all the features of the radiated light of an observed scene [1-2]. The light is an electromagnetic field characterized by its wavelength, its amplitude, its phase and its polarization; each can be selectively modified by an optical component such as a filter, a lens, a prism or a quarter-wave plate.

On the same timeframe, there has been a miniaturization of the detectors pixels. They are now reaching, in the infrared, dimensions close to the diffraction limit, which will prevent future designs to be only downsizing of conventional refractive optics [3]. To overcome it, new optical designs have been proposed, which relies on the development of nanophotonics and of subsequent nanoscale fabrication.

Here, we review several promising nanophotonics designs, which address the need for optical components at a subwavelength scale. The first main design consists in engineering the refractive index at the nanoscale. Such designs rely on the effective medium theory and on metamaterials. Second, we study plasmonic based devices. Then, lenses based on diffraction planes. Eventually, we present planar metasurfaces made of planar nanoantenna arrays.

2. GRADIENT INDEX DIFFRACTION GRATING

In the case of a conventional refractive optical component, *i.e.* having typical dimensions larger than the incident wavelength, the modification of the wavefront phase pattern is realized by the surface topography and the optical index of the chosen bulk medium. It must be emphasized that this latter is limited by the materials available on earth and in particular to the materials which can be processed. Metamaterials were introduced with the possibility to reach artificial index. In particular, the patterning of a dielectric medium can be described thanks to the effective medium index theory [4].

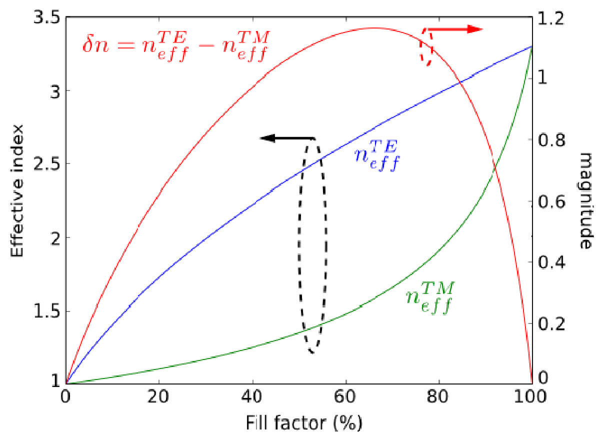

Figure 1: Effective index of the propagative mode in an air (n=1)/GaAs (n=3.3) waveguide as a function of the fill factor of the two materials in TM (green curve) and TE (blue curve) polarizations in the infrared range. The corresponding birefringence is plotted in red.

In these cases, the artificial index is expressed as a function of the fill factor of each material, e.g. air and the patterned dielectric medium, as shown on Fig. 1. Noteworthily, the artificial index obtained is not the same in each polarization, and this can be used to design artificial birefringent devices like Wollaston prisms [5]. The incident wave upon such artificial material perceives an effective optical index that depends on the parts of each material and the wave polarization [6-7]. Thus, in the two materials case, the effective optical index ranges from the lower to the upper bulk index. The juxtaposition of increasingly filled factor pattern leads to the realization of a gradient index diffraction component.

References [8-10] present designs of lenses based on the 1D (or 2D) etching of grooves (or pillars) in a dielectric substrate with sampling period smaller than the wavelength. All structures have identical depth and their sections are modified in order to create the required gradient index modulation.

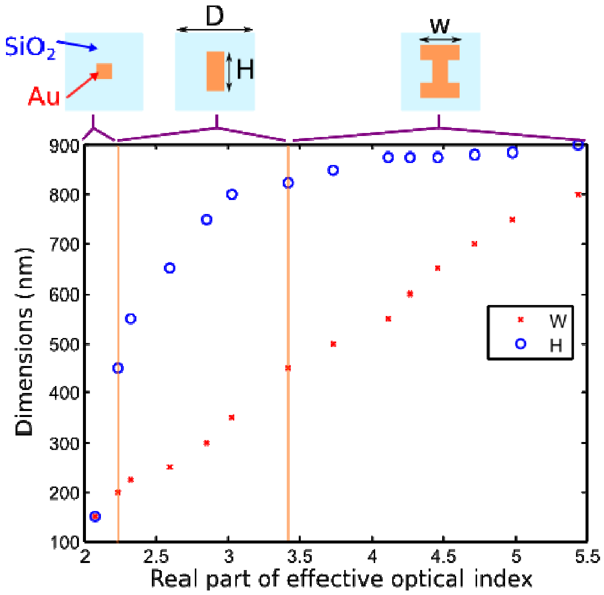

Figure 2 : Evolution of the real part of effective optical index of the gold nanostructures, with geometries as depicted above, as a function of their dimensions W and H for a period D = 1µm and λ=10.6 µm.

Another way to implement a phase is to use multilayered planar metallic nanostructure embedded in a dielectric substrate. Figure 2 shows the optical index of a gold nanostructure embedded in a SiO_2 substrate as a function of the geometrical parameters and shape of the nanostructure at λ=10.6 µm. It demonstrates that the index can be modulated over a [2-5.5] range.

Nevertheless, the gradient index in all these methods is always modulated on a length scale greater than the wavelength. In the next section, plasmonic optical devices which overcome this issue are presented.

3. PLASMONIC OPTICAL DEVICES

An alternative approach to improve the compactness of planar optical component consists in using the properties of the surface plasmons polaritons (SPP) that propagate on a metallic surface. It has been demonstrated that the etching of discontinuities such as periodic structure on a metallic surface allows the excitation of SPP by a TM-polarized (magnetic field perpendicular to the structured direction) incident free space wave [11] [12]. Plasmonic excitations can be used to do either near-field optics [13-20], or far-field optics.

In this latter case, patterning of the phase has been suggested using metal-insulator-metal (MIM) waveguides. This abrupt structure allows a strong coupling inside insulator layer of SPPs propagating along its metallic walls [21-24]. These structures react as metallic waveguides that present an effective optical index depending on their geometrical parameters such as their depth, height, width and the optical index of the insulator [25-26]. Despite their subwavelength dimensions, MIM structures are able to extraordinary impact the impinging light by modifying with a high efficiency the phase and the amplitude of the reflected or transmitted optical fields [27]. The MIM waveguides can be placed either horizontally or vertically with regards to the incoming wave.

The horizontal distribution, corresponding to MIM ribbons or MIM patches nanostructures, placed on a metallic mirror permits to conceive flat lens mirror [28] or flat prism mirror [29] working in reflection. The phase modulation achievable by these metasurfaces is limited to π due to the insensitivity of MIM response to the sign of the field amplitude [30].

The vertical configuration, corresponding to the etching of rectangular slits or holes in a metallic layer, allows designing plane transmission optics such as lenses [31-34], prisms [35] or more complex design as angle compensation lens [36] or polarization-selective lens [37]. A phase shift over the [0-2π] range is achievable [38] but this requires etching heterogeneous arrays of high aspect ratio nanoslits with a high nanometric precision [39]. Fig. 3(a) shows the design of a 3 µm focal length plasmonic lens for a normal incident plane wave at λ=650 nm. The corresponding simulated electric field map intensity is represented in Fig. 3(b). These technological constraints constitute important drawbacks that limit their practical use. Moreover in both cases, the phase modulation is correlated with an amplitude modulation implying a decrease in the transmittance or reflectance efficiency of these metallic metasurfaces [40].

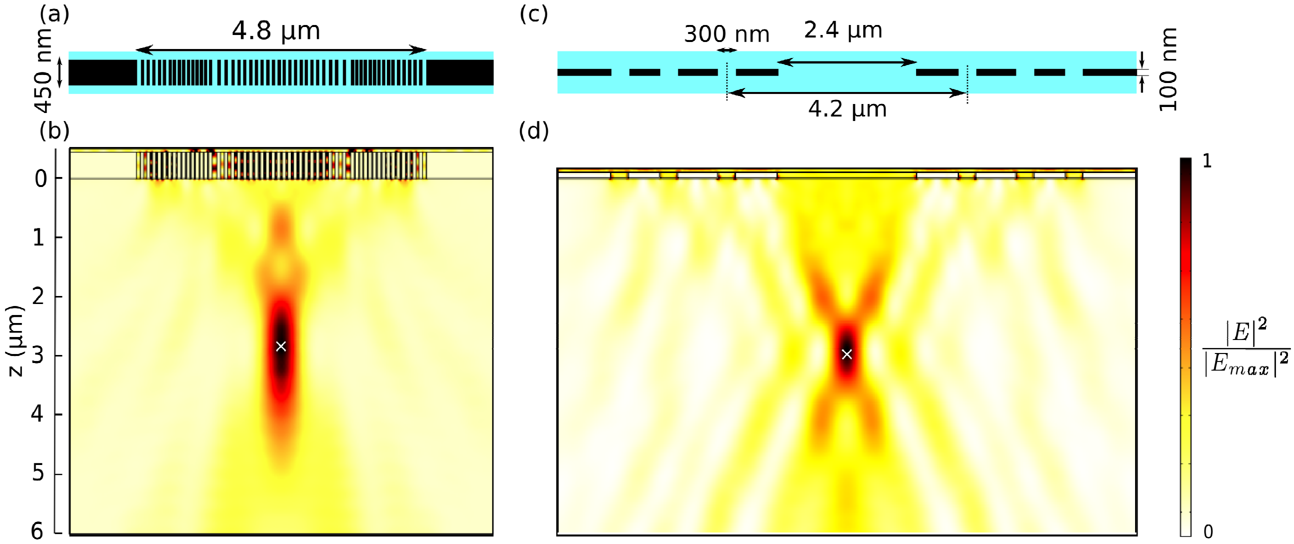

Figure 3: Design for a 3 µm focal length of a (a) plasmonic lens based on 53-slit structure and (c) the Huygens lens structure based on central aperture surrounded by 6 single mode slits. The thickness of the gold layer is respectively 450 and 100 nm surrounded by air. (b,d) Simulated electric field intensity map respectively for the structure shown in (a) and (c).

4. DIFFRACTIVE PLANE

The methods presented above are based on the phase modulation thanks to the use of dielectric or metallic nanostructures. An alternative method that consists in the control of the diffraction pattern of an array of slits has also been demonstrated. In this case, each slit presents dimensions that induce an identical phase delay to the exiting wave. According to the Huygens-Fresnel principle, all the waves emitted beyond the structured layer can spatially interfere constructively or destructively according to their path difference phase value [41-42]. Thus, an optical function can be realized by choosing the position and the width of the slits in the structured layer in order to keep only the spatial part that contributes to constructive interference of the corresponding phase pattern. The medium in which the slits are etched must be opaque at the working wavelength, so that the contribution of destructive interferences is reduced.

This diffractive method leads to designs, technologically producible, based on analytical models. It permits to miniaturize even further classical optical functions such as Huygens lenses [43], Fresnel lenses [44-45] or super-oscillatory-lenses [46]. Fig. 3(c) depicts a Huygens lens design obtained by a combination of a central pinhole surrounded symmetrically by 6 identical single mode metallic waveguides engraved in a 100 nm-thick gold layer. Fig 3(d) represents the related electric field intensity map. Similar focusing performances than a plasmonic lens are obtained with a Huygens lens (see Fig. 3(b) and Fig. 3(d)).

5. METALLIC SUB-λ ANTENNA

A metasurface, based on plasmonic effects, induces a phase modulation which is limited to π as a consequence of the symmetry of MIM structure. The 2π range phase modulation can be reached by working with the cross-polarized light, *i.e.* polarized perpendicularly to the polarization of the incident light [45,47]. According to these considerations, references [48-49] have demonstrated successfully that metallic V-shaped nano-antennas metasurface can realize a beam shaping of the cross-polarized scattered light. They show that an arbitrary phase pattern can be implemented by tuning the dimensions and the in-plane angle of the arms of the antennas. Figure 4 shows the phase shift obtained with a gold V-shaped antenna illuminated by a y-polarized antenna (see inset). A phase shift of up to 30° on the cross-polarized scattered wave (x-polarized) is attainable in transmission, as well as in reflection, simply by varying the in-plane angle α up to 45°.

Moreover, the possibility to refract a beam with an anomalous angle leading to the generalization of the Snell-Descartes's law was demonstrated [50]. The drawback of this approach lies in its low efficiency of the cross-conversion of light [51].

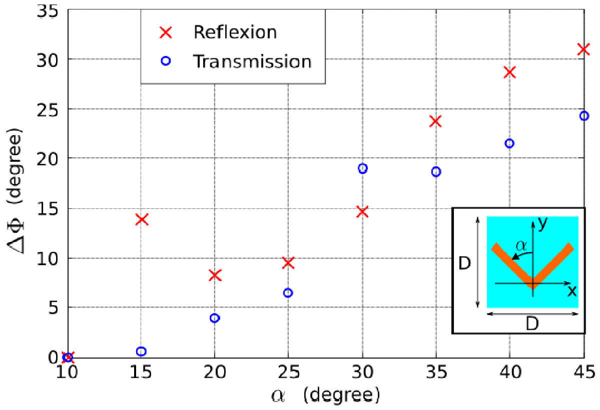

Figure 4: Evolution of the phase shift ΔΦ of the scattered cross-polarized (x-polarized) wave in transmission (cross) or in reflection (circle) as a function the in-plane angle α of the gold antenna represented in the inset. The phase at α=10°is taken as reference, D = 1.5 µm, λ = 3.5 µm. The length and the width of the antenna placed on a SiO_2substrate are respectively 1 µm and 100 nm.

6. CONCLUSION

Nanophotonics offer a promising alternative to classical optical components, with the ability to reach artificial indices and to pattern the phase at a subwavelength scale. Besides, most of the concepts reviewed here rely on planar nanostructures which make them relatively easy to fabricate. Eventually, they add degrees of freedom to modify not only the phase of the light, but also its polarization and amplitude which should pave the way to a new generation of optical components with new and appealing properties.

7. REFERENCES

1. Druart, G., Guérineau, N., Taboury, J., Rommeluère, S., Haïdar, R., Primot, J., et al. (2009). Compact infrared pinhole fisheye for wide field applications. *Applied optics , 48* (6), 1104-1113.

2. Cavanaugh, D. B., Castle, K. R., & Davenport, W. (2006). Anomaly detection using the hyperspectral polarimetric imaging testbed. *Proc. SPIE*, *6233*, p. 62331Q.

3. Völkel, R., Eisner, M., & Weible, K. (2003). Miniaturized imaging systems. *Microelectronic Engineering , 67*, 461-472.

4. Lalanne, P., & Lemercier-Lalanne, D. (1996). On the effective medium theory of subwavelength periodic structures. *Journal of Modern Optics , 43* (10), 2063-2086.

5. Haïdar, R., Vincent, G., Guérineau, N., Collin, S., Velghe, S., & Primot, J. (2005). Wollaston prism-like devices based on blazed dielectric subwavelength gratings. *Optics Express , 13* (25), 9941-9953.

6. Levy, U., Tsai, C.-H., Nezhad, M., Nakagawa, W., Chen, C.-H., Tetz, K. A., et al. (2004). Nanophotonics: materials and devices. *Integrated Optoelectronic Devices 2004*, (pp. 126-144).

7. Farn, M. W. (1992). Binary gratings with increased efficiency. *Applied optics , 31* (22), 4453-4458.

8. Levy, U., Nezhad, M., Kim, H.-C., Tsai, C.-H., Pang, L., & Fainman, Y. (2005). Implementation of a graded-index medium by use of subwavelength structures with graded fill factor. *JOSA A , 22* (4), 724-733.

9. Feng, D., Ou, P., Feng, L.-S., Hu, S.-L., & Zhang, C.-X. (2008). Binary sub-wavelength diffractive lenses with long focal depth and high transverse resolution. *Optics express , 16* (25), 20968-20973.

10. Lalanne, P., Astilean, S., Chavel, P., Cambril, E., & Launois, H. (1999). Design and fabrication of blazed binary diffractive elements with sampling periods smaller than the structural cutoff. *JOSA A , 16* (5), 1143-1156.

11. Barnes, W., Dereux, A., & Ebbesen, T. (2003). Surface plasmon subwavelength optics. *Nature , 424* (6950), 824-830.

12. Fu, Y., & Zhou, X. (2010). Plasmonic lenses: a review. *Plasmonics , 5* (3), 287-310.

13. Lalanne, P., Hugonin, J.-P., Liu, H., & Wang, B. (2009). A microscopic view of the electromagnetic properties of sub-λ metallic surfaces. *Surface Science Reports , 64* (10), 453-469.

14. Radko, I. P., Bozhevolnyi, S. I., Brucoli, G., Martìn-Moreno, L., Garcìa-Vidal, F., & Boltasseva, A. (2008). Efficiency of local surface plasmon polariton excitation on ridges. *Physical Review B , 78* (11), 115115.

15. Bozhevolnyi, S. I., Volkov, V. S., Devaux, E., Laluet, J.-Y., & Ebbesen, T. W. (2006). Channel plasmon subwavelength waveguide components including interferometers and ring resonators. *Nature , 440* (7083), 508-511.

16. Drezet, A., Koller, D., Hohenau, A., Leitner, A., Aussenegg, F. R., & Krenn, J. R. (2007).

Plasmonic crystal demultiplexer and multiports. *Nano letters , 7* (6), 1697-1700.

17. Wang, J., Wu, X., & Zhang, J. (2010). Imaging properties of Fresnel zone plate-like surface plasmon polariton launching lenses. *Optics Express , 18* (7), 6686-6692.

18. Mote, R., Yu, S., Ng, B., Zhou, W., & Lau, S. (2008). Near-field focusing properties of zone plates in visible regime-New insights. *Optics Express , 16* (13), 9554-9564.

19. Fu, Y., Zhou, W., Lim, L., Du, C., & Luo, X. (2007). Plasmonic microzone plate: Superfocusing at visible regime. *Applied Physics Letters , 91* (6), 61124-61124.

20. Devaux, E., Laluet, J., Stein, B., Genet, C., Ebbesen, T., Weeber, J., et al. (2010). Refractive micro-optical elements for surface plasmons: from classical to gradient index optics. *Optics Express , 18* (20), 20610-20619.

21. Pardo, F., Bouchon, P., Haïdar, R., & Pelouard, J.-L. (2011). Light funneling mechanism explained by magnetoelectric interference. *Physical review letters , 107* (9), 093902.

22. Koechlin, C., Bouchon, P., Pardo, F., Jaeck, J., Lafosse, X., Pelouard, J.-L., et al. (2011). Total routing and absorption of photons in dual color plasmonic antennas. *Applied Physics Letters , 99* (24), 241104-241104.

23. Bouchon, P., Koechlin, C., Pardo, F., Haïdar, R., & Pelouard, J.-L. (2012). Wideband omnidirectional infrared absorber with a patchwork of plasmonic nanoantennas. *Öptics Letters*, 37(6), 1038–1040.

24. Koechlin, C., Bouchon, P., Pardo, F., Pelouard, J.-L., & Haïdar, R. (2013). Analytical description of subwavelength plasmonic mim resonators and of their combination. *Optics express*, 21(6), 7025–7032.

25. Collin, S., Pardo, F., & Pelouard, J. (2007). Waveguiding in nanoscale metallic apertures. *Optics Express , 15* (7), 4310-4320.

26. Kong, F., Wu, B.-I., Chen, H., & Kong, J. A. (2007). Surface plasmon mode analysis of nanoscale metallic rectangular waveguide. *Optics Express , 15* (19), 12331-12337.

27. Bouchon, P., Pardo, F., Portier, B., Ferlazzo, L., Ghenuche, P., Dagher, G., et al. (2011). Total funneling of light in high aspect ratio plasmonic nanoresonators. *Applied Physics Letters , 98*, 191109.

28. Pors, A., Nielsen, M. G., Eriksen, R. L., & Bozhevolnyi, S. I. (2013). Broadband Focusing Flat Mirrors Based on Plasmonic Gradient Metasurfaces. *Nano letters , 13* (2), 829-834.

29. Sun, S., Yang, K.-Y., Wang, C.-M., Juan, T.-K., Chen, W. T., Liao, C. Y., et al. (2012). High-Efficiency Broadband Anomalous Reflection by Gradient Meta-Surfaces. *Nano letters , 12* (12), 6223-6229.

30. Lin, L., Goh, X., McGuinness, L., & Roberts, A. (2010). Plasmonic lenses formed by two-dimensional nanometric cross-shaped aperture arrays for Fresnel-region focusing. *Nano letters , 10* (5), 1936-1940.

31. Verslegers, L., Catrysse, P., Yu, Z., White, J., Barnard, E., Brongersma, M., et al. (2008). Planar lenses based on nanoscale slit arrays in a metallic film. *Nano letters , 9* (1), 235-238.

32. Yu, Y., & Zappe, H. (2011). Effect of lens size on the focusing performance of plasmonic lenses and suggestions for the design. *Optics Express , 19* (10), 9434-9444.

33. Goh, X., Lin, L., & Roberts, A. (2010). Planar focusing elements using spatially varying near-resonant aperture arrays. *Optics Express , 18* (11), 11683-11688.

34. Ishii, S., Shalaev, V. M., & Kildishev, A. V. (2012). Holey-metal lenses: sieving single modes with proper phases. *Nano letters , 13* (1), 159-163.

35. Roy, T., Nikolaenko, A. E., & Rogers, E. T. (2013). A meta-diffraction-grating for visible light. *Journal of Optics*, 15(8), 085101.

36. Verslegers, L., Catrysse, P., Yu, Z., & Fan, S. (2009). Planar metallic nanoscale slit lenses for angle compensation. *Applied Physics Letters , 95* (7), 71112-71112.

37. Ishii, S., Kildishev, A. V., Shalaev, V. M., Chen, K.-P., & Drachev, V. P. (2011). Metal nanoslit lenses with polarization-selective design. *Optics letters , 36* (4), 451-453.

38. Shi, H., Wang, C., Du, C., Luo, X., Dong, X., & Gao, H. (2005). Beam manipulating by metallic nano-slits with variant widths. *Optics Express , 13* (18), 6815-6820.

39. Yu, N., Genevet, P., Aieta, F., Kats, M., Blanchard, R., Aoust, G., et al. (2013). Flat Optics: Controlling Wavefronts with Optical Antenna Metasurfaces.

40. Lévesque, Q., Bouchon, P., Pardo, F., Pelouard, J.-L., & Haïdar, R. (2013). Energetic analysis of the plasmonic lens structure: a first step to simplification. *International Society for Optics and Photonics*, (pp. 87810T--87810T).

41. Pfeiffer, C., & Grbic, A. (2013). Metamaterial huygens' surfaces: Tailoring wave fronts with reflectionless sheets. *Physical review letters , 110* (19), 197401.

42. Pfeiffer, C., & Grbic, A. (2013). Viewpoint: Wave-Shaping Surfaces. *Phys. Rev. Lett , 110*, 197401.

43. Lévesque, Q., Bouchon, P., Pardo, F., Pelouard, J.-L., & Haïdar, R. (2013). Compact planar lenses based on a pinhole and an array of single mode metallic slits. *Journal of the European Optical Society-Rapid publications , 8*.

44. Hao, F., Wang, R., & Wang, J. (2010). Design and characterization of a micron-focusing plasmonic device. *Optics express , 18* (15), 15741-15746.

45. Ye, H., Qiu, C.-W., Huang, K., Teng, J., Luk'yanchuk, B., & Yeo, S. P. (2013). Creation of a longitudinally polarized subwavelength hotspot with an ultra-thin planar lens: vectorial Rayleigh--Sommerfeld method. *Laser Physics Letters , 10* (6), 065004.

46. Rogers, E. T., Savo, S., Lindberg, J., Roy, T., Dennis, M. R., & Zheludev, N. I. (2013). Super-oscillatory optical needle. *Applied Physics Letters , 102* (3), 31108-31108.

47. Zhao, Y., & Alù, A. (2011). Manipulating light polarization with ultrathin plasmonic metasurfaces. *Physical Review B , 84* (20), 205428.

48. Yu, N., Genevet, P., Kats, M., Aieta, F., Tetienne, J., Capasso, F., et al. (2011). Light propagation with phase discontinuities: generalized laws of reflection and refraction. *science , 334* (6054), 333-337.

49. Blanchard, R., Aoust, G., Genevet, P., Yu, N., Kats, M. A., Gaburro, Z., et al. (2012). Modeling nanoscale V-shaped antennas for the design of optical phased arrays. *Physical Review B , 85* (15), 155457.

50. Aieta, F., Genevet, P., Yu, N., Kats, M., Gaburro, Z., & Capasso, F. (2012). Out-of-plane reflection and refraction of light by anisotropic optical antenna metasurfaces with phase discontinuities. *Nano Letters* .

51. Aieta, F., Genevet, P., Kats, M. A., Yu, N., Blanchard, R., Gaburro, Z., et al. (2012). Aberration-free ultrathin flat lenses and axicons at telecom wavelengths based on plasmonic metasurfaces. *Nano letters , 12* (9), 4932-4936.