Cost-effective solution for increased light collection in noble-element detectors with metalenses

Roxanne Guenette*[a], Justo Martín-Albo[b], Vinvent Basque[e], Carlos Escobar[d], Juan Jose Gomez Cadenas[c], Adam Para[d], and Michelle Stancari[d]

[a]*Harvard University, Cambridge, MA, USA*
[b]*Instituto de Física Corpuscular (IFIC), Universitat de València & CSIC, Valencia, Spain*
[c]*Donostia International Physics Center (DIPC), Spain*
[d]*Fermi National Accelerator The University of Manchester, Manchester M13 9PL, United Kingdom*

31 August 2020

Introduction

Scintillation light offers great handles to study particle interactions in noble-element detectors. From the detection of the fast component (∼ns time scale) of the scintillation to provide trigger and precise information on the starting time of the event, to the collection of amplified optical signals from the ionisation charges to either image or identify particle types, scintillation light has been central to *time projection chambers* (TPCs). For the next generation of experiments, scintillation will continue to play an essential role and increasing the amount of light detected could significantly enhance the capabilities of these future detectors. However, solely increasing the number of photosensors may not be viable at very large scale, as the cost of channel proliferation will be prohibitive.

Metalenses, nanostructures that allow the focusing of light, could be a cost-effective solution to increase the light collection while maintaining the number of photosensors reasonable.

*Point of Contact: Roxanne Guenette, Harvard University (guenette@fas.harvard.edu)

Metalenses principle

Metalenses consist of arrays of subwavelength-spaced dielectric nanostructures on a substrate serving as phase shifters that allow for unprecedented control over the wavefront of transmitted light. For instance, TiO_2, SiO_2 and GaN nanostructures of varying dimensions have been found to efficiently modulate phases in the visible range [1, 2, 3]. Due to their diffractive nature, metalenses produce multiple foci, each corresponding to a different diffraction order.

Application to Noble Element Detectors

It was recently demonstrated that metalenses combined with Silicon PhotoMultipliers (SiPMs) offer a considerable increase in the light collection [4]. However, this demonstration was done in the red (638 nm) and the metalenses used were not optimised for efficient light concentration, but rather to limit diffraction effects. It is clear that designing optimised metalenses for noble element detector application could have a significant impact on future detectors.

Future noble element detectors may want to take advantage of metalenses for many different application. High pressure gas xenon TPCs, such as the one from the NEXT experiment [5, 6], could benefit from VUV-sensitive metalenses behind the electroluminescence region to keep high resolution imaging capabilities when the tracking plane is placed further away from the amplification region, or could provide 100% light coverage for the tracking plane by large area metalenses focusing the light onto smaller SiPMs. Large liquid argon detectors, such as DUNE [7] could use blue metalenses to increase the wavelength-shifted light collection at reasonable costs. By inserting those planar compact devices inside wire planes, and by aligning optimally the foci for each lens to concentrate the light in a modest amount of SiPMs, the total light collection of the large-scale detector could be significantly increased, leading to potentially lower energy thresholds benefiting the supernovae and solar neutrino science program. Finally, in liquid xenon detectors, VUV-sensitive metalenses could be use to increase the light collection area by large lenses focusing light into smaller VUV-sensitive SiPMs.

For noble element applications, R&D will be required to design metalenses that can focus VUV light, appropriate for xenon (175 nm) and argon (128 nm) scintillation. While the former should be achievable with substrates such as fused silica or MgF_2, the latter may require higher precision lithography techniques. Alternatively, incorporating wavelength-shifting material within the substrate could offer interesting solution for the argon application. Exploratory test bench studies for a variety of lenses and applications are needed to understand the capabilities and limitations of this new technology. The versatile metalens designs should be tailored case by case to the exact detector applications in order to achieve the highest possible improvement in the light collection.

Finally, the application of metalenses could go beyond noble element detectors used in high energy and nuclear physics. Detector components that use light detection could benefit from specific design of these adaptable devices.

References

[1] R.C. Devlin, M. Khorasaninejad, W.T. Chen, J. Oh and F. Capasso, *Broadband high-efficiency dielectric metasurfaces for the visible spectrum*, *Proceedings of the National Academy of Sciences* **113** (2016) 10473.

[2] J.-S. Park, S. Zhang, A. She, W.T. Chen, P. Lin, K.M.A. Yousef et al., *All-glass, large metalens at visible wavelength using deep-ultraviolet projection lithography*, *Nano Letters* **19** (2019) 8673.

[3] B.H. Chen, P.C. Wu, V.-C. Su, Y.-C. Lai, C.H. Chu, I.C. Lee et al., *Gan metalens for pixel-level full-color routing at visible light*, *Nano Letters* **17** (2017) 6345.

[4] A.L. Villalpando, J. Martin-Albo, W. Chen, R. Guenette, C. Lego, J. Park et al., *Improving the light collection efficiency of silicon photomultipliers through the use of metalenses*, `2007.06678`.

[5] NEXT collaboration, *The NEXT-White (NEW) detector*, *JINST* **13** (2018) P12010 [`1804.02409`].

[6] NEXT collaboration, *NEXT-100 Technical Design Report (TDR): Executive Summary*, *JINST* **7** (2012) T06001 [`1202.0721`].

[7] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV Far Detector Single-phase Technology*, *JINST* **15** (2020) T08010 [`2002.03010`].