Designing Disordered Structures to Manipulate Antenna Radiation

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Abstract: We derive a simple and efficient method for designing wave-shaping materials composed of dipole scatterers. We apply our theory to design aperiodic metasurfaces that re-structure the radiation from a dipole emitter in many ways. Our proposed technique is relevant to designing metamaterials for a wide class of applications, and has the key benefit of including all interactions within the system of scatterers.

Related publications:
– J. R. Capers et al., arXiv:2011.13274

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Background and research question/challenge

Antenna are key to most aspects of modern life, from mobile communications to self-driving cars. In recent years there has been a drive to miniturise antenna and for them to have more novel properties. Miniturisation leads to a degradation of efficiency and bespoke directionality may be key to the future communications platforms: 5G and beyond.

One way to modify antenna functionality is to surround the antenna with several passive scatterers, manipulating the radiation. However, this requires a method of deciding where to place the scatterers. Currently, the design of this kind of system relies either on numerically expensive full-wave methods, coupled to gradient descent or genetic algorithms [1], or on methods which neglect coupling between the scatterers. This coupling can often be key to optimal performance [2].

In this work, we derive a new method for designing aperiodic scattering structures to manipulate antenna radiaiton. Our analytic method, based on the discrete dipole approximation [3], is simple, fast and versatile.

References
[1] Molesky, S. et al., Nat. Phot. **12** 659-670 (2018)
[2] Asadchy, V. S. et. al., Phys. Rev. B **94** 075142 (2016)
[3] Purcell, E. M. et. al., Astrophys. J. **186** 705 (1973)

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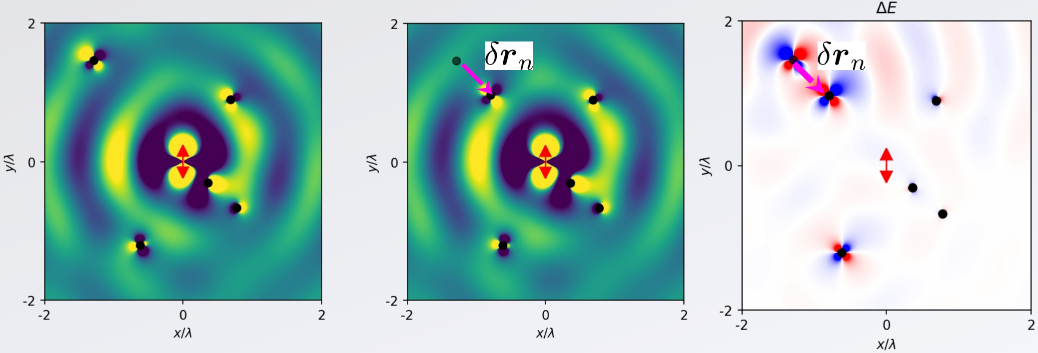
Techniques and Methods

Our proposed design method is based on the discrete dipole approximation, and works as follows:

1) Starting from an initial distribution of scatterers, use the discrete dipole approximation to calculate the fields.
2) Find, analytically, how the fields change if one of the scatterers is moved by a small amount.
3) Given some figure of merit, use the changes in field to find an update equation. This lets us calculate the step the scatterer should take to increase the figure of merit.
4) Iteratively update scatterer locations to increase the figure of merit.



$$\delta \boldsymbol{E}(\boldsymbol{r}) = \left\{\xi^2 \boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}_n)\boldsymbol{\alpha}_E \nabla \boldsymbol{E}(\boldsymbol{r}_n) + i\xi \boldsymbol{G}_{EH}(\boldsymbol{r},\boldsymbol{r}_n)\boldsymbol{\alpha}_H \nabla \boldsymbol{H}(\boldsymbol{r}_n)\right\} \delta \boldsymbol{r}_n$$

$$\delta \boldsymbol{H}(\boldsymbol{r}) = \left\{\xi^2 \boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}_n)\boldsymbol{\alpha}_H \nabla \boldsymbol{H}(\boldsymbol{r}_n) - i\xi \boldsymbol{G}_{EH}(\boldsymbol{r},\boldsymbol{r}_n)\boldsymbol{\alpha}_E \nabla \boldsymbol{E}(\boldsymbol{r}_n)\right\} \delta \boldsymbol{r}_n$$

$\boldsymbol{E}, \boldsymbol{H}$: Electric and Magnetic Fields
$\delta \boldsymbol{r}_n$: Change in position of scatterer n
$\boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}')$: Electromagnetic Green's Function
$\boldsymbol{G}_{EH} = \nabla \times \boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}')$
$\boldsymbol{\alpha}_E, \boldsymbol{\alpha}_H$: Scatterer electric and magnetic polarisabilities
ξ : Unitless wave number

Fig. 1: **Schematic of the method**. Emitter is shown as red arrow at the center, scatterers as black dots. The change in field, right hand plot, due to moving one of the scatterers by a small amount can be found analytically.

Key results

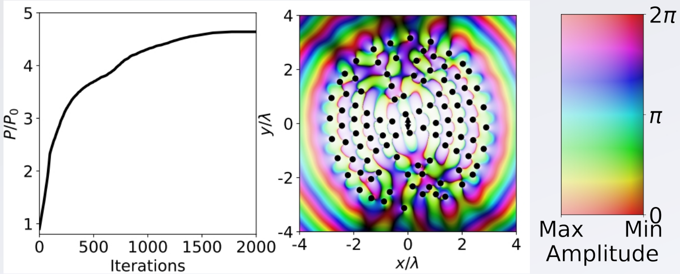
By applying our design framework to several different figures of merit that can be expanded in terms of these small changes in fields, many key aspects of antenna radiation can be engineered.

Power Emission

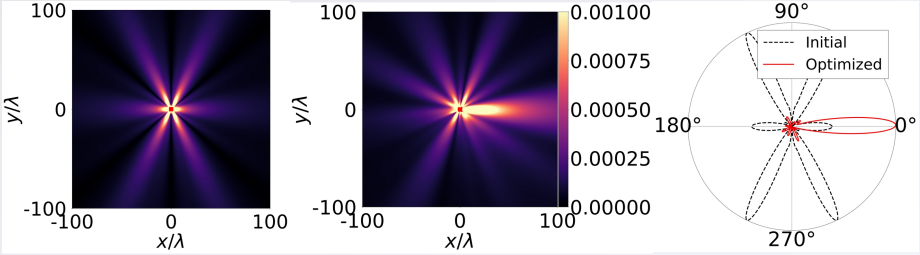
- ➔ Dipole emitter with polarization vector **p** located at **r'**.
- ➔ Figure of merit is the Partial Local Density of Optical States.
- ➔ This can be expanded in terms of the calculated change in electric field.
- ➔ For each scatterer, we can choose a small position change so that the figure of merit increases with every iteration.

$$P \sim \mathrm{Im}[\hat{\boldsymbol{p}} \cdot \boldsymbol{E}(\boldsymbol{r'})]$$

$$\delta P \sim \mathrm{Im}[\hat{\boldsymbol{p}} \cdot \{\xi^2 \boldsymbol{G}(\boldsymbol{r'},\boldsymbol{r}_n)\boldsymbol{\alpha}_E \nabla \boldsymbol{E}(\boldsymbol{r}_n) + i\xi \boldsymbol{G}_{EH}(\boldsymbol{r'},\boldsymbol{r}_n)\boldsymbol{\alpha}_H \nabla \boldsymbol{H}(\boldsymbol{r}_n)\}]\delta \boldsymbol{r}_n$$



Directivity



Shape of |**S**| in the far-field