Designing, Simulating, and Optimising Nanoantennas that utilise Nonlinear Effects

A literature review

Project: EXSS-Sapienza-1
Project partner: Taran Attavar
Supervisor: Riccardo Sapienza
Assessor: Cynthia Vidal

Jakub Bartosz Dranczewski

Imperial College London

Word count: NaN (max is 2500)

Abstract

Morbi luctus, wisi viverra faucibus pretium, nibh est placerat odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetuer a, feugiat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetuer. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

1 Introduction

The goal of our project is to investigate, both experimentally and computationally, the applicability and efficiency of different nanoantenna designs for enhancing nonlinear optical effects at the nanoscale. Light manipulation using the nonlinear response of materials has existing and promising future applications in a number of areas, including frequency control for laser light, optical communications, spectroscopy, data storage, and sensing[1]. Nonlinear effects often require large interaction volumes and high laser powers to occur, and nanoantennas are one of the proposed ways to alleviate this and bring nonlinear optics to small-scale applications.

2 Nonlinear optics

When considering the propagation of light in matter, it is often assumed that the response of the material is linear[2], giving a simple expression for the polarisation:

$$\boldsymbol{P} = \epsilon_0 \chi \boldsymbol{E}, \tag{1}$$

with ϵ_0 being the permittivity of free space, and $\boldsymbol{E}$ the electric field. As outlined in [3], this expression can be generalised to include terms that only gain significance at higher field magnitudes, and can be thought to correspond to potentials for the electrons in the material deviating from the simple harmonic approximation:

$$\begin{aligned} \boldsymbol{P} &= \epsilon_0(\chi^{(1)}\boldsymbol{E} + \chi^{(2)}\boldsymbol{E}^2 + \chi^{(3)}\boldsymbol{E}^3 + ...) && (2) \\ &= \boldsymbol{P}^{(1)} + \boldsymbol{P}^{(2)} + \boldsymbol{P}^{(3)} + ..., && (3) \end{aligned}$$

where $\chi^{(n)}$ is known as the n^{th} order nonlinear susceptibility, and is in general a tensor.

Now if we allow $\boldsymbol{E}$ to vary in time we will also get time variation in $\boldsymbol{P}$, and that movement of charges drives a further electric field oscillation. One can then see how the nonlinear terms in (2) lead to additional frequency components in this new oscillation. For a simple example adapted from [3], we can take $\boldsymbol{E}(t) = \boldsymbol{E}_0 \cos(\omega t)$ and look at the second order polarisation:

$$\boldsymbol{P}^{(2)} = \frac{\epsilon_0 \chi^{(2)}}{2} \boldsymbol{E}_0^2 \left(1 + \cos(2\omega t)\right). \tag{4}$$

This then drives an electromagnetic wave (the *signal*) at angular frequency 2ω, compared to ω for the incoming (*pump*) wave. The process is known as second harmonic generation (SHG).

Other basic nonlinear processes of note include third harmonic generation (THG), sum and difference frequency generation ($\omega' = \omega_1 \pm \omega_2$), changes to the refractive index (a third order process), and others[3].

The *phase matching* parameter, $\Delta k = k' - k$ is crucial in designing most nonlinear processes that involve a change in frequency[3]. As both the pump (wavevector k) and signal (k') fields interact with the same electric dipoles, the best conditions for coupling between them is when they are in phase such that they don't interfere destructively. While achieving $\Delta k = 0$ is possible through anomalous dispersion, it is more feasible to do this by utilising birefringence. This is only possible for some materials, but if done correctly it can lead to quadratic dependence of the signal density on the interaction distance. On the other hand, if $\Delta k \neq 0$, choosing the wrong sample length can lead to a total loss of signal.

3 Material considerations

Various considerations to be made while thinking of materials to use. Start with the nonlinear part I guess. Asymmetry for second-order effects. High χ, spectral dependence of it. Absorption - this is why metals suck. Dielectrics as our new hope, high refractive index makes them good for field concentration. Displacement current vs normal current (plasmonics). ENZ as an option. How common the material is as a factor (ITO as an example).

4 Nanoantennas

Coupling from the far to the near field (plane waves fine for bulk, but some confinement nice for smaller things). Need for miniaturisation if we want devices. Talk about modes, the way they lead to field enhancement, probably a bit about Mie somehow? Dark modes, bound states in continuum. ENZ and coupling out. Directivity, copying real antennas threaded in somehow.

Talk about shapes? Like the fancy 'few spheres' thing, compared to the trusty, Mie-compatible(?) cylinder.

Intro to antenna properties - directivity, efficiency.

5 Enhancing nonlinear effects with nanoantennas

Smaller - we need to go around that, as we've previously seen that the more material the better. No requirement for phase matching, nice, simplifies the whole thing. Talk about the steps from [4]. Trivial effects like the increased area can be important for second order effects.

6 Predicting and optimising the nonlinear signal of an antenna

Small derivation from Lorenz reciprocity. Explain why this method is good. Finite-difference time domain stuff. Mention Lumerical.

Talk about the steps from [4] (again?). Experimental methodology, computing. Combining materials. This section seems a bit useless...

7 Conclusion

You wish you were concluding[5].

References

[1] E. Garmire, "Nonlinear optics in daily life," vol. 21, no. 25, pp. 30 532–30 544. [Online]. Available: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-25-30532

[2] J. D. Jackson, *Classical Electrodynamics*, 3rd ed. Wiley.

[3] R. W. Boyd, *Nonlinear Optics*, 3rd ed. Academic Press.

[4] K. Koshelev, S. Kruk, E. Melik-Gaykazyan *et al.*, "Subwavelength dielectric resonators for nonlinear nanophotonics," vol. 367, no. 6475, pp. 288–292. [Online]. Available: https://science.sciencemag.org/content/367/6475/288

[5] A. Alù and N. Engheta, "Theory, Modeling and Features of Optical Nanoantennas," vol. 61, no. 4, pp. 1508–1517.