

Phase-matching in Dirac-cone-based zero-index metamaterials



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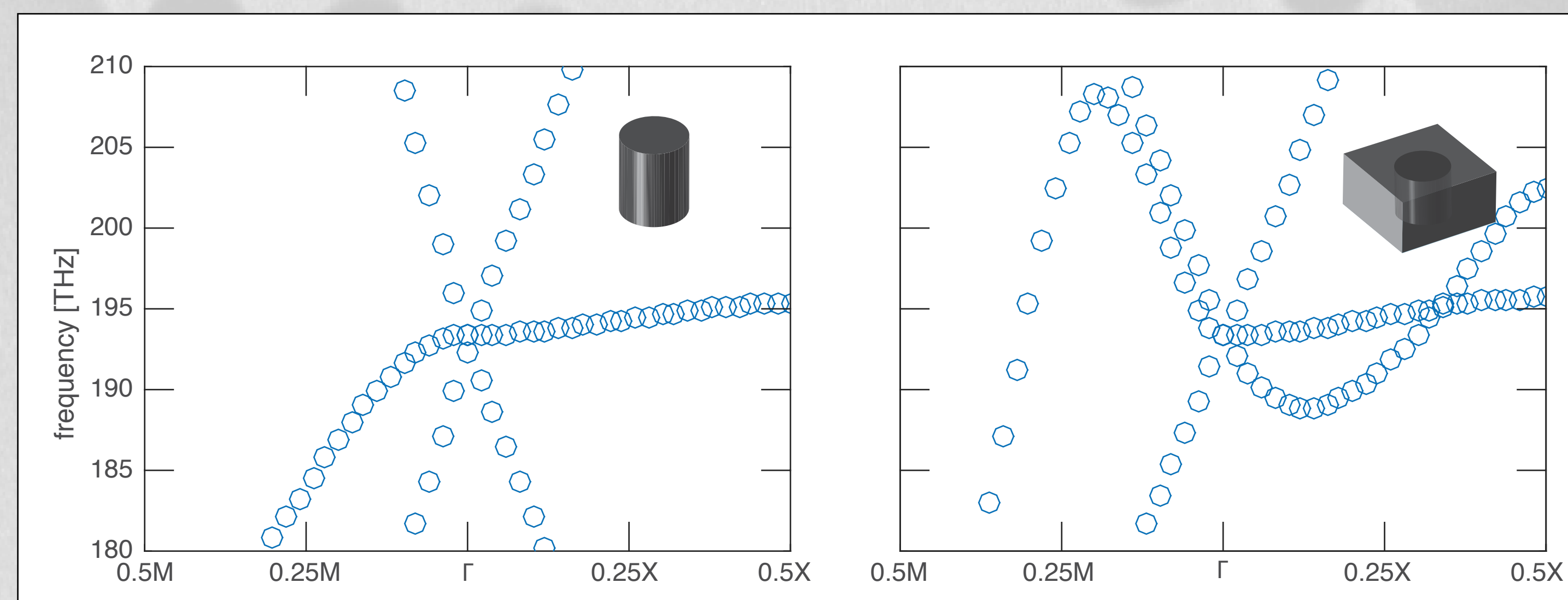
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Overview

A Dirac cone at the center of the Brillouin zone has been used to demonstrate a refractive index of zero, providing access to a wealth of novel nonlinear phenomena and potential applications [1–3]. Previously, simultaneous bi-directional phase-matching behaviour has been demonstrated using an anisotropic zero-index metamaterial (ZIM) [4]. Here, we use nonlinear scattering theory [5–6] to simulate an isotropic on-chip ZIM based on photonic Dirac cones and demonstrate simultaneous phase-matching in all directions.

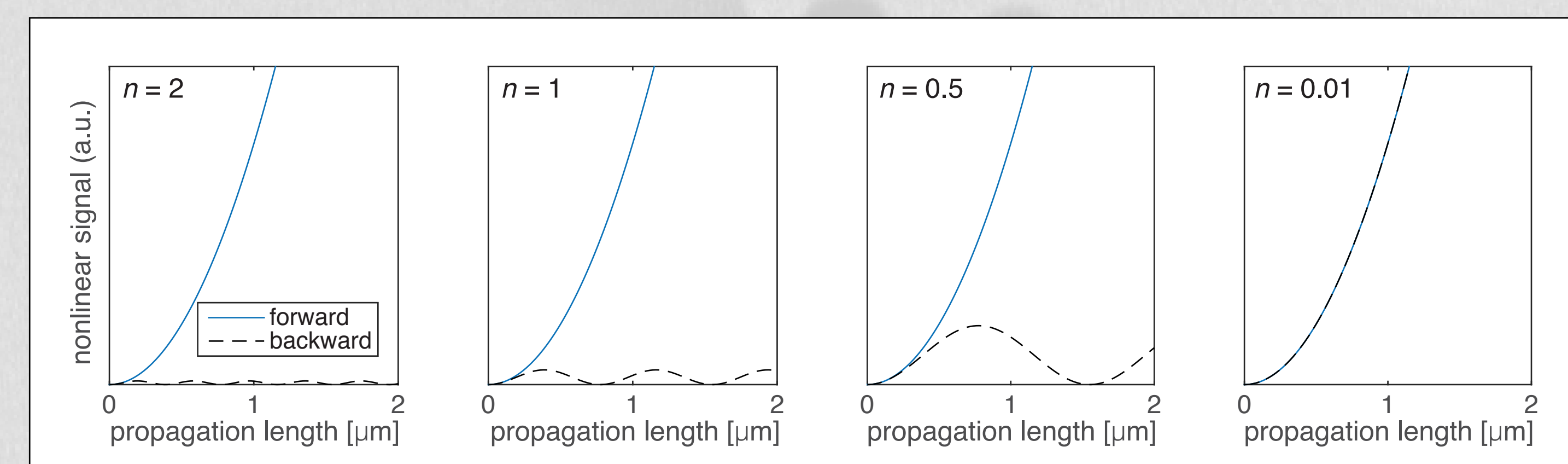
Photonic Dirac-cone-based ZIMs

We investigate two platforms: a 2D square array of silicon pillars in air and a 2D square array of air holes in a silicon bulk. These metamaterials are designed to exhibit a Dirac cone at the center of the Brillouin zone, indicating an effective refractive index of zero.



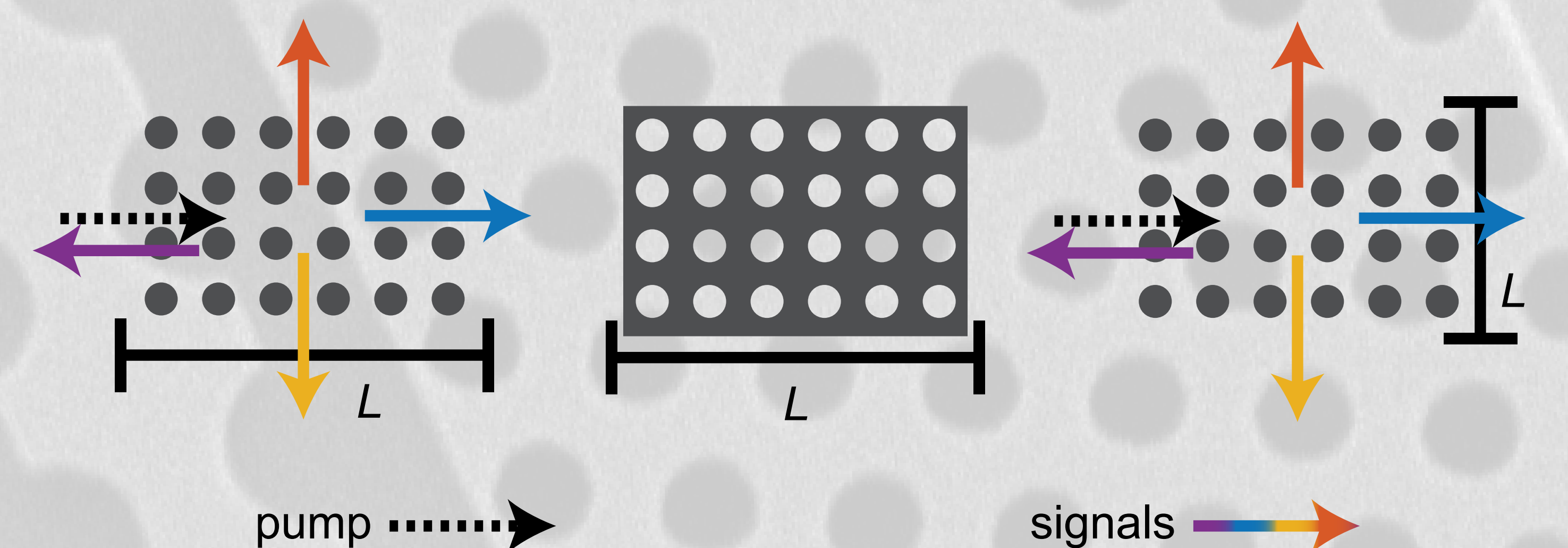
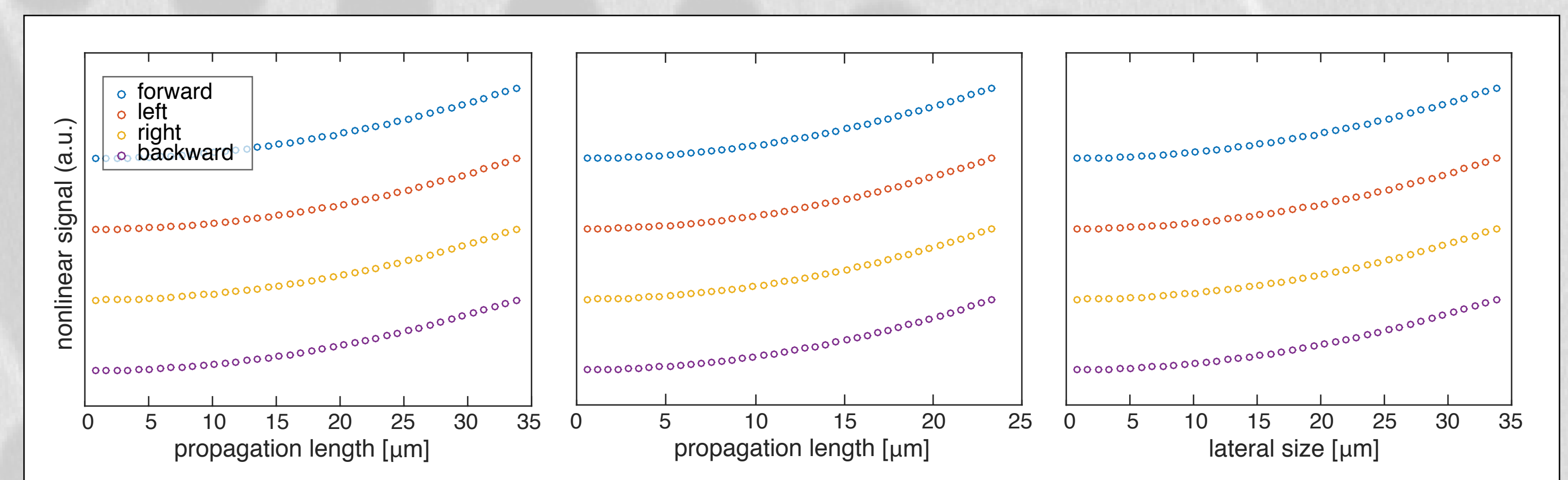
Phase-matching in bulk media

We use nonlinear scattering theory to simulate degenerate four-wave mixing (FWM) within dispersionless bulk materials. As expected, the coherence lengths for these interactions are infinite for light that is generated in the forward-propagating direction, regardless of the material index. On the other hand, the coherence length increases in the backward-propagating direction as the index decreases, in good agreement with the predicted value of $L_{\text{coh}} = \pi c / 2\omega n \approx 400 \text{ nm} / n$.



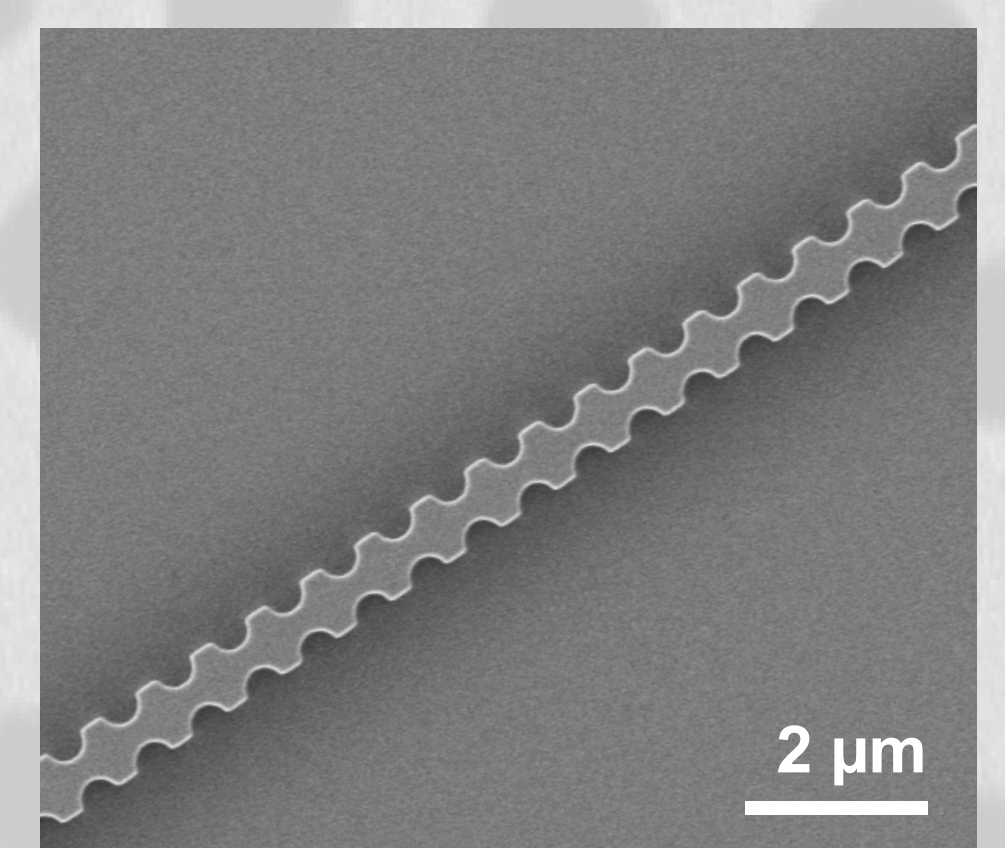
Phase-matching in Dirac-cone-based ZIMs

Using nonlinear scattering theory, we calculate the nonlinear signal generated in both platforms as a function of propagation length. The generated intensities all grow quadratically, indicating perfect phase-matching in all propagation directions. We also observe phase-matching behaviour when increasing the size of the ZIM laterally, orthogonal to the direction of the input pump.



Future work

The design of 3D structures are complete, and fabrication and characterisation of devices is underway. We are currently pursuing experiments to demonstrate on-chip optical parametric amplification and phase-conjugation, which have applications in on-chip image restoration and aberration correction.



References:

- [1] Y. Li *et al.*, Nature Photonics, 738–742 (2015).
- [2] X. Huang *et al.*, Nature Materials, 582–586 (2011).
- [3] P. Moitra *et al.*, Nature Photonics, 791–795 (2013).
- [4] H. Suchowski *et al.*, Science, 1223–1226 (2013).
- [5] K. O'Brien *et al.*, Nature Materials, 379–383 (2015).
- [6] J. Butet *et al.*, JOSA B, A8–A15 (2016).