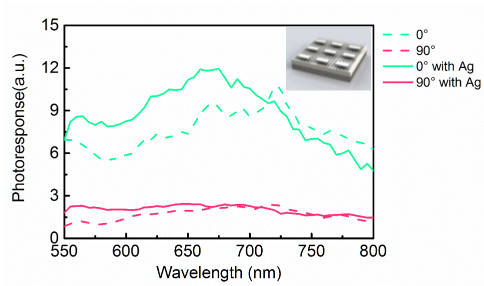
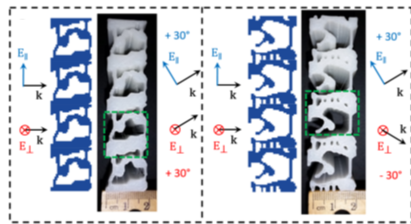
Increased Photocurrent in **Black Phosphorus** *and* **Inverse design** of photonic devices





Zizhuo Liu and Francois Callewaert

Aydin's Group

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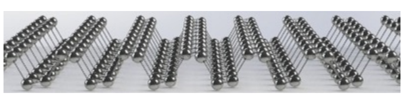
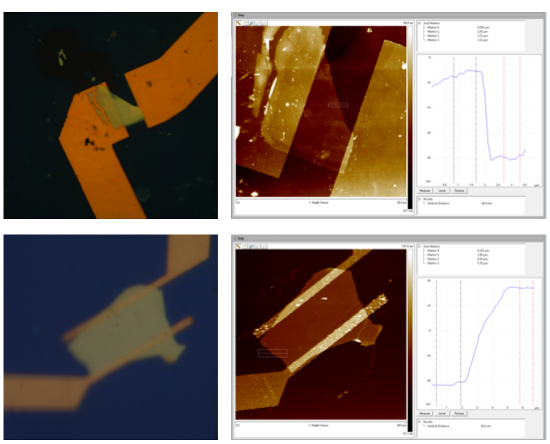
Black Phosphorus



Black phosphorus (BP) is known to have **anisotropic** properties due to its **puckered crystal structure**.



BP thin films of thicknesses varying around 10-40 nm were provided by Hersam's group with contact pads.

Zizhuo Liu, Spencer Wells, Edgar Palacios, Mark Hersam, Koray Aydin

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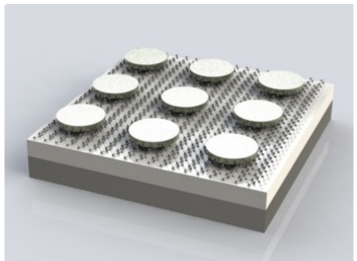
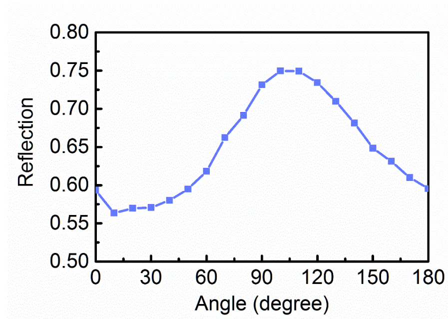
Anisotropic Optical Response



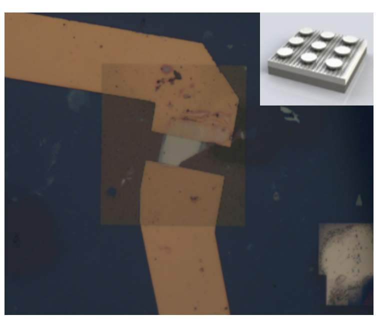


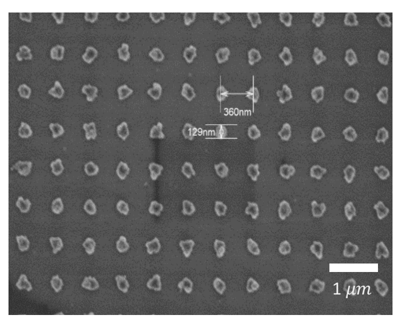
Planar BP film shows anisotropic optical response for incident light with **different polarization angels**.

Measured reflection spectra reveal the anisotropic behavior and help determine the **crystal orientation**.

Lintao Peng, Spencer Wells, Zizhuo Liu, Koray Aydin, Mark Hersam, Matthew Greyson

Photocurrent Enhancement

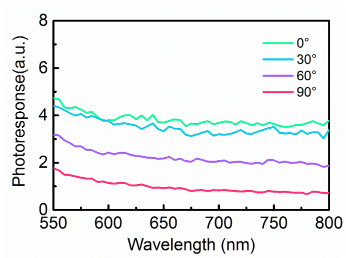


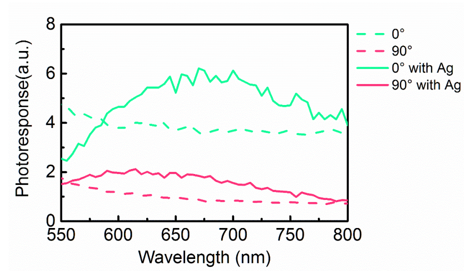


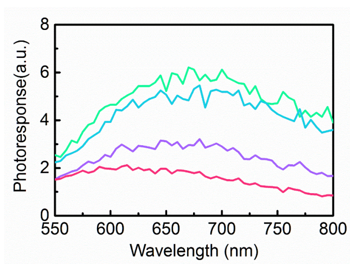
Disk design for 15 nm thick BP film: enhance photocurrent **in both direction.**

P = 350 nm, D = 120 nm

Photocurrent Enhancement







Photocurrent is enhanced in all the polarizations after patterning the structures around 650 nm wavelength.

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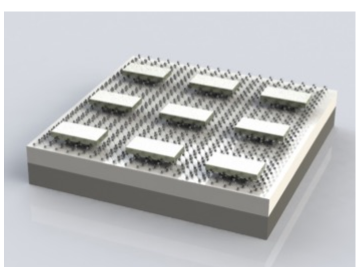
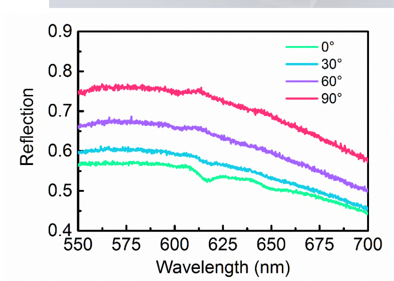
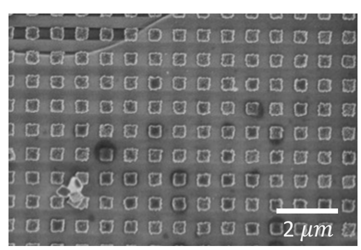
Anisotropic Photocurrent Enhancement



Rectangle structures can be used to to **enhance the BP anisotropic photoresponse**, i.e., only enhance the photoresponse on *x*-direction.

Rectangle design for 40 nm thick BP film: enhance photocurrent around wavelength of 650 nm in *x*-direction
P = 420 nm, X = 270 nm, Y = 200 nm





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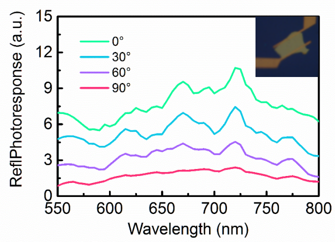
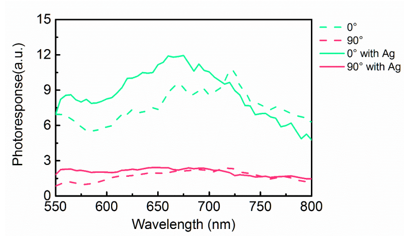
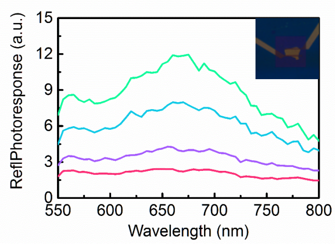
Anisotropic Photocurrent Enhancement







The photocurrent is enhanced around 650 nm for *x*-direction and stays almost the same for *y*-direction.

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Future Work

- **Oxide thickness** dependence of the photocurrent enhancement
- **Robust structure design** for anisotropic light-matter enhancement
- **Chiral antennas** coupled with BP's anisotropic response

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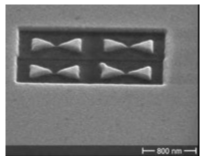
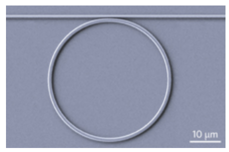
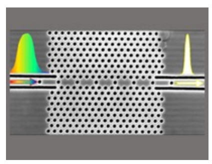
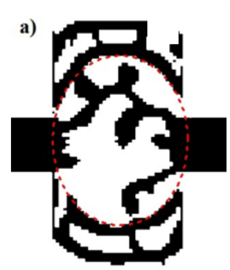
Inverse design









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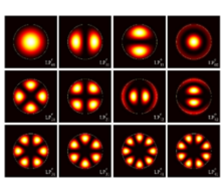
The wave equation

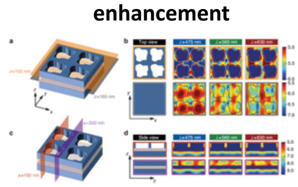
$$\nabla\times\nabla\times \boldsymbol{E} = -\boldsymbol{\varepsilon}\frac{\partial^2 \boldsymbol{E}}{\partial t^2}$$

ε = properties of the matter
E = electromagnetic field

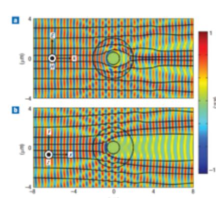
Multi-mode fiber



Broadband absorption enhancement



Optical cloak



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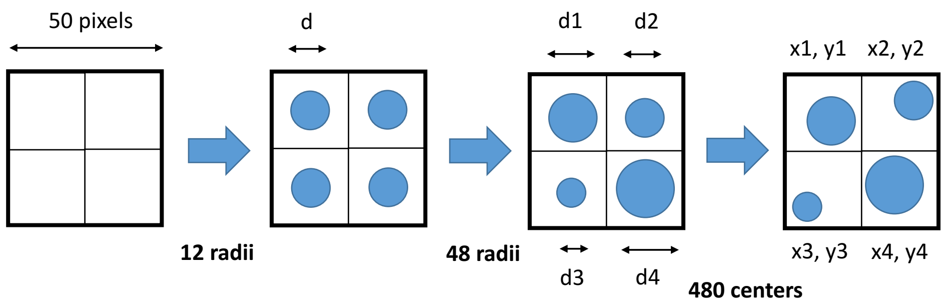
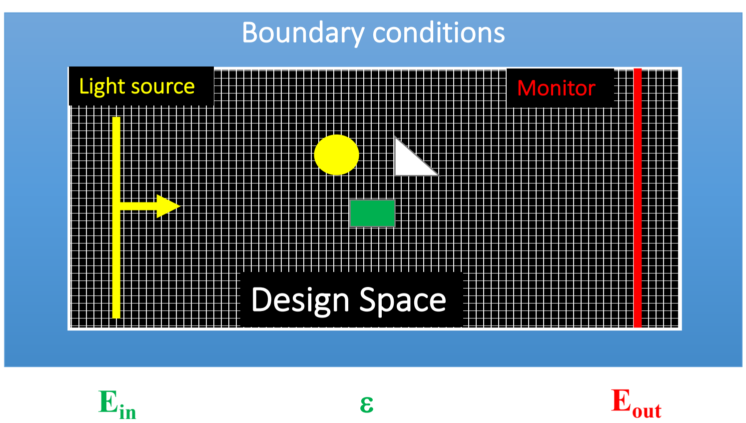
The design process illustrated



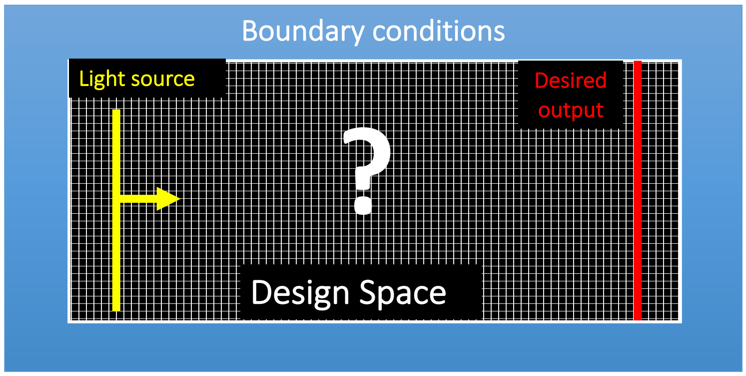
- 540 configurations tested in one day
- 10^{15} combinations of 4 disks
- 10^{752} combinations pixel by pixel

The simulation process



$$\nabla \times \nabla \times E = -\varepsilon \frac{\partial^2 E}{\partial t^2}$$

Inverse-design



E_{in} ε E_{out}

$$\nabla\times\nabla\times E = -\varepsilon \frac{\partial^2 E}{\partial t^2}$$

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Inverse-design formulation

Given some boundary conditions (input and output)
Find E and ε inside the design space such that:

$$\nabla\times\nabla\times E = w^2 \varepsilon E$$

[+ some conditions on ε]

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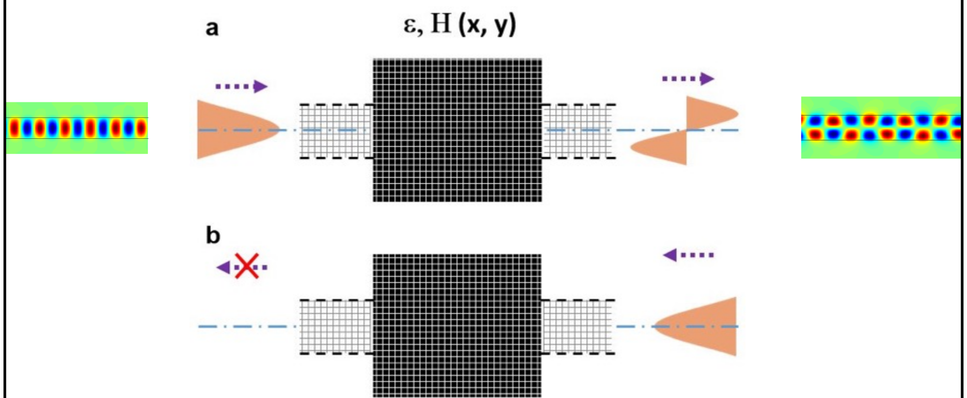
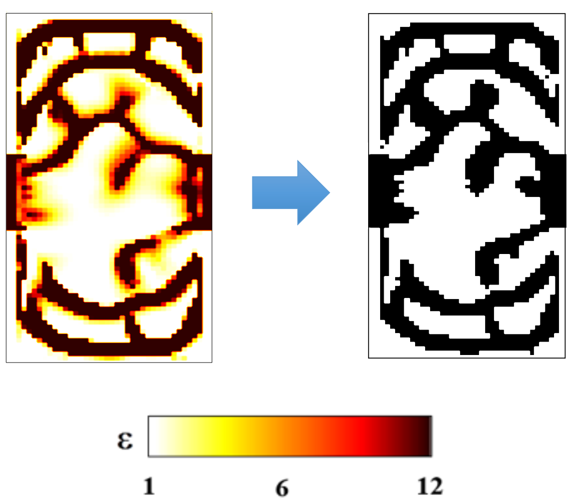
Optical diode

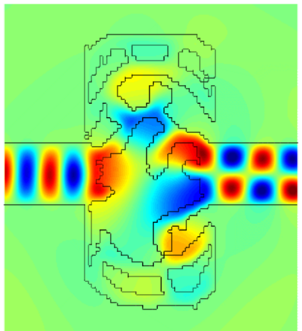


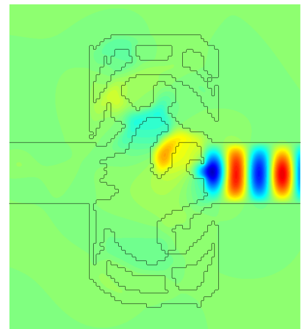
Initial condition: **ε = constant**
Material constraints: **1 (air) < ε < 12 (Si)**

The optimized device



It works!



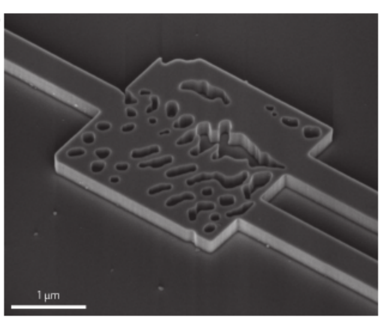


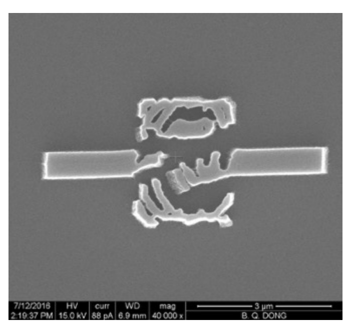
$T_{L \rightarrow R} = 90\%$ $T_{R \rightarrow L} = 1\%$

Callewaert, F., et al. (2016). "Inverse design of an ultra-compact broadband optical diode based on asymmetric spatial mode conversion." Scientific Reports **6**: 32577

On-chip devices for visible/IR

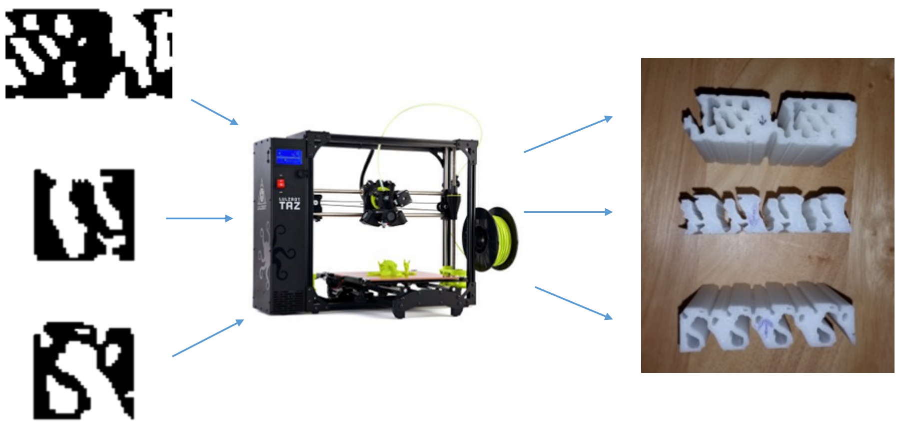
b





Piggott, A. Y., et al. (2015). Nature Photonics **9**(6): 374 [Vuckovic group, Stanford]
Aydin, K. (2015) Nat Photon **9**(6): 353-355.

3D-printed devices for microwave applications



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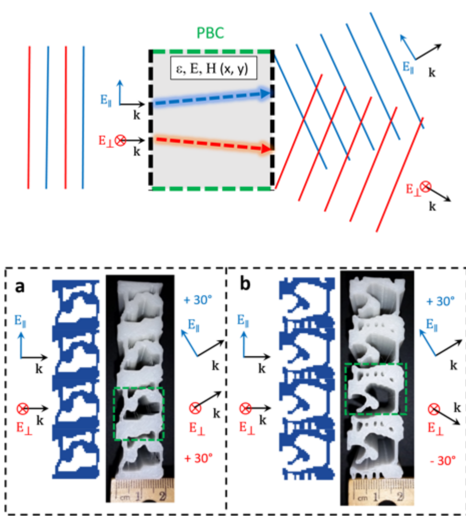
Microwave devices: design process



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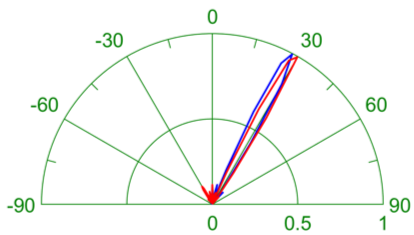
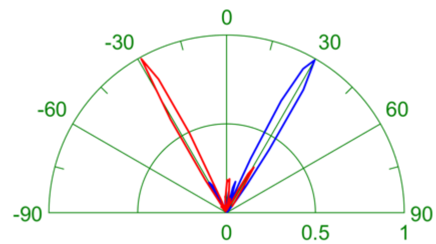
Microwave devices: first results

Polarization independent
bend (30deg)



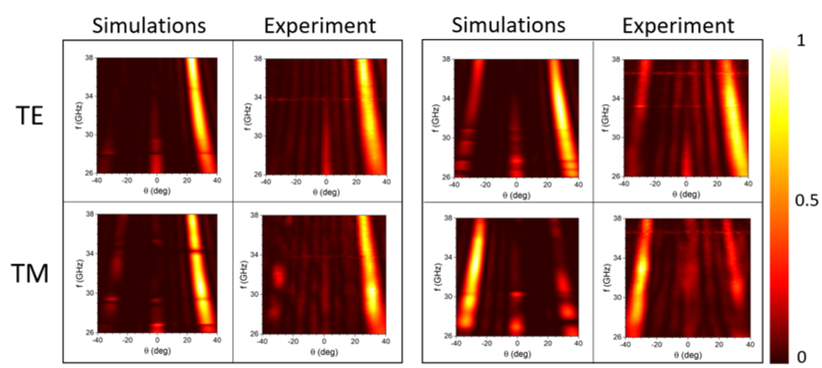
Polarization splitter
(30deg)



Microwave devices: broadband results

Polarization independent
bend (30deg)

Polarization splitter
(30deg)



Future works

- Silicon devices for telecommunications
- Polymer devices for visible light
- 3D algorithm + parallel computing
  (goal: 1-10M pixels)