Beam Steering in Plasma Photonic Crystals via Evolution Strategies

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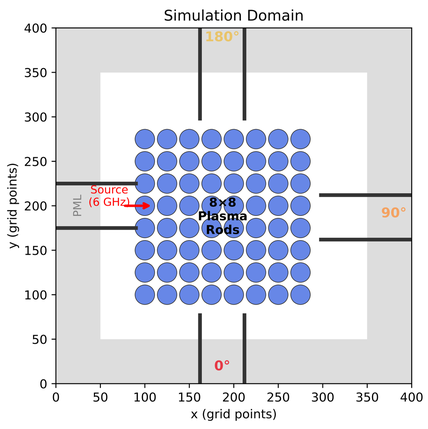
Problem & Physical System

Goal: Steer EM beam to target angles using tunable plasma rods.



Plasma rods: $\varepsilon(\rho) = 1 - (\rho\omega_p^{\max}/\omega)^2$
Design: 64 parameters $\boldsymbol{\rho} \in [0,1]^{64}$
Simulation: FDFD, 400×400 grid, 6 GHz

Methods

ES-Single: One design per angle θ^*

$$R = P_{\theta^*} - 0.5 \sum_{\theta \neq \theta^*} P_\theta$$

ES-Multi: One design for all angles

$$R = \sum_\theta P_\theta - 0.5 \cdot \mathrm{Var}(P_\theta)$$

ES+NN: Neural network $f_\phi : [\sin\theta, \cos\theta] \mapsto \boldsymbol{\rho}_{8\times 8}$

$$R = \sum_{\theta \in \Theta} \left[P_\theta - 0.5 \sum_{\theta' \neq \theta} P_{\theta'} \right]$$

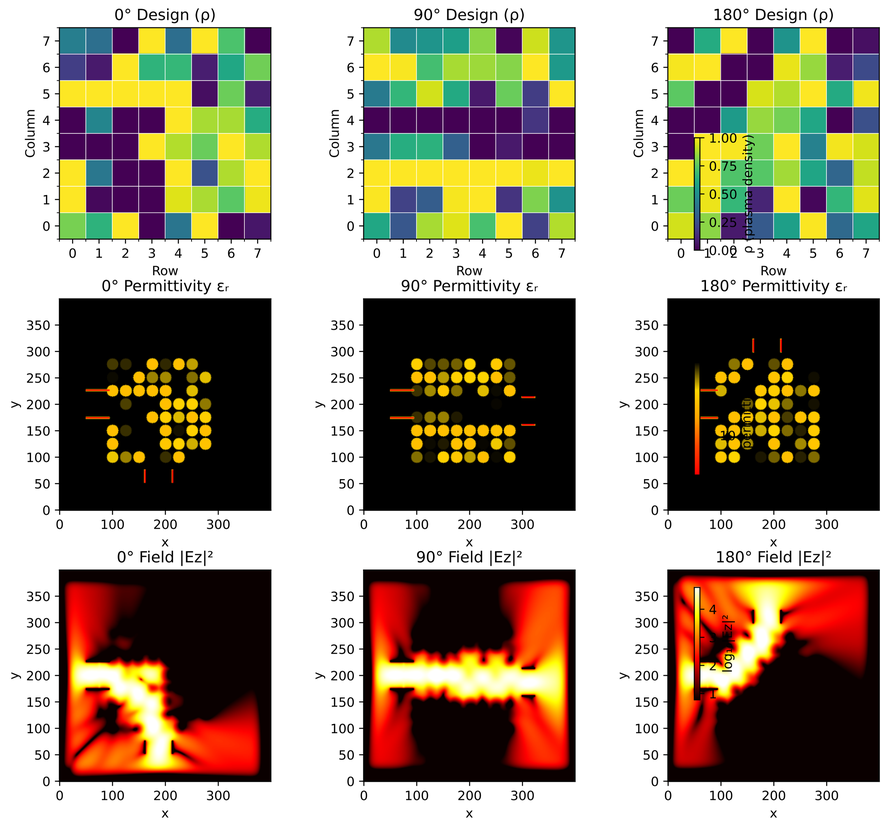
ES Algorithm

1. Sample $N = 100$ perturbations $\boldsymbol{\epsilon}_i \sim \mathcal{N}(0, I)$
2. Evaluate $R_i = R(\boldsymbol{\theta} + \sigma\boldsymbol{\epsilon}_i)$
3. Gradient: $\hat{\mathbf{g}} = \frac{1}{N\sigma} \sum w_i \boldsymbol{\epsilon}_i$
4. Update with Adam ($\eta = 0.02$, $\sigma_0 = 0.3$)

ES+NN Algorithm

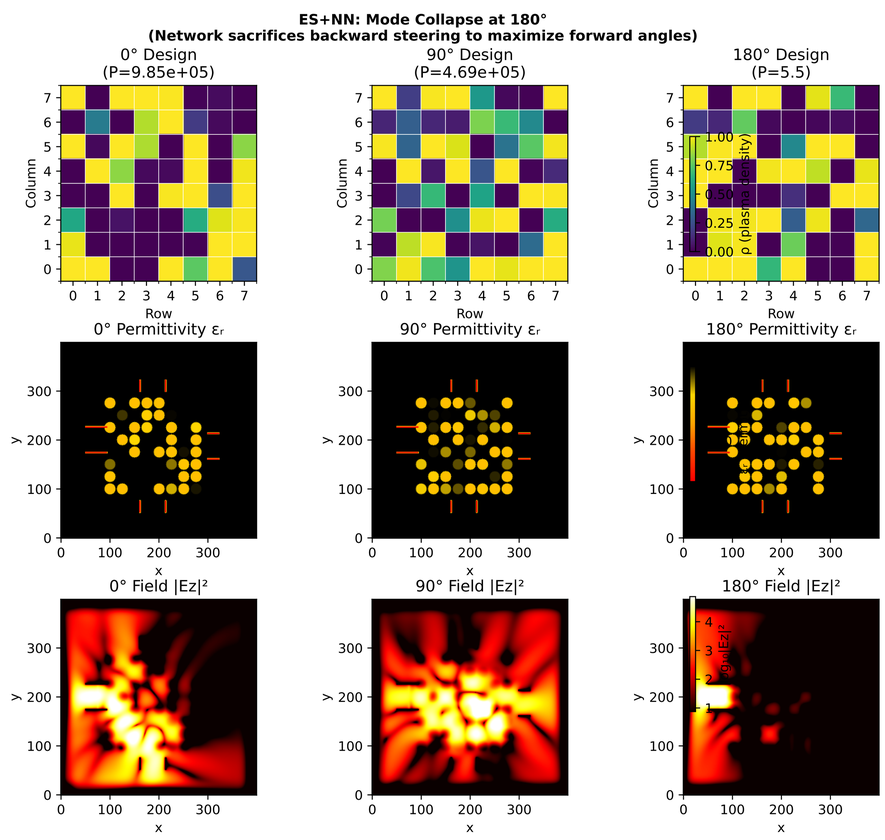
1. Sample perturbations $\boldsymbol{\epsilon}_i$ for NN weights ϕ
2. For each $\theta \in \{0°, 90°, 180°\}$:
   Generate design $\boldsymbol{\rho} = f_{\phi+\sigma\boldsymbol{\epsilon}_i}(\theta)$
   Simulate and compute P_θ
3. Compute total reward R_i across all angles
4. Update NN weights (20,928 params) with Adam

Results: ES-Single



Key Result: <0.005% crosstalk — near-perfect steering without gradients

Results: ES+NN Mode Collapse



$P_0 = 9.8 \times 10^5, \quad P_{90} = 4.7 \times 10^5, \quad P_{180} = 5.5$ (collapsed!)

Conclusions

ES-Single Results:
$0°$: $P = 1.453 \times 10^6$, crosstalk 0.003%
$90°$: $P = 1.452 \times 10^6$, crosstalk 0.005%
$180°$: $P = 1.448 \times 10^6$, crosstalk 0.003%

- **ES-Multi** confirms no universal design exists
- **ES+NN** mode collapse reveals $0°/90°$ compatible, $180°$ incompatible
- Gradient-free approach is **viable** for inverse EM design

Future Work

- Continuous angle interpolation with NN
- Multi-frequency optimization
- Hardware validation of designs
- Alternative NN architectures (CNN, attention)

References

[1] Rodriguez et al., Phys. Rev. Applied, 2021
[2] Salimans et al., arXiv, 2017
[3] Hughes et al., ACS Photonics, 2019

Code: github.com/szertan/cs229-beam-steering