

TAILORING ROBUST PHOTONIC COMPONENTS USING STOCHASTIC TOPOLOGY OPTIMIZATION

Philip Elbek, Rasmus Ellebæk Christiansen, Niels Aage, Ole Sigmund

Technical University of Denmark

Keywords: Stochastic Topology Optimization, Photonics, Density-based Topology Optimization, Randomness, Manufacturing Errors

Abstract

Photonic devices are highly sensitive to geometric perturbations, and achieving satisfactory performance typically requires either extensive trial-and-error procedures or low-tolerance manufacturing control. To address this longstanding challenge, we introduce a density-based stochastic topology optimization framework capable of producing photonic devices with highly improved robustness to non-uniform geometric variations compared with conventional deterministic methods [1].

Our approach employs a Monte Carlo strategy to sample a collection of random fields that non-uniformly perturb the device boundaries through the second Heaviside filter in a double-filter scheme [2]. The resulting set of objective values is combined using a p-mean formulation, encouraging the optimizer to simultaneously account for a wide range of perturbation scenarios. This effectively drives the optimization toward designs that maintain strong performance under practical fabrication imperfections. The scalar Helmholtz equation, governing out-of-plane, time-harmonic polarized light, is discretized with Q4 finite elements, and eigenmodes as well as effective indices are extracted to precisely control modal inputs, outputs, and attenuation in the PML regions.

To demonstrate the method, we consider a TM0–TM1 mode converter in which the fundamental guided mode at the input is transformed into the second guided mode at the output. The results show that the stochastic approach yields geometries that are not only simpler and exhibit lower field intensities, but also dramatically more robust to both geometric perturbations and input-frequency variations. We further observe that selecting correlation lengths in the random fields close to the diffraction limit imposes constructive design pressure, ultimately leading to superior device performance and smoother geometries.

Beyond robustness improvements, we also explore more computationally efficient stochastic optimization strategies. In particular, the use of Stochastic Gradient Descent results in a six-fold speedup while requiring eight times fewer function evaluations, with only a miniscule loss in mode conversion efficiency. These efficiency gains make it more feasible to tackle complex photonic design problems,

including full-vector 3D Maxwell simulations for next-generation, fully three-dimensional photonic components.

References

- [1] P. Elbek, R. E. Christiansen, N. Aage, O. Sigmund, "Tailoring robust photonic components using stochastic topology optimization," *Optica Open*. Preprint. (2025) <https://doi.org/10.1364/opticaopen.30675803.v2>
- [2] R. E. Christiansen, B. S. Lazarov, J. S. Jensen, O. Sigmund, "Creating geometrically robust designs for highly sensitive problems using topology optimization: Acoustic cavity design," *Struct. and Multidiscip. Optim.* 52, 737-754 (2015)