













insertion loss  $-0.13\text{dB}$ , after 1500 simulations using particle swarm optimization. (Note that for such small attenuation, the simulation results are very sensitive to the simulation parameters, which may not have been perfectly identical to ref [3].).

Thus adjoint steepest descent, with much lower computational cost, can yield as good or better results than particle swarm optimizations, which take no advantage of the underlying Maxwell equation physics.

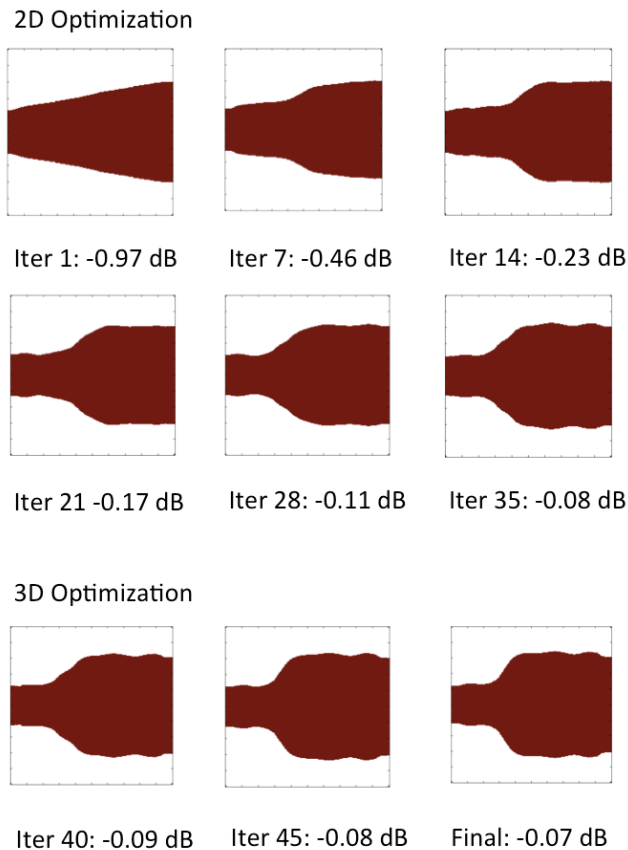


Fig. 4. Geometry evolution during the optimization process and total coupling efficiency to the output waveguides. Iter indicates the iteration number, and the insertion loss is given in dB. The optimization is first carried out using a 2d approximation with an effective waveguide index = 2.8, which mimics the 3d in-plane propagation constant. The final iterative steps are carried out in full 3d FDTD.

The figure of merit evolution, as well as intermediate optimization steps, is presented in Figs. 3. and 4 respectively. There is a visible change between the 2d solution and the 3d solution, with a non-negligible efficiency improvement. This 3d improvement was only possible with the adjoint method, as the 3d computational cost limits the multiple simulations in particle swarm methods. The electric field intensity distribution of the final iteration is shown in Fig. 5. The large operating bandwidth of the optimized structure is shown in Fig. 6. and is good indication of the robustness of the design generated by the optimization.

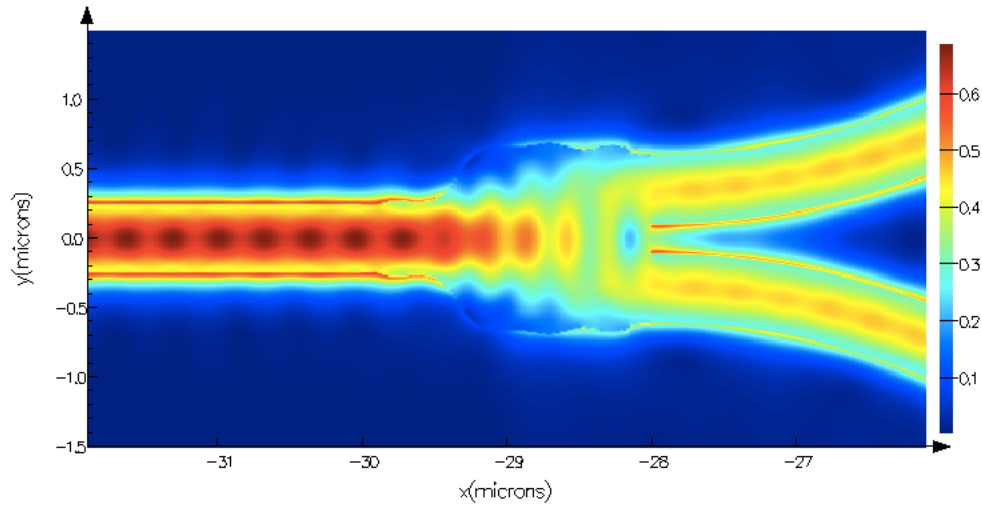


Fig. 5. Simulated field intensity  $|E|^2$  for the optimized structure at  $\lambda = 1550\text{nm}$  for a slice in the middle of the device.

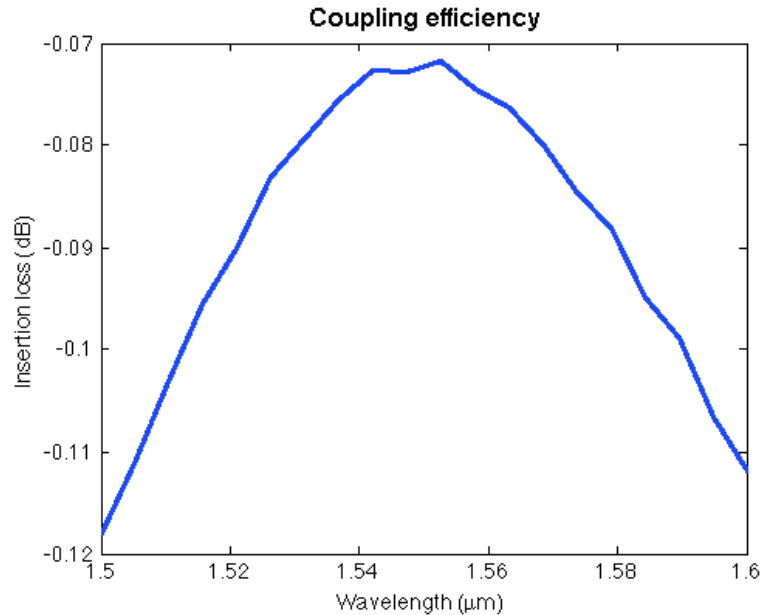


Fig. 6. Simulated insertion loss of the optimized device for wavelengths between 1.5 and 1.6  $\mu\text{m}$ . The broad operating spectrum of the device is a good indicator of the robustness of the design.

#### 4. Conclusion

As photonic and wireless components become an increasingly important part of electronics, it is evident that many problems will require electromagnetic optimization. The computational cost of solving Maxwell's equations is significant, and inefficient design optimization algorithms will become unacceptable. We have shown that the adjoint gradient decent method for shape optimization of sub-wavelength photonic devices can be readily implemented by embedding commercial Maxwell solvers within an inverse optimization algorithm.



For exploration of larger solution spaces where local optima may exist, this method may be augmented with a clever choice of Figure-of-Merit, as well as global optimization routines such as simulated annealing to provide efficient and powerful automated design of photonic components.

Adjoint-gradient-steepest-descent has already beaten the previous record for a manufacturable splitter within current Silicon photonics technology, at much less computational cost than previous methods. This opens the pathway to a more systematic, efficient, photonic component design optimization. The code used for this optimization is available at [21].

### **Acknowledgments**

This work is supported by the Defense Advanced Research Projects Agency (DARPA) E-PHI program under Grant No. HR0011-11-2-0021, the NSF E3S Center under NSF award 0939514, and the U.S. Department of Energy “Light–Material Interactions in Energy Conversion” Energy Frontier Research Center under Grant DE-SC0001293