Optimization in optical systems revisited
Beyond genetic algorithms
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Optimization in physics
Optimization problems are ubiquitous in physics. Notable instances include:
- Design of integrated optical devices
- Design of injectors and magnets in accelerator design
- Topological solvers in nonlinear classical field theories
- Using models in condensed matter physics
Most real-life optimization problems cannot be solved analytically and are NP-hard. The most common approach is to use metaheuristics, algorithms based on empirical rules for exploring large solution spaces.

Two key concepts for metaheuristics
1. **Diversification**: Global exploration of the solution space in order to identify regions containing “good” solutions.
2. **Intensification**: More thorough investigation of promising solution regions [1].

Genetic algorithm
Developed by J. Holland in the 1970s. Commonly used in photonics research, for instance in waveguide design [2].
- **Stochastic**: population-based, nature-inspired algorithm
- **Memoryless method**: The escape from local minima relies on random mutations
- **Best suited for diversification**: This stems from the population-based nature of the algorithm
- **3 adjustable parameters to specify**: Population size, mutation rate, and crossover rate

Application to single-objective optimization
When the fitness function (scattered topological solitons in integrated optical devices) is used for a research fellowship. Computations were made on the supercomputer Colosse from Université Laval, managed by Calcul Québec and Compute Canada.

Parallel tabu search
First proposed by F. Glover in the 1980s. More commonly used in scheduling and networking problems.
- **Deterministic**, local, non-nature-inspired algorithm [1]
- **Uses a short-term memory** to escape from local minima
- **Best suited for intensification of search**: Parallel implementation allows to combine exploration and intensification.
- **Initialization of solutions is the only random process**
- **Only 1 adjustable parameter**: Number of entries in the Tabu list

Outlook
- **Engineering of non-diffracting beams**
- **Non-diffracting beams can be used in many applications, like atom guiding and microscopy**. Various generation methods have been proposed.
- **Phase plates optimized via GA** [P. A. Samchen-Serrano et al., Opt. Lett. 37, 3046 (2012)]
- **Huygens’ surfaces, composed of 2D arrays of polarizable particles (C. Pfeiffer and A. Gebir, PRL 110, 197401 (2013))

Optimization of random laser action
Recent studies have shown that optimizing the pump shape allows for a better overall convergence, and emission directivity. This optimization process implies the computation of a special kind of eigenstate, the constant-flux state [3].

Summary
1. Since parallel tabu search combines search diversification and intensification, it outperforms the SGA in the case of the model problem of beam shaping
2. The performance gain associated with PTS allows for a multi-objective optimization in photonics design
3. Optimization of random lasers and engineering non-diffracting beams are potential applications of our algorithms in optics and photonics

References
(1) F. G. Tabu, Multiobjective: From design implementations (Wiley, 2000)

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Fig. 1: Blackbox scenario for fitness function evaluation [1].
Fig. 2: Basic scatterer grid for the optimization problem. There are 2^28 possible solutions.
Fig. 3: Generating a = 1 Hermite-Gauss beam using a generally optimized photonic crystal lattice. Diameter of index 0.004 nm, core index 0.5 ± 0.05%. The incident field is a Yp-polarized quasiround beam with halfwidths w0 = 0.05X and incident wavenumber k0 = 1.67(3).
Fig. 4: Evolution diagram of the standard genetic algorithm (SGA) applied to the incoherent beam shaping problem. The algorithm exhibits rapid convergence to an “acceptable” solution, but tends to remain stuck to local minima (see definition of g, in bottom panel).
Fig. 5: Performance assessment of SGA. Each simulation requires 5000 generations, with an average of 64 objective function evaluations per generation.
Fig. 6: Evolution diagram of one parallel tabu search (PTS) process applied to the incoherent beam shaping problem. Although initial convergence is slow, the short-term memory of the algorithm allows for “hill-climbing” thus avoiding getting stuck in local optima.
Fig. 7: Performance assessment of PTS. The algorithm exhibits better overall convergence, and finds some solutions inaccessible to the SGA. Each simulation requires 5000 iterations, with at least 56 objective function evaluations per iteration.
Fig. 8: Multiobjective optimization results obtained via PTS. (Left) Sampling of the Pareto front (set of optimal solutions satisfying both objectives) for the coherent beam shaping problem. The dotted lines indicate the best possible value for each of the two objectives. This sampling is achieved using an appropriate cost function. (Center) Optimized Hermite-Gaussian beam profile at device output, with the best possible reproduction of the amplitude profile. (Right) Best possible trade-off between the two objectives. Since the phase is controlled, the Hermite-Gaussian profile shape is preserved over a greater propagation distance. In other words, controlling both the amplitude and the phase allows for a greater field depth. This can be seen in the smaller number of ridges in the profile (4).
Fig. 9: Constant-flux state of an asymmetric photonic molecule composed of 4 dielectric atoms. Emission profile compared to a gaussian (Left) and a Hermite-Mie theory (Right). Constant-flux states are more physically meaningful than conventional quasi-bound states.

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