Inverse Design of Optimal Photonic Structures with Nonlinear Properties

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Abstract

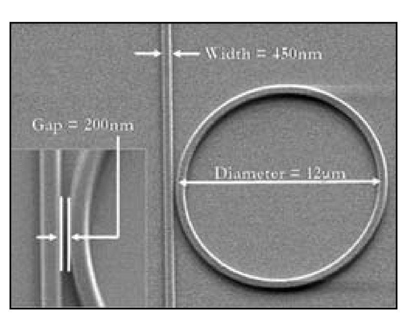
The cross-sectional structure of multiple index optical guides such as optical fibers and waveguides determines the electromagnetic field modes which will propagate most effectively in the guide. In selecting a structure for a guide with nonlinear optical features this difficulty is compounded by a need for the structure to facilitate both $X^{(1)}$ and $X^{(n)}$ modes. Using the method of moving asymptotes, a structure may be designed de novo to accommodate desired electrical current parameters.

In this fashion, a pseudorandom structure may be optimized for a specified wavenumber. Such nonlinear optimization may be used with various materials and optical device paradigms, and yields structures with well confined modes. Here this approach is used for 2D optimization of optical fiber cross-sections and 1D optimization of waveguides.

Background

Traditional Photonic Structures
- Periodic
- Highly symmetric
- Designed for single modes

Examples
- Traditional fiber optics
- Waveguides
- Toroidal resonators (pictured right)



Brute Force Nonlinear Optimization

Objectives
- Optimize structure for multiple resonant modes
- Low leakage (high radiative quality factor Q) or guided modes
- Large overlap between the two modes

Gradient (topology) nonlinear optimization
- Begin with vacuum or pseudorandom structure
- Algorithm takes current structure (n) and generates potential modification (n+1) to structure
- If n+1 structure increases the value of the objective function, apply modification and iterate again
- If n+1 structure does not increase the value of the objective function, changes not applied, new n+1 structure generated

Objective Function

* Optimize for integral of J•E (rate at which field does work)

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{E}(\mathbf{r}) - \omega^2 \epsilon(\mathbf{r}) \mathbf{E}(\mathbf{r}) = i\omega \mathbf{J}(\mathbf{r})$$

$$\mathbf{J}(\mathbf{r}, \mathbf{r}') = \hat{\mathbf{e}}_j \delta(\mathbf{r} - \mathbf{r}')$$

$$\text{Objective: } \mathrm{Re}\left[\int \mathbf{J}^* \cdot \mathbf{E}\, d\mathbf{r}\right]$$

- Instead of computationally expensive eigenvalue problems, scattering problems are much easier: given current $\mathbf{J}(\mathbf{r})$ ➔ finds $\mathbf{E}(\mathbf{r})$

Liang, X. D. and Johnson, S. G. Opt. Express 21(25) 30812 (2013)

Nonlinear Optical Phenomena

Linear Optics
- Induced polarization of material is linearly proportional to strength of the incident optical field
- P = XE

Nonlinear Optics
- Induced polarization is proportional to some nonlinear combination

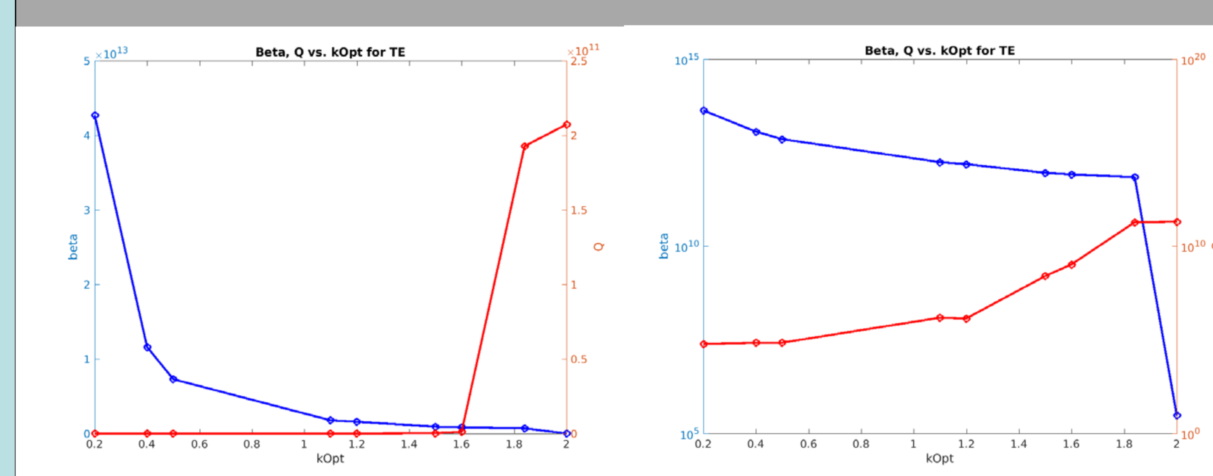
  $P = X_1E + X_2E + \dots + X_nE$
- Nonlinear components represent harmonic generation within material

Harmonic Generation
- Special case of sum-frequency generation
- n photons of frequency ω are absorbed by material and then emitted as a single photon of frequency $n\omega$

Mode Confinement in Nonlinear Materials
- Structure must confine both X_1 and X_n mode
- So-called "intuitive" structures typically only confine one mode
- De novo optimization enables design of structures capable of confining multiple modes

Results

Figures of Merit for Structures by Optimization Wavenumber

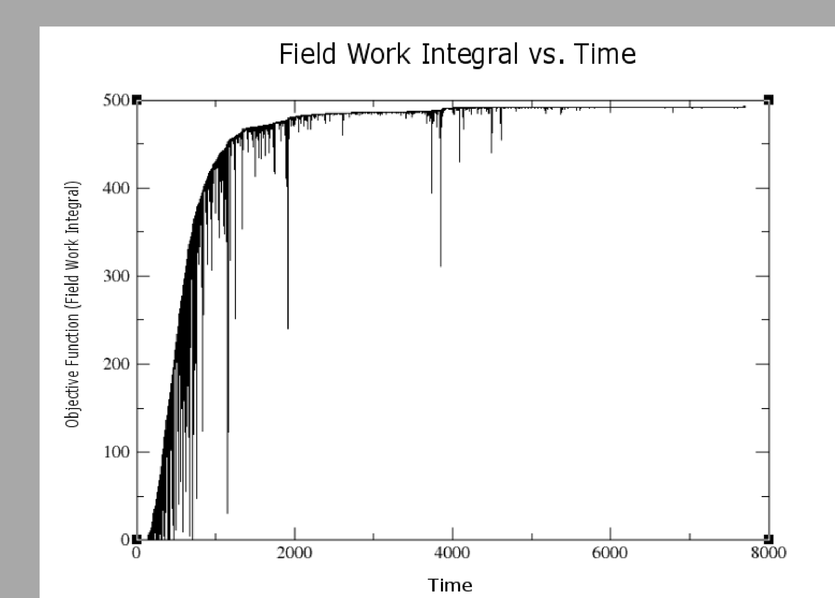


Beta is the attenuation factor, a unitless value representing the reduction in field strength as the mode propagates through the fiber. Q, the radiative quality factor, is relatively low for unguided modes, then increases substantially once the light line (a function of the refractive indices in the material) has been crossed. Q for guided modes is infinite in reality, and the large values above are computational approximations. All values above are for the fundamental mode.

kOpt is the wavenumber for which a structure has been optimized. $K = \omega/2\pi\nu$, where ω is the frequency and ν is the speed of the wave within the medium.

The left graph is linearly scaled, and the right graph is logarithmic along the y-axis.

Measuring Algorithm Progress



Values of objective function as algorithm proceeds. Initial rapid optimization declines to plateau, signaling optimization has reached local minimum.

Optimized Structures and Guided Modes

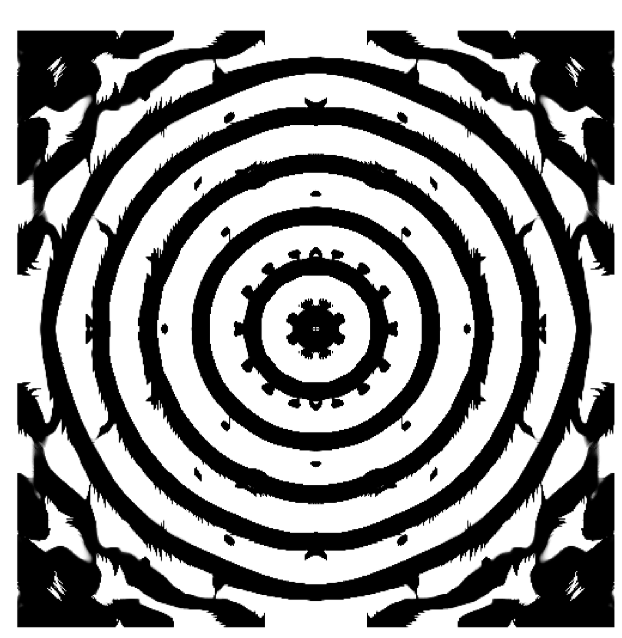


Figure 1

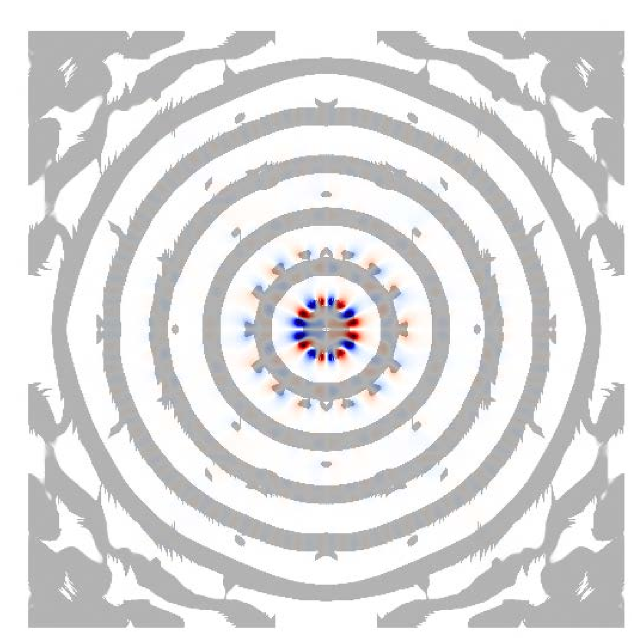


Figure 2

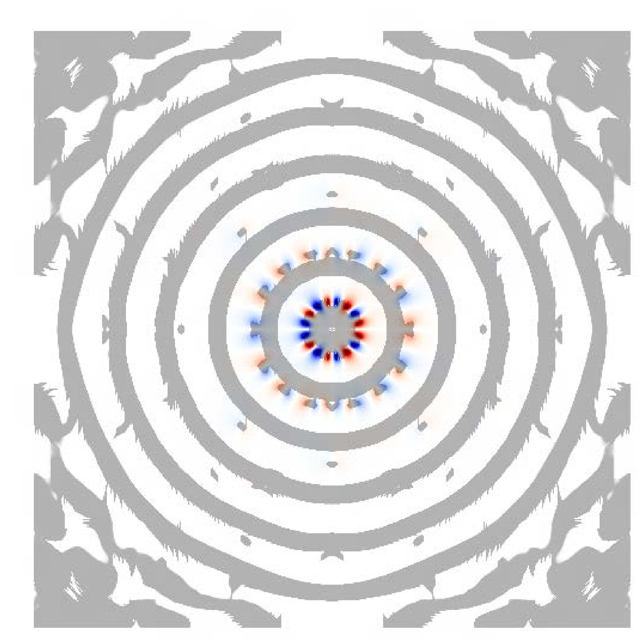


Figure 3

Figure 1 is the output of the optimization algorithm for a wavenumber k=1.5. This output is the cross-sectional structure of an optical fiber optimized for guided modes in the fundamental mode (k=1.5) and the corresponding third harmonic mode (k=4.5).

Figure 2 is the electromagnetic field of the fundamental mode within the structure in Figure 1.

Figure 3 is the electromagnetic field of the third harmonic mode within the structure in Figure 1.

Both modes are highly contained within the fiber and exhibit excellent overlap, indicative of the algorithm's success in optimizing a structure for both frequencies.

Current and Future Directions

Further Data
- Additional datapoints for various field source patterns
- Application of method to design of optimized optical devices of other types (i.e. waveguides)

Publication
- Once the remaining data is compiled, a paper on the use of this optimization method in photonics will be submitted for publication.

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