1. Experimental setup

High Q-factor scheme-doped silica annular cavities are ideal candidates for integrated directional lasers. Non-uniform emission can be achieved without significantly spoiling the Q-factor of the unperturbed cavity (no inclusion).

2. Boundary element method for annular cavities

The wave dynamics of the annular cavity is described by the 2D Helmholtz equation

\[ \nabla^2 + n^2(r^2) \psi(r) = 0. \]

Using Green’s second identity, one obtains the following boundary integral equation

\[ \psi(r') = \frac{1}{4\pi} \int_{\partial \Omega} \nabla \cdot \left[ G(r,r',k) \right] \psi(r') dS, \]

where \( G(r,r',k) \) is the homogeneous medium Green's function. We have implemented a generalization of the boundary element method [2]. This generalization allows to find resonant modes of annular cavities (more generally, to solve the problem in multiply connected domains). The numerical procedure can be summarized as follows:

1. A boundary integral equation is obtained for the three-di- electric domains (inclusion, disk, surroundings) shown on Fig. 2.
2. The boundary is discretized in order to transform integral equations in a non-linear eigenvalue problem.
3. The complex resonant modes are found using analytic (unperturbed) solutions as starting-points for the eigenvalue search [2].

4. Ray-wave correspondence and universality of far-field emission

Comparison of far-field intensities computed via the boundary element method and ray-escape simulations (blue). Odd (red) and even (green) symmetry modes of the inhomogeneous annular cavity are quasi-degenerate, and the far-field intensity is therefore computed as \( I = |\psi|^2 + |\psi|^2 \) (black). (a) Resonant mode with unperturbed \( Q < 10^7 \). (b) Resonant mode with unperturbed \( Q > 10^7 \). (c) A case close to experimental reality (infrared wavelength, \( R = 50 \mu m \)) which is at present beyond the limit of our wave simulations.

The ray-wave and ray escape results agree quite well with respect to the dominant emission directions, even for relatively low wavenumbers. The global shape for a given configuration displays universal behaviour regardless of the wavenumber regime as long as \( m > 5 \).

3. Ray-escape simulations

The annular cavity consists of a circular disk of radius \( R \) and refractive index \( n_2 \), surrounded by a medium of index \( n_1 \) with a circular inclusion of radius \( R_0 \) and index \( n_0 \), displaced a distance \( d \) from the cavity center.

4. How to improve collimation?

Ray-wave and ray escape results suggest that the triple-peaked far-field profile observed for silica cavities is similar for an inner inclusion, regardless of the geometry.

A simple model based on paraxial ray-optics can help improve collimation. Circular cavities (the backside of annular cavities) are approximated as paraxial lenses and focal points are found. A point source placed at a focal point will result in highly collimated emission. For a silica cavity, this point is located outside the boundary.

Promising designs

While this model is mostly accurate in the regime \( R_0 < \lambda ^* (\text{point inclusion}) \), it suggests many interesting configurations for which further work is needed.

- \( \text{Fig. 3a} \): Replacing an inclusion by an exclusion (coupled silica cavities, photonic molecules)
- \( \text{Fig. 3b} \): Cavities with a defect on the boundary, e.g. [4]
- \( \text{Fig. 3c} \): Silicon-On-Insulator (SOI) annular cavities

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6. Conclusions and outlooks

The ray-wave correspondence allowed us to infer universal far-field properties of silica annular cavities. This permits computation beyond the limit of wave simulations.

A simple geometric model was developed in order to help improve emission directionality via new designs (modified geometries as well as different refractive indices).

The next experimental step is to obtain reliable far-field measurements, while a numerical investigation of promising geometries/medium combinations is being made.

References