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Benchmarking state-of-the-art optical simulation methods for analyzing large nanophotonic structures

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Five computational methods are benchmarked by computing quality factors and resonance wavelengths in photonic crystal membrane L⁵ and L⁹ line defect cavities. Careful convergence studies reveal that some methods are more suitable than others for analyzing these cavities.

Geometry under study

The photonic crystal (PhC) membrane represents a platform for planar integration of components, where cavities and waveguides may play a key role in realizing compact optical components. A finite-length defect waveguide forms an Lⁿ cavity, where n denotes the length of the cavity. Such Lⁿ cavities support spectrally discrete optical modes, and the fundamental cavity mode profile of an L⁹ cavity is shown in Fig. 1. Light may be confined to such an Lⁿ cavity for extended periods, as quantified by the quality (Q) factor. The Q factor thus represents a key parameter in the design of a PhC membrane cavity.

Table 1: Calculated Q factors and resonance wavelengths λ.

<table>
<thead>
<tr>
<th></th>
<th>FDTD</th>
<th>FDFD</th>
<th>FEM</th>
<th>SIE</th>
<th>FMM</th>
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</thead>
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<tr>
<td>λ⁵</td>
<td>1568</td>
<td>1572</td>
<td>1571</td>
<td>1572</td>
<td>1567</td>
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<tr>
<td>λ⁹</td>
<td>1574</td>
<td>1580</td>
<td>1578</td>
<td>1579</td>
<td>1570</td>
</tr>
<tr>
<td>Q⁵</td>
<td>1670</td>
<td>1725</td>
<td>1705</td>
<td>1707</td>
<td>1700</td>
</tr>
<tr>
<td>Q¹⁹</td>
<td>104,000</td>
<td>108,000</td>
<td>105,000</td>
<td>104,000</td>
<td>60,000</td>
</tr>
</tbody>
</table>

Methods and results

The combination of the large size of the PhC Lⁿ cavity and the full 3D nature of the geometry makes the calculation of the cavity Q factor an extremely demanding numerical challenge. In this work, we focus on two structures, a low-Q L⁵ cavity and a high-Q L⁹ cavity. We employ five different computational methods, the finite-difference time-domain (FDTD) technique, the finite-difference frequency-domain (FDFD) technique, the finite-element method (FEM), the surface integral equation (SIE) approach and the Fourier modal method (FMM), to compute the cavity Q factor and the resonance wavelength for both structures. For each method, the relevant computational parameters are systematically varied to quantify the computational errors. The final results summarized in Table 1 show that the resonance wavelengths agree fairly well for the two geometries among the five methods. On the other hand, significant deviations are observed for the Q factor. Our study highlights the importance of careful convergence checks and systematic estimation of the computational error, both of which are generally missing in the literature.