Comparison of five computational methods for computing Q factors in photonic crystal membrane cavities

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ABSTRACT

Five state-of-the-art computational methods are benchmarked by computing quality factors and resonance wavelengths in photonic crystal membrane L5 and L9 line defect cavities. The convergence of the methods with respect to resolution, degrees of freedom and number of modes is investigated. Special attention is paid to the influence of the size of the computational domain. Convergence is not obtained for some of the methods, indicating that some are more suitable than others for analysing line defect cavities.

Keywords: Photonic crystal, microcavity, line defect cavity, quality factor, numerical simulations.

1. INTRODUCTION

An important platform for planar optical integration is the photonic crystal (PhC) membrane platform, where cavities and waveguides may play a key role in realizing compact optical components with classical functionality [1] such as switches, lasers [2], and amplifiers or quantum optical functionality [3] such as integrated sources of quantum light. By leaving out a row of holes in an otherwise perfect PhC membrane lattice, a line defect is created as illustrated in Fig. 1 in which light may be guided. If the waveguide is terminated at both ends, the finite-length waveguide forms an L*n* cavity, where *n* denotes the length of the cavity. Such L*n* cavities support spectrally discrete optical modes, and the fundamental cavity mode profile of an L9 cavity is shown in Fig. 2.

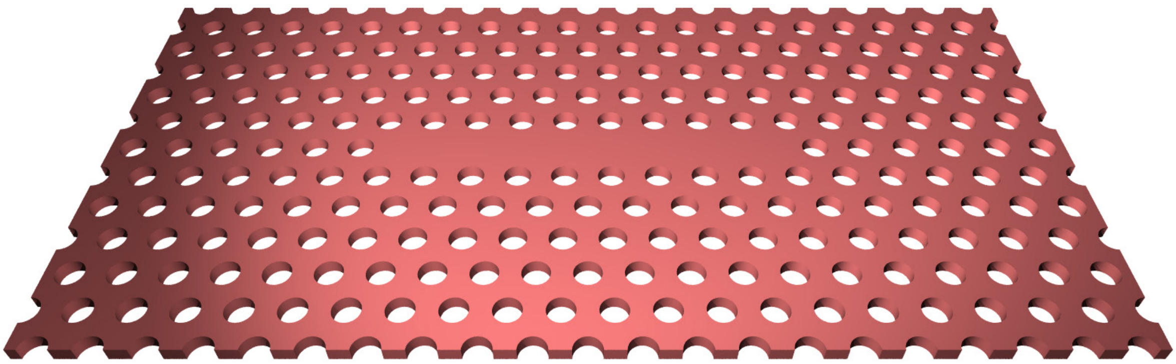

Figure 1: Sketch of the geometry of the PhC membrane L9 cavity.

Light may be confined to such an L*n* cavity for extended periods, as quantified by the quality (Q) factor. For laser applications, the Q factor governs the onset of lasing, and for cavity quantum electrodynamics applications, it governs the onset of strong coupling. The Q factor thus represents a key parameter in the design of a PhC membrane cavity.

The combination of the large size of the PhC L*n* cavity and the full 3D nature of the geometry makes the calculation of the cavity Q factor an extremely demanding numerical challenge. No matter which numerical method is used, careful convergence checks with respect to the degrees of freedom must be made. Additionally, most numerical simulations methods rely on a closed simulation domain, and here the influence of the boundary conditions requires carefully study. A study of PhC nanobeam cavities using four numerical techniques has previously been reported [4], where cavity frequencies and Q factors were investigated as function of structural parameters. While qualitative agreement between the methods was found, quantitative discrepancies were in some cases as large as an order of magnitude, and estimates for the computational error and the influence of the size of the computational domain were not given.

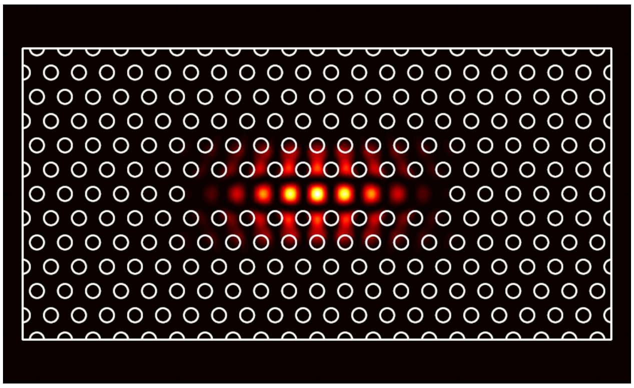

Figure 2: Optical field $|E_y|^2$ profile for the fundamental L9 cavity mode.

2. COMPUTATIONAL METHODS

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 [5], 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. In particular, we investigate the influence of the size of the computational domain.

3. RESULTS

The final results summarized in Table 1 show that both the resonance wavelength and the Q factor agree fairly well for the L5 cavity among the five methods. On the other hand, significant deviations are observed for the Q factor in the L9 cavity. The origins of these discrepancies will be discussed at the conference.

Table 1: Calculated Q factors and resonance wavelengths λ.

	FDTD	FDFD	FEM	SIE	FMM
λ^{L5} (nm)	1568	1571	1571	1572	1568
λ^{L9} (nm)	1575	1580	1578	1579	1569
Q^{L5}	1671	1715	1716	1706	1733
Q^{L9}	103,000	101,000	106,000	104,000	69,000

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.

ACKNOWLEDGMENTS

Support from the Villum Foundation via the VKR Centre of Excellence NATEC II is gratefully acknowledged.

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