An L3-type silicon photonic crystal cavity with a quality factor exceeding 20 million

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Abstract: We present an L3-type photonic crystal cavity in silicon with a theoretical quality factor of 20.9 million. This highly-optimized design is made by shifting the positions of the holes surrounding the cavity, and was obtained through an automated global optimization procedure.

In Ref. (Minkov and Savona, 2014) we presented a global optimization of the quality factors (Q) of several of the most widely-used photonic crystal (PhC) cavities. This resulted in a tremendous improvement – typically of one or more orders of magnitude – in this important figure of merit. In particular, the L3-type cavity, consisting of three missing holes in the PhC, was optimized to a theoretical Q of 4.1 million, and a Q of 2 million for this design was measured in a subsequent experiment (Lai et al., 2014). Here, we present an additional improvement of the theoretical Q of this cavity, accomplished by including three extra parameters in the optimization. We use the same overall PhC parameters as in Ref. (Minkov and Savona, 2014): slab refractive index $n = 3.46$ (as for silicon); hole radius $R = 0.25a$; slab thickness $d = 0.55a$, with a the PhC lattice constant.

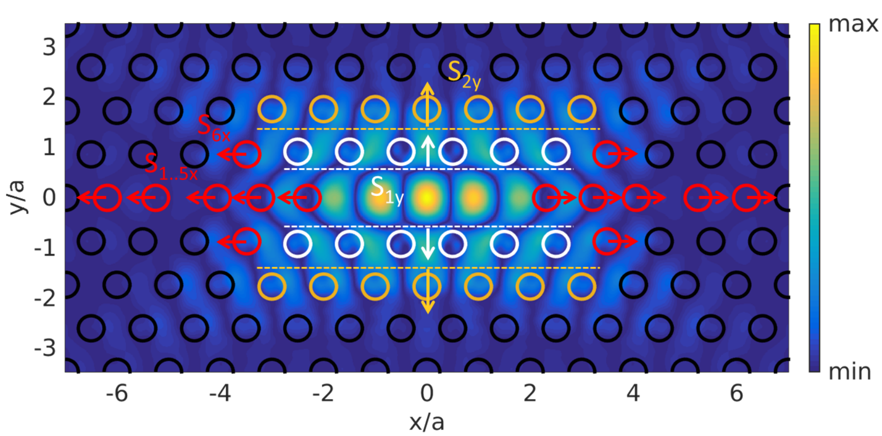

Figure 1: Design of the 8-shift L3 cavity. The shifts S_{1x} to S_{5x} are defined in the same way as in Ref. (Minkov and Savona, 2014). Additionally, a 6-th shift in the x-direction is introduced as marked, as well as two shifts in the y-direction. The latter consist of moving **all** holes marked in white by a distance S_{1y} in the y-direction, and all holes marked in brown – by a distance S_{2y}. The color map shows the absolute value of the y-component of the electric field of the fundamental cavity mode.

The L3 design presented in Ref. (Minkov and Savona, 2014) was optimized through the positions of the five holes on each side of the cavity, i.e. the parameters $S_{1..5x}$ marked in Fig. 1. Intuitively, it is straightforward to expect that the holes closest to the cavity have the highest influence on the electromagnetic mode, and, correspondingly, on the cavity quality factor. We thus introduced shifts in the holes above and below the cavity, trying various parameter configurations and running the automated optimization for each one. This optimization, discussed in detail in Ref. (Minkov and Savona, 2014), uses the guided-mode expansion (GME) (Andreani and Gerace, 2006) to quickly and effectively compute the Q of a given PhC structure. The best result was obtained with the 8-parameter design illustrated in Fig. 1. The optimal design was found for $S_{1-6x} = [0.312, 0.209, 0.040, 0.227, 0.177, -0.014]a$, $S_{1y} = 0.058a$, $S_{2y} = 0.037a$. This structure was then simulated using a finite-difference time-domain (FDTD) commercially available software (Lumerical Solutions, Inc.), and the theoretical Q was found to be 14.2×10^6. In the consequent analysis of this L3 cavity, it was found that the Q can be further increased by a slight change of the overall hole radius. This brought the maximum FDTD-computed Q of the design, obtained for $R = 0.255a$ instead of $0.25a$, to 20.9×10^6 (GME-computed Q: 20.0×10^6). The resonance frequency of this cavity mode is $\omega/(2\pi) = 0.254a/c$, which, for the standard slab thickness 220nm (which sets $a = 400$nm), gives a wavelength of 1574nm.

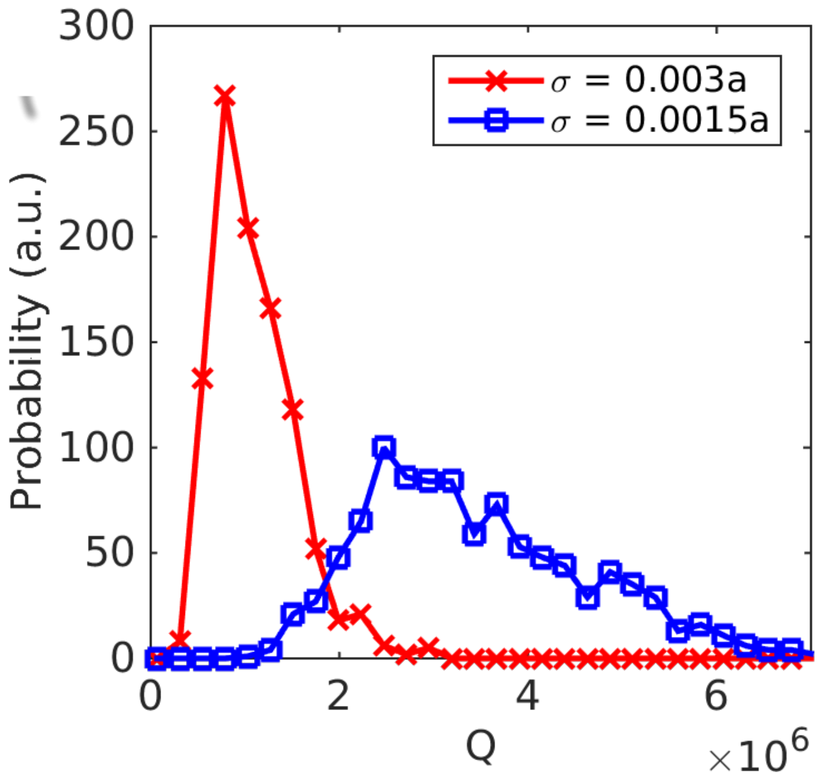

Figure 2: Histograms of the probability distribution of the quality factor Q_e in presence of disorder for the optimized 8-shift cavity. 1000 disorder realizations were computed using the GME.

In Fig. 2, we perform a statistical analysis of the expected experimental quality factor in presence of fabrication imperfections, Q_e. This was done as in Ref. (Minkov and Savona, 2014), namely by simulating 1000 disorder realizations using the GME. We used two disorder magnitudes $\sigma = 0.003a$ and $\sigma = 0.0015a$, which, if we assume $a = 400$nm, means 1.2nm and 0.6nm, respectively – realistic values for silicon. For the larger disorder magnitude, the mean value is $\langle Q_e \rangle = 1.1 \times 10^6$, which is only marginally better than the mean value of the 5-shift design of Ref. (Minkov and Savona, 2014), $\langle Q_e \rangle = 0.93 \times 10^6$. This is expected, since the disorder-induced losses clearly dominate the intrinsic loss rate of the cavity (Minkov et al., 2013). For $\sigma = 0.0015a$ the difference between the two designs is more pronounced: $\langle Q_e \rangle = 3.5 \times 10^6$ for the current design, versus $\langle Q_e \rangle = 2.5 \times 10^6$ for the 5-shift design of Ref. (Minkov and Savona, 2014). This illustrates that the design presented here can bring a significant improvement in state-of-the-art fabricated devices. On the other hand, this also shows that a further increase of the theoretical Q of this type of cavity cannot bring a large improvement in the expected Q_e, at least not before a significant improvement in fabrication precision is achieved.

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