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# Design of tapering one-dimensional photonic crystal ultrahigh-$Q$ microcavities

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**Abstract**

One-dimensional (1D) photonic crystal (PC) microcavities can be readily embedded into silicon-on-insulator waveguides for photonic integration. Such structures are investigated by 2D Finite-Difference Time-Domain method to identify designs with high transmission which is essential for device integration. On-resonance transmission is found to decrease with the increasing mirror pairs, however, the quality factor ($Q$) increases to a saturated value. The addition to the Bragg mirrors of tapered periods optimized to produce a cavity mode with a near Gaussian shaped envelope results in a major reduction in vertical loss. Saturated $Q$ up to $2.4 \times 10^6$ is feasible if the internal tapers are properly designed. The effect of increasing transmission is also demonstrated in a structure with the external tapers.


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## 1. Introduction

Photonic crystals (PC) have attracted wide interest in the applications of low threshold lasers [1], high finesse filters [2], single photon devices [3], nonlinear optics [4], and slow light [5] in the last 20 years. A waveguide based one-dimensional (1D) PC is the simplest PC structure [6–12], in which the light confinement is realized by refractive index contrast in the two transverse directions and by photonic bandgap effect in the longitudinal direction. Joannopoulos and co-workers first proposed a novel air-bridge microcavity and predicted a quality factor ($Q$) of $10^4$ in 1995 [6]. Two years later, they fabricated a 1D PC cavity in a silicon-on-insulator (SOI) optical waveguide with a measured $Q$ of 265 [7].

One main loss source in this kind of 1D PC cavity is the etched air gaps, where there is no refractive index contrast in the vertical direction. The out-of-plane scattering loss, either into the air or into the substrate, causes a serious degeneration of $Q$. Krauss and De La Rue suggested that semiconductor-rich lattices with small air gaps could suppress the diffractive spreading loss [8]. Lalanne and co-workers concluded that the mode mismatch is the main cause of the loss and inserted both outside and inside tapers in their PC cavities with 1D gratings [9]. Jugessur et al. also applied the tapers in the structure discussed in Joannopoulos's paper [10]. However, all the measured $Q$s were still several hundreds.

Recently, significant improvements have been reported. Lalanne and co-workers demonstrated a 1D PC cavity with tapered reflectors on SOI wafers and

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obtained a $Q$ of $8.9 \times 10^3$ [11]. Using a Fabry-Perot model, they estimated that an intrinsic $Q$ of $3.8 \times 10^5$ could be obtained in a cavity with two tapered semi-infinite mirrors. Pruessner et al. observed a resonance with a $Q$ of $2.7 \times 10^4$ in a 1D PC with a long cavity on SOI wafer by using a 4-micron-deep Si etch [12]. Although almost two-order improvement has been obtained, the $Q$s in 1D PC cavities are still much smaller than that in 2D PC cavities, such as the measured $Q$ of $9.5 \times 10^5$ reported by Noda and co-workers in their double-hetero-PC cavity in which the lattice constant was changed at the interfaces [13], and the recorded experimental $Q$ of $1.2 \times 10^6$ and theoretical $Q$ of $7 \times 10^7$ realized in a photonic crystal nanocavity by the local width modulation of a line defect [5,14].

In this paper, the effect on $Q$ and transmission of different kinds of microcavity formed by Bragg mirrors comprising aperiodic 1D PCs with tapering period etched into 2D SOI structures is investigated by the two-dimensional Finite-Difference Time-Domain (FDTD) method. Momentum space analysis of the localized mode reveals that the improvement results from the tapers suppressing the amplitude of the wave vector components in the leaky region of the resonant mode, thereby suppressing the vertical radiation loss.

## 2. Method

Fig. 1 shows the basic structure used in the simulation work reported here. It comprises a block of SOI material consisting of a Si substrate, $SiO_2$ buffer layer of 1.5 μm, the top Si guide layer of 360 nm and the air cladding layer. The refractive indices of silicon and silicon dioxide are 3.48 and 1.46, respectively. It is assumed that a central cavity layer is then formed by etching Bragg mirrors, each comprising $N$ pairs of Si and air gap layers. In the 2D FDTD simulations, the corrugated waveguide is assumed to be illuminated from the input waveguide by the transverse magnetic

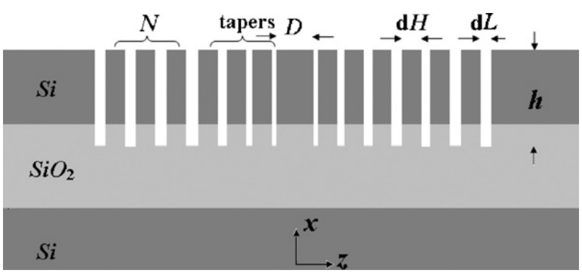


Fig. 1. Schematic of a 1D PC cavity on SOI material with $N = 3$ pairs of untapered Si/air mirrors and 3 pairs of internal tapers at each side the central cavity.

(TM, $H_y = 0$) fundamental mode, which is a Gaussian-modulated cosine impulse covering a wide frequency band [15]. The ''bootstrapping'' technique is used to set the exciting source [15]. The perfectly matched layer (PML) absorbing boundary is used to terminate the FDTD calculation window, with the PML thickness of 0.5 and 1 μm in the $x$ and $z$ directions, respectively. The spatial cell size is 10 nm, and the time step is Courant limit [15]. The transmission, reflection and loss spectra are calculated from the power flux recorded at the detector planes, which are normalized by the source value [16]. For the reflection calculation, double FDTD runs are conducted. The output in the first run without gratings is subtracted from the output in the second run with the full structure to exclude the effect of the source in the detector plane. The resonance wavelength is found by fitting a Lorentzian to the transmission peak and $Q$ is given by the ratio of the peak wavelength to its 3-dB bandwidth.

The mode field distributions from the FDTD simulation are obtained by compressing the incident impulse spectral width into a range narrow enough to ensure that only on-resonance modes can be excited. The spatial Fourier transformation spectra, which represent the plane wave components of the cavity mode, are then calculated from these field distributions.

The analysis is valid for 1D PC structures in 2D cross section geometry, which is an approximation to the actual 3D structures. In the case of air slots without transverse waveguide confinement, our 2D model neglects the scattering loss in the third dimension, i.e. $Q$ reported here is the upper limit. In practice, the width of the access waveguide must be finite, even tapered [10], to ensure single mode behaviour in the PC cavity part and low insertion loss at each end of the device.

## 3. 1D PC cavities with non-tapered mirrors

The basis of the simulations is a 1D PC microcavity with each reflector comprising 8 pairs of Bragg mirrors. Instead of quarter wave stacks, Si-rich mirrors ($dH = 200$ nm, $dL = 90$ nm) are used to suppress scattering losses at the interface between Si blocks and air slots [8]. The grating depth, $h$, is set to 650 nm, which covers the mode distribution in the vertical direction and provides a strong Bragg reflection.

### 3.1. Number of mirror periods

Fig. 2 shows the transmission and $Q$ as functions of the number, $N$, of mirror pairs for a structure of the