

Bloch wave engineering for high Q's small V's optical microcavities

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Introduction

Many important devices use periodic microstructures of alternating layers of dielectric materials to enhance reflection. Usually the refractive index contrast of dielectric layers is low, typically 1% in a distributed Bragg reflector, and a large number of small reflections over a long propagation distance are needed to warrant high reflectivity [1]. Alternatively, periodic microstructures deeply etched into a semiconductor waveguide offer high refractive-index contrasts and much shorter interaction lengths. Examples include photonic wires or air-bridge microcavities [2,3] and very compact Bragg reflectors [4,5,6]. Responding to the quest for miniaturization in optoelectronics, these new mirrors implemented in short cavities additionally offer interesting perspectives: large free spectral ranges, small modal volumes as is required for controlling the spontaneous emission of atoms in microcavities [7], and low threshold lasers. However, for strong corrugations, the Bragg mirror cannot be considered as a perturbation of the uncorrugated waveguide and out-of-plane scattering losses (radiation) in the claddings are inevitable. Apparently strong corrugations required for short interaction lengths and small radiation losses required for high performance seems to be two conflicting objectives.

Two routes are known to achieved high Q's and small V's in optics. The first one refers to the complete 3D photonic crystal approach (the cage for light [8]). Another exploits a judicious refractive index engineering of the core and cladding layers [9]. Both approaches provide theoretically lossless operation, but requires a complex 3D refractive-index engineering. *We proposed another approach which can be fully implemented in planar systems.* As shown by numerical computations in [10] and by experimental results in [11], tapered mirrors that incorporate a series of etches whose feature dimensions vary progressively can provide short interaction lengths and low radiation losses.

The radiation-loss problem

To illustrate our purpose, let us consider the one-dimensional photonic-bandgap air-bridge cavity shown in Fig.1. The periodicity constant Λ is 450 nm and the hole diameter w is 250 nm. Hereafter, we assume that the semiconductor bridge ($n = 3.48$) is 340-nm-thick, 500-nm-wide. Similar microcavities have been studied previously [3], and Q's of ≈ 300 for $V \approx 0.03 \mu\text{m}^3$ have been observed at $\lambda = 1.5 \mu\text{m}$. In the wavelength range of interest, the waveguide supports a single TE-like mode (electric field primarily horizontal at the center of the waveguide) with a double mirror symmetry. For $\lambda = 1.56 \mu\text{m}$, the calculated losses L of

the semi-infinite mirrors illuminated by the fundamental mode of the bridge are 4.5%. Thus one expects that a short microcavity formed by the association of these two mirrors has a Q factor $Q_{FP} = m\pi(R)^{1/2}/L$. For a cavity order $m=3$ (as it is the case for a single hole defect cavity), one expects that $Q_{FP} \approx 200$.

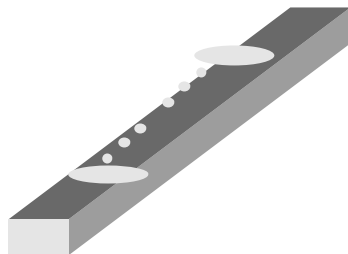


Figure 1. Microcavity discussed in this work. The cavity is formed by two-periodic holes arrays separated by a small defect, typically a single hole defect.

Engineered mirrors and cavities

As shown hereafter, this low Q value can be increased by several orders of magnitude while keeping constant the mode volume V of the cavity. Let us first explain the reason for this low Q value. In [10], the authors propose an approximate model that interpretes the origin of the loss at the interface between the waveguide and the mirror as an impedance mismatch between the incident guided mode and some electromagnetic quantity directly to the fundamental Bloch wave associated to the mirror (we will refer this quantity to as a half-Bloch mode). The losses vary as the square of the integral overlap η between the half-Bloch mode and the incident guided mode [10]. An immediate consequence is that if one desires to reduce the radiation losses to increase the cavity Q, one must engineer the periodic mirrors to taper the incident guided mode into the fundamental Bloch mode of the mirrors. As suggested in [10], a possible solution consists in designing tapered mirrors formed by a series of “segments” whose feature dimensions vary progressively. An illustration of an engineered mirror is shown in Fig. 2, where two “segments” are inserted between the waveguide and the periodic mirror.

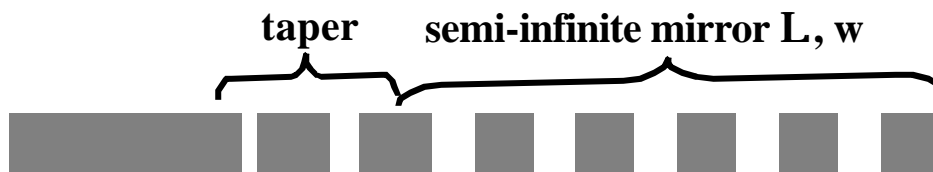


Figure 2. Example of tapered mirror obtained by varying the two first hole dimension and spacing of the periodic mirror.

Microcavities with high Q's and small V's

As will be shown at the conference, two different approaches can be used to design microcavities with high Q's and small V's.

The first approach is simple in its principle. It consists in designing mirrors with small radiation losses. At the conference, we will show that the design mainly consists an engineering of the fundamental Bloch mode, and that the main degree of freedom to be used for the design is the length Λ of the segments.

The second approach is more counterintuitive. It can be shown [12] that the performance of microcavities formed by a defect surrounded by two short Bragg mirrors is not ultimately driven by the modal mirror reflectivity and transmission, i.e. by the mirror losses. In other words, cavities formed with quite lossy mirrors can exhibit unexpected high Q factors. As shown in [12], this anomalous Q's of microcavities can be explained by a radiation recycling mechanism, a pure electromagnetism effect on transient fields at subwavelength scale in the cavity defect. Once appropriately engineered, the recycling boosts the Q's and peak transmissions by several orders of magnitude.

The two approaches can cooperate in practice. To illustrate our purpose, we performed calculations for symmetric cavities with slightly different hole geometries. Only two degrees of freedom, namely the location and the diameter of the two inner holes, were varied for optimizing the intrinsic Q factor. Due to the great computational loads, the configuration space was not thoroughly explored, but many cavity geometries with Q's much larger than that achieved with the periodic mirror were obtained. The three-dimensional computation is performed with the frequency-domain Fourier modal method described in [13]. One of the best performance is achieved for a geometry which corresponds to a 30-nm reduction of the hole diameter and to a 65-nm outer displacement of the center hole locations. Circles in Fig. 3 represent the calculated Q's of the engineered cavity for $\lambda = 1.56 \mu\text{m}$ and for the third cavity order ($m = 3.15$) as a function of the number N of holes.

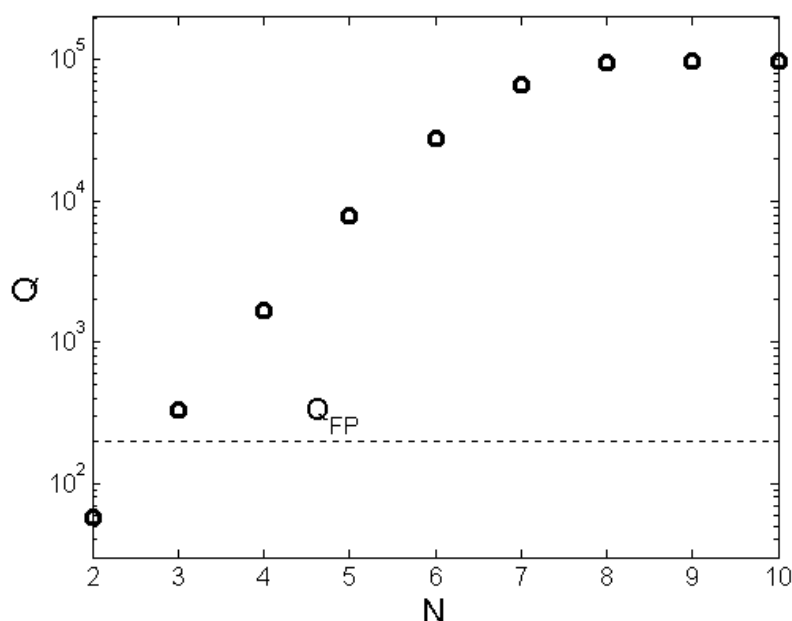


Figure 3. Calculated Q of the engineered cavity as a function of the number of holes. The horizontal dashed line represents the Q factor in the absence of recycling for the cavity formed with the semi-infinite periodic mirrors.

The Q's of the engineered cavity are several order of magnitude higher than the predicted value $Q_{FP} \approx 200$ (horizontal dashed line in the Figure) for the cavity with fully periodic mirrors. This increase has two causes. First, the engineered mirror losses are smaller than those of the periodic mirror increasing the cavity Q from 200 to 750, and secondly, the

radiation recycling is responsible for an other increase by more than a factor one hundred. Finally let us note that, since the modal volume of the engineered cavity is only 6% larger than that of the cavity with fully periodic mirrors, the engineering results in an enhancement of the Purcell factor (Q/V) by a factor 500.

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¹ L.A. Coldren and S.W. Corzine, Diode lasers and photonic integrated circuits, First ed. (Wiley, New York, 1995).

² J.P. Zhang, D.Y. Chu, S.L. Wu, W.G. Bi, R.C. Tiberio, R.M. Joseph, A. Taflove, C.W. Tu, S.T. Ho, IEEE Photon. Technol. Lett. **8**, 491 (1996).

³ J.S. Foresi, P.R. Villeneuve, J. Ferrera, E.R. Thoen, G. Steinmeyer, S. Fan, J.D. Joannopoulos, L.C. Kimerling, H.I. Smith and E.P. Ippen, Nature **390**, 143 (1997).

⁴ T.F. Krauss and R. M. De La Rue, Appl. Phys. Lett. **68**, 1613 (1996).

⁵ T. Baba, M. Hamasaki, N. Watanabe, P. Kaewplung, A. Matsutani, T. Mukaiharu, F. Koyama and K. Iga, Jpn. J. Appl. Phys. **35**, 1390 (1996).

⁶ T.F. Krauss, O. Painter, A. Scherer, J.S. Roberts, R. M. De La Rue, Opt. Eng. **37**, 1143 (1998).

⁷ *Spontaneous emission and laser oscillation in microcavities*, edited by H. Yokoyama and K. Ujihara, Boca raton, FL: CRC Press, 1995.

⁸ D. Normile, Science **286**, 1500 (1999).

⁹ J. Ctyroky, J. Opt. Soc. Am. A **18**, 435 (2001). See also, M. R. Watts, S.G. Johnson, H.A. Haus and J.D. Joannopoulos, Opt. Lett. **27**, 1785 (2002).

¹⁰ M. Palamaru and Ph. Lalanne, Appl. Phys. Lett. **78**, 1466 (2001).

¹¹ D. Peyrade, E. Silberstein, P. Lalanne, A. Talneau, Y. Chen, Appl. Phys. Lett. **81**, 829 (2002).

¹² Philippe Lalanne, Jean-Paul Hugonin, « Radiation recycling in microcavities », submitted for publication.

¹³ E. Silberstein, Ph. Lalanne, J.P. Hugonin and Q. Cao, J. Opt. Soc. Am. A. **18**, 2865 (2001).