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# Recycling losses and tapered lineic microcavities on SOI

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## Abstract

Short microcavities consisting of two identical tapered hole mirrors etched into silicon-on-insulator ridge waveguides are investigated. They are designed for operating at telecom wavelength. We describe theoretically and experimentally two different ways to boost quality factors to some thousands. In one hand, we investigate the adaptation of mode profile to suppress mismatch losses. In an other hand, we explore the recycling of the losses. We obtained quality factor up to 3000, which opens the route to WDM applications.

## 1 - Introduction

Since two decades, the photonic crystals (PCs) research field is growing exponentially due to PCs capabilities to control and manipulate light in different ways: Photonic Band Gap (PBG) mirrors [1], small volume confinement, low group velocities, band gap engineering. Tailoring nanophotonics structures and understanding their mechanisms are key points for future integrated photonic applications and to develop new applications allowed by PCs [2, 3].

An important point to these photonic functions is the availability of good microcavities that permit functions like wavelength filtering and switching. Microcavities are composed of two mirrors generally made of periodic array of holes. In order to obtain high quality factors (Q) many works present different designs [4, 5]. Very high values with PCs has been achieved but for the moment only on membrane structures and with a tiny length tolerance.

There are two ways to propagate light into an integrated device: photonic crystal waveguide (PCW) [6] and ridge waveguide [7]. In terms of bandwidth, density and in-line losses the second type offers the best performances. In this work, we have studied microcavities on ridge waveguide and have explored two different physical mechanisms with the objective of obtaining large resonance quality factors and small modal volumes. One consists in tapering the field profile from the fundamental mode to the mirror mode. The other relies in exploiting the cavity leaky modes and coupling them into the fundamental mode.

Based on these new concepts, passive filters with short microcavities on SOI have been realized and studied. In a first part we will report the physical concepts used for design-

ing cavities. In a second part we will present the experimental setup to fabricate and measure samples. In a last part we will present the results obtained and the conclusions.

## 2 - Two Physical mechanisms

Cavities in ridge waveguide on SOI are composed of holes etched in the silicon ridge waveguide. Microcavities realized with two periodic mirrors present low Q factors (200) [8]. An improvement can be obtained by slightly shifting the first period of the mirror [9, 10], Q values of 500 have been obtained. In order to increase Q factors we propose two ways based on two different physical mechanisms.

### 2.1 - Bloch mode engineering

The main limitation of the mirrors is the losses at the interface with the ridge waveguide. According to [11] losses are directly linked to the profile mismatch between the cavity mode and the Bloch mode supported by the mirror. An overlap integral  $\eta$ , define below, represents this mismatch.

$$\eta = \frac{\Re \left\{ \left[ \iint dx dy (\mathbf{E}_L \times \mathbf{H}_T^*) \cdot \mathbf{e}_z \iint dx dy (\mathbf{E}_T \times \mathbf{H}_L^*) \cdot \mathbf{e}_z \right] / \left[ \iint dx dy (\mathbf{E}_T \times \mathbf{H}_T^*) \cdot \mathbf{e}_z \right] \right\}}{\Re \left\{ \iint dx dy (\mathbf{E}_L \times \mathbf{H}_L^*) \cdot \mathbf{e}_z \right\}}$$

This overlap integral between the incident guided mode and the half-Bloch wave of the mirror represent an electromagnetic quantity associated to the fundamental evanescent Bloch mode of the mirror. The losses are shown to be equal to  $1 - \eta^2$ .

According to this definition, we compute losses ( $1 - \eta^2$ ) at the interface (dotted line Figure 1 c) of a ridge waveguide and a semi-infinite mirror of holes for several diameters of holes as a function of  $a/\lambda$  (Figure 1 a). The curves exhibit a minimum of losses near the PBG.

Mode profiles have been calculated for two points (1) (2) of the 230 nm diameter solid dark curve : it is clear that high losses correspond to high mode mismatch (1) and low losses to low mode mismatch (2). Thus, the resonance wavelength have to be chosen closed to the minimum of losses, which correspond to a position close to the gap. By this way, the quality factor (Q) can be increased. But it is convenient to put the resonance wavelength at the middle of the band gap. For this reason we add a taper to the PBG mirror. The first hole of the taper will be determined by point A corresponding to very low losses. Then, the second and the third holes will be determined by points B and C in order to have a gradual transition from point A to point D that corresponds to the periodic mirror. Diameter and position of holes are determined using Figure 1.

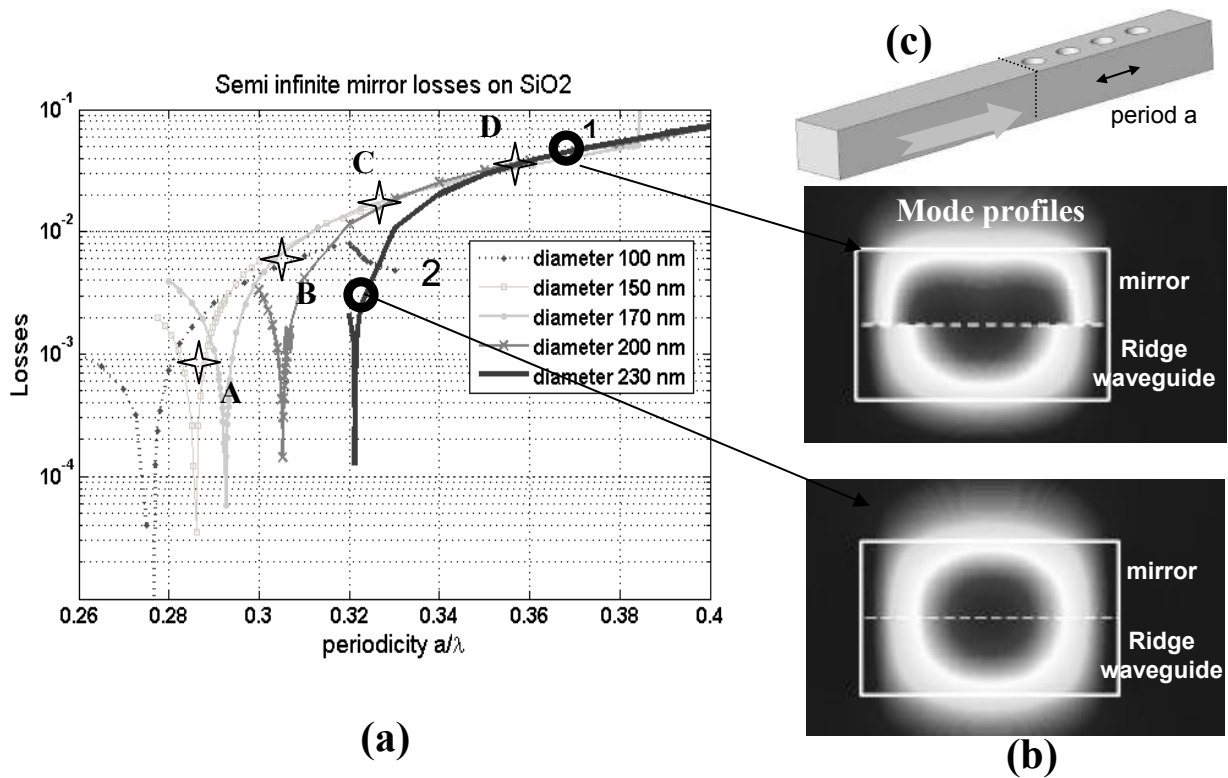


Figure 1 – (a) Evolution of the losses on an infinite mirror mirror in function of  $a/\lambda$  for different diameter (b) profile shape of the y-component of the transverse magnetic field of the fundamental mode in the ridge waveguide and of the half-Bloch wave in 1 and 2 cases. White solid lines indicate the semiconductor boundaries. (c) 3D view of the computed system

## 2.2 - Recycling losses

Instead of suppressing losses at the interface ridge waveguide /mirror, an other strategy consists in re-injecting these ones into the cavity. Mirrors present losses, which can be seen as a coupling between the fundamental mode of the ridge waveguide with a leaky mode. This leaky mode has a complex wave vector, that is to say, it leaks onto radiative air modes. The field has an exponential decay in the propagation direction. But if the cavity is small enough that light doesn't vanish when it reaches the opposite mirror. Moreover if the cut-off wavelength of the leaky mode is close to the resonance wavelength the decay will be slow. A phase match can be done to authorize the leaky mode to couple with the fundamental mode. We changed the first hole diameter and period of the mirror to optimise this recycling.

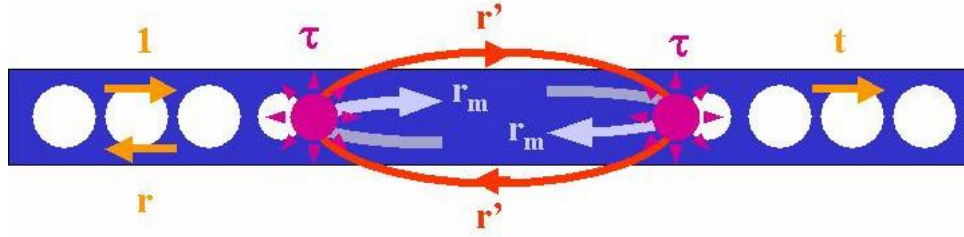


Figure 2 - Model for recycling radiation in microcavities. Gray and red arrows correspond to the fundamental and leaky modes, respectively.

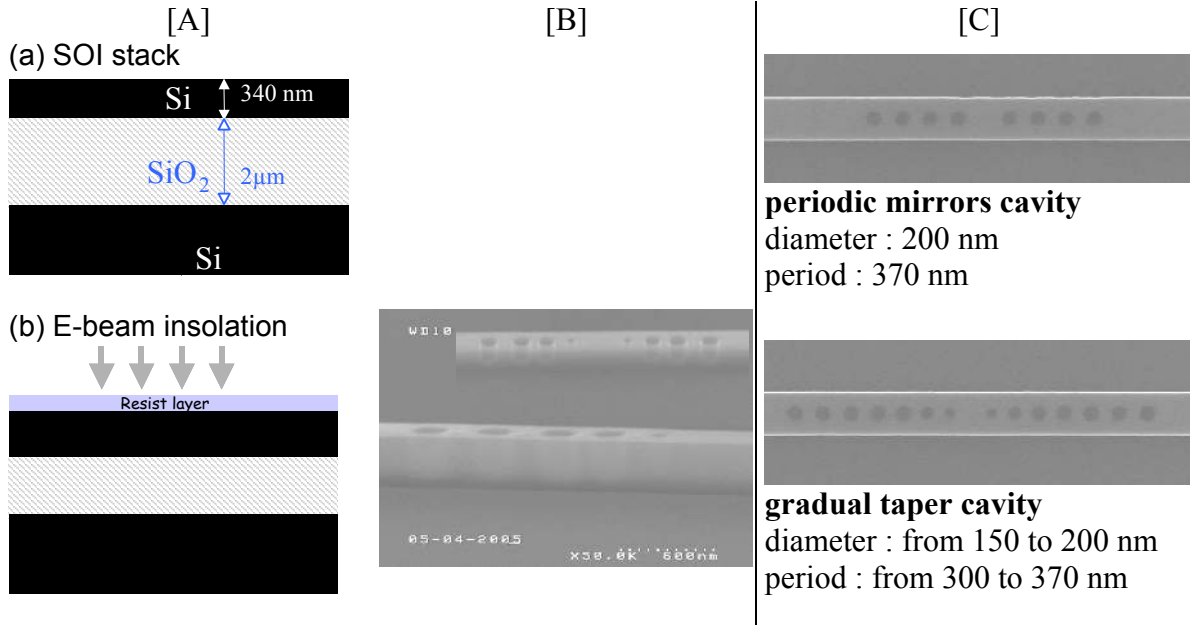
According to [12] the reflectivity of the mirror can be reevaluate to  $r_{eff}$ :

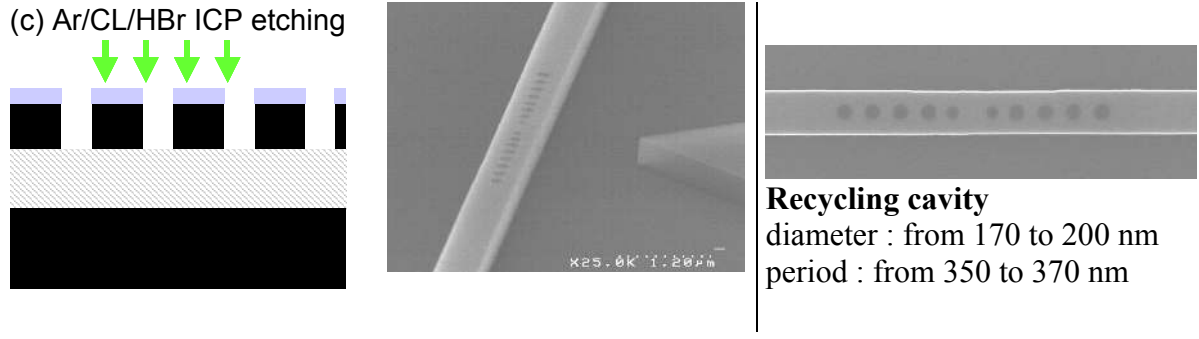
$$\frac{r_{eff}}{r_m} = 1 + \left| \frac{r'}{r_m} \right|^2 \exp(-k_o n' h) \exp \left[ i k_o (n' - n_{eff}) h + 2i\theta \right],$$

Where  $n'+i.n''$  is the effective complex refractive index of the leaky mode,  $h$  is the cavity length and  $\theta = \arg(r'/r_m)$ . Therefore, we can express the Q factor as  $m\pi |r_{eff}| / (1 - |r_{eff}|^2)$ . An optimisation of the coupling between the leaky mode and the fundamental mode permits to increase drastically the effective reflectivity and thus the Q factor. This optimisation was made on the first hole of the mirror.

### 3 – Experimental setup

#### 3.1 - Process fabrication

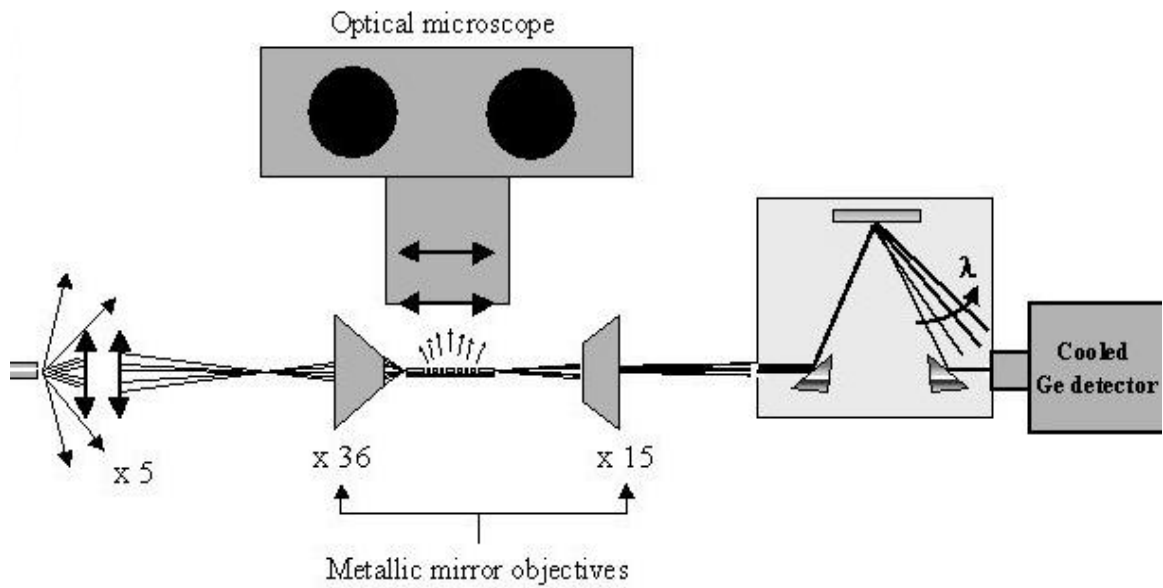




**Figure 3 – [A] Fabrication process (a) SOI stack used (b) E beam lithographic (c) ICP etching**  
**[B] SEM pictures of different steps.**  
**[C] The three type of microcavities fabricated**

Soitec silicon-on-insulator wafers with a 0.34- $\mu\text{m}$  Si-core thickness and a 2- $\mu\text{m}$  thick  $\text{SiO}_2$  buried spacer are used in this work. The ridge and hole patterning is done by electron-beam lithography with a Leica VB6 ebeam on a single layer NEB22 (Sumitomo) resist spin coated on top of the sample. The electron beam energy is 100 keV resulting in a 5 nm diameter probe beam. After developing the resist, direct transfer is done into the top silicon layer. Inductively Coupled Plasma etching process is used to achieve low roughness and vertical sidewalls. The silicon dioxide cladding is used as an etch stop. After etching, the resist mask is removed. Figure 1 shows a scanning electron microscope picture of a cavity formed by defect surrounded by two identical mirrors. The ridge width is 500 nm, a typical hole diameter is 200 nm and the period is 370 nm.

### 3.2 - Sample characterization



**Figure 4 - Transmission board**

The Figure 4 represents the experimental setup to characterize samples, which permit to acquire transmission spectra. We used a broadband white source ( $1,2 \mu\text{m} \rightarrow 1,8 \mu\text{m}$  Santec®). The light is then collected and focuses on a cleaved edge of the sample through different objective lens according to the source employed. Waveguides entrance (Figure 5) are larger than the “monomode waveguide” and typically measure  $8 \mu\text{m} \times 350 \text{ nm}$ . Then, the transmitted light can be collected by an objective lens and the output is imaged onto an InGaAs photodiode, or a nitrogen cooled Ge photodiode, equipped with an optical spectrum analyser. In order to suppress substrate guided light, a slit is put at the enter of the spectrometer. Synchro detection could be used when the signal is too weak. Identical waveguides without any structure have been implemented on samples and took as the reference signal that permits us to normalize transmission spectra.



**Figure 5 - waveguide configuration**

## 5 – Results

For the ridge waveguide, the main characteristic is the line loss and nowadays the state of the art loss is 3.6 dB/cm for a photonic wire on SOI at telecom wavelength [7]. Thus, to evaluate our current fabrication process we measure the losses of the ridge waveguide we use. We find a value of about 10 dB/cm at 1.5  $\mu\text{m}$  which shows the quality of our fabrication process. We measure the transmission spectra of modified and non-modified cavities with an increasing number of holes. Examples of transmission spectra are presented below and explained in details. The different tested designs are finally compared in term of Q factors.

### 5.1 - Bloch mode engineering

According to the design procedure of part 2.1, a numerical optimisation has been made and the corresponding structure fabricated. The Figure 6 show the transmission spectra realized with a broadband white source. Before 1350 nm we observe the edge of the PBG and after a transmission near zero as expected in a PBG. The spectrum exhibits a peak of resonance at 1.57  $\mu\text{m}$ . A Q value of 4500 has been measured for a cavity with five holes in the mirror. For comparison, the same cavity without any taper has a Q value of about 70. This represent at least a 65 times increase. The experimental values are limited by the spectrometer resolution. We expect a higher enhancement in view of the trend in Figure 8. Moreover, the maximum of transmission ( $T_{\text{max}}$ ) is probably biased and that explains the values attained.

Theoretically, the intrinsic Q (infinite number of holes) of the classical cavity is assumed to be 500. The intrinsic Q of the tapered cavity is evaluated to 100000. A 200-time improvement of the Q factor is predicted, consistent with the increase of experimental values.



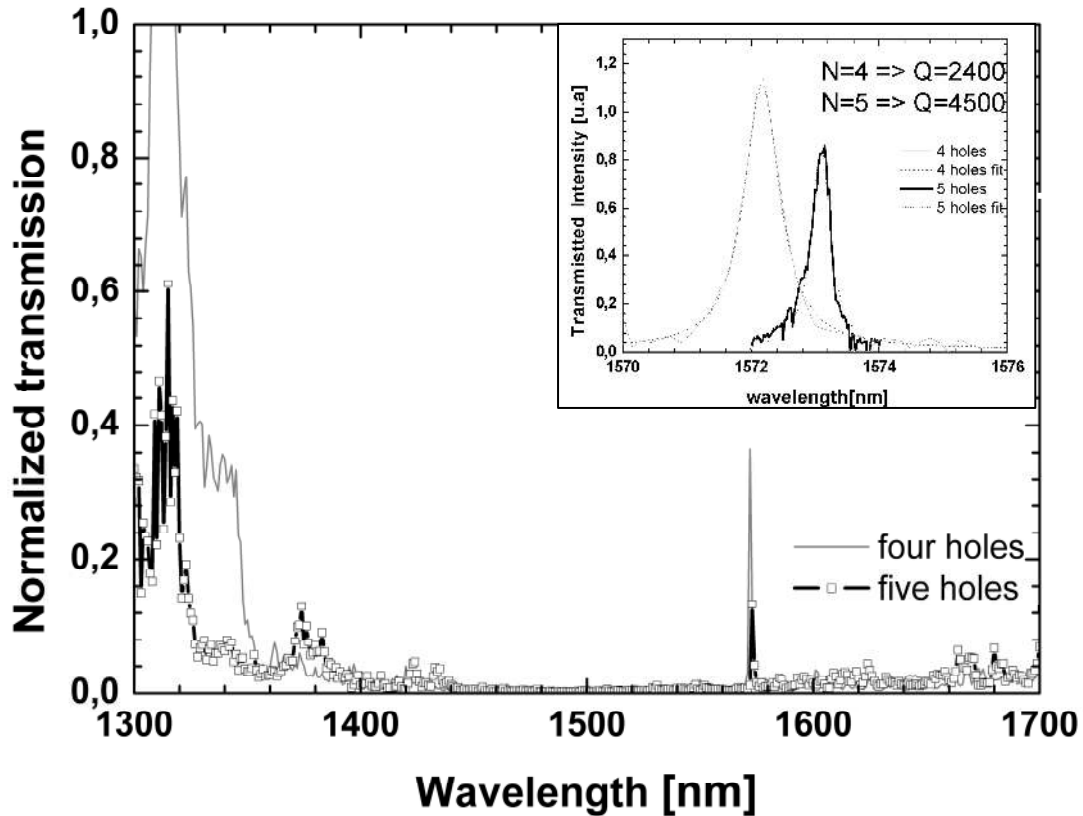


Figure 6 – Two examples of broadband white source transmission spectra of a tapered cavity normalised with the transmission of an identical waveguide without cavity. The inset represents a zoom of the resonant peak in arbitrary units and the lorentzian fit to extract the Q factor.

## 5.2 - Recycling losses

The Figure 7 shows the transmission spectrum of losses recycling cavities. The same trend is observed in the white light spectrum : a PBG starting at 1400 nm , a weak transmission in the gap and a resonant peak. The Q value achieved is about 1800 that represents an enhancement of 25 times. The estimated Tmax is 50 %. It is limited by the spectrometer resolution. That shows the efficiency of recycling losses.

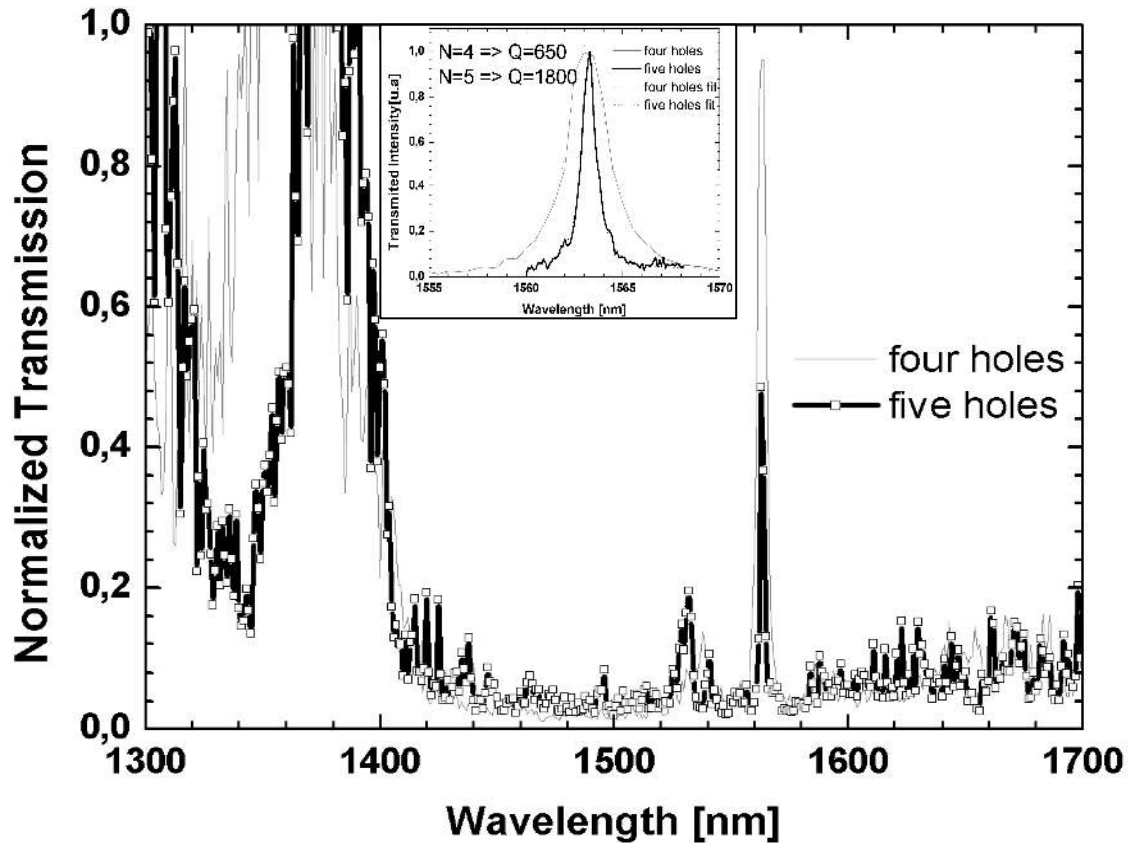


Figure 7 - Two examples of Broadband white source transmission spectra of a recycling cavity normalised with the transmission of an identical waveguide without cavity. The inset represents a zoom of the resonant peak in arbitrary units and the lorentzian fit to extract the Q factor.

### 5.3 – Overview

The Figure 8 gathers the Q factors of the different types of cavities for an increasing number of holes from two to five. As expected, the Q factor increases with the number of holes since the reflectivity increase also. Classical cavities with only periodic mirrors show Q factors under 100 whereas modified cavities attain maximum Q factors of 4500 in the case of adapted cavities and 1800 for recycling cavities. The two effects improve drastically the Q factor. The recycling shows a lower enhancement than adaptation process but at the contrary the estimated  $T_{max}$  is higher in the recycling case.

Finally, we believe that the measured Q factors are lower than calculated (dotted lines) due to the defects induced by process fabrication.

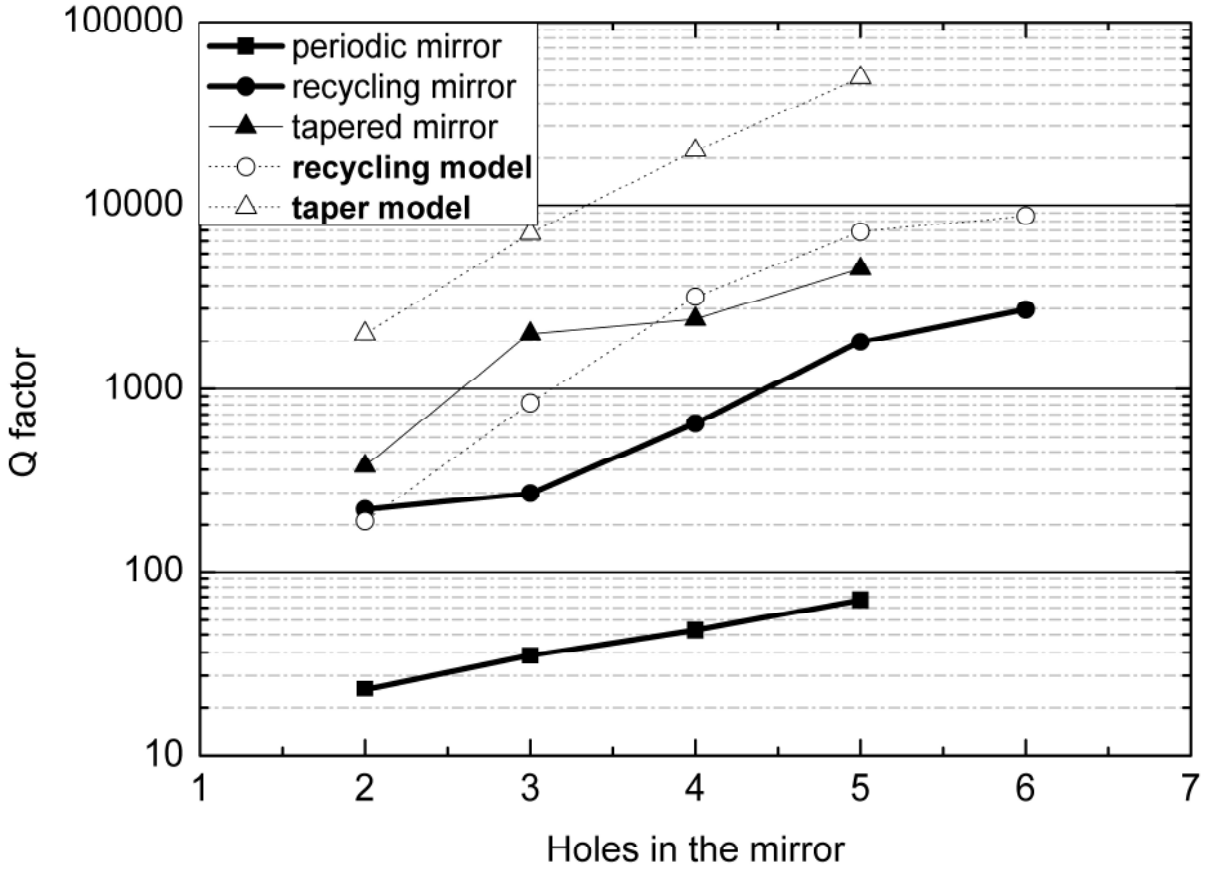


Figure 8 - Evolution of the Q factor with the number of holes in the mirror for all the different type of cavities

## 6 - Conclusion

In summary, two efficient designs to improve the Q factor in lineic microcavities on SOI are reported. The transmission spectra of the structures fabricated upon these two physical mechanisms show a boost in the Q factors up to some thousand. It is high enough for most of the actual WDM specification. The adaptation of the mode profile shows the best improvement of the Q factor with a value of 4500. The recycling of the losses shows a high-transmitted intensity but a smaller Q factor of 1800. Future optimization should improve these performances and give a powerful way to realize ultrahigh Q/V devices for CQED applications.

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