# High-$Q$ Weakly Modulated Nanobeam Cavity Based on a Suspended Silicon Dioxide Waveguide

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**Abstract**— Photonic crystal (PhC) cavities have drawn plenty of attentions during the past several decades for the advantages of ultra-high $Q$ factor and small mode volume. PhC cavities have various applications such as quantum information processing, low threshold lasers, optomechanics, and nonlinear optics. PhC cavities based on silicon material have been heavily investigated due to their compatibility with complementary metal-oxide-semiconductor (CMOS) technology, small feature size and low cost. However, apart from the advantage of high $Q$ factor, silicon based PhC cavities suffer from the drawbacks of high insertion loss because of the mode mismatch with fiber and relatively low sensitivity especially for the sensing application. On the other hand, silicon dioxide (silica) waveguide experience relatively smaller loss and owns a similar refractive index to numerous liquid materials to be detected, which will leads to high sensitivity for a silica based PhC cavity sensor. In this paper, we propose a high $Q$ factor ($Q = 15500$) silica based PhC nanobeam cavity with high sensitivity (the wavelength shift per refractive index unit (RIU) is $S = 338\,\text{nm/RIU}$) at the telecommunication wavelength (1550 nm). Since the refractive index contrast for silica waveguide is low for the realization of the photonic bandgaps, it is essential to utilize a silica waveguide suspended in free space. The PhC nanobeam cavity is then formed by etching a series of elliptical holes, whose dimensions linearly decrease from the center to both ends, directly into the silica waveguide. For the sake of high transmission on-resonance wavelength while maintaining high $Q$ factor, it's important to etch partly into the waveguide, which results in a low-refractive-index perturbation structure. The calculated on-resonance transmission is about 0.26. The novel proposed PhC nanobeam cavity shows a sensitivity 3 times larger than the one based on silicon counterparts and outperforms other low-index-contrast PhC cavities by a higher on-resonance transmission. Such a structure can also be used in spectrally filtering system and nonlinear optics.

## 1. INTRODUCTION

Silicon photonics have attracted extensive research interests due to the features of low fabrication cost, tiny footprint, low power consumption and the ability to be integrated with various materials. PhC cavities play an important role in the silicon photonics field because they allow for both ultra-high $Q$ factor and small mode volume. Massive applications can be found in optical communications [1], chemical sensing [2], ultrasmall lasers [3], nonlinear optics [4] so on and so forth. Among these examples, silicon material is dominant on account of the relatively large refractive index contrast, which leads to a small feature size. However, drawbacks such as high coupling loss with fiber and low sensitivity for the sensing application also arise from this character.

Materials with lower refractive index such as polymers and silica are able to overcome the high coupling loss problem and realize high sensitive sensors. The main obstacle in implementing PhC cavities with these materials is the low $Q$ factor resulting from the low refractive index contrast. Qimin Quan et al. [5] proposed and demonstrated a polymeric PhC nanobeam cavity with high $Q$ factor ($Q = 36,000$) and sensitivity ($S = 386\,\text{nm/RIU}$). The situation becomes a little different when it comes to the silica material because the refractive index contrast further decreases compared to the polymer used in Ref. [5].

In this paper, we propose a novel PhC nanobeam cavity operating at the telecommunication band (1550 nm). The features of high $Q$ factor ($Q = 15500$) and transmission ($T = 0.26$) enable the structure to be applied in spectrally filtering systems and nonlinear optics. Besides, when used in the sensing realm, the PhC nanobeam cavity shows a high sensitivity ($S = 338\,\text{nm/RIU}$) as a result of the large extension of cavity mode into the background material.

## 2. DEVICE STRUCTURE

The geometry and mode distribution of the PhC nanobeam cavity are depicted in Figure 1. Figures 1(a) and (b) illustrate the top view and cross section of the schematic structure respectively and Figure 1(c) shows the mode distribution of the nanobeam cavity. The PhC nanobeam cavity consists of a channel waveguide suspended in the air. There are 100 elliptical holes in total being etched into the waveguide on both sides. The first 50 holes are ellipsis with dimensions linearly decrease from the center to the ends, followed by 50 elliptical holes maintaining the same geometry as the smallest one of the first 50 holes. The detailed parameters of the elliptical holes are designed based on the method proposed by Qimin Quan et al. [6]. The size of the ellipsis is varied from 1186 nm × 172 nm (the major axes multiplied by the minor axes) to 698 nm × 101 nm. In order to obtain a high transmission for the PhC nanobeam cavity, the etching depth is smaller than the height of the waveguide as shown in Figure 1(b).

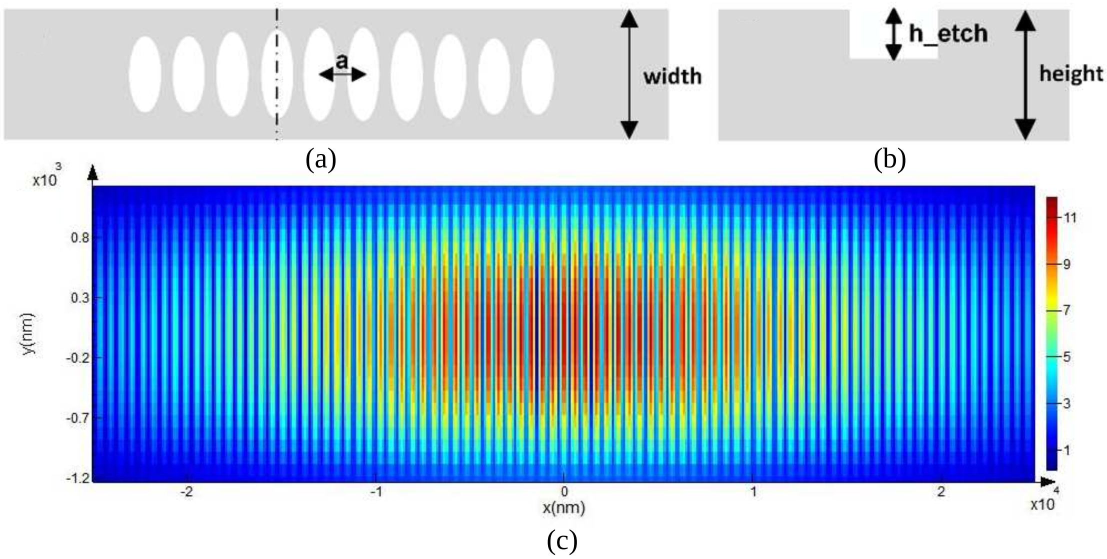



Figure 1: The geometry of the PhC nanobeam cavity and the mode distribution: (a) top view of the structure; (b) cross section of the structure; (c) the cavity mode distribution in the top view.

## 3. CHARACTERIZATION

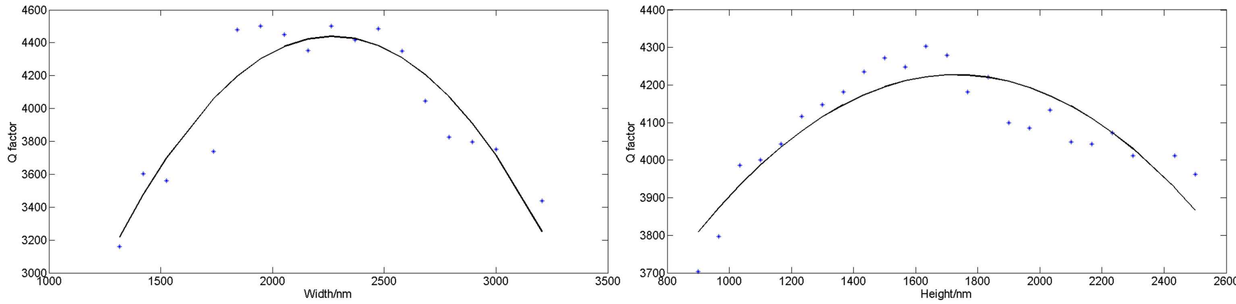
The width and height of the waveguide have much impact on the performance of the PhC nanobeam cavity. As indicated in Figure 2, both the width and height of the waveguide have an optimal value in view of a highest $Q$ factor. The phenomenon can be understood intuitively as follows. Larger width of the waveguide leads to a better restriction of the optical field in the channel waveguide and thus reducing the in-plane radiation loss. However, larger beam width will allow for higher order modes, which will results in a decrease in the $Q$ factor. The mechanism of the influence of the height of the waveguide on the $Q$ factor is the same to the above explanation. It is necessary to mention that the relations in Figure 2 are obtained by varying the width and height of the waveguide of a PhC nanobeam cavity consists of 40 full-etching ellipsis in total for convenience. For PhC nanobeam cavity with more elliptical gratings, the relations between $Q$ factor and width or height of the waveguide stay the same.

Another parameter of the waveguide that has crucial impact on the performance of the PhC nanobeam cavity is the etching depth. Larger etching depth leads to higher $Q$ factor and will result in lower transmission in the meanwhile. Thus, we chose to etch the waveguide partly in order to obtain a relatively high $Q$ factor while keeping the transmission high. The eventual parameters of the PhC nanobeam cavity are as follows. The width and height of the waveguide are 2.5 microns and 1.3 microns, respectively. The etching depth is 500 nanometers. To operate at the telecommunication wavelength, the lattice constant is chosen to be 570 nm.

The transmission spectrum and the enlargement of the on-resonance peak of the PhC nanobeam cavity is depicted in Figures 3(a) and (b), respectively. The on-resonance wavelength is 1556 nm and the $Q$ factor can be derived as:

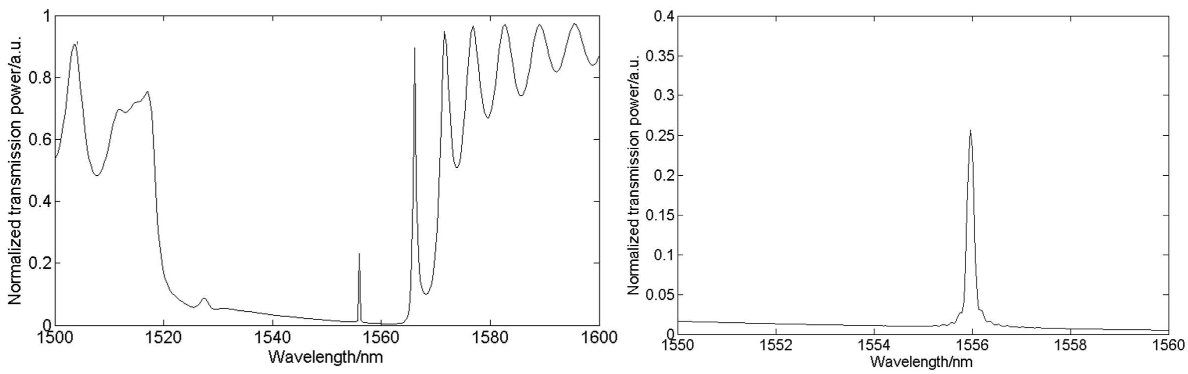
$$Q = \frac{\lambda_{res}}{\Delta\lambda} = \frac{1556\,\text{nm}}{0.1\,\text{nm}} = 15560, \tag{1}$$

where $\lambda_{res}$ represents the resonant wavelength and $\Delta\lambda$, the Full Width at Half Maximum (FWHM)




(a) (b)

Figure 2: The impact of (a) the width and (b) height on the $Q$ factor of the PhC nanobeam cavity. The points are simulations results and the solid lines represent the quadratic polynomial fit curve. The calculation accuracy should account for the fluctuations of the $Q$ factor.




(a) (b)

Figure 3: (a) The transmission spectrum and (b) the enlargement of the on-resonance peak of the PhC nanobeam cavity.

of the extracted transmission peak. As we can see, the cavity mode has an on-resonance transmission 26% with a $Q$ factor about 15500.

As the refractive index of the waveguide is similar to those materials to be detected provided that the PhC nanobeam cavity being used as a sensor, the evanescent field of the silica cavity will extend partly into the background materials. In other words, the background materials have a vital influence on the effective refractive index of the cavity mode, which means that the sensor will show a high sensitivity. The FDTD simulation results agree with this intuitive assumption for the resonant wavelength red shifts 3.38 nm as we increase the background index by 0.01.

## 4. CONCLUTIONS

We propose a novel weakly modulated PhC nanobeam cavity based on a suspended silica waveguide. The cavity shows a high $Q$ factor ($Q = 15500$), a high on-resonance transmission ($T = 0.26$) and a high sensitivity ($S = 338$/RIU). These features outperform silicon based PhC cavities by a high sensitivity and the high transmission enables the cavity to be used in spectral filtering systems. Also the stucture can be utilized in the nonlinear optics combined with proper materials.

## ACKNOWLEDGMENT

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