Second-harmonic generation enhancement in high-contrast micropillar AlGaAs resonator in bound states in the continuum regime

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Abstract. It has been shown that the use of micropillar resonators, which comprise a cylindrical semiconductor cavity sandwiched between the Bragg mirrors can substantially increase the quality factor preserving the mode volume, and thus substantially enhance the local fields. Here, we show that these structures indeed can facilitate the significant enhancement of the SHG efficiency. We provide a specific design of the AlGaAs pillar microcavity and use the numerical modelling to directly show the resonant enhancement of the SHG efficiency. We believe that the presented results would be of high interest to the nanophotonic community, especially in nonlinear optics field.

It has been demonstrated that high-index resonant photonic nanostructures are a highly efficient tool to increase the efficiency of nonlinear optical processes [1], such as e.g. second [2], third [3] and higher harmonic generation [4]. Combining nonlinear materials and subwavelength high quality factor \( Q \) resonators, where light can be stored in a small volume \( V \), can lead to increasing in the nonlinear conversion efficiency since it is proportional to the ratio \( Q/V \) [5], also known as Purcell factor. Photonic crystal cavities demonstrate large values of nonlinear frequency conversion efficiency [6] but creation of such structures require sophisticated fabrication techniques, since their quality factor is extremely sensitive to the geometry imperfections. On other hand, as has been recently shown, engineering of the shape of the isolated subwavelength semiconductor nanoantennae allows to create the high quality optical modes due to the destructive interference of the low order multipole modes [7, 8] and these high-\( Q \) modes are usually referred to as quasi-BIC states since the effect is similar to the bound states in the continuum (BIC) found in periodic structures [9]. It has been shown experimentally that these states in AlGaAs microresonator increase the efficiency of second harmonic generation [10].

We have recently shown, that the at certain ratios of cavity radius to cavity height, the destructive interference occurs similar to the one in the quasi-BIC state, which suppresses the side-wall leakage and resonantly increases the quality factor without strong affecting on the effective mode volume [11]. Here, we show that this quasi-BIC state occurring in pillar microcavities can be used to substantially increase the efficiency of the second harmonic generation.

We investigate the second-harmonic generation (SHG) in a pillar cavity microresonator with radius 500 nm, consisting of an AlGaAs cylinder, sandwiched between two DBR mirrors.
(AlGaAs-SiO$_2$, 8 layers on top and bottom), as shown in Fig. 1(a). The pillar cavity microresonator is tuned to the quasi-BIC regime [12, 7]. Refractive indices used in study are 3.48 and 1.45 for GaAs[13] and SiO$_2$, respectively, while their imaginary parts are neglected due to they are relative small.

The cavity is placed in the background field (pump), which is a superposition of two orthogonal linearly polarized Hermite-Gauss beams [14] and it produce an azimuthally polarized field with the azimuth number $m = 0$:

$$\mathbf{E}_b(\omega, \mathbf{r}) = \text{HG}_{01}(\omega, \mathbf{r})\mathbf{e}_x + \text{HG}_{10}(\omega, \mathbf{r})\mathbf{e}_y.$$  \hspace{1cm} (1)

The AlGaAs has a non-vanishing tensor of the second-order nonlinear susceptibility $\chi^{(2)}_{ijk}$ which contains only off-diagonal elements in the principal axis system of the zinc blende crystalline structure [15], with the components being non-zero only if $i \neq j \neq k$, $\chi^{(2)}_{yzz} \equiv \chi^{(2)} = 290 \text{pm/V}$. Here we consider the two modes of the pillar cavity: $\mathbf{E}_{1,2}$ with the real and imaginary parts being equal to $\omega_{1,2}$ and $\gamma_{1,2}$, respectively. The resonator is placed in the background field with the frequency $\omega$ equals to $\omega_1$, and the frequency $\omega_2$ of the mode $\mathbf{E}_2$ is found to be close to $2\omega$ as shown in Fig. 1(b). So in our simulations we consider TE$_{012}$ mode as $\mathbf{E}_1$ since it has a confirmed quasi BIC, and the TE$_{215}$ mode as $\mathbf{E}_2$ because of the proximity of $\omega_2$ to $2\omega$ (the modes field spatial distributions are shown as insets on the Fig. 1(b)). The cavity radius is fixed in our study and we vary only its height as well as the Bragg layers period to make the center of the bandgap tuned to the mode frequency.

The purpose of work is to calculate the nonlinear conversion coefficient, showing the efficiency of the second-harmonic generation, and defined as the ratio between the total SHG power and the pump power squared: $P(2\omega)/P_0(\omega)^2$. Pump peak power in our calculations was about 0.002 W. The corresponding expression for the total SHG power is given by [10]

$$P(2\omega) = \frac{8\pi}{c} \left(\frac{2\omega}{c}\right)^2 \kappa_2 Q_2 L_2(2\omega)\kappa_{12} [Q_1 L_1(\omega)\kappa_1(\omega)P_0(\omega)]^2.$$  \hspace{1cm} (2)

Here $Q_j = \omega_j/(2\gamma_j)$ is the mode quality factor. The spectral overlap factor is defined as

$$L_j(\omega) = \frac{\gamma_j^2}{(\omega - \omega_j)^2 + \gamma_j^2},$$  \hspace{1cm} (3)
The quality factor of the $E_1$ mode achieves its highest value $Q \approx 4 \times 10^5$ at the aspect ratio $r/h$ of AlGaAs cavity is approximately equal to 0.7475, see Fig. 2(a) and such large value of the quality factor allows us to neglect the material losses. Since we consider the case of high contrast Bragg reflectors the low-quality modes do not arise and the quality factor of $E_1$ has a single peak [11] at the aspect ratio $r/h = 0.7475$. In the same region of the aspect ratio the mode $E_2$ has an oscillating quality factor since its frequency is far away from the center of Bragg reflectors bandgap which is tuned to the $E_1$ frequency. Because of this fact it can be seen from field distributions shown in Fig. 2(b) that $E_2$ does not effectively decay in the reflectors. And

Figure 2. (a) The quality factor of the modes $E_1$ and $E_2$. The vertical line represents the position of the highest value of $Q$ at $r/h = 0.7475$. On the right picture the modes field distributions for points A and B of plot are presented.

and the so-called coupling $\kappa_1$, cross-coupling $\kappa_{1,2}$ and decoupling $\kappa_2$ coefficients [10], where they can be defined from the spatial mode profiles $E_{1,2}(r)$. Note that in our calculations we consider the second harmonic generation only in the AlGaAs.

Figure 3. (a) Nonlinear conversion coefficient versus $r/h$ of the cavity with fixed beam waist radius $w_0 = 1.3 \mu m$. (b) Nonlinear conversion coefficient versus the beam waist radius $w_0$. Zone filled by red color represents the values of beam waist radius where nonlinear conversion coefficient is bigger than $1 W^{-1}$ (green dotted line).
because of this the Q factor of $E_2$ remains quite low.

The dependence of second harmonic nonlinear coefficient on the aspect ratio $r/h$ was studied with a fixed beam waist radius equal to 1.3 $\mu$m (see Fig. 3 (a)). As it can be seen from this plot, the nonlinear coefficient has a pronounced maximum at $r/h = 0.7475$, where the coefficient is at least an order of magnitude larger in comparison with the rest of the aspect ratio area, and it is about $1.4 \times 10^{-4} \text{1}/W$.

And as an important step we study the dependence of the nonlinear coefficient on the beam waist radius of the background field (see Fig. 3(b)). The maximal achieved value of nonlinear conversion coefficient is greater than 1 ($\approx 8 \text{1}/W$) at the value of $w_0$ equal to the half of wavelength of the $E_1$ mode with $r/h = 0.7475$. As it can be seen, $P(2\omega)/P_0(\omega)^2$ value strongly depends on the beam waist radius of background field and simple decreasing of radius leads to significant enhancement of SHG but it requires taking into account higher order nonlinear effects such as generation of higher harmonics and difference frequency generation. It can be the next step in the study of quasi-BIC in pillar cavity microresonators since it has not been considered in the presented study.

To conclude, in this work we have studied the second harmonic generation in the pillar AlGaAs/SiO$_2$ cavity microresonator, and have shown its significant enhancement due to resonant increase of quality factor of first mode due to the destructive interference of two leaky modes. Results of this work may be of interest in study of nonlinear effects in micropillar resonators, especially in practical realization of sub-wavelength devices for nonlinear optics.

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