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Enhancement of second-harmonic generation in micropillar resonator due to the engineered destructive interference

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It has been recently shown that the engineering of the shape of the dielectric nanoantenna allows to achieve the destructive interference of the low order multipole modes [1, 2]. As a result these structures may support high quality optical modes, characterized at the same time by relatively small mode volumes. Since the effect of the emergence of the dark modes due to the destructive interference is analogous to the bound states in the continuum (BIC) arising in periodic structures [3], these modes are usually referred to as quasi-BIC states. It has been shown experimentally that these states, supported by the AlGaAs pillars, facilitate substantial increase in the second harmonic generation efficiency [4].

At the same time, even at the quasi-BIC regime, individual semiconductor pillars are characterized by fairly modest quality factors in mid-infrared and optical frequency ranges. The quality factor can be substantially increased if the pillar is sandwiched between Bragg reflectors, which suppress the radiation losses through the top and bottom of the pillar. The resulting structures, pillar microcavities, are conventionally characterized by large values of Q/V ratio and are routinely used to enhance the light-matter interactions at the nanoscale [5, 6].

The main source of the radiation losses in pillar microcavities is due to the radiation leakage through the sidewalls, which increase as the diameter of the cavity is decreased. 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 while preserving the effective mode volume [7]. 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 micropillar resonator with radius 500 nm, consisting of an AlGaAs cylinder, sandwiched between two DBR mirrors (GaAs-AlGaAs, 30 layers on top and bottom), as shown on the inset in Fig. 1. The micropillar resonator is tuned to the quasi-BIC regime [1, 8]. It means that we consider the same structure where the Q/V ratio enhancement for cavity mode has been observed for micropillar resonator with low-contrast Bragg reflectors [8] and for high-contrast Bragg reflectors [7] due to destructive interference of two radiating modes.

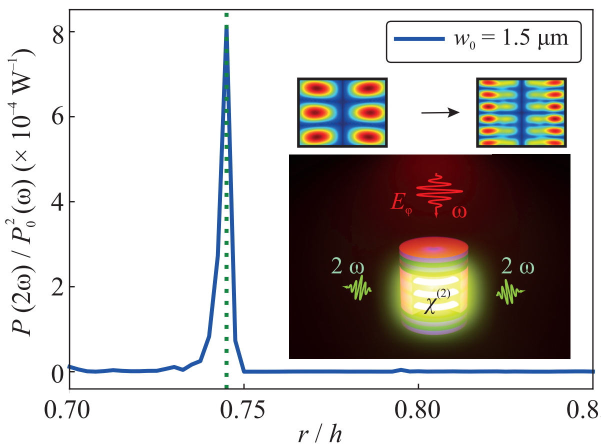

Fig. 1. (Color online) (a) – The sketch of the system under consideration. (b) – Dependence of the wavelength of the modes on the r/h ratio of the cavity. The wavelength of the mode $\mathbf{E}_2$ is doubled for better comparison (to demonstrate that ω_2 is close to $2\omega_1$)

The cavity is placed in the background field (pump), which in our case is supposed to be a superposition of two linearly polarized Hermite–Gauss beams [9] that result in an azimuthally polarized field with the azimuth number $m = 0$. The AlGaAs has a non-vanishing tensor of the second-order nonlinear susceptibility $\chi^{(2)}_{ijk}$. This

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tensor contains only off-diagonal elements in the principal axis system of the zinc blende crystalline structure [10], with the components being non-zero only if $i \neq j \neq k$, $\chi^{(2)}_{xyz} \equiv \chi^{(2)}_{\mathrm{AlGaAs}} = 290\,\mathrm{pm/V}$. As for the GaAs its tensor of the second-order nonlinear susceptibility $\chi^{(2)}_{xyz}$ also has non-zero components if $i \neq j \neq k$, $\chi^{(2)}_{xyz} \equiv \chi^{(2)}_{\mathrm{GaAs}} = 180\,\mathrm{pm/V}$ [11]. The second harmonic generation was considered in whole micropillar resonator (both in AlGaAs cavity and AlGaAs/GaAs Bragg reflectors). In our analysis we focus on the two modes of the pillar: $\mathbf{E}_{1,2}$ with the real and imaginary parts of the eigenfrequencies being equal to $\omega_{1,2}$ and $\gamma_{1,2}$, respectively. The pillar is pumped at the frequency ω close to ω_1, and the frequency ω_2 of the mode $\mathbf{E}_2$ is assumed to be close to 2ω. 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 ω_2 to 2ω. 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.

Our main goal 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: $P(2\omega)/P_0(\omega)^2$. The corresponding expression for the total SHG power is given by [4]

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

Here $Q_j = \omega_j/(2\gamma_j)$ is the mode quality factor, L_j is the spectral overlap factor, κ_1, $\kappa_{1,2}$ and κ_2 are the so-called coupling, cross-coupling, and decoupling coefficients, respectively, where they are expressed in terms of the spatial mode profiles $\mathbf{E}_{1,2}(\mathbf{r})$ and the pillar parameters. The dependence of second harmonic nonlinear coefficient on the aspect ratio r/h was studied with a fixed beam waist radius equal to 1.5 μm (see Fig. 1). As it can be seen from this plot, the nonlinear coefficient has a pronounced maximum at $r/h = 0.745$, 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 $8 \times 10^{-4}\,\mathrm{W}^{-1}$. At this point the nonlinear coefficient dependence on the background field frequency in the frequency domain looks like a narrow peak ($\sim 1 \times 10^{10}$ rad/s) because of the small value of γ_1, which enters the spectral overlap factor $L_1(\omega)$. In addition, an important parameter is the beam waist radius, since its decrease with fixed peak power will lead to a stronger localization of the field inside the cavity and, accordingly, an increase in the coefficient κ_1, which will lead to a significant enhancement of the second harmonic power.

To conclude, in this work we have investigated the second harmonic generation in a micropillar AlGaAs/GaAs resonator, and have shown that it gets significant enhancement in the quasi-BIC regime. Compared to a single resonator [4], the achieved theoretical values are higher by at least an order of magnitude, despite the fact that the Q-factor is much higher (10^5 versus 10^2). Thus, we believe that the presented results can be applied in problems of nonlinear nanophotonics and in the practical implementation of quantum devices, where high nonlinearity plays an important role.

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