Dynamic trapping and releasing photonics beyond delay-bandwidth limit in cascaded photonic crystal nanocavities

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Abstract

Controlling the flow of light on-chip is of great importance for quantum computing and optical signal processing. In this paper, we present a theoretical study to reveal the underlying physics of how to effectively trap, store and release a signal pulse, and eventually break the delay-bandwidth limit, based on controllable EIT-like effect in dynamically tuned standing-wave cascaded nanocavities. Using this mechanism, we design a compact silicon photonic crystal system with long storing time and a delay-bandwidth product over 460, which is about two orders of magnitude greater than the reported results obtained by other methods based on static resonator system, and the trapped signal pulse can be released on demand.

Controllable trapping, storing and releasing photonics is crucial for quantum computing and optical signal processing. To store photons on-chip, the speed of light should be significantly slowed down and even stopped. In past decades, electromagnetically induced transparency (EIT), a quantum destructive interference effect in multi-level atomic systems, is widely used in slowing/stopping light [1, 2]. In such systems, specific wavelengths of light are required, and the bandwidth for operation is ultranarrow, which limits their applications. Recently, the slow-light effect has also been realized in photonic crystal (PC) waveguides (WGs) and coupled-cavity WGs (CCW) [3–5]. However, these static resonator systems are fundamentally constrained by the delay-bandwidth product and cannot slow down the group velocity of an optical pulse to zero [6]. To break this limit, dynamic tuning the coupling strength between the resonators and WGs is demanded [6, 7]. So far, various mechanisms have been proposed to realize dynamically tuning the coupling strength, e.g., through destructive/constructive interferences in a cavity–mirror system [8], or by using an all-optical analogue of EIT on a silicon chip [9]. These mechanisms suffer different challenges: e.g., the first method request a rigorous dynamic-phase-matching condition, and the delay time is short (less than 20 ps) [8]; while for the latter method, most of the proposed EIT-like effects are realized in coupled travelling-wave resonators (such as microrings or microtoroids [9, 10]), which commonly have large modal volumes accompanied by many undesirable resonant modes.

To break through these difficulties, in this paper we present a novel light storing and releasing approach, based on controllable EIT-like effects in dynamically tuned standing-wave cascaded PC cavities, which have few fundamental modes and the mode volumes are commonly far smaller than that in travelling-wave resonators. Thus, the desired pump power consumption for resonator’s frequency tuning will be significantly reduced, and this system is not subjected to the constraint of the dynamic-phase-matching condition as that in reference [8]. Although PC cavities have been employed to act as optical buffer [11–13], these PC systems are essentially static, and therefore cannot break the delay-bandwidth limit [11–13]. Here we present a general theory to describe a dynamic PC system, revealing the underlying physics of how to effectively trap, store and release a signal pulse, and eventually break the delay-bandwidth limit by dynamically compressing photon bandwidth. Based on these analytical results, we design a compact silicon
PC system with a long storing time over 240 ps and a delay-bandwidth product over 460, and the trapped signal pulse can be released on demand. We start by considering a PC structure as sketched in figure 1(a), which consists of a triangular lattice of air holes in silicon with a radius of $r = 0.275a$ (where $a = 412$ nm is the lattice constant). The refractive index of silicon is $n_0 = 3.4$, and the thickness of the slab is $h = 0.52a$. A pair of nanocavities (C1 and C2) are placed at either side of the WG, so that the coupling between the two cavities is indirect and mainly through the intermediate WG. Both cavities are monomode and the resonant frequencies of C1 and C2 are $\omega_{01}$ and $\omega_{02}$, respectively. To dynamically control the flow of light, we suppose $\omega_{01}$ or $\omega_{02}$ can be slightly tuned (e.g., via free-carrier dispersion effect or Kerr effect). For cavity C1 ($i = 1, 2$), the coupling rate of the cavity mode amplitude into the WG is $\gamma_{Ci}$, and the intrinsic decay rate of the cavity is $\gamma_{0i}$, which commonly originates from the absorption or radiation in PC cavity. Thus, the half of the linewidth of the cavity mode is $\gamma_i = \gamma_{Ci} + \gamma_{0i}$.

According to temporal coupled-mode theory (TCMT) [14, 15], the dynamic equations for the amplitudes of the cavity modes in C1 and C2 can be written as

$$\begin{cases}
\frac{dA_i}{dt} = [j\omega_{0i} - \gamma_i] A_i + \kappa_i f_i + \kappa_i b_{i+1} \\
f_{i+1} = \xi f_i + \kappa_i A_i \\
b_i = \xi b_{i+1} + \kappa_i A_i
\end{cases}
$$

(1)

for $i = 1, 2$. Here $A_i$ is the mode amplitude to represent the electromagnetic energy $|A_i|^2$ stored inside C$i$; $f_i$ and $b_i$ represent the field amplitudes of the forward and backward transmitted waves in waveguide, respectively, as shown in figure 1(b). $\kappa_i = j e^{i\phi_i}/\sqrt{\gamma_{Ci}}$ is the coupling coefficient between the transmitted waves and the cavity mode of C$i$; $\phi_i$ is the phase shift when the signal light propagates from C1 to C2 or conversely. $\xi = e^{i\phi}$ is the coupling coefficient between the incoming and outgoing waves through a direct pathway. These coupling coefficients can be derived from energy-conservation and time-reversal symmetry constraints [14]. Without loss of generality, here we consider the forward-transmitted case, namely, $b_j = 0$, and $f_2$ represents the incident signal light filed (thus $f_3$ is the transmitted field).

We firstly investigate the transmission spectra of the system. To do this, we can use a continuous-wave (CW) probe source and scan the wavelength. We suppose the stable field of the CW probe light has the form of $f_i = \sqrt{P_{in}} e^{i\phi}$, where $P_{in}$ is the input power, and $\omega$ is the carrier frequency. By substituting it into equation (1) and utilizing the initial condition $A_i(0) = 0$, the stable total transmission coefficient $T$ can be derived:

$$T = \left| \frac{f_3}{f_1} \right|^2 = \left| \frac{(\omega - \omega_{01} - j\gamma_{01})(\omega - \omega_{02} - j\gamma_{02})}{[j(\omega - \omega_{01}) + \gamma_1][j(\omega - \omega_{02}) + \gamma_2] - e^{i\phi}\gamma_{Ci}\gamma_{C2}} \right|^2.
$$

(2)

The influence of $\phi$ on the transmission characteristics has been discussed in detail in several references [12, 16], here we will focus on the most important case for our study, that is $\phi = m\pi$ ($m$ is an integer), which can be reached by precisely tuning the center-to-center distance $l$ of the two cavities. In this case, the
coherent interference between the two cavities results in a supermode (an EIT-like peak) at \( \omega_{\text{EIT}} = (\omega_{01} + \omega_{02})/2 \), as shown by dashed curve in figure 1(c). One can see that the EIT peak is narrow and symmetric.

From equation (2), we can further obtain the maximum transmission and linewidth (FWHM) of the supermode

\[
T_{\text{max}} \sim \frac{(\omega_{02} - \omega_{01})^4}{[(\omega_{02} - \omega_{01})^2 + 2(\gamma_{102} + \gamma_{201})]^2 + 4(\omega_{02} - \omega_{01})^2(\gamma_2 - \gamma_1)^2},
\]

\[
\Delta_{\text{EIT}} \sim \gamma_{01} + \gamma_{02} + \frac{(\omega_{02} - \omega_{01})^2}{2(\gamma_{10} + \gamma_{20})},
\]

where the condition of \( \gamma_{01} \ll \gamma_{12} \) is taken, since the intrinsic loss decay rate of a nanocavity is commonly far less than the coupling rate between cavity and WG.

Known by equation (3), if \( \omega_{01} = \omega_{02} \), then the EIT peak from the supermode will disappear, as shown in figure 1(c) (the solid curve). Simultaneously, according to equation (4), the coupling rate between the supermode and waveguide is \( (\omega_{02} - \omega_{01})^2/[2(\gamma_{10} + \gamma_{20})] \), which will drop to zero when \( \omega_{01} \) and \( \omega_{02} \) are tuned to be equal. This means the supermode will be decoupled from the waveguide, so that we cannot see the EIT peak from the transmission of the waveguide. Thus, if the signal light is coupled into the supermode beforehand (when EIT peak exists, as will be discussed in detail later), once \( \omega_{01} = \omega_{02} \), the signal light will be tightly trapped in the two cascaded nanocavities, because the supermode is now completely isolated from the waveguide. However, this does not imply that the storing time of the trapped signal light will be infinite, since according to equation (4), the storing time is eventually determined by \( \gamma_{01} + \gamma_{02} \) even if the supermode is isolated from the waveguide. Therefore, to ensure a long storing time, the intrinsic loss inside cavity should be controlled to a very low level, as will be shown below.

Equation (4) clearly shows that the linewidth of the supermode is linearly dependent on \( (\omega_{02} - \omega_{01})^2 \). Therefore, by dynamically tuning the frequency distance between \( \omega_{01} \) and \( \omega_{02} \), the linewidth of the EIT peak, as well as the lifetime of the trapped signal photons, can be freely controlled. If we change the linewidth (or Q value) of the EIT peak in the order of "low Q, ultrahigh Q" and low Q' when capturing, storing, and releasing signal light, the delay time \( \Delta T \) of the trapped signal pulse will be significantly prolonged, with a broad operation bandwidth much greater than \( 1/\Delta T \). In this way, the delay-bandwidth limit can be broken.

To show how to effectively store and release a signal pulse, we further use TCMT to describe the whole dynamical process. We consider a signal pulse centered at a carrier frequency \( \omega \) incident from the left WG.

The signal has a Gaussian shape of \( f = \sqrt{p_{00}} e^{i\omega t} e^{-\left((t - t_0)^2/t_4^2\right)} \), where \( p_{00} \) is the peak power, \( t_0 \) is the pulse duration, and \( t_4 \) is the delay time of the signal pulse relative to the time origin. To isolate the supermode from WG and store the signal light, the two resonators should be tuned into resonance. For convenience but without loss of generality, here we suppose \( \omega_{01} \) is fixed, and only tune \( \omega_{02} \):

\[
\omega_{02} = \omega_{02} + (\omega_{01} - \omega_{02})U(t)
\]

\[
U(t) = \begin{cases} 
1 & (t_1 \leq t < t_2) \\
0 & (\text{else})
\end{cases}
\]

where \( U(t) \) is the controlling function, and \( U(t) = 1 \) means storing, while \( U(t) = 0 \) corresponds to trapping or releasing (so that the storage time is \( t_2 - t_1 \)). By substituting \( f = \sqrt{p_{00}} e^{i\omega t} e^{-\left((t - t_0)^2/t_4^2\right)} \) and equation (5) into equation (1), and using four-order Runge–Kutta method [17] to solve these equations, we can calculate the dynamic evolution of the whole trapping, storing and releasing processes, as shown by figure 2.

Initially, the carrier frequency of the signal pulse is set to be \( \omega = \omega_{\text{EIT}} \), so that the signal energy resonantly flows into the supermode of the cascaded nanocavities and then reaches a peak. When without modulation, the trapped signal energy inside the cavities will decay exponentially to the output waveguide at a rate of \( \Delta_{\text{EIT}} \), as shown by gray dashed line in figure 2(a). To store the signal energy, we should switch the cavity state from low Q to a much higher one. To do this, \( \omega_{02} \) is tuned to be equal to \( \omega_{01} \) at \( t_1 = 25 \) ps just when the trapped signal power reaches its peak. One can see the decay rate of the cavity energy becomes very little immediately. In this case, the supermode is actually decoupled from the WG, and the energy decay rate is only determined by the intrinsic losses of the cavities. In addition, from figure 2(a) we also observe that after the initial oscillations, the two curves (blue and red) coincide completely, and there is no energy exchange between the two cavities any longer, which is quite different from what is observed in references [18, 19]. This means the signal energy is ‘quietly’ and equally stored inside the cavity system in standing-wave fashion, and the coupling between the two cavities is cancelled due to the interference between them. Figure 2(c) is the corresponding waveform of the output signal when storing happens.

To release the stopped signal light on demand, we can make the two resonances detuned again from
Figure 2. Temporal evolutions of the intracavity energy and the output waveforms when refractive-index modulation is applied to C2 cavity. (a) and (c) Storing starts at $t_1 = 25$ ps. (b) and (d) On-demand releasing at $t_2 = 175$ ps. The green dashed-dotted lines in (a) and (b) denote the total energy (the sum of C1 and C2); for comparison, the case when without tuning is also plotted, as shown by the gray dashed line in (a). The parameters of the pulse used for calculations are: $\omega = 0.266056 \left(2\pi/\lambda\right)$, $t_0 = 10$ ps, and $t_d = 20$ ps.

each other, to switch the cavity state from ultrahigh $Q$ to a much lower one. Figure 2(b) shows that the signal light is released at $t_2 = 175$ ps after an arbitrary given delay of $t_2 - t_1 = 150$ ps. We see that the stored signal energy escapes from the cavity system quickly and leaks into the output WG, so that a second pulse appears, with a transmission less than the original peak because of the intrinsic losses of the cavities, as shown by figure 2(d).

To verify the above theoretical predictions, finite-difference time-domain (FDTD) simulations [20] are performed on the PC structure shown in figure 1(a), as an example of the general theory. Each cavity is designed by filling in one air hole, and the radii of the surrounding air holes denoted by ‘A’ and ‘B’ are decreased to $r_A$ and $r_B$, respectively. Here $r_B$ for C1 and C2 are slightly different, so that $\omega_{01}$ and $\omega_{02}$ are initially detuned (the detailed parameters can be seen in the caption of figure 1). Besides, the end holes ‘B’ for both cavities are shifted $0.1a$ outward from their original positions to increase the vertical radiation $Q$ factors (over 150,000). The center distance $l$ of the two cavities is tuned to be $l = 3a$ to make sure the propagation phase between C1 and C2 satisfies $\phi \sim m\pi$ ($m$ is an integer). The system thereby represents an all-optical analogue of EIT. Figure 3(a) shows the EIT peak at $\lambda_{EIT} = 1548.59$ nm (dotted line). The shape is some asymmetric since its resonant feature is superimposed with a background of Fabry–Pérot oscillations, which originate from the interference effect caused by the partial reflections at the WG terminations [21].

In the following simulation, a 10 ps Gaussian signal pulse, whose center frequency and bandwidth are coincident with that of the EIT peak, is launched at the left end of the input waveguide. As expected, the signal energy flows into the cavities efficiently and quickly. As soon as the trapped signal energy reaches its peak, a sudden index modulation of $\Delta n/n_0 = 3.7 \times 10^{-4}$ is added to C2 at $t_1 = 25$ ps, to redshift $\omega_{02}$ and make it equal to $\omega_{01}$. The red solid line in figure 3(a) is the corresponding transmission spectrum. From figure 3(b), we really see that the decay rate of the cavity energy becomes very little immediately, and the temporal evolution of the trapped signal energy inside the two cascaded cavities exhibits almost the same dynamic features as what we predict theoretically in figure 2(a). Figure 3(c) is the corresponding waveform of the output signal. Figure 3(c) further shows the field patterns of the energy distributions at two arbitrary moments marked by ‘A’ and ‘B’ when storing, which provides an intuitive insight that the signal energy is perfectly stored inside the cavity system in standing-wave fashion, with nearly the same amount in each resonator.

We also investigate the dependence of the decay rate of the stored energy on different $|\omega_{02} - \omega_{01}|$, by changing the index modulation intensity on C2. The simulation results (red dots in figure 3(d)) clearly implies that the energy decay rate grows linearly with increasing $(\omega_{02} - \omega_{01})^2$, which agrees very well with the theoretical prediction of equation (4). Specially, when $\omega_{02} = \omega_{01}$, we obtain the minimum decay rate $8.9 \times 10^{-7} \left(2\pi/\lambda\right)$, which is nearly equal to the intrinsic cavity loss $\gamma_01 + \gamma_02$. Thus, a photon lifetime of over 0.24 ns $\sim 1/(\gamma_01 + \gamma_02)$ can be achieved, which is much longer than that of a static cavity without dynamic modulation (about 3.4 ps, $\sim 1/\Delta_{EIT}$, where $\Delta_{EIT}$ is the linewidth of the EIT peak shown in figure 3(a)).
The bandwidth of the system is order can be achieved via Kerr (e.g., using polymer material, which has instantaneous response time and much larger Kerr nonlinearity coefficient than silicon [22]), carrier-plasma, and electro-optic effects [8, 9, 23]. All the effects are very fast (ps or less) [8, 9, 23], which is crucial for experimental realization of this approach, since our further numerical experiments (see figure4) reveal that even when the index tuning delay-bandwidth product, trying to decrease the intrinsic losses in cavities is of great importance. In actual systems with high-loss). However, these intrinsic losses can be well controlled to an extremely low level by current techniques, and ultrahigh-loss). Therefore, the theoretical proposal is experimentally feasible, and can be naturally applied to other photonic designed cavities [24–26], the intrinsic losses are even lower than that of the system shown in figure1(a). To release the trapped light after a given delay, we can add another sudden index modulation to C1 or C2, to make them detuned from each other again. As an example, figure 3(f) shows the temporal evolution of the output optical power for different releasing time \(t_2\), and the storage time, \(t_2 - t_1\), is completely determined externally. We can see after the releasing time \(t_2\), the signal pulse appears again immediately. More importantly, compared to the temporal shape of the released pulse proposed in reference [9], the signal distortion in figure 3(f) is relatively slight. One possible reason is that in our case, the bandwidth of the EIT peak (which determines the trapping and releasing rates) is deliberately designed to be aligned with that of the incident signal pulse.

From the above-mentioned processes, we can see the trapping, storing, and releasing a signal light are actually accompanied by the reversible bandwidth-change of the light, in the order of \(\Delta \omega \sim \Delta_{\text{EIT}}\), as predicted by the theory and observed in the FDTD simulations. Considering that the operation bandwidth of the system is \(\Delta \omega \sim \Delta_{\text{EIT}}\), and the characteristic delay time is \(\Delta \tau \sim 2\pi/((\gamma_{01} + \gamma_{02})\), the delay-bandwidth product can therefore be written as \(\Delta \omega \Delta \tau = 2\pi\Delta_{\text{EIT}}/(\gamma_{01} + \gamma_{02})\). For the system sketched in figure 1(a), the delay-bandwidth product is about 460, which is far greater than that of a static resonator system (no more than \(2\pi\) ) [4, 10–13].

To ensure a perfect storage, the initially detuned two nanocavities should be tuned into resonance. In our case, the required frequency shift is \(|\omega_{02} - \omega_{01}|/\omega_{02} = 3.72 \times 10^{-4}\), which corresponding to an extremely small refractive index variation in cavity of \(\Delta n \sim 1.26.3 \times 10^{-3}\). Note that \(\Delta n\) of \(10^{-3}\) and \(10^{-2}\) order can be achieved via Kerr (e.g., using polymer material, which has instantaneous response time and much larger Kerr nonlinearity coefficient than silicon [22]), carrier-plasma, and electro-optic effects [8, 9, 23]. All the effects are very fast (ps or less) [8, 9, 23], which is crucial for experimental realization of this approach, since our further numerical experiments (see figure 4) reveal that even when the index tuning time \((\Delta t)\) is increased to a relatively long one (e.g., \(\Delta t = 20\) ps), the light storing system still works well, and exhibits similar storage feature as that in figure 3(b) where a transient index tuning is taken \((\Delta t = 5\) fs). In addition, as demonstrated above that in this dynamic storage system, the delay-bandwidth product is inversely proportional to \((\gamma_{01} + \gamma_{02})\). Accordingly, in order to further improve the delay-bandwidth product, trying to decrease the intrinsic losses in cavities is of great importance. In actual photonic systems, the cavity system might have losses (such as absorption loss, scattering loss, and radiation loss). However, these intrinsic losses can be well controlled to an extremely low level by current techniques, and ultrahigh-Q (over \(10^6\)) PC cavities have been experimentally achieved [24–26]. In these optimally designed cavities [24–26], the intrinsic losses are even lower than that of the system shown in figure 1(a). Therefore, the theoretical proposal is experimentally feasible, and can be naturally applied to other photonic systems with high-Q standing-wave cavities.

In summary, we analytically and numerically present a general yet simple approach for effectively trapping, storing and releasing a signal pulse, and eventually breaking the delay-bandwidth limit, based on controllable EIT-like effect in dynamically tuned standing-wave nanocavities. This approach will be important for on-demand controlling the flow of light on-chip.
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References

[1] Liu C, Dutton Z, Behroozi C H and Hau L V 2001 Observation of coherent optical information storage in an atomic medium using halted light pulses Nature 409 490
[2] Sayrin C, Clausen C, Albrecht B, Schneeweis P and Rauschenbeutel A 2015 Storage of fiber-guided light in a nanofiber trapped ensemble of cold atoms Optica 2 353
[3] Notomi M, Yamada K, Shinya A, Takahashi J, Takahashi C and Yokohama I 2001 Extremely large group-velocity dispersion of line-defect waveguides in photonic crystal slabs Phys. Rev. Lett. 87 253902
[4] Xie F, Sekaric I and Vaslov Y 2007 Ultracompact optical buffers on a silicon chip Nat. Photon. 1 65
[5] Schulz S A, O’Faolain L, Beggs D M, White T P, Melloni A and Krauss T F 2010 Dispersion engineered slow light in photonic crystals: a comparison J. Opt. 12 104004
[6] Yanik M F and Fan S 2004 Stopping light all-optically Phys. Rev. Lett. 92 083901
[7] Yanik M F and Fan S 2007 Slow light–dynamic photon storage Nat. Phys. 3 372
[8] Tanaka Y, Upham J, Nagashima T, Sugiyama T, Asano T and Noda S 2007 Dynamic control of the Q factor in a photonic crystal nanocavity Nat. Mater. 6 862
[9] Xu Q, Dong P and Lipson M 2007 Breaking the delay-bandwidth limit in a photonic structure Nat. Phys. 3 406
[10] Otsuka K, Kobayashi N and Tomita M 2007 Slow light in coupled-resonator-induced transparency Phys. Rev. Lett. 98 213904
[11] Kocaman S, Yang X, McMillan J F, Yu M B, Kwong D L and Wong C W 2010 Observation of temporal group delay in slow-light multiple coupled photonic crystal cavities Appl. Phys. Lett. 96 221111
[12] Hu C, Schulz S A, Liles A A and O’Faolain L 2018 Tunable optical buffer through an analogue to electromagnetically induced transparency in coupled photonic crystal cavities ACS Photon. 5 1827
[13] Jiang F, Deng C-S, Lin Q and Wang L-L 2019 Simulation study on active control of electromagnetically induced transparency analogue in coupled photonic crystal nanobeam cavity-waveguide systems integrated with graphene Opt. Express 27 32122
[14] Fan S, Suh W and Joannopoulos J D 2003 Temporal coupled-mode theory for the Fano resonance in optical resonators J. Opt. Soc. Am. A. 20 569
[15] Li C, Wang M and Wu J-F 2017 Broad-bandwidth, reversible, and high-contrast-ratio optical diode Opt. Lett. 42 334
[16] Zheng C, Jiang X, Hua S, Chang L, Li G, Fan H and Xiao M 2012 Controllable optical analog to electromagnetically induced transparency in coupled high-Q microtoroid cavities Opt. Express 20 18319
[17] Iserles A 1996 A First Course in the Numerical Analysis of Differential Equations (Cambridge: Cambridge University Press)
[18] Sato Y, Tanaka Y, Upham J, Takahashi Y, Asano T and Noda S 2012 Strong coupling between distant photonic nanocavities and its dynamic control Nat. Photon. 6 56
[19] Wang B, Wu J-F, Li C and Li Z-Y 2018 Dynamic tuning of the Q factor in a photonic crystal nanocavity through photonic transitions Opt. Lett. 43 3945
[20] Taflove A and Hagness S C 2000 Computational Electrodynamics (Boston: Artech House)
[21] Li C, Wu S-Y and Wu J-F 2019 Broad-bandwidth, reversible nonreciprocal light transmission based on a single nanocavity Opt. Express 27 16530
[22] Hu X, Xin C, Li Z and Gong Q 2010 Ultra-high-contrast all-optical diodes based on tunable surface plasmon polaritons New J. Phys. 12 023029
[23] Reed G T, Mashanovich G Z, Gardes F Y, Nedeljkovic M, Hu Y, Thomson D J, Li K, Wilson P R, Chen S-W and Hsu S S 2013 Recent breakthroughs in carrier depletion based silicon optical modulator Nanophotonics 3 229
[24] Song B-S, Noda S, Asano T and Akahane Y 2005 Ultra-high-Q photonic double-heterostructure nanocavity Nat. Mater. 4 207
[25] Ashida K, Okano M, Ohtsuka M, Seki M, Yokoyama N, Koshino K, Mori M, Asano T, Noda S and Takahashi Y 2017 Ultrahigh-Q photonic crystal nanocavities fabricated by CMOS process technologies Opt. Express 25 18165
[26] Asano T, Ochi Y, Takahashi Y, Kishimoto K and Noda S 2017 Photonic crystal nanocavity with a Q factor exceeding eleven million Opt. Express 25 1769

Figure 4. (a) Refractive index variation as a function of time. Δt is the index tuning time. (b) Dynamics of the intracavity energy when the index tuning time is Δt = 20 ps.