Manipulating photons in a way like an optical tweezer

Jun-Fang Wu, Jia-Hui Chen and Chao Li

School of Physics and Optoelectronic Technology, South China University of Technology, Guangzhou 510640, People’s Republic of China

Author to whom any correspondence should be addressed.
E-mail: lichao@scut.edu.cn

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Abstract

Arbitrary control of photon flow is of fundamental significance in many applications of light. Here, we propose a new approach that can trap, store, and move the signal photons to arbitrary desired place, just like what optical tweezers do on micro particles. In addition, the trapped photons can also be released at a given direction. The mechanism is based on an ultrahigh-Q nanocavity formed by two dynamically-generated potential barriers in a photonic crystal (PC) waveguide. Different from the traditional fixed ultrahigh-Q nanocavities, this new-type cavity can be formed instantaneously at any moment and any position in a PC waveguide, and is completely movable while keeps ultrahigh Q factor simultaneously. These novel features make controlling the flow of light like an optical tweezer possible, and open up new opportunities for dynamic light–matter interactions and on-chip optical signal processing.

Optical tweezer is known as a revolutionary tool that can trap and manipulate neutron micro particles, e.g., trapping and displacing an atom or biological cell to any desired location, which is of great importance in many fields [1–3]. However, such optical tweezers cannot manipulate photons in the way as they do on the micro particles. To trap and store photons, there are several methods have been developed in past decades, e.g., using electromagnetically induced transparency (EIT) effect in multi-level atomic systems via quantum destructive interference effect [4], and the coherent population oscillation effect in solid-state systems [5]. In such systems, specific wavelengths of light are required, and the bandwidth for operation is ultranarrow, which may limit their applications in information technologies. Another promising method is based on dynamic Brillouin grating, i.e., by converting the signal light into acoustic excitations in an optical fiber through the process of stimulated Brillouin scattering [6–8]. The generation of dynamic Brillouin grating needs two intense optical waves coherently counter-propagating along a fiber, and the wavelengths of the signal light and the pump light should match specific conditions [6–8], which adds the complexity of the system, and the working bandwidth is also narrow. Actually, to realize on-chip light storage and break the delay–bandwidth limit, micro/nanocavities with tunable Q factors are ideal candidates [9–14]. So far, various mechanisms have been proposed to realize dynamically tuning the cavity Q factors, e.g., by using an all-optical analogue of EIT on a silicon chip [9–12], or through destructive/constructive interferences in a cavity–mirror system [13], or via controllable intermode photonic transitions between a low-Q mode and an ultrahigh-Q mode inside a nanocavity [14]. These methods can trap and store signal photons effectively, however, they cannot move the trapped light, since all of the involved cavities are fixed relative to the waveguides [9–14]. Although in reference [15], Birowosuto et al proposed a movable nanowire cavity via placing a nanowire into a grooved photonic crystal (PC) waveguide filled with liquid, the Q factor is relatively small (several thousands) and is hard to be dynamically tuned as that in references [9–14]. Besides, the use of liquid makes the response slow and adds the system’s complexity. Consequently, how to deliver the trapped signal photons to arbitrary desired place just like what optical tweezers do on micro particles remains a challenge.

In this paper, we will explore a new approach to realize this optical-tweezers-like action. The mechanism is based on an ultrahigh-Q nanocavity formed by two dynamically-generated potential barriers in a PC waveguide, as will be shown in detail below. Different from the traditional fixed ultrahigh-Q PC
nanocavities [16–18] (which are commonly formed by local spatial-structure tuning, e.g., using a double-heterostructure [17, 18]), this new-type dynamically-generated cavity is reconfigurable, since it can be formed instantaneously at any moment and any position in a PC waveguide, and is completely movable while keeps ultrahigh Q factor simultaneously. For the traditional resonators, the signal light flowing into them is ‘passive’, so that to trap and store photons, we have to employ some sophisticated interference techniques to dynamically tune the Q factor [9–13]. While for this dynamically-generated cavity, the capture of light is ‘active’, so that we can trap a traveling signal pulse freely without interference control. Besides, the moving speed of the cavity (as well as the trapped photons) can be freely controlled, which is more flexible than the other proposed slow light waveguides [19–21]. More interestingly, the trapped photons can be released at a given direction, rather than at two opposite directions along the waveguide as most of the previously reported resonator-based light storage systems [9–14]. These novel features make trapping, storing, displacing, and releasing the signal light like optical tweezers possible, and open up new opportunities for quantum computing and on-chip optical signal processing.

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 $r = 110$ nm. The refractive index of silicon is $n_0 = 3.4$, the lattice constant is $a = 420$ nm, and the thickness of the slab is $h = 0.5a$. A W1 line-defect waveguide is formed by removing one line of air-holes along the ΓK direction. The band diagram for the structure is shown in figure 1(b), which exhibits two waveguide modes within the bandgap region, with odd symmetry (the blue curve) and even symmetry (the green curve), respectively. The corresponding magnetic-field profiles of the odd and even waveguide modes are depicted in figures 1(c) and (d), respectively. Without loss of generality, here we select the even mode to illustrate the underlying physical mechanism for our approach. Noticing that the area above the even-mode curve is a transmission-permitted region, while the area below it is a mode-gap region where propagation is inhibited. If the refractive index of the waveguide region is slightly decreased, the band diagram of the W1 waveguide will rise a little correspondingly, as shown by the dashed lines in figure 1(b). In the meantime, the transmission and mode-gap regions will also rise. Thus, if we simultaneously alter the permittivity of the two adjacent local regions (the red-shadowed areas in figure 1(a)) in the waveguide, we obtain the frequency diagram along the waveguide direction, as sketched in figure 1(e), where two potential barriers emerge. These two potential barriers act as perfect mirrors with the help of mode gap, and an ultrahigh-Q Fabry–Pérot (F–P) nanocavity is then formed. Considering that the index variation could be realized by transient optical nonlinearity induced by light beam illumination from the top, we thus refer to this new-type resonator as ‘photogenerated’ (PG) nanocavity. This PG nanocavity should be distinguished from the dynamic grating, since the latter is generated by coherent effect with two intense optical waves counter-propagating along a fiber, and the working bandwidth is relatively narrow (GHz) [6–8]; while for the PG cavity presented here, the mechanism is based on dynamic band-gap effect, rather than coherent effect, so that the working bandwidth (which can be as high as THz) is far greater than that of the dynamic gratings.

Next, we will show how to utilize the PG cavity to trap, store and release signal photons, in a way quite different from the other dynamically-tuning-Q mechanisms [9–14]. Initially, an incident signal pulse is traveling along a W1 PC waveguide. Since there is no resonator at present, the signal pulse will transmit freely, as depicted in figure 2(a). If we want to trap the signal light at any desired moment or location, we can suddenly alter the local refractive index of the waveguide to form two potential barriers (e.g., by casting two pump light beams from the top) to capture the signal photons and store them inside the PG nanocavity, as shown by figure 2(b). The resonant frequency of the cavity mode is designed to be the same as the center frequency of the incident signal pulse in advance, simply via tuning the distance of the two potential barriers. When we want to release the trapped light, just remove one of the potential barriers by stopping index modulation on it, and the trapped light will leak out at a given direction, as illustrated by figure 2(c). This dynamic process is accompanied by a reversible bandwidth compression of the signal light, as shown below.

To verify the above-mentioned physical mechanism, finite-difference time-domain simulations [22] are performed on the PC structure shown in figure 3(a). The spatial grids in the horizontal and vertical directions are all chosen to be $a/30$, and the corresponding temporal grid is set to be $0.02(a/c)$. A perfectly matched layer of 1 μm is employed as absorbing boundary. The length of the system is set to be 87a, which is long enough to observe the following dynamic process, and all the other parameters are the same as that in figure 1(a). In the tuned waveguide, the refractive index of the dielectric material for each rectangular red-shadowed area sketched by figure 3(a) is decreased by $\Delta n/n_0 = 1\%$ to form two potential barriers acting as the mirrors of a F–P cavity. The length and width for each tuned area are 6a and 4a, respectively, and the center distance $l$ of the two rectangular regions can be tuned to make the resonance of the PG cavity match the carrier frequency of the incident signal pulse. Besides, in real experiments, the PC waveguides may suffer from scattering loss due to random variations of the air holes [23–25]. However, as
Figure 1. (a) 2D triangular-lattice PC slab with a W1 waveguide. The two red-shadowed rectangular areas denote index modulation regions. (b) Calculated band structure for (a). The solid lines represent the waveguide mode when without refractive-index tuning, while the dashed lines denote the case when $\Delta n/n_0 = -1\%$. The gray-dashed straight line is light line. (c) and (d) Field profiles of the odd and even waveguide modes, respectively. The dashed lines denote waveguides. (e) Sketch of the band diagram along the waveguide direction when index modulations are simultaneously added to the red-shadowed regions in (a). The two dynamically-generated potential barriers form a F–P cavity between them.

Figure 2. Schematic diagram of the principle for light storage and release. (a) Signal light travels freely when without index modulation. (b) Trapping and storing the signal light inside an ultrahigh-Q cavity with two potential barriers when index modulations are added. (c) Releasing the signal light at specified direction when a ‘door’ is open.

demonstrated numerically and experimentally by Notomi et al, the PC cavities are much less sensitive to disorder than the PC waveguides [23]. As a result, an ultralong photon lifetime (1.1 ns) for fabricated PC cavities has been observed, which is about four times as long as that estimated from the scattering loss of the PC waveguides (with a typical value of 2 dB cm$^{-1}$) [23]. To mimic the real case, here we intensively introduce a little imaginary component to the refractive index of the cavity region, with an imaginary value of $n_i = 1.9 \times 10^{-6}$, which is equivalent to a waveguide scattering/absorption loss 2.4 dB cm$^{-1}$ [25] and a cavity intrinsic decay rate $\gamma_{in} = 1.42 \times 10^{-7} \ (2\pi/\alpha)$. As an example, when $l = 14\alpha$, the resonant frequency of the PG cavity is $\omega_0 = 0.2518 \ (2\pi c/\alpha) \ (or \ \lambda_0 = 1670.14 \ nm)$, and the Q factor is calculated to be $\sim 830\ 000$. 

Figure 3. (a) An signal pulse at $\omega = 0.2518 (2\pi c/a)$ is launched at the left end of the waveguide. (b)–(h) Snapshots of field distributions during optical trapping and storing process. At $t = 14$ ps, a sudden index modulation of $\Delta n/n_0 = -1\%$ is added to the red-shadowed regions in (a) (also denoted by the red arrows in (e)), to trap and store the signal pulse.

by an exponential fit of the electromagnetic energy decay. This $Q$ factor is slightly lower than that derived from $n_i = 1.9 \times 10^{-6}$ (for which $Q = \omega_0/(2\gamma_{in}) \sim 890 000$), since except for the scattering/absorption loss, the vertical radiation loss should also be taken into account [23, 24]. The calculated vertical radiation $Q_r$ is $\sim 1.1 \times 10^7$, which indicates the vertical radiation is well suppressed because the index variation at the cavity boundary is very gentle [16–18]. Thus, we can immediately form an ultrahigh $Q$ nanocavity via dynamical index tuning on the waveguide, without changing the local spatial structure as the other ultrahigh-$Q$ PC devices [16–18, 23, 24].

These unique features of the PG cavity offer us more flexibility in manipulating the photons. In the following simulation, a 5 ps Gaussian signal pulse with center wavelength at $\lambda = 1670.14$ nm (or $\omega = 0.2518 (2\pi c/a)$, as shown by the red point in figure 1(b)), which is exactly the resonance of the to-be-formed PG cavity, is launched at the left end of the waveguide. To trap this freely traveling pulse, we can create a dynamically-formed PG cavity at any desired location when the signal pulse passes there. For instance, at $t = 14$ ps, the light pulse arrives at the center of the waveguide. We then add sudden index modulations of $\Delta n/n_0 = -1\%$ on the red-shadowed areas in figure 3(a), forming two potential barriers to trap the passing pulse. Noticing that spectral width of the signal pulse ($\Delta\omega \sim 2.8 \times 10^{-4} (2\pi c/a)$) is much less than the ‘height’ of the potential barriers ($\Delta\omega_h \sim 2.5 \times 10^{-3} (2\pi c/a)$, as shown in figure 1(e)), so that the trapped portion of the signal will be safely stored inside the PG cavity with a long photon lifetime ($\Delta\tau \sim 0.74$ ns for $Q \sim 830 000$). Thus, the delay-bandwidth product ($\Delta\omega \Delta\tau$), which characterizes the storage capacity of a resonator system, is calculated to be 2680. This value is far greater than the other reported results [10–14]. Figures 3(b)–(h) show the field-pattern evolution of the energy distributions at different moments. These figures provide an intuitive insight to understand how to transform a traveling light into a frozen state.

More interestingly, this trapping process is accompanied by a bandwidth compression of the signal light: from its initial spectral width of $\Delta\omega \sim 2.8 \times 10^{-4} (2\pi c/a)$ to a much narrower one of the ultrahigh-$Q$ cavity mode ($\sim 3.0 \times 10^{-7} (2\pi c/a)$). We think this bandwidth compression originates from a dynamic frequency conversion process. As soon as the signal pulse is trapped inside an ultrahigh-$Q$ cavity, since the
Figure 4. Dynamic releasing process after a given delay. At $t = 60$ ps, the right potential barrier disappears when we stop index modulation on it while keep the left barrier alive. The trapped light flows out quickly and travels rightward along the waveguide.

initial spectral width of the pulse is much broader than the cavity mode, the components beyond the resonant frequency cannot form ‘steady’ standing waves when they are reflected back and forth between the two potential barriers. Therefore, the phases of these components will be periodically altered for each round-trip time, which leads to the excitation of the cavity mode [26, 27]. In an ultrahigh-$Q$ cavity, the aforementioned process repeats itself for many rounds, so that eventually the energy of the other spectral components will all be transferred into the cavity mode, and the spectral width of the signal pulse is therefore significantly compressed. As a result, the delay-bandwidth limit [9], which characterizes the storage capacity of a resonator system, is naturally broken during this dynamic process, without any complicated tuning-$Q$ techniques as that in references [9–14].

To release the trapped light after a given delay, we can simply stop index modulation on any of the two red-shadowed regions in figure 3(a). Thus, the corresponding potential barrier will disappear immediately, and the trapped signal energy will flow out quickly along a specified direction from the ‘open door’. This direction-controllable releasing is useful for robust light manipulations. In contrast, for most of the previously reported resonator-based light storage systems [9–14], the released signal pulses always flow along the waveguide in two opposite directions simultaneously, rather than in a specified one.

As an example, figure 4 exhibits the dynamic releasing process follows behind the trapping and storing process in figures 3(b)–(g). At $t = 60$ ps, we stop the refractive index modulation on the right shadowed area, so that the right potential barrier will disappear immediately while the left one still exists. It can be seen that the trapped light waves instantly flow out and travel rightward along the waveguide, while the leftward transmission is forbidden. Thus, we can control the releasing direction in a quite simple way.

Figures 5(a) and (b) further shows the simulation results for the temporal evolutions of the intracavity energy and the output waveforms during the above-mentioned releasing process. From figure 5(a), one can see before release, the signal energy is perfectly stored inside the PG cavity, with a very little decay rate $2\gamma_0 \sim 3.0 \times 10^{-7} (2\pi c/a)$, which corresponds to a long photon lifetime of about 0.74 ns (i.e., $Q \sim 830,000$). When the trapped light is released at $t = 60$ ps after a given delay, we see that the stored signal energy escapes from the PG cavity quickly (with a decay rate $2\gamma_1 \sim 3.2 \times 10^{-3} (2\pi c/a)$) and leaks into the output waveguide, so that a second pulse appears, with a transmission less than the original peak because of the intrinsic loss of the cavity, as shown by figure 5(b).

Actually, the above-mentioned novel phenomena can also be well described by temporal coupled mode theory. Without loss of generality, we suppose the incident Gaussian signal pulse with normalized power has the form of $e^{\omega t} \cdot e^{-(t-t_0)^2/2t_0^2}$, where $\omega$ is the carrier frequency, $t_0$ is the pulse during time, and $t_0$ is the delay time of the signal pulse relative to the time origin. The dynamic ultrahigh-$Q$ cavity is supposed to be formed at $t = t_1$, which means that the pulse will travel freely along the waveguide before $t = t_1$, but will be trapped when the dynamic cavity is formed. Finally, the trapped power is released at $t = t_2$ after a given storage time. Thus, the cavity filed during the whole dynamic process can be described as [27]:

\[ e^{\omega t} \cdot e^{-(t-t_0)^2/2t_0^2} e^{-(t-t_1)^2/2t_1^2} e^{-(t-t_2)^2/2t_2^2} \]
Figure 5. Temporal evolutions of the intracavity light energy and the output waveforms when the trapped signal pulse is released at \( t = 60 \text{ ps} \) after a given delay. (a) and (b) Simulation results. (c) and (d) Theoretical predictions. The physical parameters used for calculations are: \( t_0 = 5 \text{ ps}, t_d = 13 \text{ ps}, \omega = \omega_0 = 0.2518 \left( \frac{2 \pi c}{a} \right), \gamma_0 = 1.5 \times 10^{-7} \left( \frac{2 \pi c}{a} \right), \gamma_1 = 1.6 \times 10^{-3} \left( \frac{2 \pi c}{a} \right), \text{ and } \kappa = 2.1 \times 10^{-4} \left( \frac{2 \pi c}{a} \right), \) which can be obtained by fitting the simulation curve in (a).

\[
\frac{dA}{dt} = (j\omega_0 - \gamma)A + \kappa e^{j\omega t} e^{-\left(\frac{(t-t_0)^2}{t_0^2}\right)} \quad (t \geq t_1),
\]
\[
A = e^{j\omega t} e^{-\left(\frac{(t-t_d)^2}{t_0^2}\right)} \quad (t < t_1),
\]
\[
\gamma = \gamma_0 U(t) + \gamma_1 [1 - U(t)],
\]
\[
U(t) = \begin{cases} 1 & (t_1 \leq t < t_2) \\ 0 & (t \geq t_2) \end{cases}
\]

where \( \omega_0 \) is the resonant frequency of the to-be-formed dynamic cavity, and \( A \) is the normalized mode amplitude to represent the electromagnetic energy \( |A|^2 \) stored inside cavity. \( \kappa \) is called excitation factor, which characterizes the strength of the cavity mode excited by the trapped pulse. \( \gamma \) represents the decay rate of the trapped cavity mode amplitude, and is variable for different dynamic process: during the trapping and storing process, \( \gamma = \gamma_0 \); while for releasing process, \( \gamma = \gamma_1 \). \( \gamma = \gamma_0 \) or \( \gamma = \gamma_1 \) is determined by a controlling function \( U(t) \), and \( U(t) = 1 \) means trapping and storing, while \( U(t) = 0 \) corresponds to releasing.
Obviously, $\gamma_0$ is far less than $\gamma_1$, and they can all be calculated by exponential fits of the electromagnetic energy decays during the storing and releasing processes as shown in figure 5(a).

By using four-order Runge–Kutta method [28] to solve equation (1), we obtain the dynamic evolutions of the intracavity energy and output waves during the whole trapping, storing and releasing processes, as shown by figures 5(c) and (d). The detailed parameters employed for calculations can be found in the caption. We really see the signal pulse is successfully trapped by a dynamically-formed ultrahigh-$Q$ cavity at the moment $t_1 = 14$ ps, and is then perfectly stored with a characteristic photon lifetime $1/(2\gamma_0) \sim 0.74$ ns. After a given storing time, the trapped signal is released at $t_2 = 60$ ps, we can see the intracavity energy drops quickly, and a second pulse is observed in figure 5(d), with a peak power less than the original one. The theoretical predictions agree very well with the first-principles calculations, and is helpful to understand the mechanism for these novel phenomena.

So far, we have shown how to utilize a PG cavity composed of two dynamically-formed potential barriers to trap, store and release signal photons, in a unique but quite efficient way. Besides that, another appealing feature of this PG cavity is that it is movable relative to the waveguide while keeps an ultrahigh $Q$ factor simultaneously. This can be realized via several methods, e.g., shifting the two pump beams to make the two potential barriers move synchronously, together with the PG cavity among them. Thus, we can shift the trapped light energy to any desired location to join (or quit) desired light–matter interactions, including nonlinear process and quantum computing, which will greatly enrich the means for light manipulation.

Figure 6(a) is a schematic diagram for this purpose. After trapping the signal light at $t = 14$ ps and storing it locally, the two rectangular red-shadowed index modulation areas (i.e., potential barriers) begin to move along the waveguide synchronously from $t = 40$ ps, at an arbitrary given speed, e.g., 0.001$c$ ($c$ is the velocity of light in vacuum) in this simulation, and the location enclosed by a green dashed box is the destination, which is 26$a$ away from the initial position. The whole moving dynamics of the PG cavity and the stored signal energy is shown in figures 6(b)–(g). From these field distribution snapshots, we see clearly that the signal energy is always tightly trapped inside the cavity, no matter the cavity is moving (figures 6(b)–(d)), or stop (figures 6(e)–(g)). This implies that the PG cavity is not only movable, but also holds an ultrahigh-$Q$ factor during the whole moving process. More importantly, this effect provides us with a novel tool to control the light speed freely, making the light travel at an arbitrary desired speed far below $c$, which is more flexible than the other proposed slow light effects [19–21].

Finally, we discuss the experimental feasibility of the theoretical proposal. To further prolong the photon lifetime, the intrinsic loss of the dynamic cavity should be significantly suppressed. We note that in some experimental works, the fluctuations in the radii and positions of the air holes are reduced to less than 1 nm, and the propagation losses of the PC waveguides below 1 dB cm$^{-1}$ have been achieved [25]. Moreover, the PC cavities are much less sensitive to disorder than the PC waveguides [23]. Therefore, the cavity intrinsic loss can be well controlled to an extremely low level, and ultrahigh-$Q$ (over 10$^8$) mode-gap nanocavities based on modified PC waveguides have been experimentally realized [23, 24, 29]. Besides, to trap and store the signal light inside the PG cavity effectively, the ‘height’ of the potential barriers $\Delta \omega_0$ should be greater than the spectral width of the signal pulse. Since $\Delta \omega_0$ is proportional to $\Delta n$, a relatively big $\Delta n$ ensure a broader operation bandwidth. For a 10 ps signal pulse, $\Delta n/n_0 \sim 0.1\%$ is enough; while for a 1 ps pulse, $\Delta n/n_0 \sim 0.8\%$ is required. Reference [13] experimentally demonstrated that $\Delta n = 10^{-3}$–$10^{-2}$ could be achieved via ultrafast (ps or less) carrier plasma effect in Si waveguide when a pump light energy of 10–50 pJ was absorbed. Moreover, in Si-based photonic crystals, where the carrier lifetime is on ns scale, the refractive index change can be preserved for a similar length of time [13, 30]. To remove the potential barriers, the previously modulated refractive index should be recovered rapidly. This can be done by sweeping out the carriers via a reverse-biased pn junction [31, 32]. Actually, the scheme is fully compatible with silicon optoelectronics, as the required refractive-index change can be produced by carrier injection or depletion [31–33]. Thus, the theoretical proposal presented here can also be realized electrically.

In summary, we have proposed a new-type ultrahigh-$Q$ nanocavity composed of two dynamically-generated potential barriers. Different from the traditional resonators, here the cavity can be formed instantaneously at any moment and any position in a PC waveguide, and is completely movable while keeps ultrahigh $Q$ factor simultaneously. Taking advantage of these novel features, we have demonstrated that we can trap, store, deliver, and release the signal photons to arbitrary desired place, just like what optical tweezers do on micro particles. As mentioned above, the combination of this method with electronic control (e.g., utilizing electrical carrier injection and extraction to modify the refractive index of Si) is promising for on-chip applications. This enables novel functionalities such as dynamically tuning the cavity $Q$ factors and resonances, controllable quantum dots-cavity interactions, photon memories and pulse compression.
Figure 6. (a) Schematic diagram of shifting the PG cavity and the stored signal energy. The two rectangular red-shadowed index modulation areas (i.e., potential barriers) move along the waveguide synchronously to the location enclosed by a green dashed box, which is 26a away from the initial position. (b)–(g) Snapshots of the moving process. The PG cavity begins to move at $t = 40$ ps and arrives at the destination at 76 ps, and then stay there.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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