Supplementary information

“The sub-femtojoule all-optical switching using a photonic crystal nanocavity”

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Theoretical computation of carrier decay

In the procedure for computing the carrier decay, we performed a two-dimensional carrier diffusion analysis, in which we modeled the two-dimensional cavity structure and resonant modal profile \(I(x, y)\) calculated by the FDTD method\(^{34,40}\). The instantaneous carrier density distribution \(N(x, y, t)\) is given as

\[
\frac{dN(x, y, t)}{dt} = D_{\text{am}} \nabla^2 N(x, y, t) - \frac{N(x, y, t)}{\tau_s} \tag{S1}
\]

where \(D_{\text{am}}\) is the ambipolar diffusion constant, \(e\) is the elementary charge, and \(v_{sr}\) is the surface recombination velocity. \(\tau_s\) is the recombination lifetime in the slab, which is determined by the bulk recombination lifetime \(\tau_b\) and the surface recombination at the slab surface as \((\tau_b^{-1} + 2v_{sr}/d)^{-1}\) where \(d\) is the slab thickness. For the calculation, we employed \(\tau_b = 4\) ns, \(v_{sr} = 2 \times 10^4\) cm/s, and \(D_{\text{am}} = 18\) cm\(^2\)/s as typical InGaAsP parameters. In the computational calculation, the cavity mode profile \(I(x, y)\) and the carrier density \(N(x, y, t)\) are assigned to the two-dimensional space divided by a small unit cell with a size of 10 nm. The position \((x, y)\) is expressed by the discrete coordinate \((i, j)\), while the time \(t\) is expressed by the step number \(n\). Then, \(N(x, y, t)\) and \(I(x, y)\) are denoted as \(N_{i,j}^n\) and \(I_{i,j}\), respectively, and the derivatives in Eq. (S1) are expressed by a finite different formula. We calculated the carrier behavior just decaying after impulse pump light given to the nanocavity (Fig. 2), in which the initial carrier density distribution is determined by \(I_{i,j}\). Thus, Eqs. (S1) and (S2) are solved with respect to the initial carrier density, and the dynamic behavior of \(N_{i,j}^n\) after any time steps are obtained. Here, the averaged carrier density over the cavity mode is given as

\[
\langle N^n \rangle = \frac{\sum N_{i,j}^n I_{i,j}}{\sum I_{i,j}}.
\]

Theoretical computation of switching dynamics

To understand the switching dynamics shown in Fig. 4b and 4d, we employed a combined analysis of a photon energy rate equation and the carrier diffusion equations.
In the computation, we modeled the two-dimensional cavity structure and resonant modal profile \( I(x, y) \) calculated by the FDTD method. By modeling the cavity resonance as a Lorentzian function \( L(\omega, N) \), the rate equation for the photon energy in a cavity is given by

\[
\frac{dU(t)}{dt} = P_{in}(t, \omega) \cdot L(\omega, N) - \frac{U(t)}{\tau_{ph}} \tag{S3}
\]

where \( P_{in}(t, \omega) \) is the instantaneous pulse power. \( U(t) \) can be expanded into a two-dimensional energy distribution \( U(x, y, t) \) by employing the resonant modal profile \( I(x, y) \). Then the carrier density distribution \( N(x, y, t) \) is given as

\[
\frac{dN(x,y,t)}{dt} = \frac{U(x,y,t)}{\hbar \omega m} \left( \frac{1}{\tau_{LA}} + \frac{1}{2\tau_{TPA}} \right) + D \nabla^2 N(x,y,t) - \frac{N(x,y,t)}{\tau_s} \tag{S4}
\]

\[
eN(x,y,t)v_s = -eD_{an} \nabla N(x,y,t) \text{ (at air/semiconductor boundaries)} \tag{S5}
\]

where \( \tau_{LA} \) and \( \tau_{TPA} \) are the absorption lifetime of LA and TPA, respectively, which are described in Method. \( D_{an} \) is the ambipolar diffusion constant, \( e \) is the elementary charge, and \( v_s \) is the surface recombination velocity. Similar to the computation of the carrier decay described in Method, Eqs. (S3), (S4) and (S5) are solved for an input pump pulse by a finite different formula, and the dynamic behavior of a cavity transmission for a probe light is obtained.

Simulations were carried out with the parameters used in the design section of the main text. Here, the probe light was assumed to be a continuous wave, thereby monitoring a transmission change at a certain wavelength on the resonance shift. Figure S1a and b show the measured switching dynamics for switch-off and switch-on, respectively, by pump-probe technique. Figure S1c and d show the simulated results where the input pump energies are similar to the experimental values. These results show good agreement with the measured switching dynamics, although the extinction ratio for \( U_p = 0.79 \) fJ in switch-off regime is larger than the expected in the simulation presented in Fig S1c. One possible reason for the large extinction might be a strong nonlinear absorption. Although we take account a two-photon absorption and a free-carrier absorption into the calculation, the absorption coefficient for them used in our calculation seems to be low.
Figure S1  Switching dynamics of PhC nanocavity. a,b, Measured switching dynamics by pump-probe measurement. Switch-off and switch-on regimes shown in a and b, respectively. The wavelength of the probe light is set at different $\Delta \lambda_{\text{det}}$ as denoted in the figure, while the wavelength of pump light is always set at $\Delta \lambda_{\text{det}} = 0$ nm. Different colors denote the results for different pump energies $U_p$. c,d, Simulated switching dynamics by combined analysis of a photon energy rate equation and the carrier diffusion equations.