Rigorous analysis of bistable memory in silica toroid microcavity

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Effects which can change refractive index

Name	Principle	Speed	Energy consumption	$\Delta n/n$
Thermo-optic (TO) effect1)	heat	μs	pJ	**≈ 1%**
Carrier-plasma effect2)	carrier	< ns	< fJ	< 1%
Kerr effect	light	**ps**	**aJ**	≪ 1%

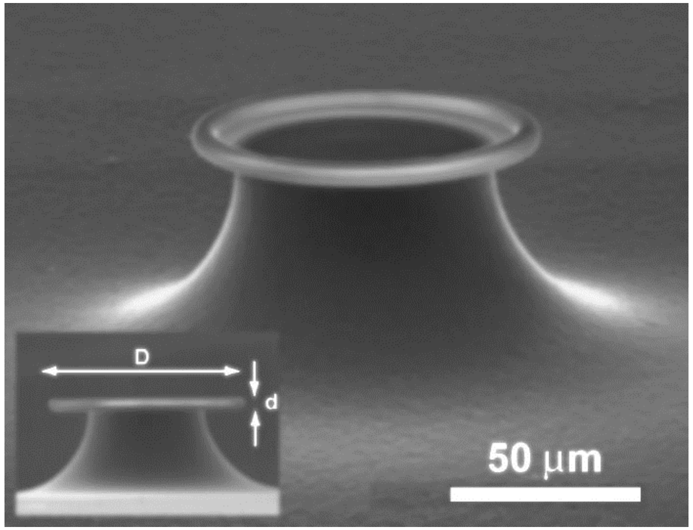
1) V. Almeida, *et al*., Opt. Lett. **29**, 2387–2389(2004).
2) A. Shinya, *et al*., Opt. Express **16**, 19382–19387(200

Material requirements

- Large bandgap
  (to eliminate a carrier-plasma effect)
- Small absorption coefficient
  (to suppressing a TO effect)

Silica

Silica toroid microcavity



T. Kippenberg, *et al*., Appl. Phys. Lett. **85**, 6113–6115(2004).

- made of Silica.
- has ultra high quality factor ($Q > 10^8$).
- can be fabricated on silicon substrate.

Potential for Kerr bistable memory

Purpose of research

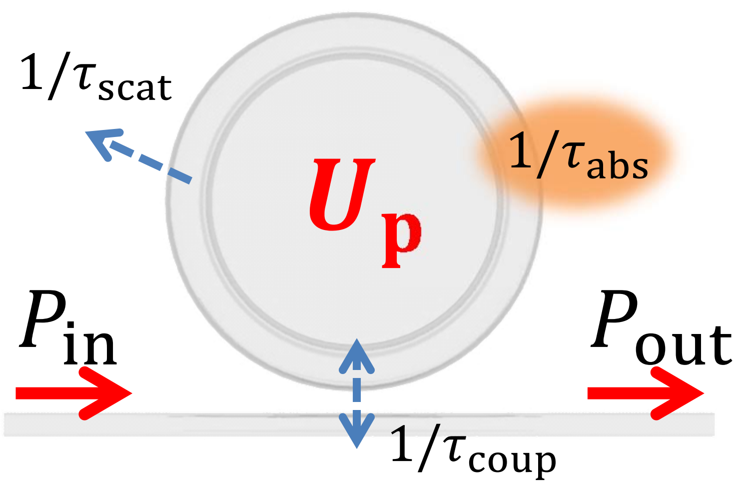
Kerr bistable memory

- ✓ Discrimination between Kerr and TO very difficult.
- ✓ The light absorption at the surface exist.
- ✓ A Kerr bistable memory never yet achieved.
  - ➢ Feasibility of Kerr bistable memory must be verified with numerical simulation.

Purpose

To verify that a Kerr bistable memory is indeed feasible in a silica toroid micro cavity by using a numerical simulation that combines coupled mode theory (CMT) and finite element method (FEM).

Modeling of Kerr bistable memory (1)



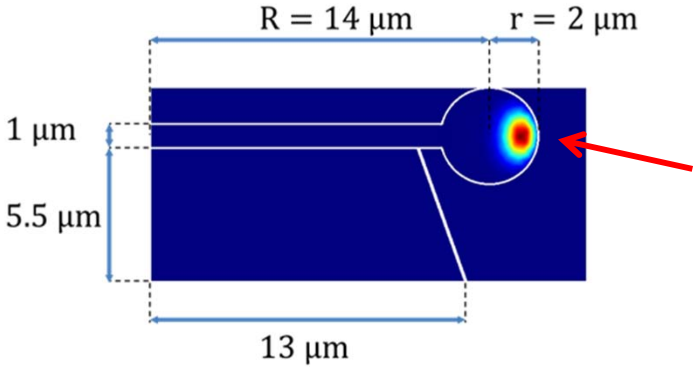
Side coupling model consists of a cavity and a waveguide

- ✓ $\sqrt{T_{\mathrm{in}}(t)}P_{\mathrm{in}}(t)$: Incident power
- ✓ $\tau_{\mathrm{abs}} = 158\ \mathrm{ns}$: Absorption loss rate
- ✓ $\tau_{\mathrm{scat}} = 205\ \mathrm{ns}$: Scattering loss rate
- ✓ τ_{coup} : Coupling to the waveguide

$$\frac{dU_{\mathrm{p}}(t)}{dt} = -\left(\frac{1}{\tau_{\mathrm{abs}}} + \frac{1}{\tau_{\mathrm{scat}}} + \frac{1}{\tau_{\mathrm{coup}}}\right)U_{\mathrm{p}}(t) + \boxed{\sqrt{T_{\mathrm{in}}(t)}}P_{\mathrm{in}}(t)$$

depends on the refractive index change

Modeling of Kerr bistable memory (2)



$$u_\mathrm{p}(x, y, t) = \frac{U_\mathrm{p}(t)}{2\pi R} \cdot I(x, y)$$

M. Oxborrow, IEEE Trans. Microw. Theory Tech. **55**, 1209 (2007).

- ✓ **Refractive index change caused by Kerr effect (Δn_Kerr)**

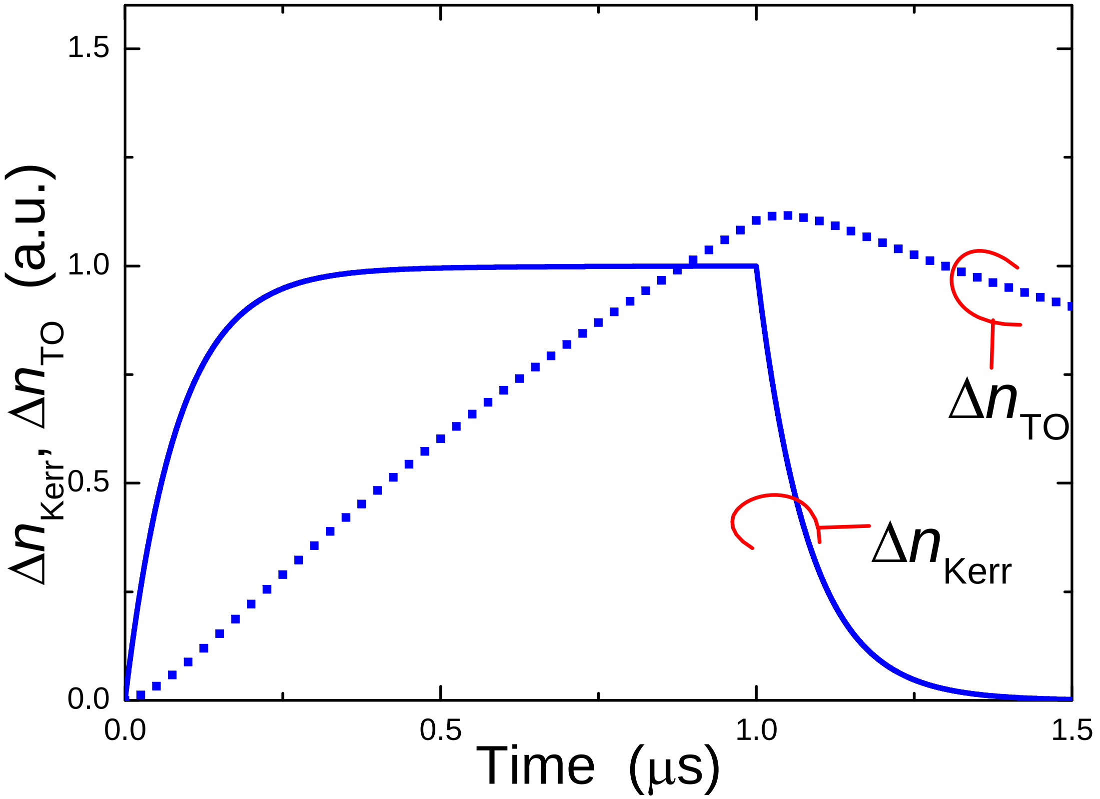
$$\Delta n_\mathrm{Kerr}(x, y, t) = \frac{2n_2 c}{n} u_\mathrm{p}(x, y, t)$$

- ✓ **Refractive index change caused by TO effect (Δn_TO)**

$$\Delta n_\mathrm{TO}(x, y, t) = nC_{TO}\{T(x, y, t) - 300\}$$

$T(x, y, z)$ can be obtained by FEM on the 2D cross-section above.
$(1/\tau_\mathrm{abs})U_\mathrm{p}(t)$ is employed as a heat source.

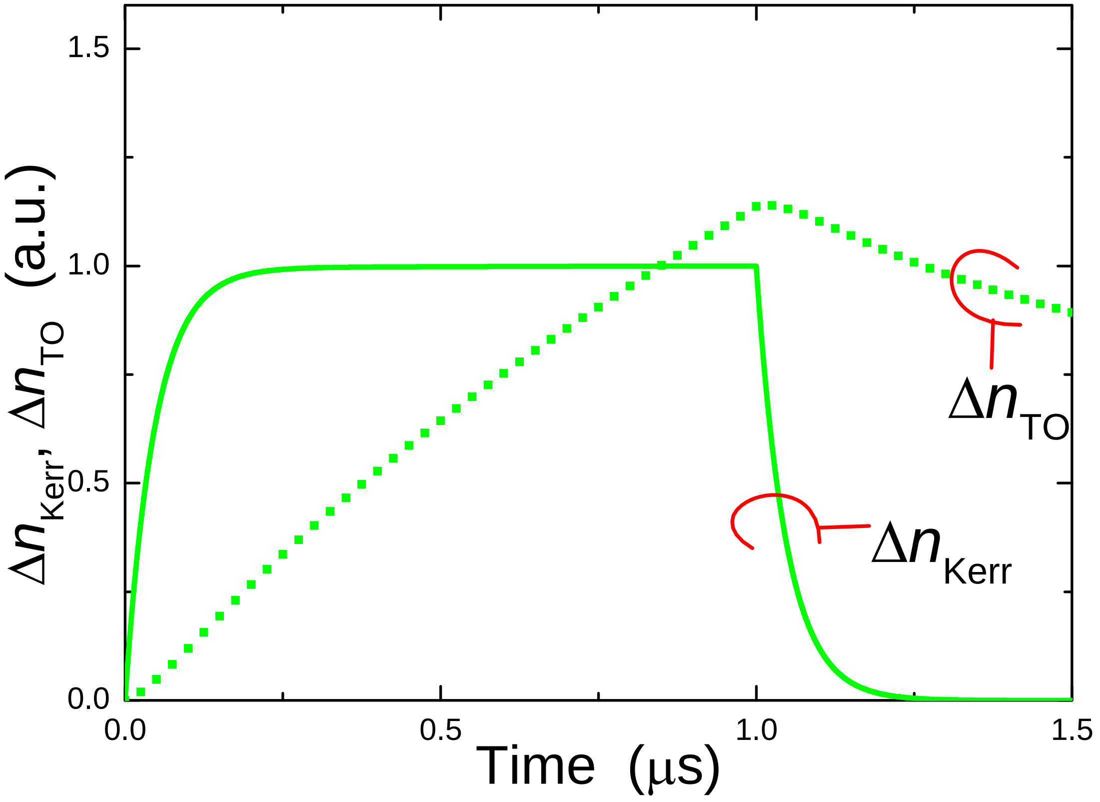
U_{p} vs. Time for different τ_{coup}



- Rectangular pulse with 1 μs is employed.
- Solid and dotted lines represent Δn_{Kerr} and Δn_{TO} , respectively.
- Normalization ($\Delta n_{\mathrm{Kerr,max}} = 1$) is used.

- $\boldsymbol{\tau_{\mathrm{coup}} = 1\ \mu\mathrm{s}}$

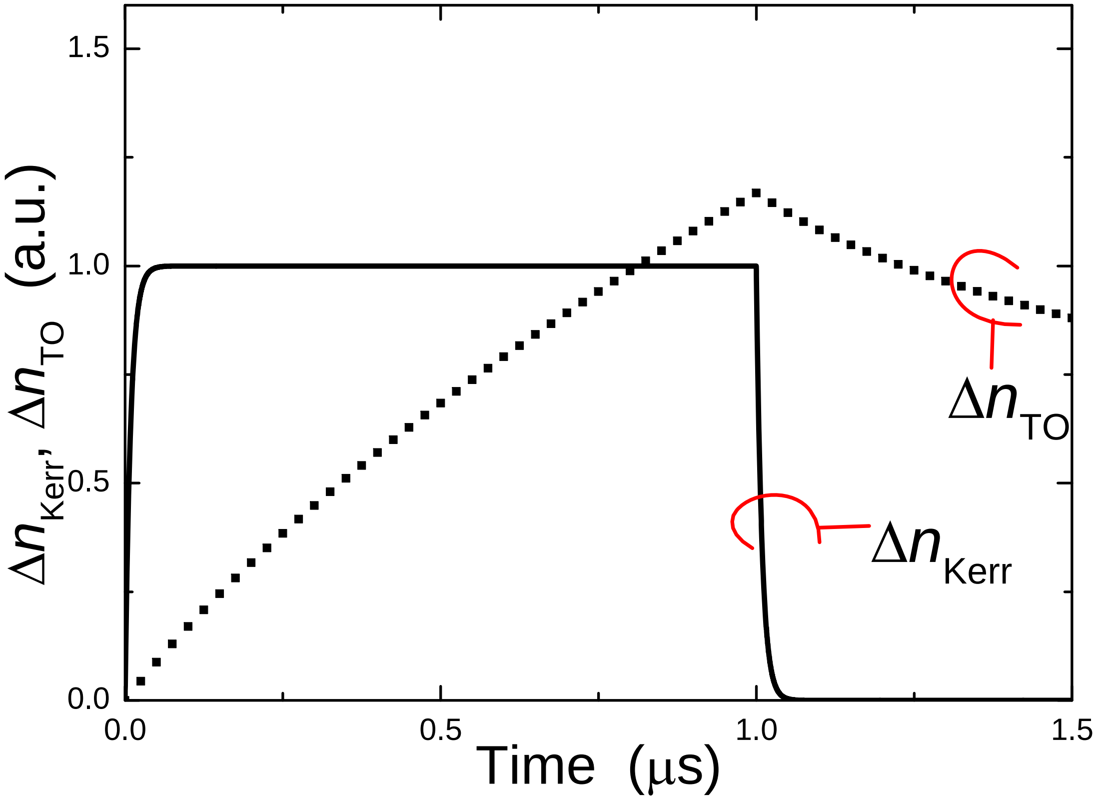
U_p vs. Time for different τ_coup



- Rectangular pulse with 1 μs is employed.
- Solid and dotted lines represent Δn_Kerr and Δn_TO , respectively.
- Normalization ($\Delta \mathrm{n}_\mathrm{Kerr,max} = 1$) is used.

- **$\tau_\mathrm{coup} = 100$ ns**

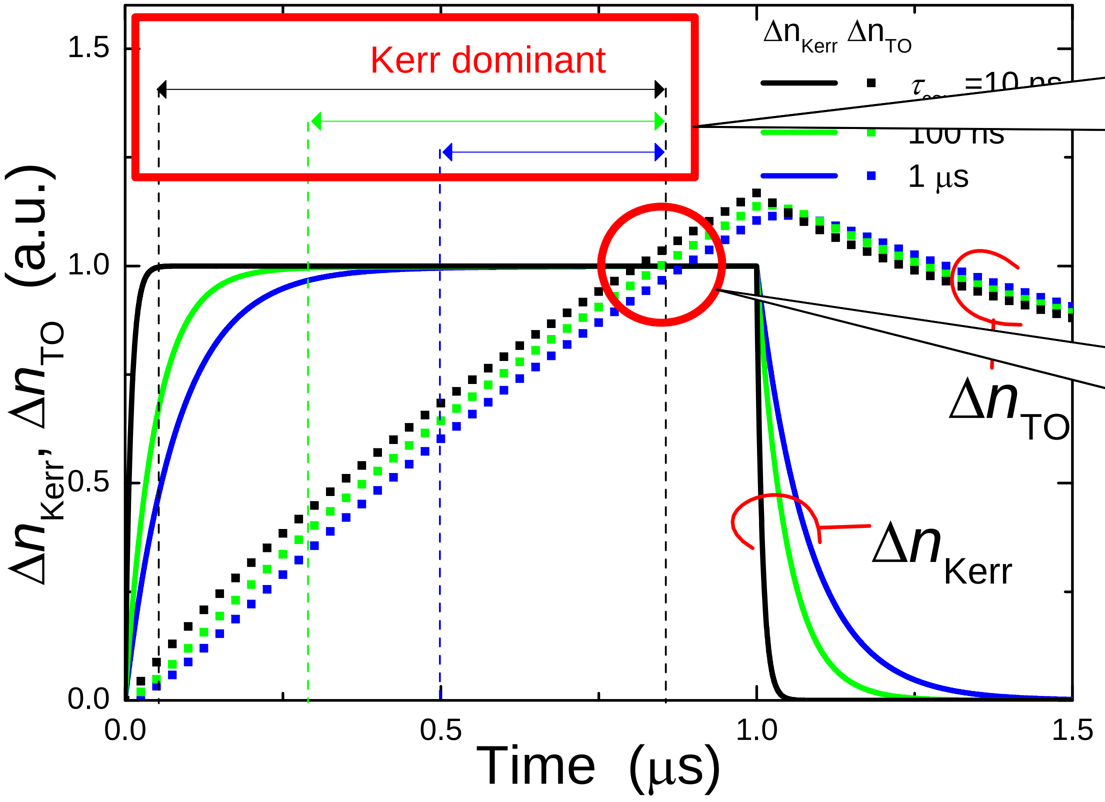
U_p vs. Time for different τ_coup



- Rectangular pulse with 1 μs is employed.
- Solid and dotted lines represent Δn_Kerr and Δn_TO , respectively.
- Normalization ($\Delta \mathrm{n}_\mathrm{Kerr,max} = 1$) is used.

- **$\tau_\mathrm{coup} = 10$ ns**

U_{p} vs. Time for different τ_{coup}

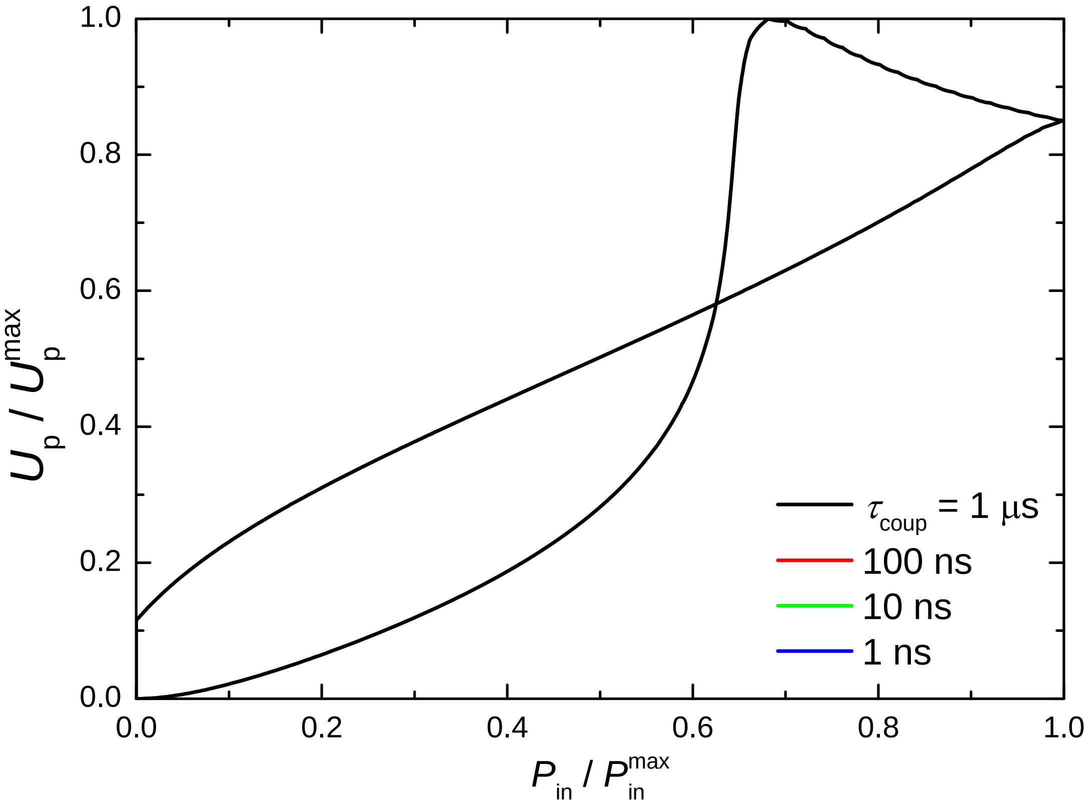


Response speed of Δn_{Kerr} is faster when τ_{coup} is shorter.

$\Delta n_{\mathrm{Kerr}} > \Delta n_{\mathrm{TO}}$ until 800 ns is passed.

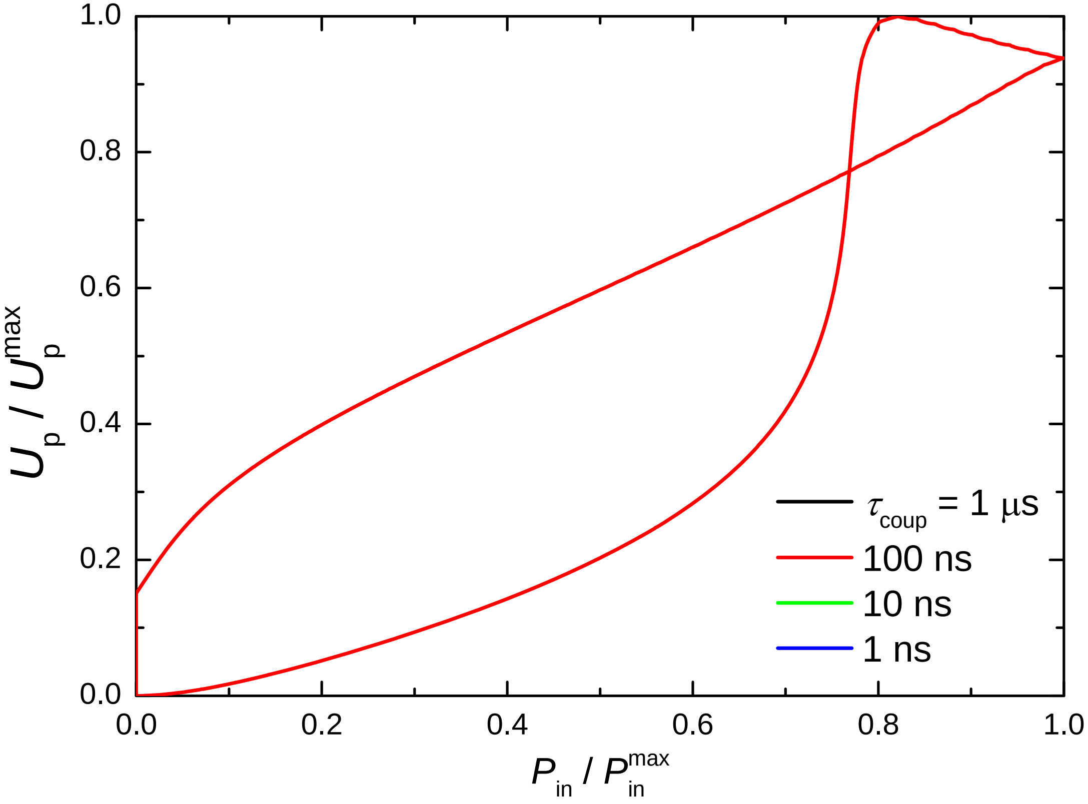
- A short τ_{coup} is preferred in terms of achieving a Kerr bistable memory.

U_p vs. P_in for different τ_coup



- ➢ Triangular pulse employed.
- ➢ y-axis and x-axis normalized as $U_\mathrm{p.max} = 1$ and $P_\mathrm{in.max} = 1$, respectively.
- ➢ **$\tau_\mathrm{coup} = 1\ \mu\mathrm{s}$**

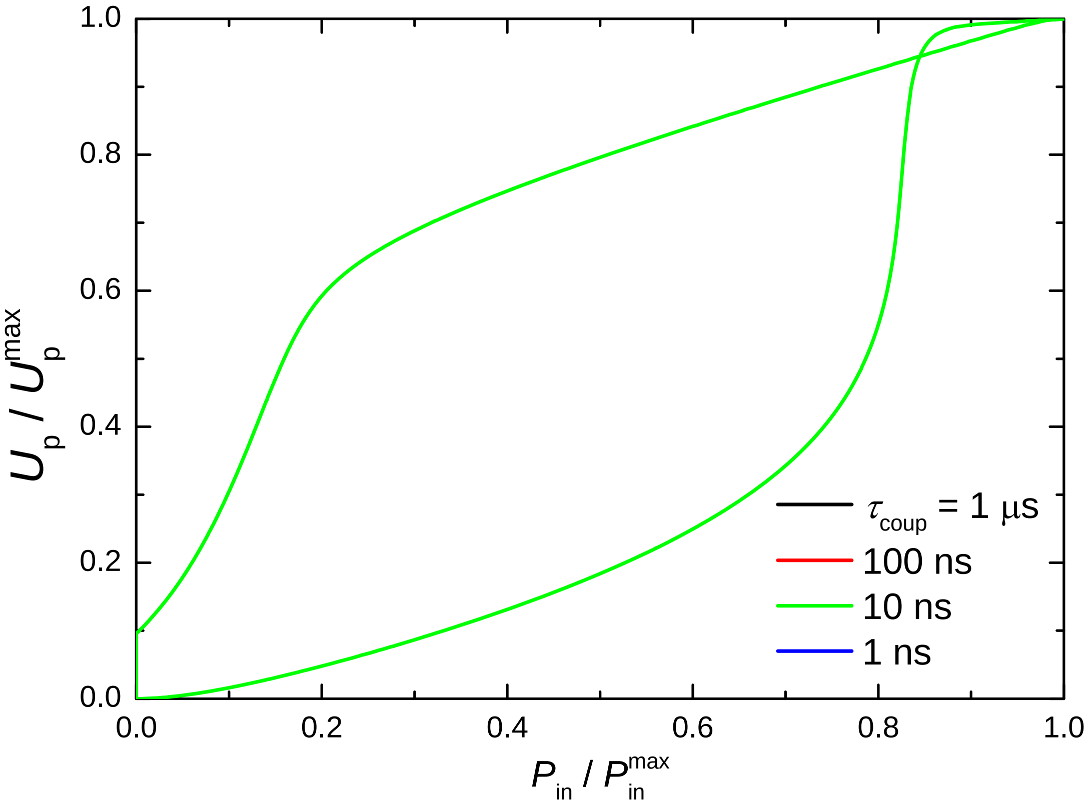
U_p vs. P_in for different τ_coup



- Triangular pulse is employed.
- y-axis and x-axis normalized as $U_\mathrm{p.max} = 1$ and $P_\mathrm{in.max} = 1$, respectively.

- **$\tau_\mathrm{coup} = 100$ ns**

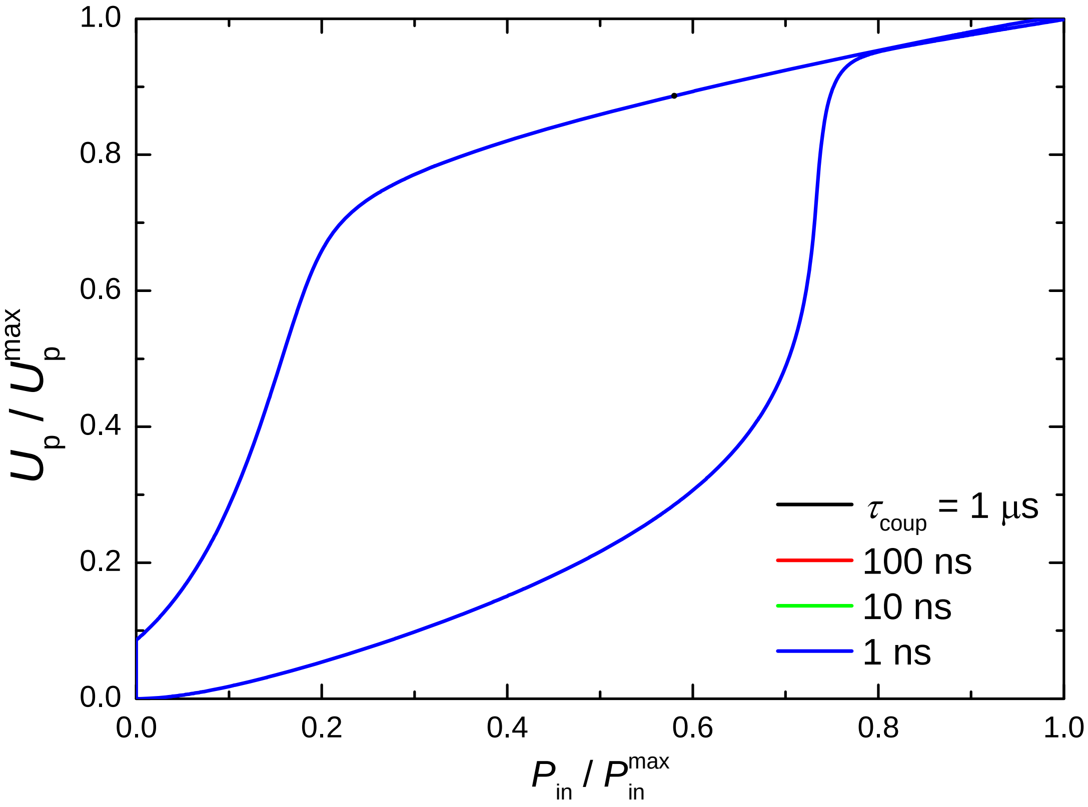
U_p vs. P_in for different τ_coup



- Triangular pulse is employed.
- y-axis and x-axis normalized as $U_\mathrm{p.max} = 1$ and $P_\mathrm{in.max} = 1$, respectively.

- **$\tau_\mathrm{coup} = 10\ \mathrm{ns}$**

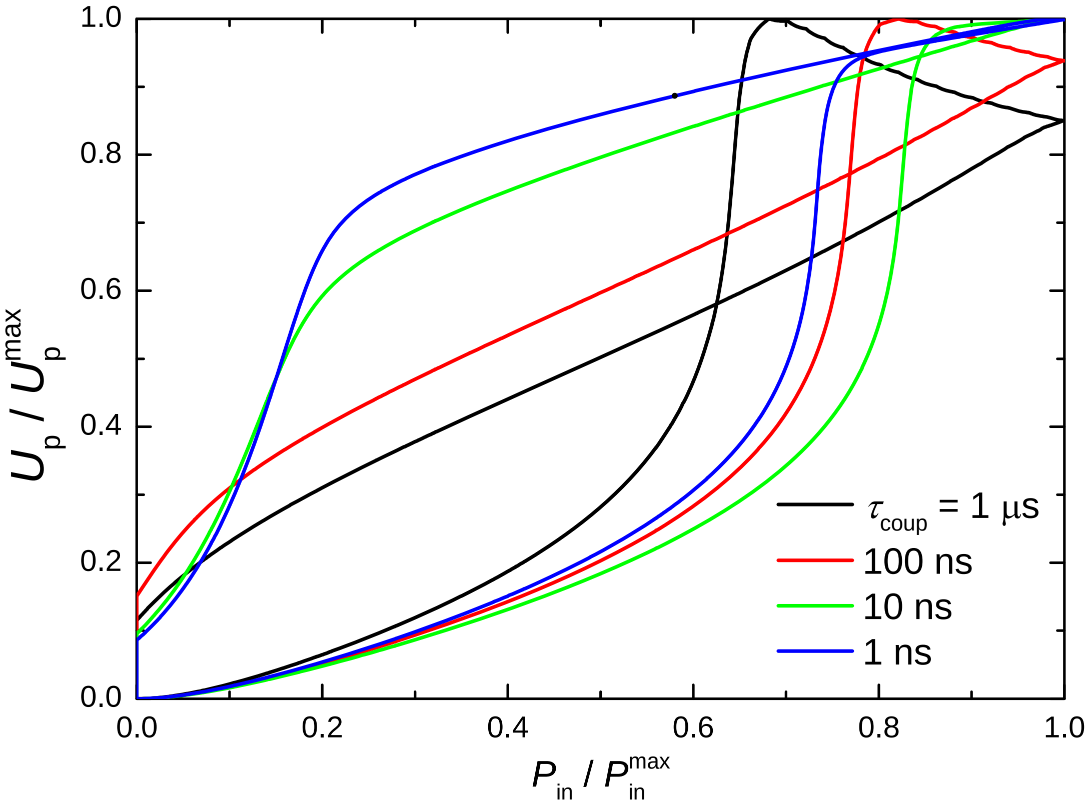
U_p vs. P_{in} for different τ_{coup}



- Triangular pulse is employed.
- y-axis and x-axis normalized as $U_{p.max} = 1$ and $P_{in.max} = 1$, respectively.

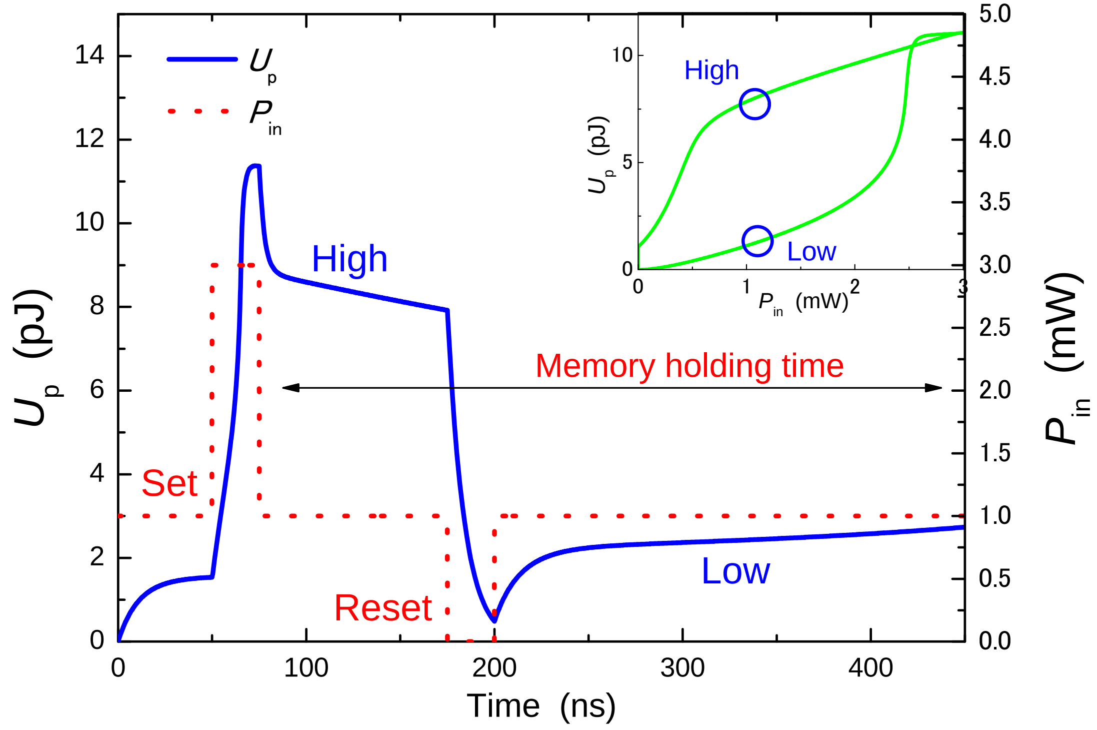
- **$\tau_{coup} = 1$ ns**

U_{p} vs. P_{in} for different τ_{coup}



- ➢ Hysteresis loop becomes more distorted due to TO effect when τ_{coup} is longer.
- ➢ Optical bistability is clearly observed when $\tau_{\mathrm{coup}} < 10$ ns.

Memory operation



- Blue and red line represent U_p and P_in ,respectively.
- $\boldsymbol{\tau}_\mathbf{coup} = \mathbf{10\ ns}$

- **We can obtain Kerr bistable memory by adjusting coupling photon lifetime τ_coup.**
- Memory time is approximately 360 ns and driving power is 1 mW.

Comparison with prior research

Cavity type	Principle	Q_{int}	P_{drive}	$E_{\mathrm{consumption}}$
Silicon microring(3)	TO	1.43×10^5	$800\ \mu\mathrm{W}$	pJ
Photonic crystal(4)	Carrier-Plasma	1.2×10^6	$250\ \mu\mathrm{W}$	$<$ fJ
Silica toroid(5)	Kerr	1.25×10^8	$1\ \mathrm{mW}$	aJ

3) Q. Xu, *et al*., Nat. Phys. **3**, 406–410 (2007).
4) T. Tanabe, *et al*., Nat. Photonics **1**, 49–52(2007).
5) D. Armani, *et al*., Nature **421**, 925–928 (2003).
6) M. Soljacic, *et al*., Phys. Rev. E **66**(2003)

- A toroidal cavity is ultra low loss.
- P_{drive} is much lower than the conventional analysis ($P_{\mathrm{drive}} = 133\ \mathrm{mW}^{6)}$).
- Energy required to change refractive index is low.

Our memory can be used for quantum optical information technology or devices that require photon conservation.

Summary

- We verified that a Kerr bistable memory is feasible in a silica toroid microcavity by adjusting the coupling between the cavity and waveguide.

- A memory time of 360 ns and a driving power of 1 mW are obtained when τ_{coup} was $10\ \mathrm{ns}$.

Thank you for your attention.