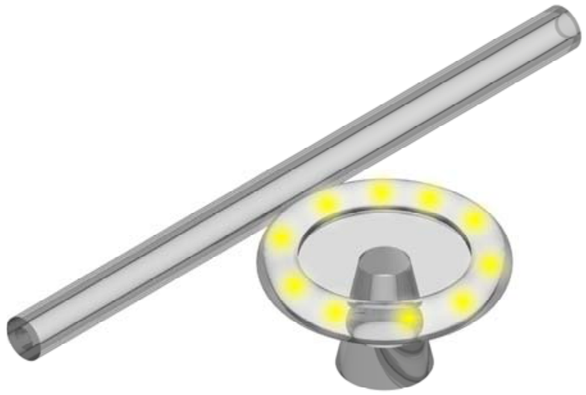
Analysis of four-port system for bistable memory in silica toroid microcavity



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Outline

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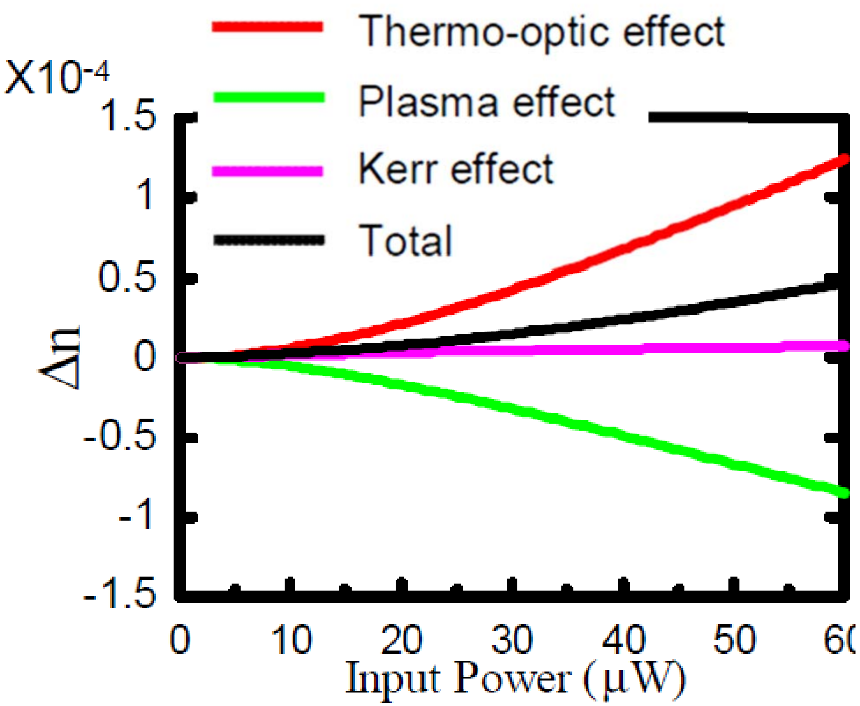
Background
- Various nonlinearities in an optical microcavity -

Nonlinearities in microcavity

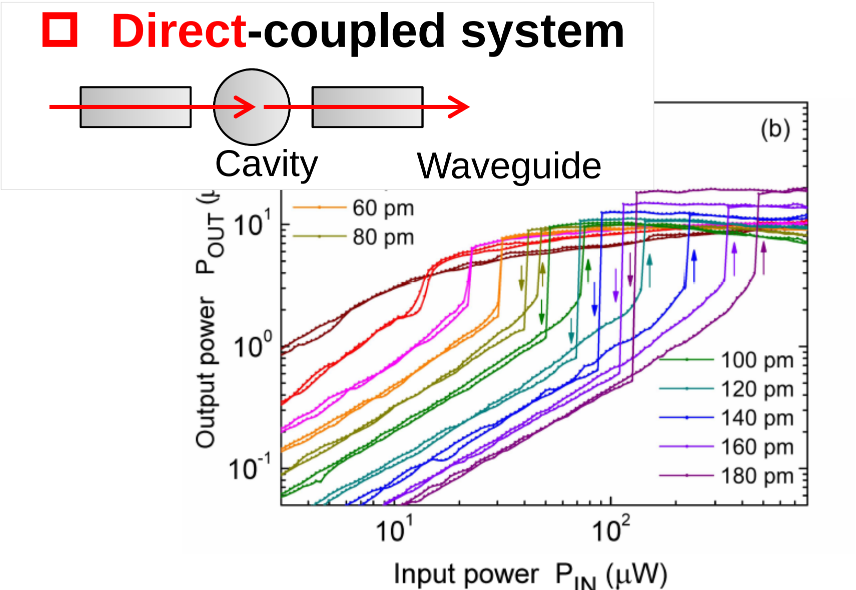


Various nonlinearities in Si

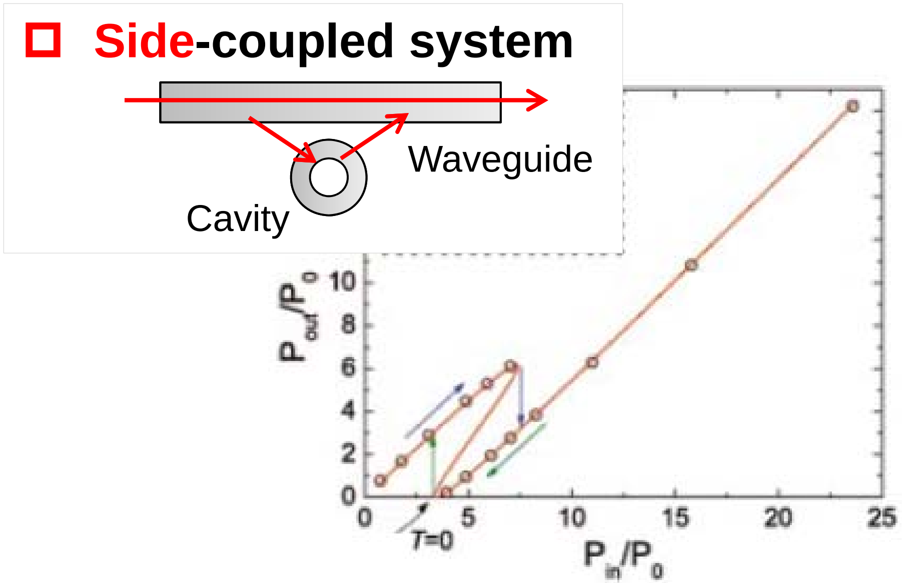
T. Uesugi, *et al*., Opt. Express 14, 377-386 (2006).

- TO effect:
  - Large coefficient but slow (ms)
  - Energy Wasted as heat
- Carrier plasma effect:
  - Large coefficient and fast (ns)
  - Suffers from free-carrier absorption
- Kerr effect:
  - Small coefficient but very fast (fs)
  - Small energy consumption

Background
- Optical bistability in a microcavity -



M. Notomi, *et al*., Opt. Express 13, 2678-2687 (2005).



M. Fatih *et al.,* Appl. Phys. Lett. **83**, 2739 (2003).

✓ Bias power required for memory in a cavity

$$P_{\mathrm{bias}} = \frac{\varepsilon_0 \varepsilon n \omega}{2 n_2} \frac{V_{\mathrm{cav}}}{Q^2}$$

- Small volume and high *Q* makes bias power low.
- Bistability demonstrated using TO and carrier effects.
- Kerr bistability in side-coupled system demonstrated numerically: Higher contrast

M. Notomi, *et al*., IET circuits, Devices & Systems **5**, 84-93 (2011).

Motivation

Problems

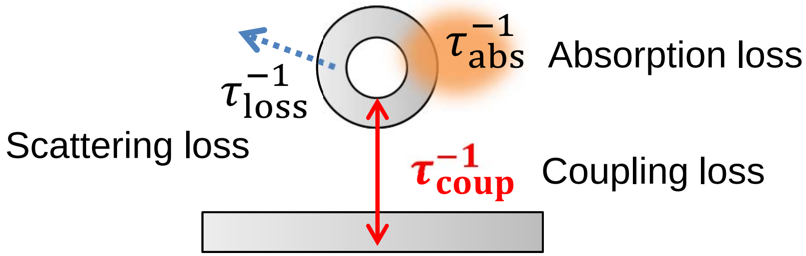
- □ **Few demonstrations of bistability using Kerr effect**
- □ **Nonlinear behavior of side coupled system unknown when Kerr and TO effects are present**

Purpose of this study

- □ **Reveal the nonlinear behavior of a side-couple ring cavity system when the material has Kerr and TO coefficients.**

Model
- Two-port and four-port systems -

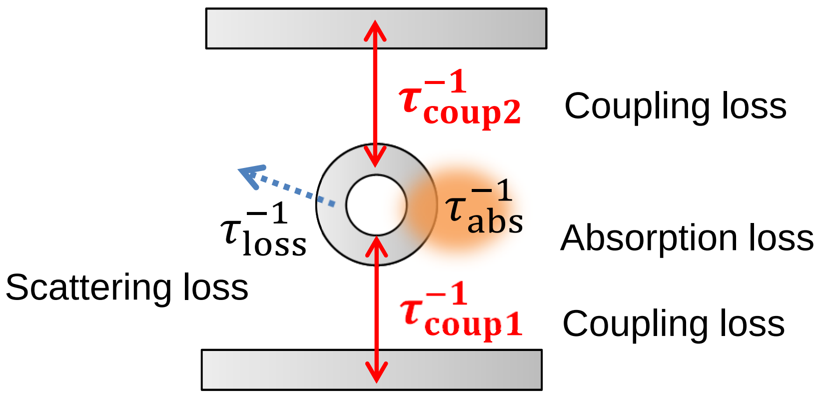
Two-port system



✓ **Photon lifetime**

$$\tau_{tot}^{-1} = \tau_{abs}^{-1} + \tau_{loss}^{-1} + \boldsymbol{\tau_{coup}^{-1}}$$

Four-port system



✓ **Photon lifetime**

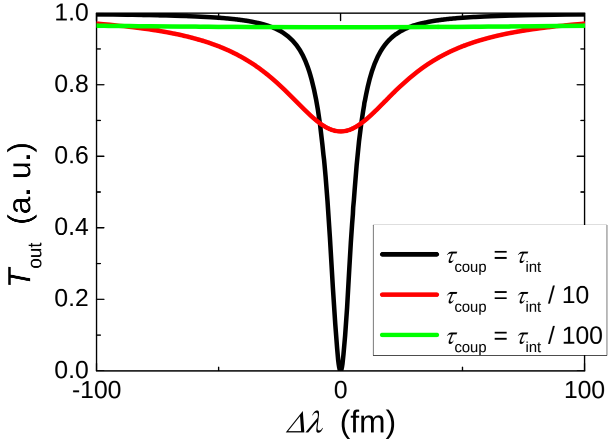
$$\tau_{tot}^{-1} = \tau_{abs}^{-1} + \tau_{loss}^{-1} + \boldsymbol{\tau_{coup1}^{-1}} + \boldsymbol{\tau_{coup2}^{-1}}$$

- Only τ_{coup} is controllable
- Small τ_{tot} is required for Kerr bistability

⇒ **Strong coupling (short- τ_{coup}) is needed for achieving Kerr**

Model
- Transmittance and coupling -

□ Transmittance of **two-port** system

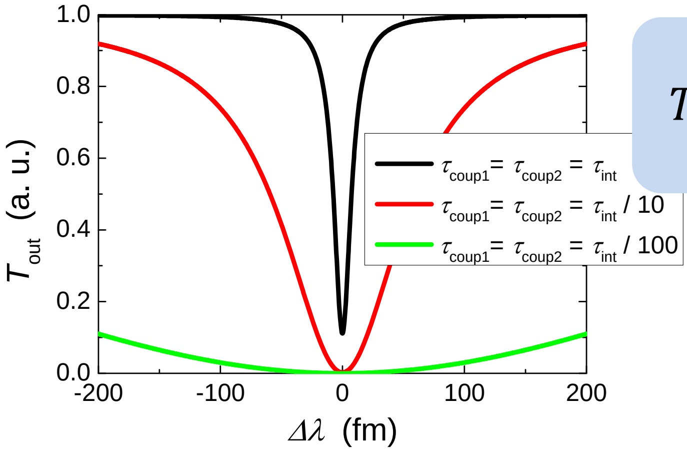


$$T_{\min} = \left(\frac{\tau_{\text{int}}^{-1} - \tau_{\text{coup}}^{-1}}{\tau_{\text{int}}^{-1} + \tau_{\text{coup}}^{-1}}\right)^2$$

$\tau_{\text{int}} \gg \tau_{\text{coup}}$ → $T_{\min} \approx 1$

- Over coupling is required for high speed ($\tau_{\text{coup}} = \tau_{\text{int}}/100$): **Dip is shallow**

□ Transmittance of **four-port** system



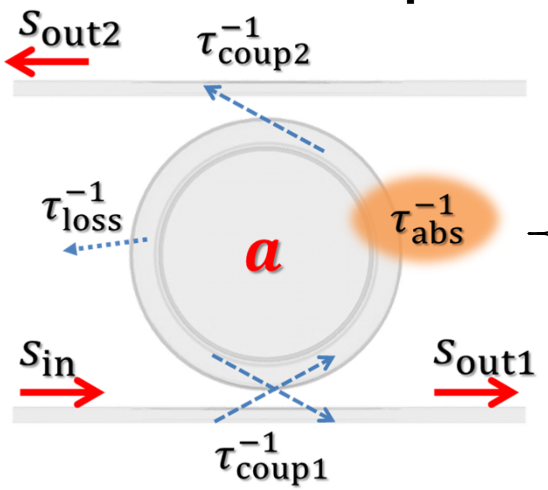
$$T_{\min} = \left(\frac{\tau_{\text{int}}^{-1} - \tau_{\text{coup1}}^{-1} + \tau_{\text{coup2}}^{-1}}{\tau_{\text{int}}^{-1} + \tau_{\text{coup1}}^{-1} + \tau_{\text{coup2}}^{-1}}\right)^2$$

$\tau_{\text{int}} \gg \tau_{\text{coup1}} = \tau_{\text{coup2}}$ → $T_{\min} \approx 0$

- Critical coupling is obtained even at a high speed ($\tau_{\text{coup1}} = \tau_{\text{coup2}} = \tau_{\text{int}}/100$): **Dip is deep**

Model – CMT and FEM -

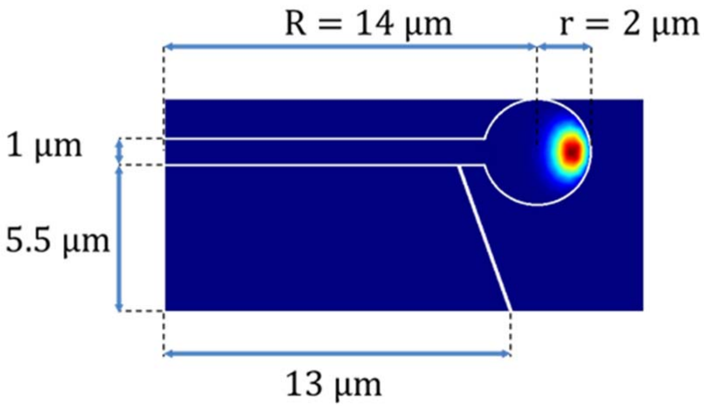
□ CMT in a 4 port system with a ring cavity



- $$\frac{\mathrm{d}a(t)}{\mathrm{d}t} = \left[j\omega_0(\Delta n) - \frac{1}{2}\left(\tau_{\mathrm{abs}}^{-1} + \tau_{\mathrm{loss}}^{-1} + \tau_{\mathrm{coup1}}^{-1} + \tau_{\mathrm{coup2}}^{-1}\right)\right] a(t) + \sqrt{\frac{1}{\tau_{\mathrm{coup1}}}}\exp(j\theta)s_{\mathrm{in}}(t)$$
- $$s_{\mathrm{out1}}(t) = \exp(-j\beta_1 d)\left[s_{\mathrm{in}}(t) - \sqrt{\frac{1}{\tau_{\mathrm{coup1}}}}\exp(j\theta)a(t)\right]$$

Light energy $U_{\mathrm{p}} = |a|^2$, Output power $P_{\mathrm{out1}} = |s_{\mathrm{out1}}|^2$

□ Effective refractive index change Δn



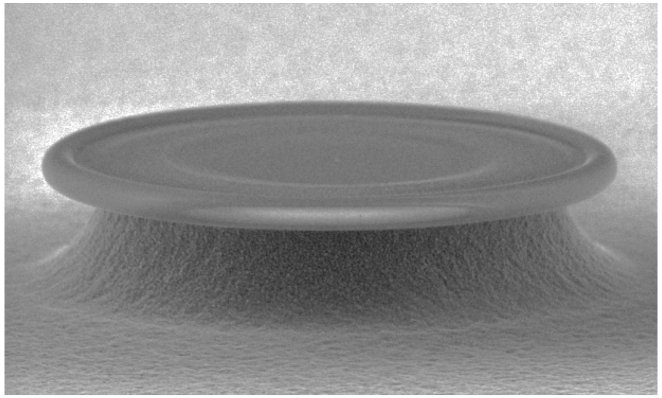
FEM

$$\Delta n(t) = \frac{\iint \left(\Delta n_{\mathrm{Kerr}}(x,y,t) + \Delta n_{\mathrm{TO}}(x,y,t)\right)\tilde{I}(x,y)\mathrm{d}x\mathrm{d}y}{\iint \tilde{I}(x,y)\mathrm{d}x\mathrm{d}y}$$

$$\begin{cases} \Delta n_{\mathrm{Kerr}}(x,y,t) = \dfrac{2n_2 c}{n_0} u_{\mathrm{p}}(x,y,z) \\ \Delta n_{\mathrm{TO}}(x,y,t) = n_0 \xi T(x,y,t) \end{cases}$$

Model
- Platform for Kerr bistable memory -

□ Silica toroid microcavity



- Has ultra-high quality factor (Q_{int} = 4x10^8 [1]).
- Mainly composed of silica.
  - Extremely low material loss ($\alpha = 0.2$ dB/m).
  - No carrier generation (no carrier effect).
- Can be fabricated on a chip.

Choose as a platform of Kerr bistable memory

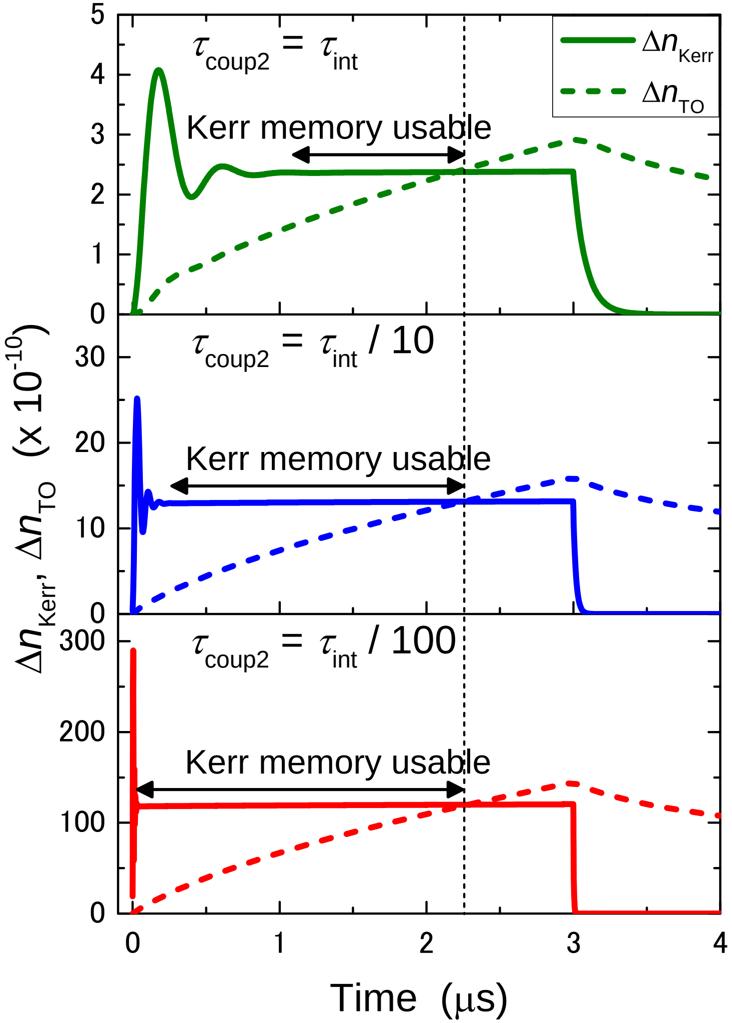
□ Parameters & assumptions used for calculation

- $\tau_{\mathrm{int}} = 329\ \mathrm{ns}$ (corresponding to $Q_{\mathrm{int}} = 4 \times 10^8$).
- Intrinsic loss is dominated by the absorption ($\tau_{\mathrm{int}} \approx \tau_{\mathrm{abs}}$).
- Critical coupling condition $\tau_{\mathrm{coup1}} = \left(\tau_{\mathrm{int}}^{-1} + \tau_{\mathrm{coup2}}^{-1}\right)^{-1}$ is satisfied.

[1] T. Kippenberg, *et al.*, Appl. Phys. Lett. 85, 6113-6115 (2004).

Result

- Refractive index change dependent on τ_{coup2} -



- **Refractive index change caused by Kerr and TO effects in 4-port system.**
- 3 μs-wide rectangular pulse inputted.
  - Only the regime, where Δn_{Kerr} is flat and Δn_{Kerr} is larger than Δn_{TO}, can be used for Kerr bistable memory.
    (shown as "**Kerr memory usable**")
  - Δn_{Kerr} is larger than Δn_{TO} until 2.3 μs is passed.
  - Rising time of Δn_{Kerr} become shorter when τ_{coup2} become shorter.

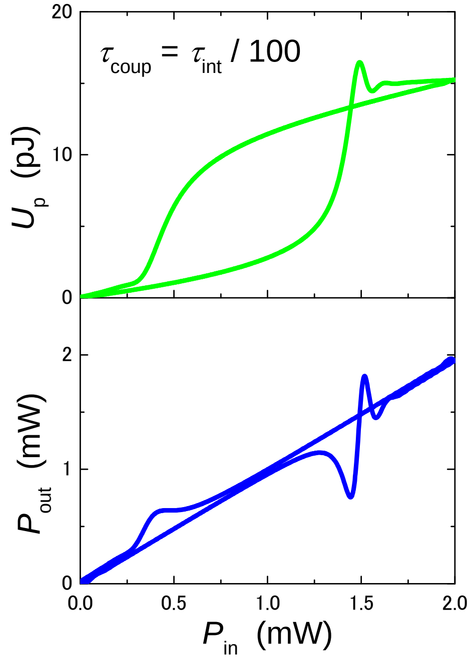
Short- τ_{coup} is desirable for the effective use of "Kerr memory usable" regime.

W. Yoshiki and T. Tanabe, J. Opt. Soc. Amer. B **29**, 3335-3343 (2012).

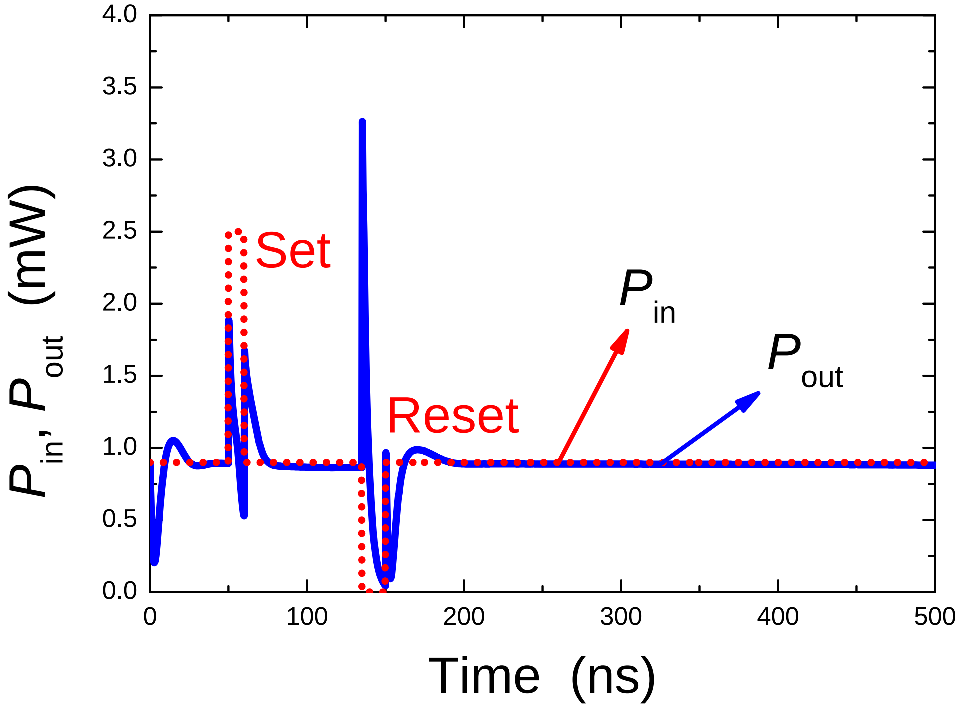
Result

- Kerr bistable memory in 2-port system -

□ Bistable operation



□ Memory operation

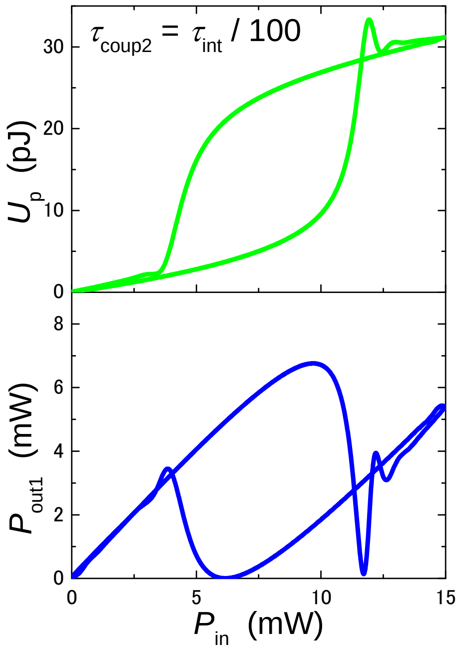


- In the both cases, U_p shows a bistable behavior.
- However, P_{out} doesn't show the bistability.
- Kerr bistable memory is **not** feasible in a 2-port system.

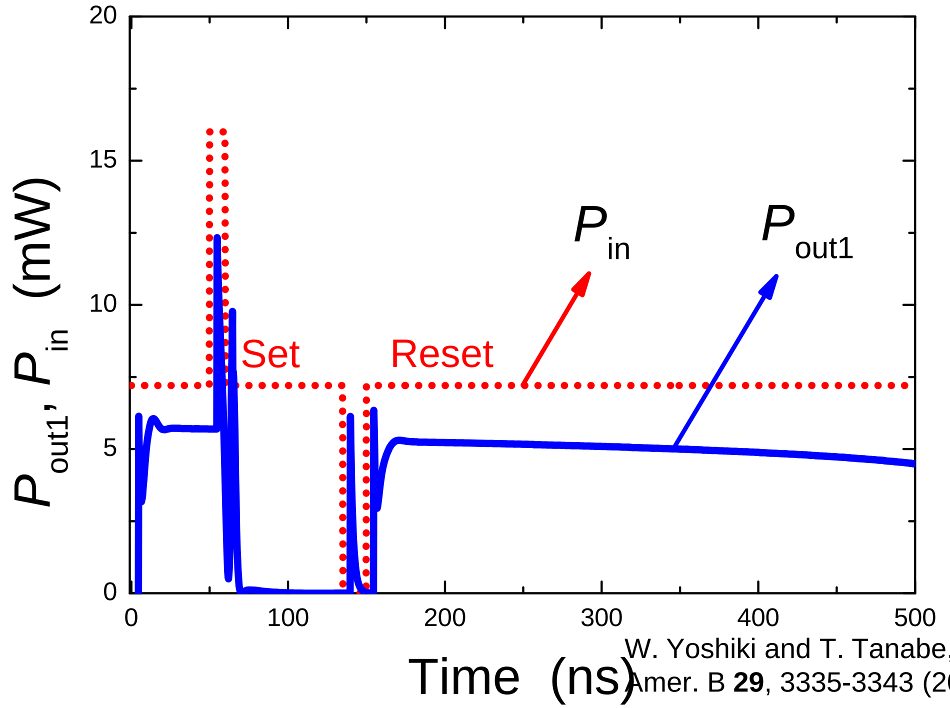
Result

- Kerr bistable memory in 4-port system -

□ Bistable operation



□ Memory operation



W. Yoshiki and T. Tanabe, J. Opt. Soc. Amer. B **29**, 3335-3343 (2012).

- In the both oeprations, U_p and P_out1 show a bistable behavior.
- **Kerr bistable memory is feasible in a 4-port system**.
  - Memory holding time: **500 ns**
  - Drive power: **7.3 mW**

Summary

- Described the behavior of a side-couple and a 4-port WGM cavity systems by using CMT and FEM.
- Reveled that optical Kerr bistable memory is feasible in a 4-port system (but it is difficult with a 2-port system) when TO effect is present

Thank you for your attention!

For more information

W. Yoshiki and T. Tanabe, "Analysis of bistable memory in silica toroid microcavity," J. Opt. Soc. Amer. B **29**, 3335-3343 (2012).

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