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

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Outline

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  - Various nonlinearities in an optical microcavity
  - Optical bistability in a microcavity

- **Motivation**

- **Model**
  - Two-port and four-port systems
  - Transmittance and coupling
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  - Refractive index change
  - Kerr bistable memory in 2-port system
  - Kerr bistable memory in 4-port system

- **Summary**
Background
- Various nonlinearities in an optical microcavity -

Nonlinearities in microcavity

- **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

Various nonlinearities in Si

Background
- Optical bistability in a microcavity -

- 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

- Direct-coupled system

- Side-coupled system

\[ P_{\text{bias}} = \frac{\varepsilon_0 \varepsilon n \omega}{2n_2} \frac{P_{\text{cav}}}{Q^2} \]


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**
- Only $\tau_{\text{coup}}$ is controllable
- Small $\tau_{\text{tot}}$ is required for Kerr bistability

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

**Four-port system**
- Strong coupling (short- $\tau_{\text{coup}}$) is needed for achieving Kerr

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

Model
- Transmittance and coupling -

**Transmittance of two-port system**

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

\( \tau_{\text{int}} \gg \tau_{\text{coup}} \)

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

**Transmittance of four-port system**

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

\( \tau_{\text{int}} \gg \tau_{\text{coup1}} = \tau_{\text{coup2}} \)

- 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

$$\frac{da(t)}{dt} = j\omega_0(\Delta n) - \frac{1}{2}(\tau_{\text{abs}}^{-1} + \tau_{\text{loss}}^{-1} + \tau_{\text{coup1}}^{-1} + \tau_{\text{coup2}}^{-1})a(t)$$

$$+ \sqrt{\frac{1}{\tau_{\text{coup1}}}} \exp(j\theta)s_{\text{in}}(t)$$

$$s_{\text{out1}}(t) = \exp(-j\beta_1 d)s_{\text{in}}(t) - \sqrt{\frac{1}{\tau_{\text{coup1}}}} \exp(j\theta)a(t)$$

Light energy $U_p = |a|^2$, Output power $P_{\text{out1}} = |s_{\text{out1}}|^2$

□ Effective refractive index change $\Delta n$

$$\Delta n(t) = \frac{\iint (\Delta n_{\text{Kerr}}(x,y,t)+\Delta n_{\text{TO}}(x,y,t))I(x,y)dxdy}{\iint I(x,y)dxdy}$$

$$\Delta n_{\text{Kerr}}(x,y,t) = \frac{2n_2c}{n_0}u_p(x,y,z)$$

$$\Delta n_{\text{TO}}(x,y,t) = n_0\xi T(x,y,t)$$

FEM

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Model
- Platform for Kerr bistable memory -

- Silica toroid microcavity
  - Has ultra-high quality factor ($Q_{\text{int}} = 4 \times 10^8$ [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
  - $\tau_{\text{int}} = 329$ ns (corresponding to $Q_{\text{int}} = 4 \times 10^8$).
  - Intrinsic loss is dominated by the absorption ($\tau_{\text{int}} \approx \tau_{\text{abs}}$).
  - Critical coupling condition $\tau_{\text{coup1}} = \left(\tau_{\text{int}}^{-1} + \tau_{\text{coup2}}^{-1}\right)^{-1}$ is satisfied.

Result

- Refractive index change dependent on $\tau_{\text{coup2}}$

- Refractive index change caused by Kerr and TO effects in 4-port system.

- 3 $\mu$s-wide rectangular pulse inputted.

- Only the regime, where $\Delta n_{\text{Kerr}}$ is flat and $\Delta n_{\text{Kerr}}$ is larger than $\Delta n_{\text{TO}}$, can be used for Kerr bistable memory.

  (shown as “Kerr memory usable”)

- $\Delta n_{\text{Kerr}}$ is larger than $\Delta n_{\text{TO}}$ until 2.3 $\mu$s is passed.

- Rising time of $\Delta n_{\text{Kerr}}$ become shorter when $\tau_{\text{coup2}}$ become shorter.

Short- $\tau_{\text{coup}}$ is desirable for the effective use of “Kerr memory usable” regime.

- Kerr bistable memory in 2-port system -

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**

- In the both operations, $U_p$ 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.

- Revealed 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

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