Rigorous analysis of bistable memory in silica toroid microcavity

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## Effects which can change refractive index

<table>
<thead>
<tr>
<th>Name</th>
<th>Principle</th>
<th>Speed</th>
<th>Energy consumption</th>
<th>Δn/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo-optic (TO) effect(^1)</td>
<td>heat</td>
<td>µs</td>
<td>pJ</td>
<td>≈ 1%</td>
</tr>
<tr>
<td>Carrier-plasma effect(^2)</td>
<td>carrier</td>
<td>&lt; ns</td>
<td>&lt; fJ</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Kerr effect</td>
<td>light</td>
<td>ps</td>
<td>aJ</td>
<td>≪ 1%</td>
</tr>
</tbody>
</table>


### Material requirements

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

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

The equation for $U_p(t)$ is given by:

$$\frac{dU_p(t)}{dt} = -\left(\frac{1}{\tau_{abs}} + \frac{1}{\tau_{scat}} + \frac{1}{\tau_{coup}}\right)U_p(t) + \sqrt{T_{in}(t)}P_{in}(t)$$

depends on the refractive index change.
Modeling of Kerr bistable memory (2)

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

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

$T(x, y, z)$ can be obtained by FEM on the 2D cross-section above.

$(1/\tau_{\text{abs}})U_p(t)$ is employed as a heat source.

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$U_p$ vs. Time for different $\tau_{coup}$

- Rectangular pulse with 1 $\mu$s is employed.
- Solid and dotted lines represent $\Delta n_{Kerr}$ and $\Delta n_{TO}$, respectively.
- Normalization ($\Delta n_{Kerr,max} = 1$) is used.
- $\tau_{coup} = 1 \mu$s
$U_p$ vs. Time for different $\tau_{coup}$

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

$\tau_{coup} = 100$ ns
$U_p$ vs. Time for different $\tau_{coup}$

- Rectangular pulse with 1 $\mu$s is employed.
- Solid and dotted lines represent $\Delta n_{\text{Kerr}}$ and $\Delta n_{\text{TO}}$, respectively.
- Normalization ($\Delta n_{\text{Kerr,max}} = 1$) is used.
- $\tau_{coup} = 10$ ns
$U_p$ vs. Time for different $\tau_{coup}$

Response speed of $\Delta n_{Kerr}$ is faster when $\tau_{coup}$ is shorter.

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

- A short $\tau_{coup}$ is preferred in terms of achieving a Kerr bistable memory.
$U_p$ vs. $P_{in}$ for different $\tau_{coup}$

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

$\tau_{coup} = 1 \mu s$
$U_p$ vs. $P_{in}$ for different $\tau_{coup}$

- Triangular pulse is employed.
- $y$-axis and $x$-axis normalized as $U_{p,\text{max}} = 1$ and $P_{in,\text{max}} = 1$, respectively.
- $\tau_{coup} = 100$ ns
$U_p$ vs. $P_{in}$ for different $\tau_{coup}$

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$\tau_{coup} = 1 \text{ ns}$
$U_p$ vs. $P_{in}$ for different $\tau_{coup}$

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

- Blue and red line represent $U_p$ and $P_{in}$, respectively.
- $\tau_{coup} = 10 \text{ ns}$

- We can obtain Kerr bistable memory by adjusting coupling photon lifetime $\tau_{coup}$.
- Memory time is approximately 360 ns and driving power is 1 mW.
Comparison with prior research

<table>
<thead>
<tr>
<th>Cavity type</th>
<th>Principle</th>
<th>$Q_{\text{int}}$</th>
<th>$P_{\text{drive}}$</th>
<th>$E_{\text{consumption}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon microring$^3)$</td>
<td>TO</td>
<td>$1.43 \times 10^5$</td>
<td>800 $\mu$W</td>
<td>pJ</td>
</tr>
<tr>
<td>Photonic crystal$^4)$</td>
<td>Carrier-Plasma</td>
<td>$1.2 \times 10^6$</td>
<td>250 $\mu$W</td>
<td>&lt; fJ</td>
</tr>
<tr>
<td>Silica toroid$^5)$</td>
<td>Kerr</td>
<td>$1.25 \times 10^8$</td>
<td>1 mW</td>
<td>aJ</td>
</tr>
</tbody>
</table>

- A toroidal cavity is ultra low loss.
- $P_{\text{drive}}$ is much lower than the conventional analysis ($P_{\text{drive}} = 133$ 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 $\tau_{\text{coup}}$ was 10 ns.
Thank you for your attention.