Broad-bandwidth pulse transmission through an ultrahigh-Q nanocavity with a chirped pulse

Zhelun Chen, Wataru Yoshiki, and Takasumi Tanabe*
Department of Electronics and Electrical Engineering, Faculty of Science and Technology, Keio University
*takasumi@elec.keio.ac.jp
Ultra-high Q microcavity

**Ultrahigh-Q microcavity**

![Transmittance graph](image1)

- FSR = 7 nm = 875 GHz

**Quality factor and mode volume**

- **Q-factor**
  \[ Q = \omega \times \frac{\text{stored energy}}{\text{power in/out}} \]

- **Photon density**
  \[ \propto \frac{Q}{V} \]

**Applications**

- All-optical switching
- Cavity QED devices
- Low-threshold lasers
- Optical sensors
- Optical frequency combs

![Detected power graph](image2)

\[ Q = 8.2 \times 10^7 \]
Optical switch in a microcavity: speed or power?


Switching principle

Mode S  Mode C

Control off  Ctrl shift

Silica toroidal microcavity

Signal  Control
Optical switch in a microcavity: speed or power?


Switching principle

Control off

Mode S

Mode C

Control on

shift

Signal

Control

Fall time: 6 ns

Modulation observed at 36 μW

Trade-off between Q and speed

Low power Kerr switch

$T_{\text{cont}} = 64 \text{ ns}$

$P_{\text{in}}^{\text{cont}} = 5.3 \text{ mW}$
Motivation

Problems

- Trade-off between power and speed (high Q or low Q?)

Purpose of this study

- Transmit broad bandwidth pulse through high-Q nanocavity with simple scheme
Basic idea – using self modulation of cavity

w/o optical nonlinear effect

Only a portion of the pulse spectrum can transmit
(i.e. narrow bandwidth)
Basic idea – using self modulation of cavity w/ optical nonlinear effect

Wavelength

transmittance

Cavity transmittance

Input pulse spectrum

w/ Kerr effect

Broad bandwidth pulse can transmit ultrahigh Q cavity
Basic idea – using self modulation of cavity

W/ optical nonlinear effect

W/ Kerr effect

Input pulse spectrum

Optimize instantaneous frequency of the input

So that $f_{in}(t) = f_{cavity}(t)$

Broad bandwidth pulse can transmit ultrahigh Q cavity
Coupled mode theory (CMT)

\[
\frac{dA(t)}{dt} = j2\pi c \left( \frac{1}{\lambda_r + \delta\lambda(t)} - \frac{1}{\lambda_{in}} \right) - \frac{1}{2} \left( \frac{1}{\tau_{loss}} + \frac{1}{\tau_{abs}} + \frac{1}{\tau_{coup1}} + \frac{1}{\tau_{coup2}} \right) A(t) + \sqrt{\frac{1}{\tau_{coup1}}} \exp(j\theta) S_{in}(t)
\]

- **Add-drop system**
  - \(A(t)\): Cavity mode amplitude
  - \(\lambda_0\): Resonant wavelength (cold cavity)
  - \(\delta\lambda(t)\): Resonance wavelength shift
  - \(\lambda_{in}\): Input wavelength
  - \(\theta\): Phase difference

**Analyze** \(S_{out}(t)\)

in Add-drop system by CMT
Optimized spectrum phase & detuning

Input energy: 28.4 pJ
FTL pulse width: 0.45 ns (1.2 GHz)       \( Q = 7.5 \times 10^5 \)  
\( T \sim 11\% \) w/ TL input

28% of input energy can be transported through cavity

(2.4 times greater than that of FTL pulse)
Optimized spectrum phase & detuning

Input energy: 28.4 pJ
FTL pulse width: 0.45 ns (1.2 GHz)  
Q = 7.5x10^5  
(T ~ 11% w/o Kerr)

28% of input energy can be transported through cavity  
(2.4 times greater than that of FTL pulse)
(Quantity of second spectrum phase: 4.5 rad/GHz², Resonance frequency (cool cavity): 194 THz, $\delta f = -0.57$ GHz)
- Why high transmittance?
How can we change the pitch when the string is already plucked?

By changing the tension of the string. But it must be done before the tone disappears.

What will happen when we change the cavity length, when the mirror is perfect and the light cannot escape?

The frequency of the light will follow the cavity resonance adiabatically!
Analysis of adiabatic wavelength conversion

Speed of the cavity resonance shift is the highest at -0.45 GHz

frequency component at -0.45 GHz changes their wavelength and then output as a low frequency light.
Obtained optimized linear chirp to permit broad-bandwidth transmittance

- 28% of input energy can transmit
- 2.4 times greater than inputting FTL pulse

Showed adiabatic wavelength conversion plays an important role in this event

Strategic Information and Communications R&D Promotion Programme (SCOPE), from the Ministry of Internal Affairs and Communications