# Coherent control of non-Markovian photon-resonator dynamics

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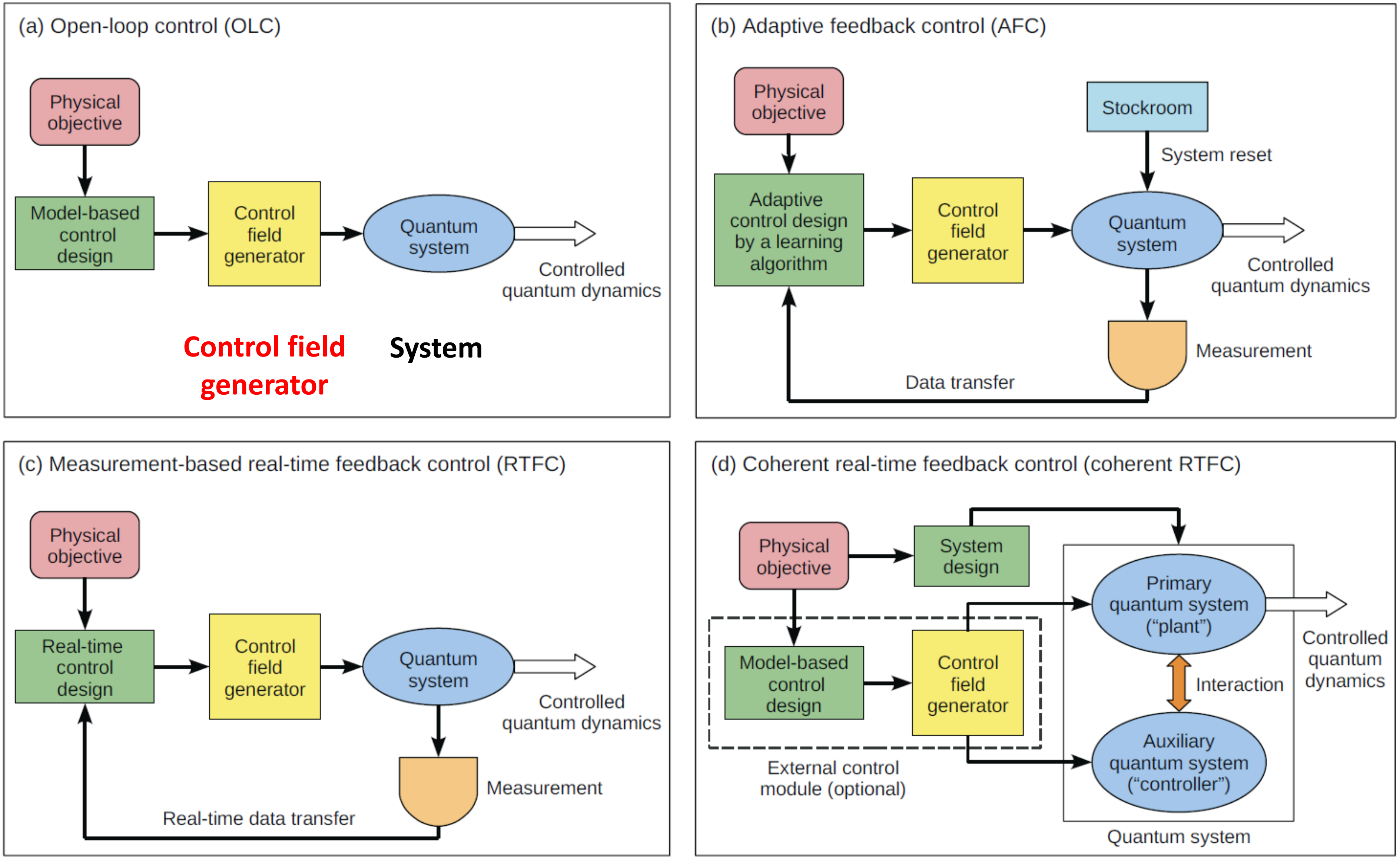
# “Coherent control of photons”

- Coherent
  - Keep track of amplitude, phase, and maintain precise timing within a characteristic length or time scale
- Control
  - Methods to modify the behavior of a system with one or more inputs
- Photon
  - A wavelike particle of energy that produces a click on a detector
- … and, there may be additional opportunities with *quantum* aspects of photons
  - Quantum
    - No accepted measure of “quantumness”
    - Classical analogies often exist (e.g. the coherent oscillator state) except for:
      - Wave-particle duality
      - Identical indistinguishable particles
      - Linearity
      - Entanglement

# Motivation: Demonstrate a path to *intuitive* control of transient photon dynamics (in quantum systems)




Modified from Rabitz et al., 2010: *General unifying features of controlled quantum phenomena:* https://arxiv.org/pdf/1003.3506

# The single photon wave function

- Single photons in a sourceless medium obey the equation
$$i\hbar\partial_t\psi_\sigma(\boldsymbol{r},t) = \hbar c\sigma\nabla \times \psi_\sigma$$
where $\sigma$ is the helicity of the photon.
- If $\psi_\sigma = \left(\frac{\epsilon_0}{2}\right)^{1/2} (E + i\sigma cB)$, thenthe above equation yields Ampere's and Faraday's Laws, i.e. Maxwell's equations (with the additional condition that the field is divergenceless).
- In other words, the real and imaginary parts of the photon wave function obey Maxwell's equations.
- Thus all methods used for solving classical electromagnetic problems can be used for the *single* photon (e.g. matrix propagation method).

# The single photon wave function

- It is (*now*) believed that a single photon wave function may be used to describe photon *energy density* $U(x,t)=|\Psi(x,t)|^2$
  - Studied theoretically, including
    - I. Bialynicki-Birula, Acta Phys. Pol. **86**, 97 (1994)
    - B. J. Smith and M. G. Raymer, New Journal of Physics **9**, 414 (2007)
- Unitary dynamics of photon wave function propagating in $x$-direction in lossless dielectric media may be modeled as phase-coherent sum of linearly polarized plane-wave basis functions, each of amplitude $a_n$ and oscillating at frequency $\omega_n$

$$\Psi(x,t)=\sum_n a_n \psi_n(x) e^{-i\omega_n t}$$

- The lossless dielectric material may be characterized by $\mu_{\mathrm{r}}$ and $\varepsilon_{\mathrm{r}}$, and $\psi_n$ satisfies

$$\nabla\times((\mu_0\mu_{\mathrm{r}})^{-1}\nabla\times\psi_n(x))-\omega_n^2\varepsilon_0\varepsilon_{\mathrm{r}}\psi_n(x)=0$$

with boundary conditions between region 1 and 2 at position $x_0$ such that

$$\psi_n\big|_{x=x_0-\delta}=\psi_n\big|_{x=x_0+\delta}$$

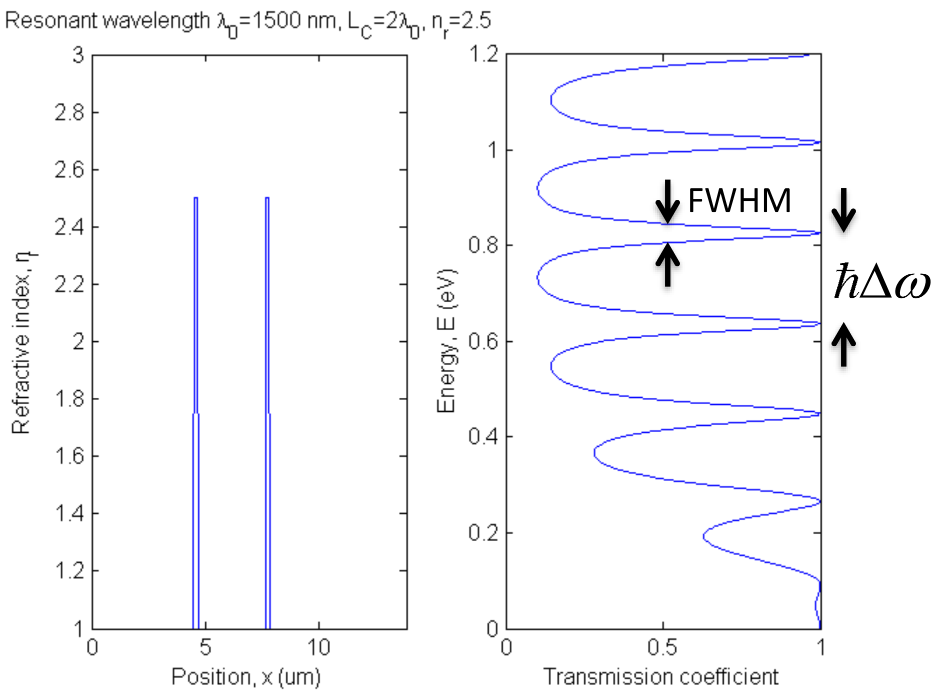
$$\frac{1}{\mu_{\mathrm{r}1}}\frac{\partial\psi_n}{\partial x}\bigg|_{x=x_0-\delta}=\frac{1}{\mu_{\mathrm{r}2}}\frac{\partial\psi_n}{\partial x}\bigg|_{x=x_0+\delta}$$

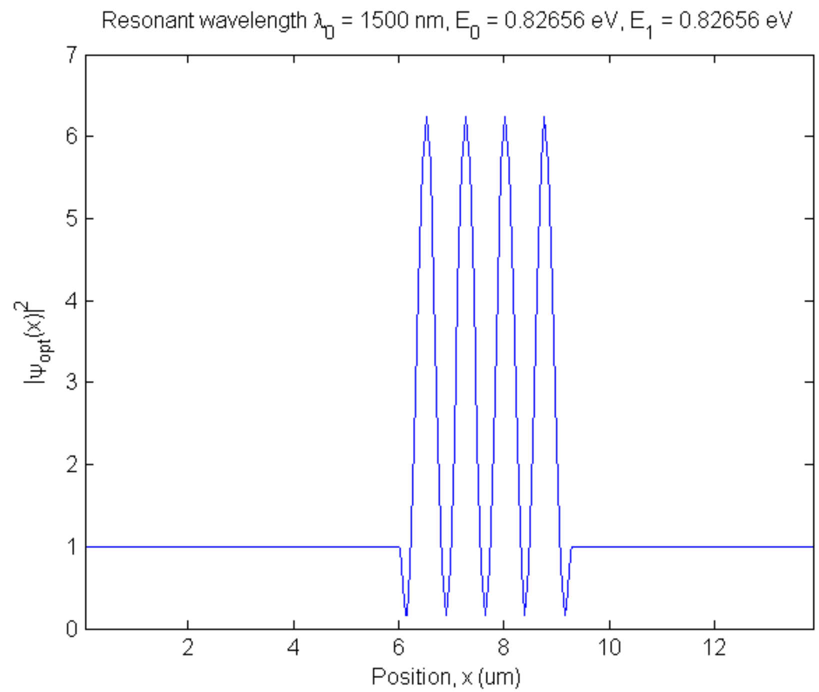
and refractive index $n_{\mathrm{r}}=\sqrt{\mu_{\mathrm{r}}}\sqrt{\varepsilon_{\mathrm{r}}}$

- Solve in space and time and assume photon coherence time, $\tau_{\mathrm{Coh}}$, greater than any other characteristic time

# The Fabry-Perot optical resonator

- Example dielectric structure: Two quarter-wave dielectric mirrors with $n_r$=2.5 spaced $L_C$ =2$\lambda_0$ apart creates Fabry-Perot optical *resonator* that is *coupled to the continuum*
- Resonant wavelength $\lambda_0$=1500 nm, $\omega_0=2\pi/\tau_0=2\pi$x200 THz, $\tau_0$=5 fs
- Resonant photon energy $E_0$=0.826 eV
- $Q=\omega_0/\gamma$, Lorentzian spectral FWHM=$\hbar/\tau_Q$, $\gamma=1/\tau_Q$
- Classical time-domain response is $e^{-t/\tau_Q}$ and $\tau_Q$ is resonant state lifetime
- Resonator round-trip time defined as $\tau_{RT}=2\pi/\Delta\omega=1/\Delta f$ where $\Delta f$ is the frequency spacing between adjacent spectral transmission peaks

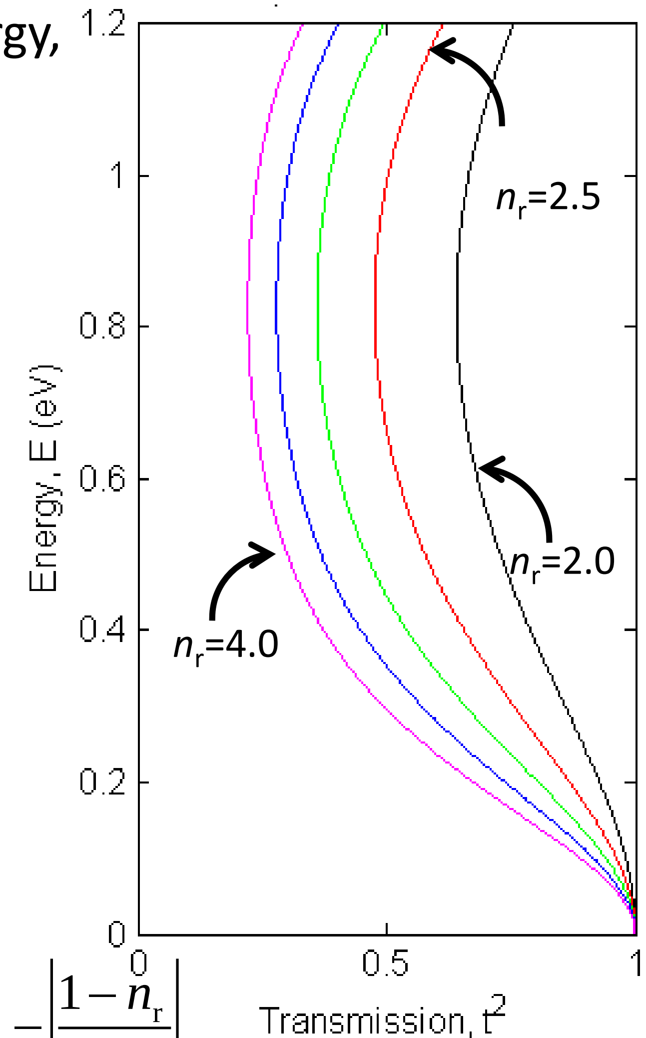


# Reflectivity of single quarter-wave dielectric mirror

- Example dielectric structure: Single quarter-wave dielectric mirror with $n_r$=2.5
- Resonant wavelength $\lambda_0$=1500 nm, $\omega_0=2\pi/\tau_0=2\pi$x200 THz, $\tau_0$=5 fs
- Resonant photon energy $E_0$=0.826 eV
- Transmission is a *slowly* varying function of photon energy,

$$t^2 = \frac{1}{1+\left(\frac{k_1^2-k_2^2}{2k_1k_2}\right)^2 \sin^2(k_2 L)}$$




- On resonance $k_1 = \frac{2\pi}{\lambda_0}$, $k_2 = \frac{2\pi n_r}{\lambda_0}$, $L = \frac{\lambda_0}{4n_r}$, so that

$$t^2 = \frac{1}{1+\left(\frac{1-n_r^2}{2n_r}\right)^2}$$

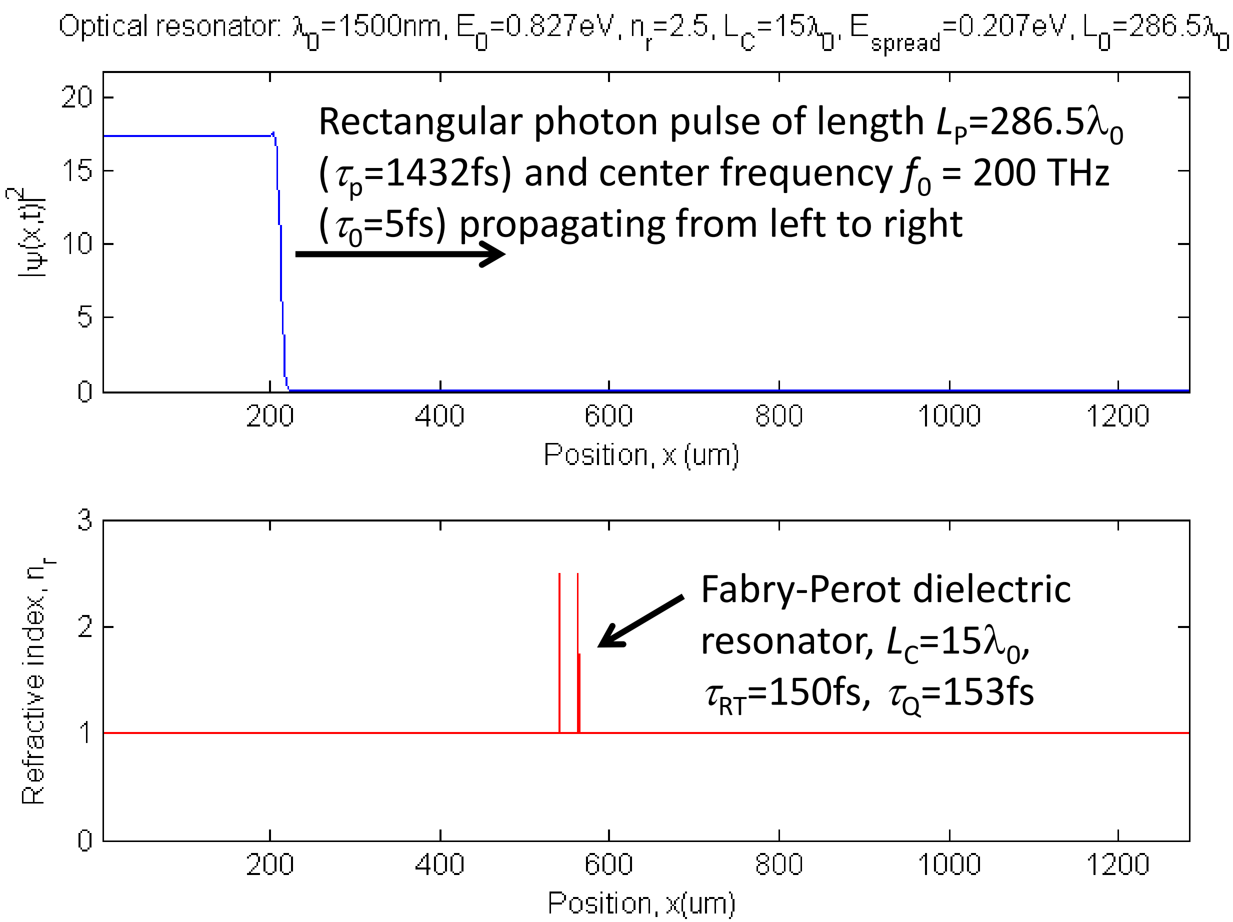
- System requires $t^2 + r^2 = 1$
- $t^2 = r^2 = 1/2$ when $n_r = 1+\sqrt{2}$
- For field $t=\sqrt{t^2}$ and $r=\sqrt{r^2}$
- $t$ and $t^2$ less dependent on photon energy as:

$$n_r \to 1, \quad t^2 \to 1$$
$$n_r \to \infty, \quad t^2 \to 0$$

- $\pi$ phase shift on reflection from semi-infinite slab, $\psi_r = -\left|\frac{1-n_r}{1+n_r}\right|$

# Transient response of single-photon (or classical E&M) pulse incident on Fabry-Perot cavity at resonance

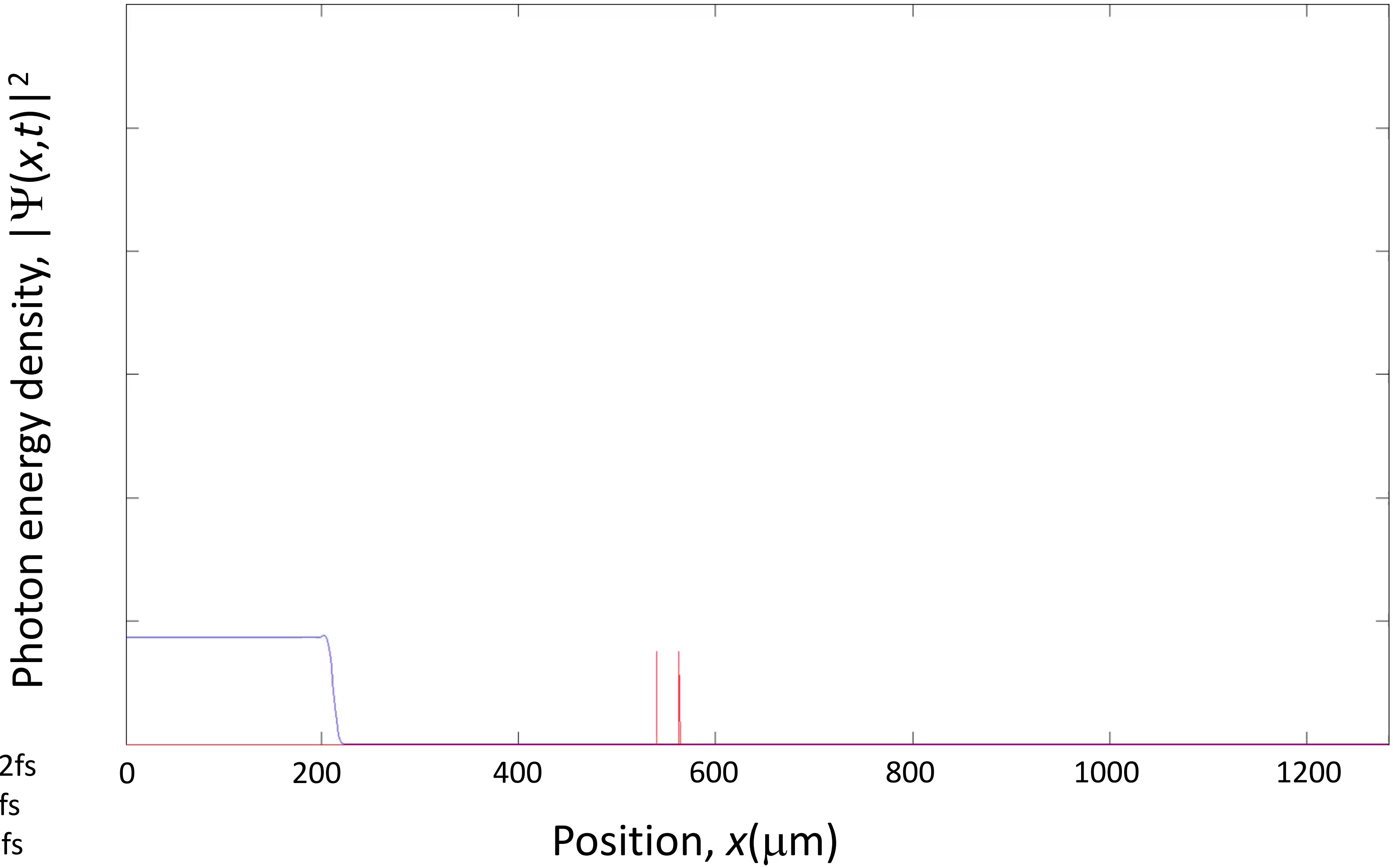
- Rectangular photon pulse with center frequency that is *on resonance at* wavelength $\lambda_0$=1500 nm, $\omega_0=2\pi/\tau_0=2\pi$x200 THz, $\tau_0$=5fs
- Quarter-wave ($\lambda_0/4n_r$) dielectric mirror with $n_r$=2.5, cavity length $L_C=15\lambda_0$, cavity round-trip time $\tau_{RT}=2\pi/\Delta\omega=30\tau_0$=150fs
- $Q$=193, $\tau_Q=Q/\omega_0$=153fs




$\tau_0$ =5fs
$\tau_p$ =1432fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Transient response of single-photon pulse incident on Fabry-Perot cavity at resonance

- When photon round-trip time in resonator $\tau_{RT}$ is comparable to envelope response time $\tau_Q$ it is possible to probe the internal (ring-down) structure of the resonator




$\tau_0$ =5fs
$\tau_p$ =1432fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

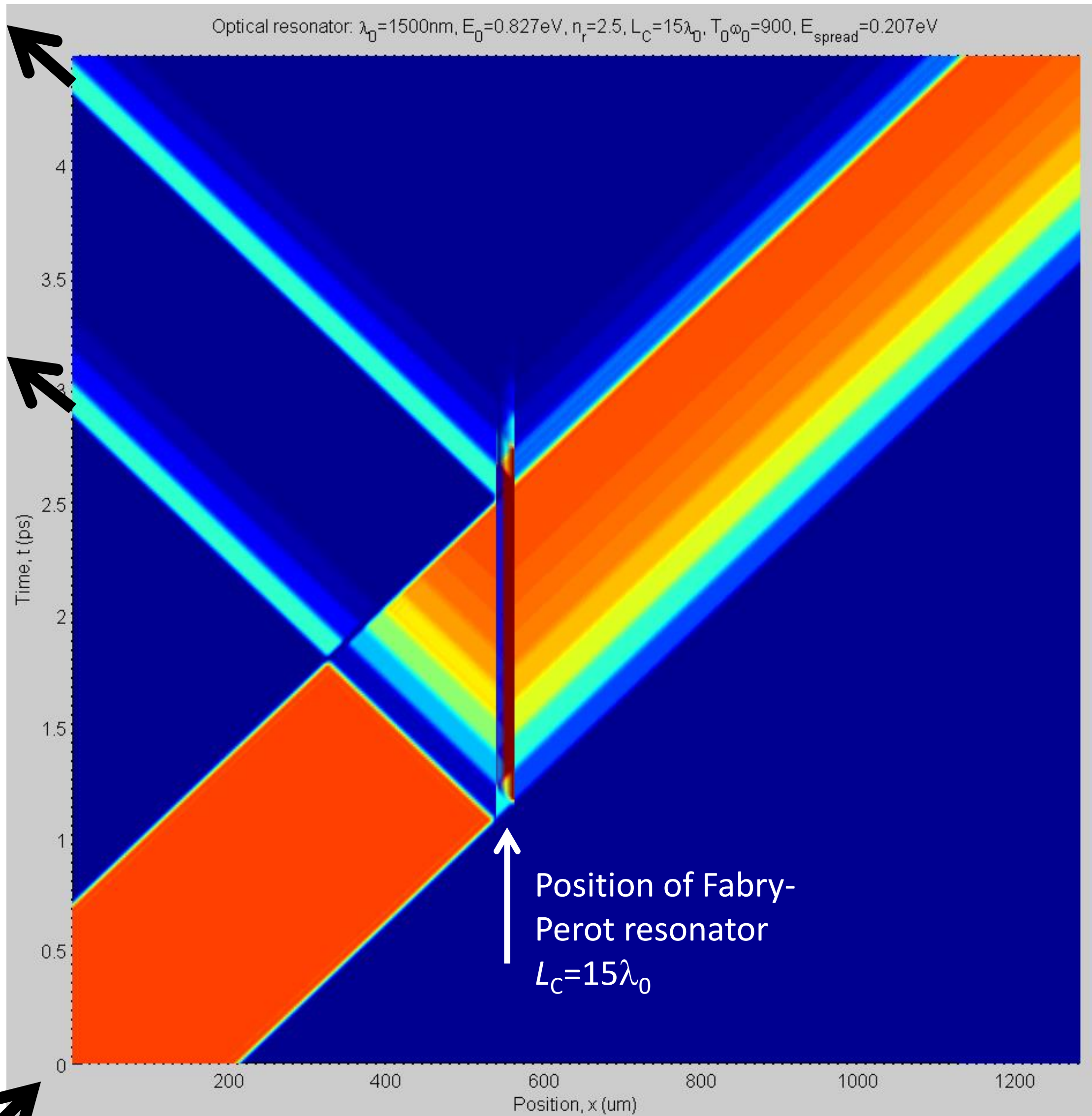
# Transient response of single-photon pulse incident on Fabry-Perot cavity at resonance

Reflection from *trailing* edge with step-wise $\tau_{RT}$ ring-down and exponential $\tau_Q$ envelope

Reflection from *leading* edge with step-wise $\tau_{RT}$ ring-down and exponential $\tau_Q$ envelope

Time

Incident photon pulse of length $L_p$=286.5$\lambda_0$ in free-space



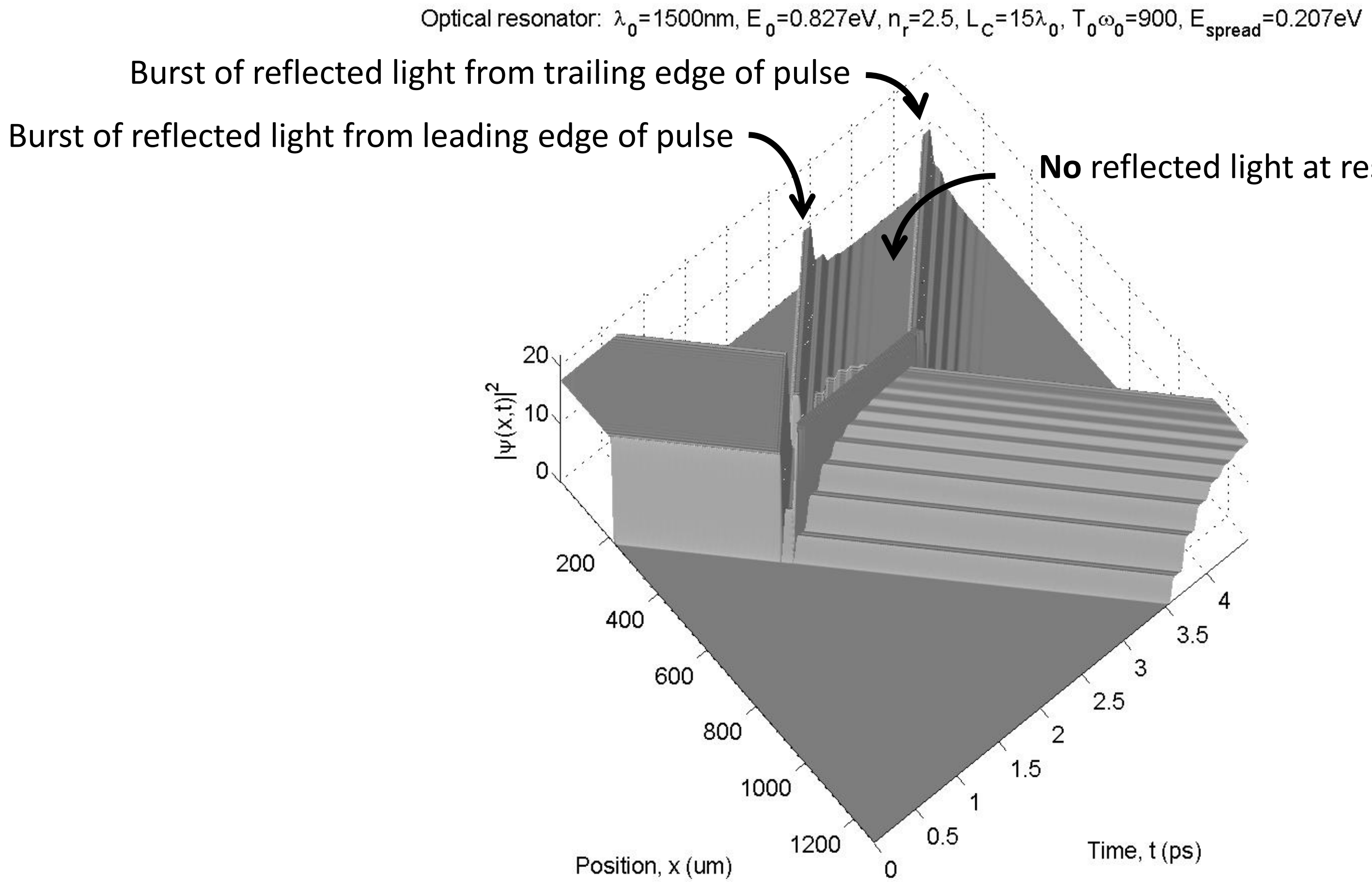

Space

Transmitted photon pulse with step-wise $\tau_{RT}$ features and exponential $\tau_Q$ envelope

$\tau_0$ =5fs
$\tau_p$ =1432fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Transient response of single-photon pulse incident on Fabry-Perot cavity at resonance

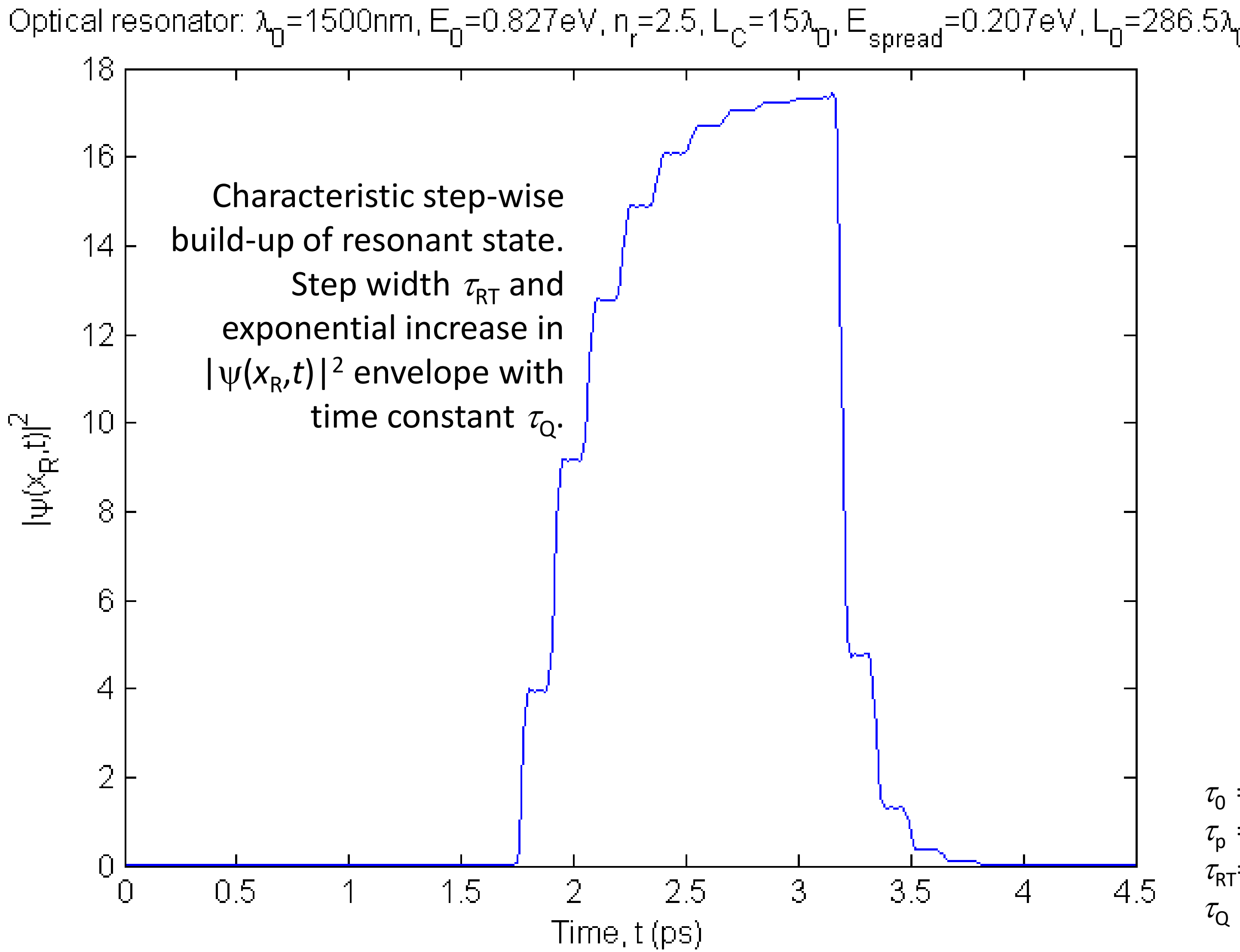
- Multiple cavity round-trip times required to build-up steady-state behavior
- Rectangular photon pulse with center frequency that is on resonance has characteristic transient reflection at leading and trailing edge
  - Reflection depends on frequency components contributing to pulse shape
  - Reflection always greater than zero for pulse




$\tau_0$ =5fs
$\tau_p$ =1432fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Transient response of single-photon pulse incident on Fabry-Perot cavity at resonance

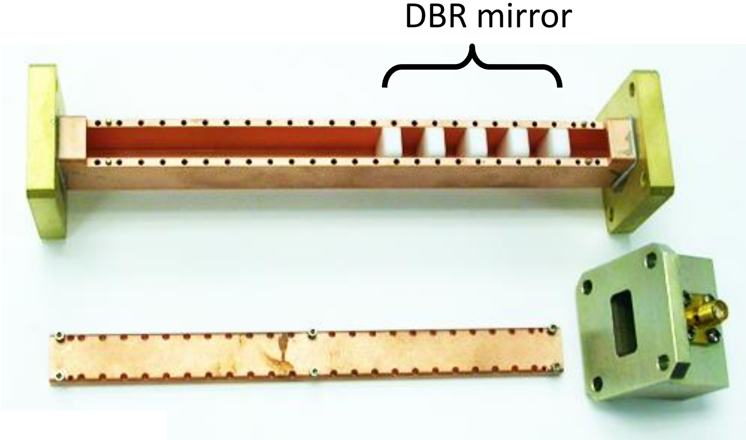
- Calculated transmitted single-photon energy density, $|\psi(x_R, t)|^2$ at $x_R$=742.8μm

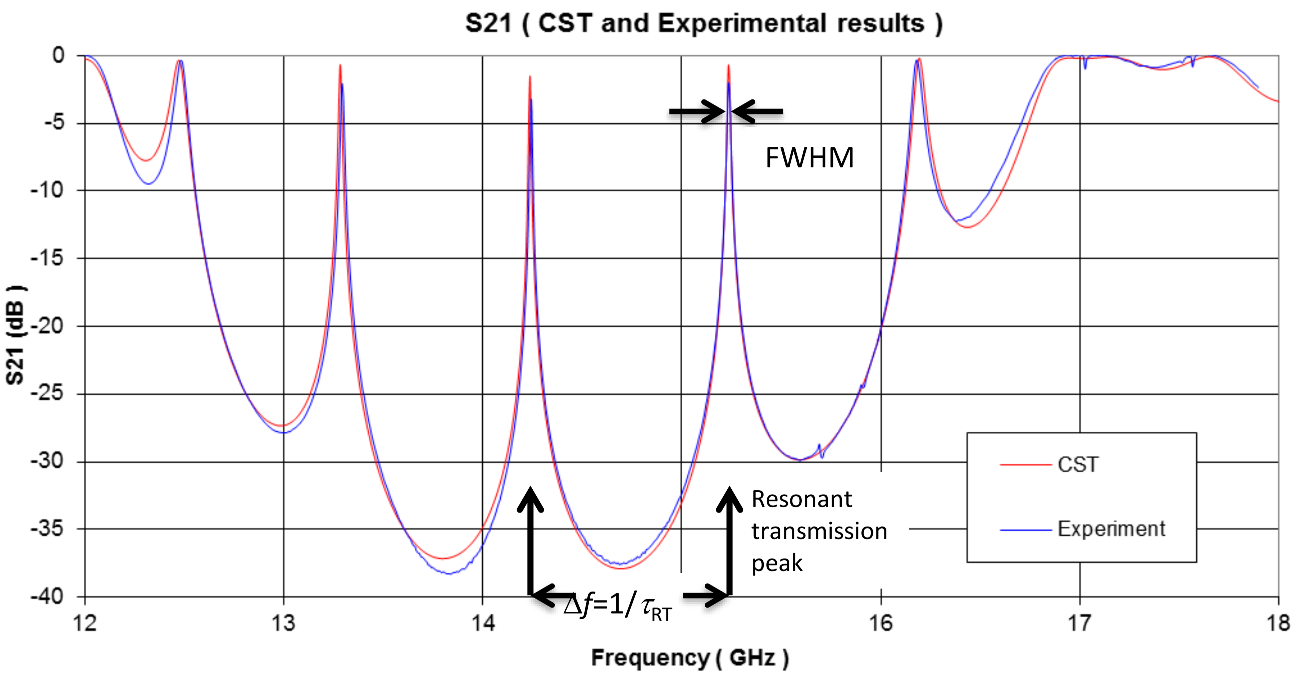


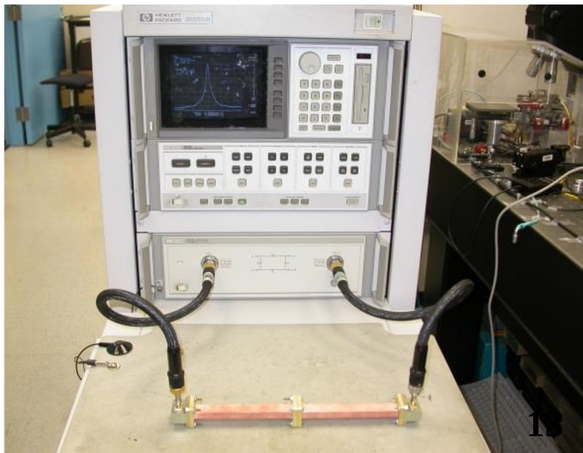

$\tau_0$ =5fs
$\tau_p$ =1432fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Experimental validation using Fabry-Perot resonator in waveguide

- Because equations governing single-photon wave function evolution are similar to the Helmholtz equation, experiments using classical electromagnetic resonators can validate qualitative behavior.
- Example:
  - Resonant frequency, $f_0$=15.234 GHz ($E_0$=63 $\mu$eV)
  - Measured permittivity of teflon, $\varepsilon_r$=2.050
  - Measured loss tangent, $\delta$=0.0005

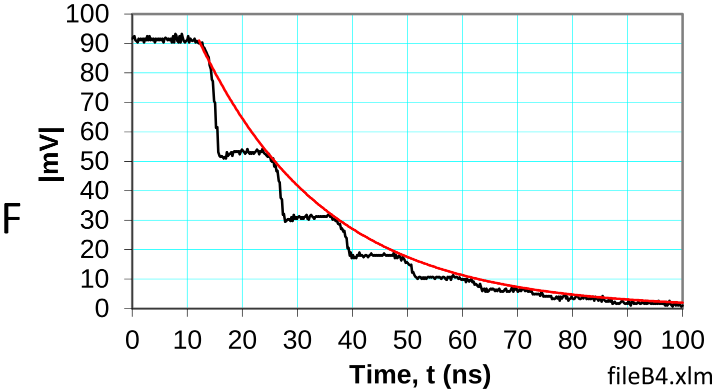


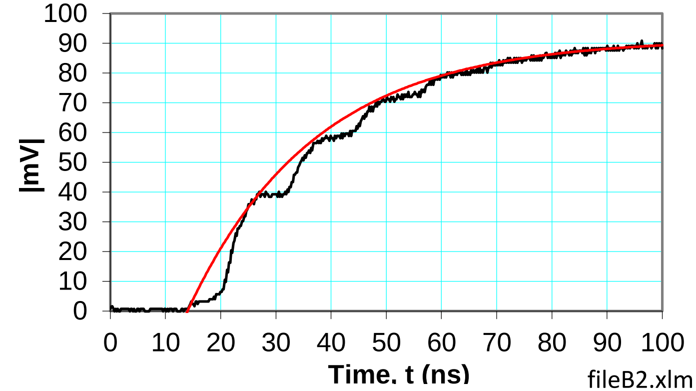



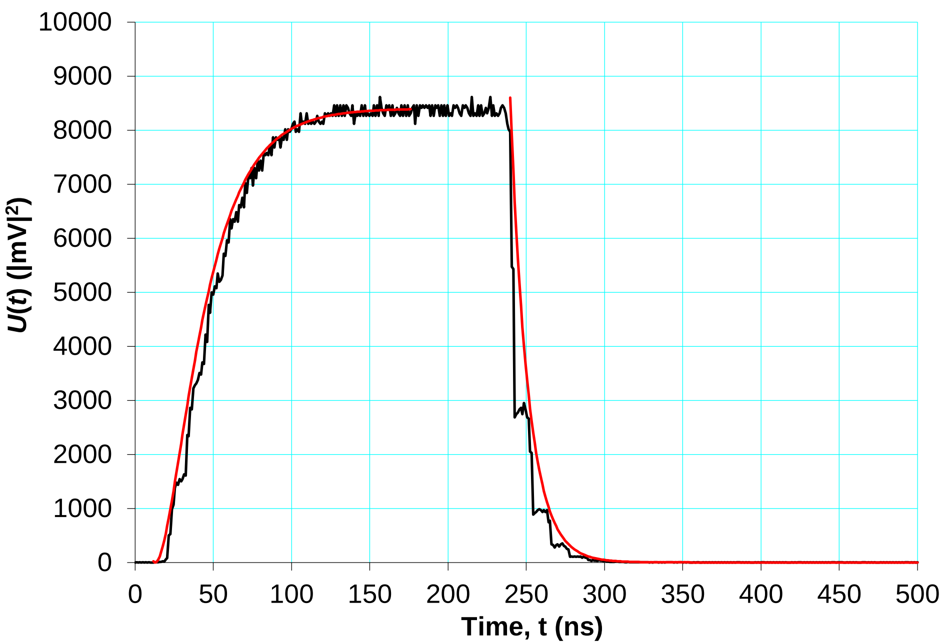



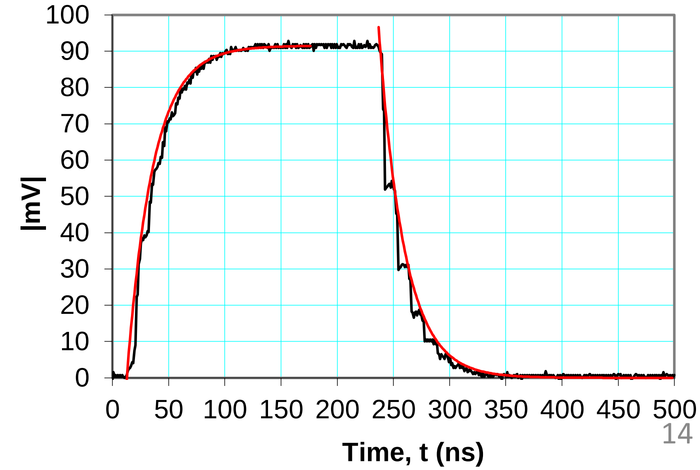
# Experimental validation using Fabry-Perot resonator in waveguide

- Measured transmitted electromagnetic energy density in time-domain $U(t)$ ($|\mathrm{mV}|^2$ into 50Ω)
- Resonant frequency, $f_0$=8.0620 GHz ($E_0$=33 μeV)
  - 1/25,000 scale reduction in frequency from optical to RF
- 3 quarter-wave pair DBR in teflon
- Round-trip time in resonator $\tau_{RT}$=12 ns
- Resonator $Q$=582 corresponds to $\tau_Q$=11.5 ns (red curve)
- *Long* pulse time $\tau_p$=230ns >> $\tau_{RT}$, $\tau_Q$

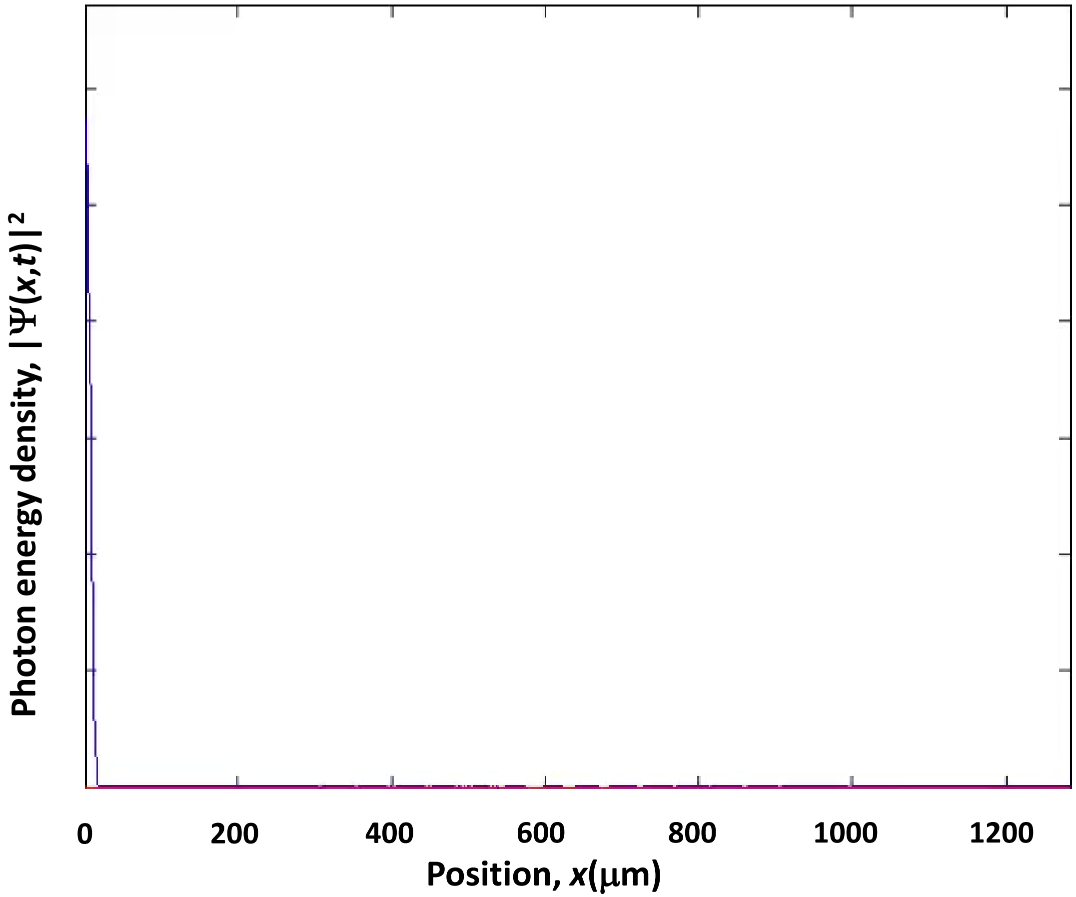


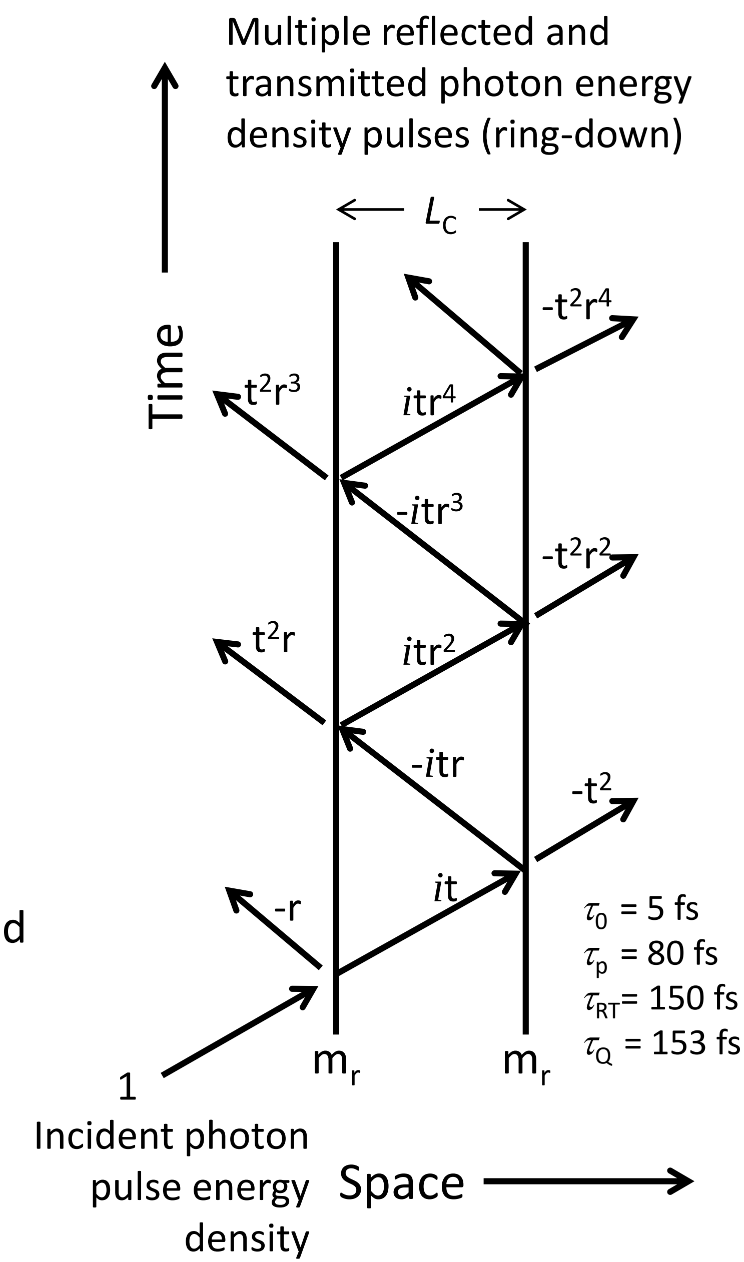



# *Uncontrolled* short single-photon pulse in cavity ring-down



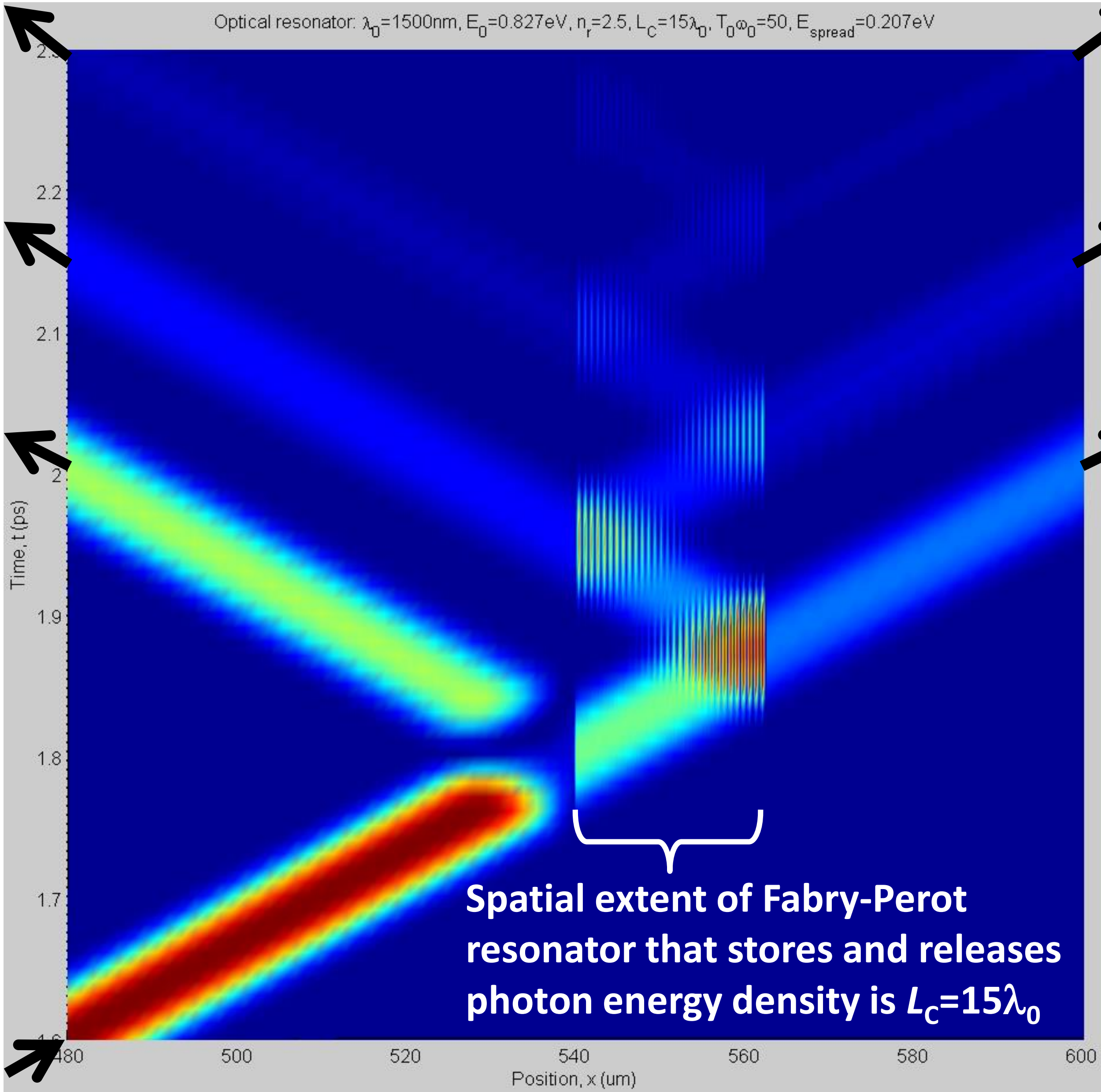




- Identical lossless dielectric mirrors $m_r$ with complex field reflectivity r and transmission t
- π phase shift on reflection of incident field
- Resonant photon field *in* resonator is geometric series $(1+re^{i\phi}+r^2e^{i2\phi}+r^3e^{i3\phi} + \ldots)=1/(1-re^{i\phi})$ where phase per round-trip is $2\phi=2\pi\omega/\Delta\omega$ and spacing between resonances is $\Delta\omega=\pi c/L_C n_r$

# *Uncontrolled* single-photon cavity ring-down

Multiple reflected photon energy density pulses (ring-down)

Multiple transmitted photon energy density pulses (ring-down)




Time

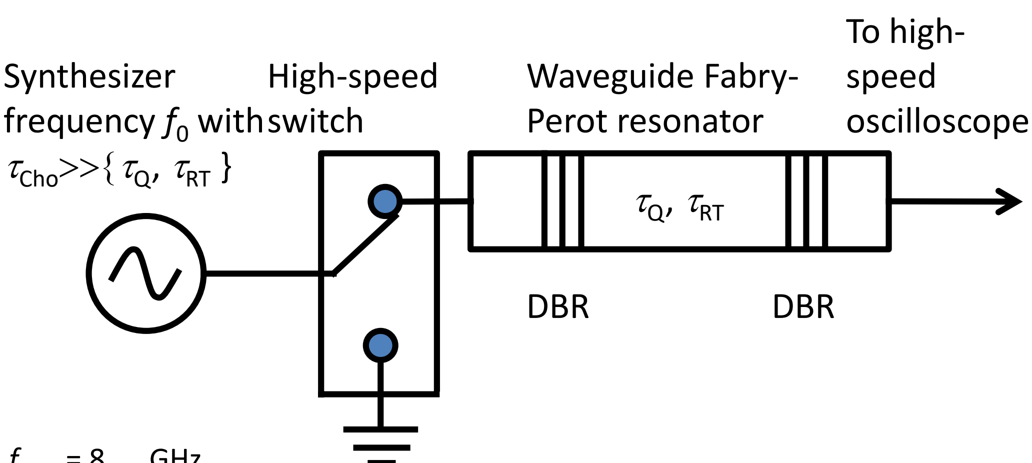
Incident photon pulse energy density

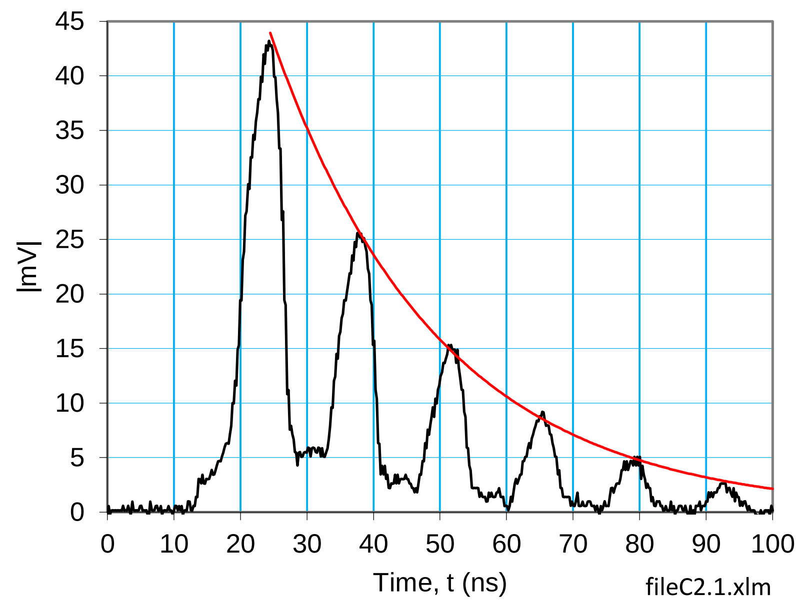
Space

$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

# Experimental validation using Fabry-Perot resonator in waveguide

- Can also probe the internal structure of the Fabry-Perot resonator using *short* electromagnetic pulse time $\tau_p$=7 ns < $\tau_{RT}$, $\tau_Q$
- Round-trip time in resonator $\tau_{RT}$=13.7 ns
- Resonator $Q$=633 corresponds to $\tau_Q$=12.5 ns (red curve)
- RF switch rise time is 2 ns
- Measured transmitted electromagnetic signal in time-domain |mV| into 50 Ω




$f_0$ = 8 GHz
$\tau_{Coh}$ = 1 s
$\tau_0$ = 125 ps
$\tau_p$ = 7 ns
$\tau_{RT}$ = 13.7 ns
$\tau_Q$ = 12.5 ns

# Coherent control of *transient dynamics*

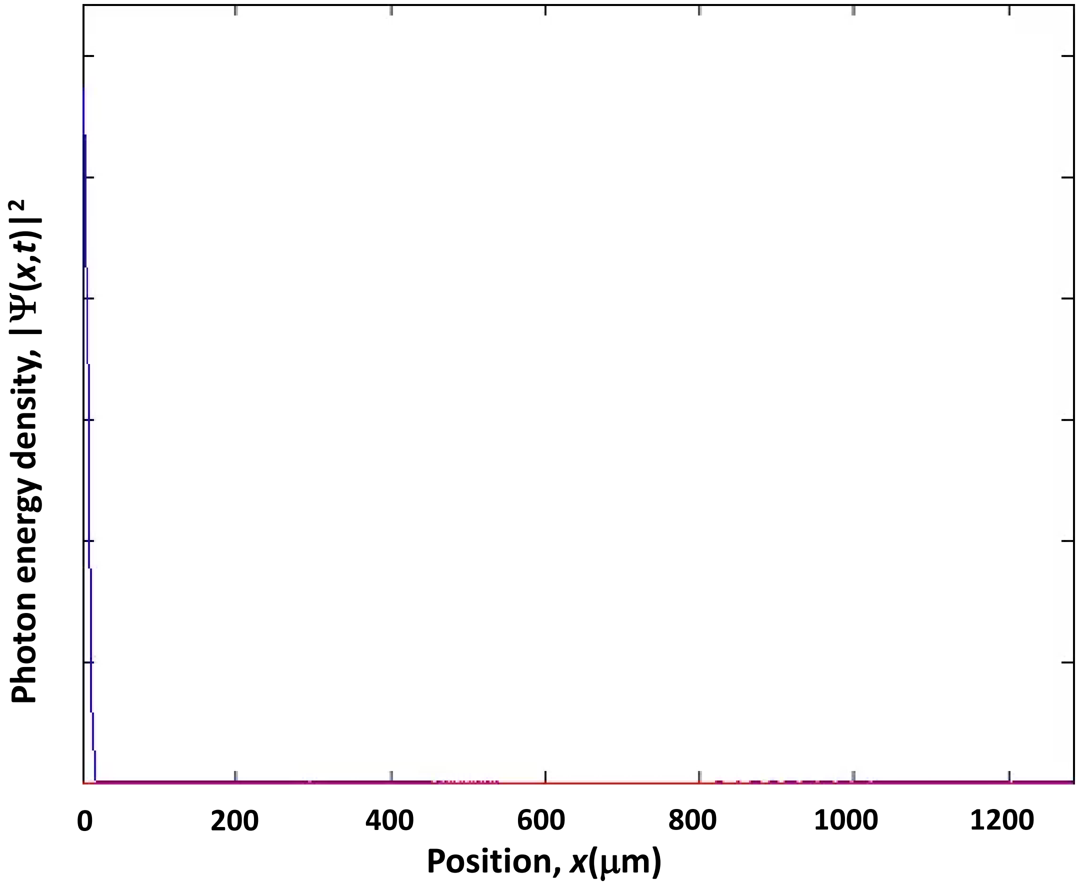
- Zero-energy ground-state is a *guaranteed* control point
- Question: How do you *stop* a bell ringing ?
  - The "ringing bell" could be *excitations* of a molecule, a crystal, a device, …

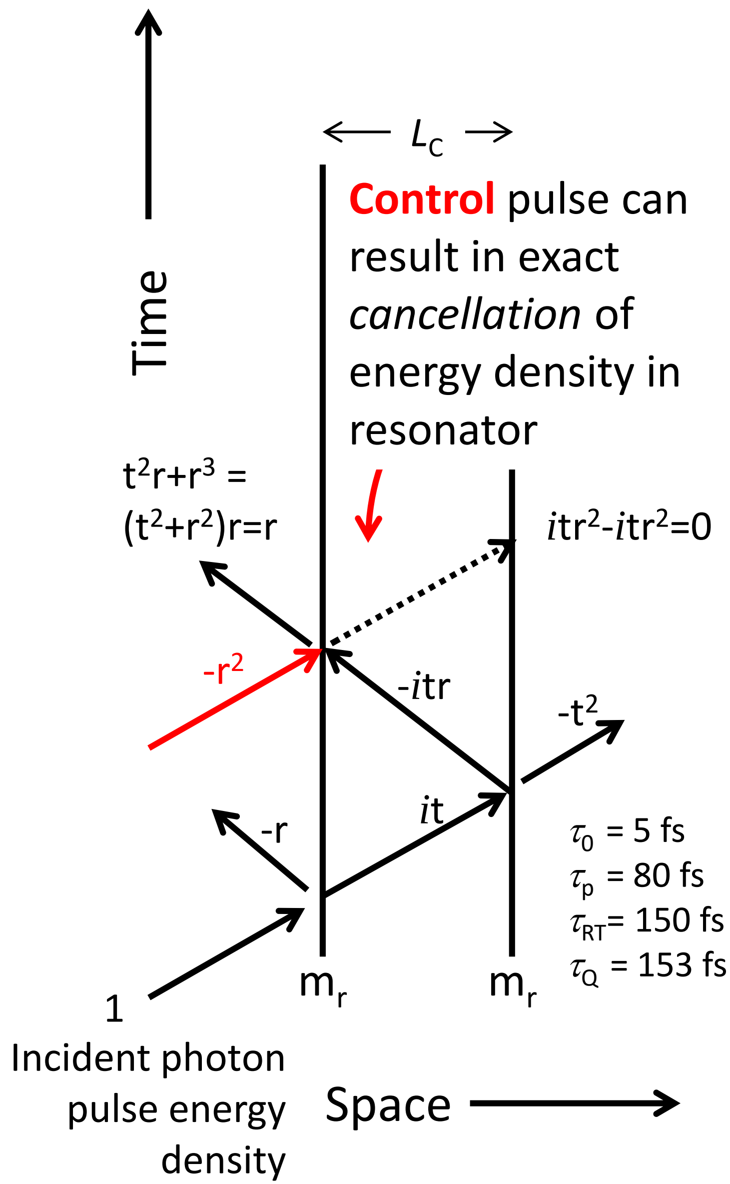
# Coherent control of *transient dynamics*

- Question: How do you *stop* a bell ringing ?
- Answer: You hit it ! ( … in a *very* controlled and precise way)

**Control field generator** **System**

# *Controlled* single-photon zero cavity ring-down



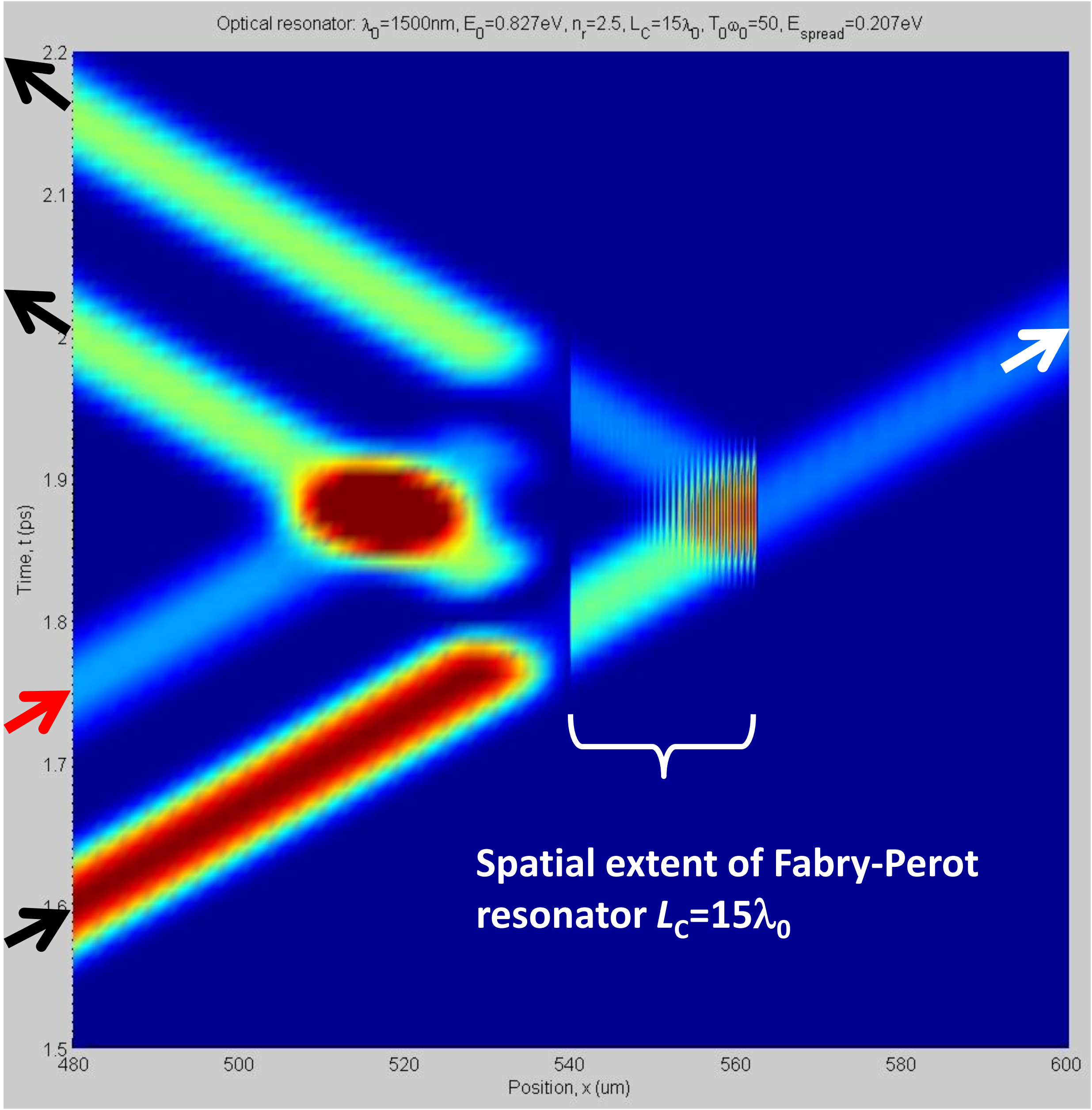

- Identical lossless dielectric mirrors $m_r$ with field reflectivity r and field transmission t
- **Control** pulse with optimal amplitude and phase shift to eliminate photon energy density in resonator
- Formal control methods replaced by *intuitive* ray-tracing of *resonant* part of photon field

# *Controlled* single-photon zero cavity ring-down

Dual reflected photon pulse energy density

Incident control photon pulse and lead pulse energy density

Time

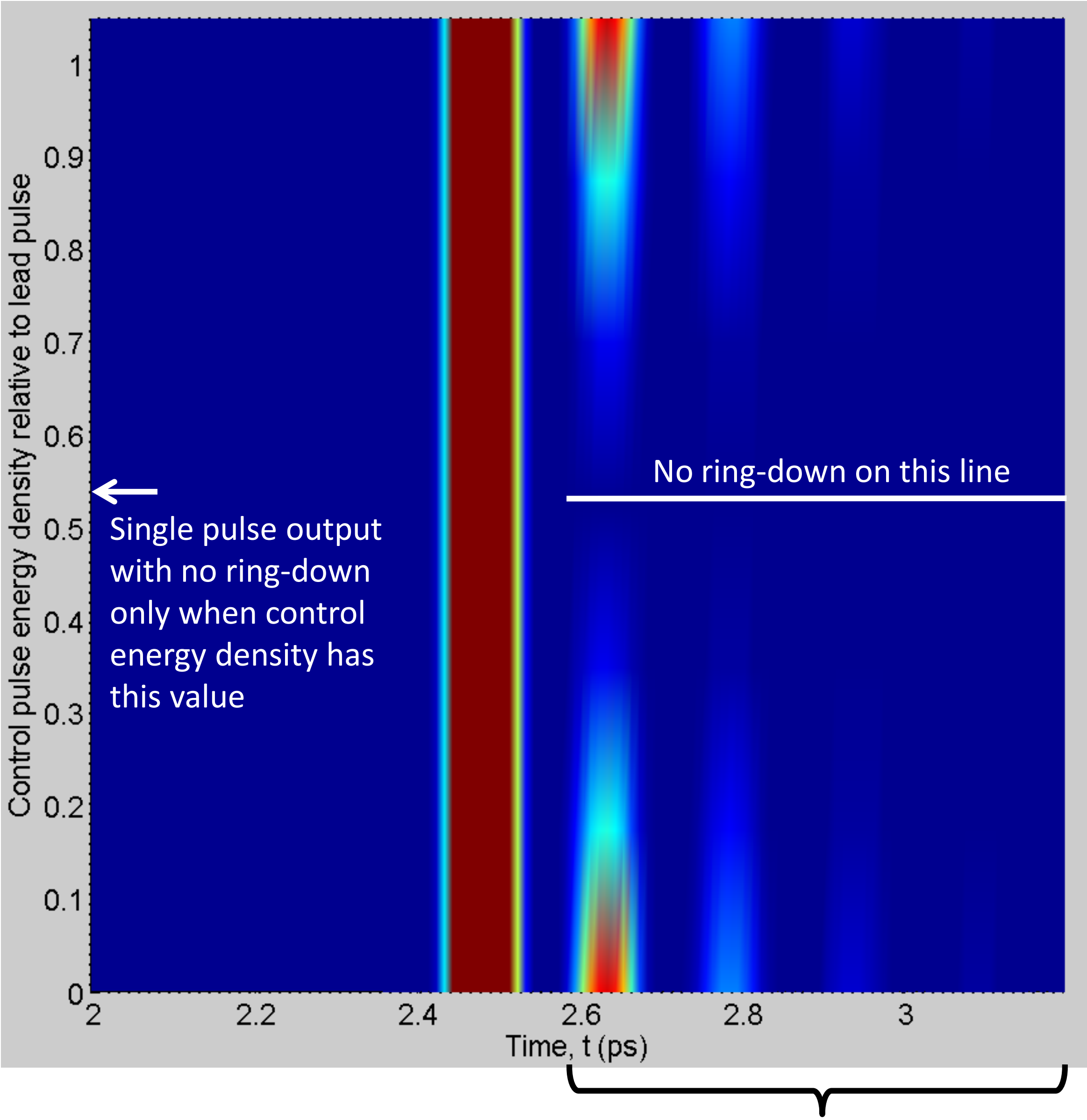



Space

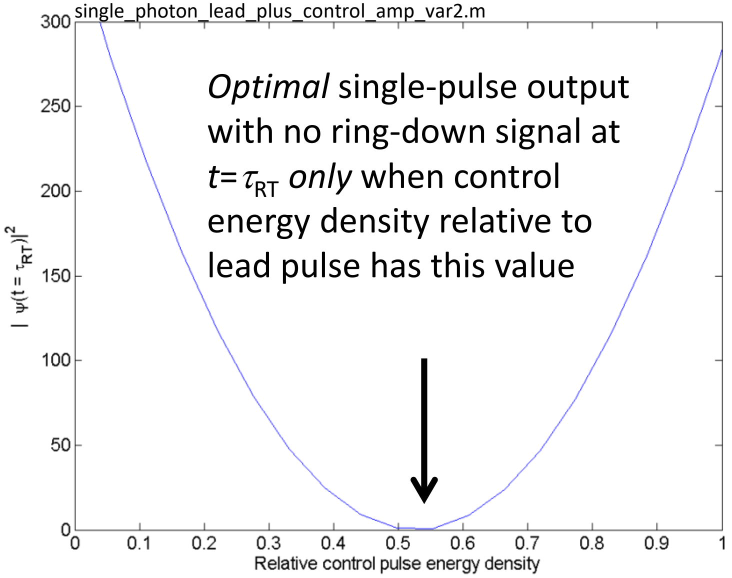
Transmitted single-photon pulse energy density (cancellation of ring-down)

$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

# Resonator energy density output as function of control pulse energy density




*Locally convex* resonator energy density output as function of control pulse energy density

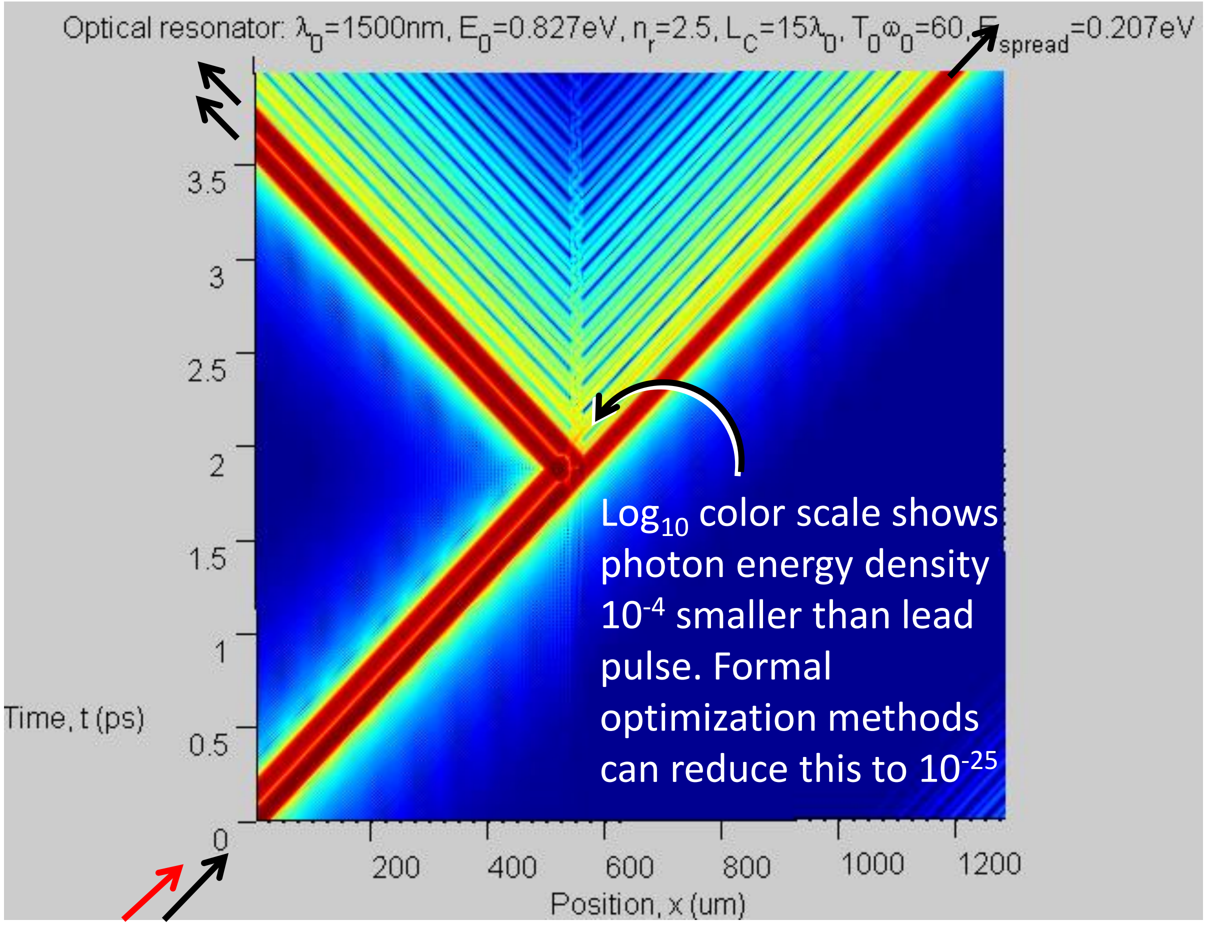



$\tau_0$ =5fs
$\tau_p$ =80fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Coherent control of single-photon resonator output pulse using control pulse

- Better than 1:$10^4$ cancellation using simple control pulse protocol
- Cancellation of residue requires better control pulse match to Fabry-Perot transfer function or slower (smaller bandwidth) operation

Dual reflected photon pulse energy density

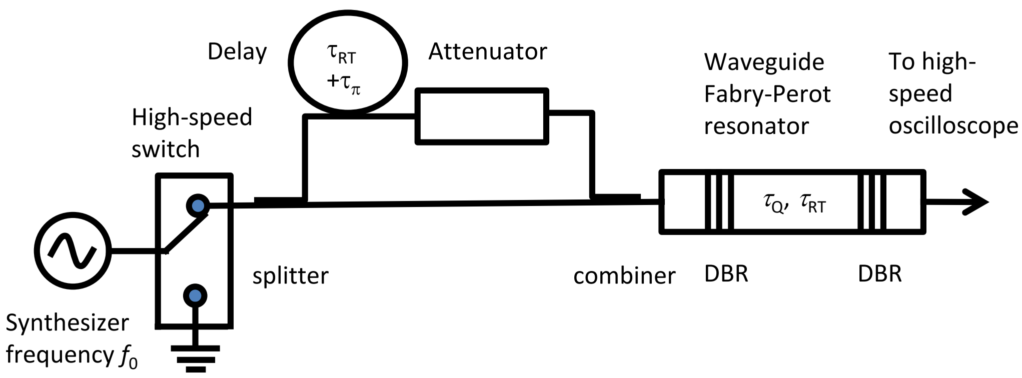



Single transmitted photon energy density pulse amplitude $t^2$

Incident lead photon pulse and control pulse energy density

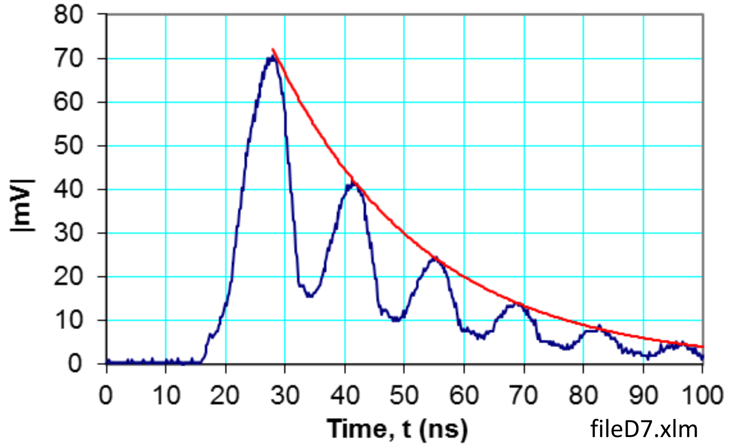
$\tau_0$ =5fs
$\tau_p$ =80fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Experimental validation using Fabry-Perot resonator in waveguide

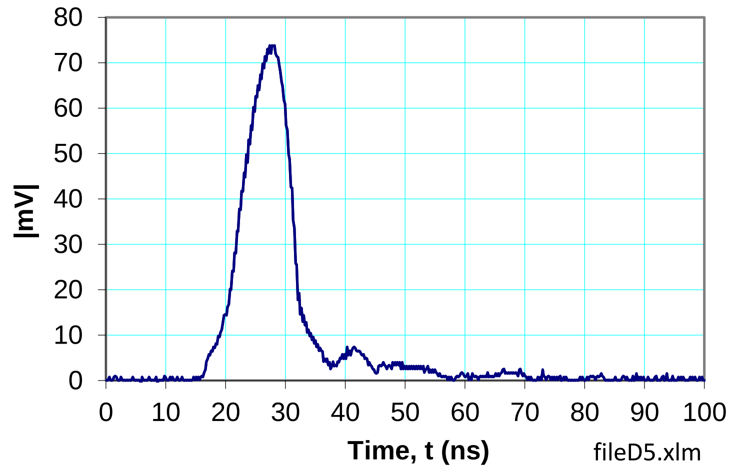



$f_0$ = 8 GHz, $\tau_{Coh}$ = 1 s, $\tau_0$ = 125 ps, $\tau_p$ = 7 ns, $\tau_{RT}$ = 13.7 ns, $\tau_Q$ = 12.5 ns

*No* control pulse

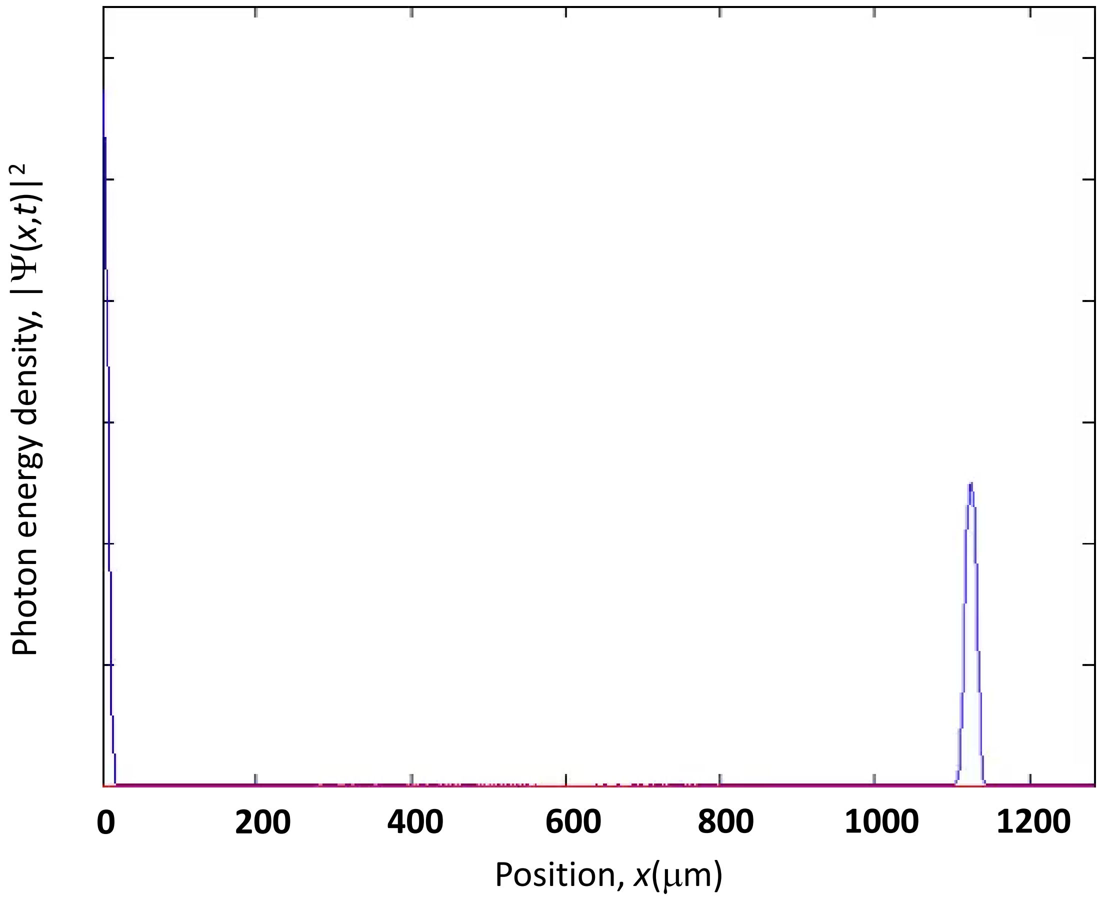


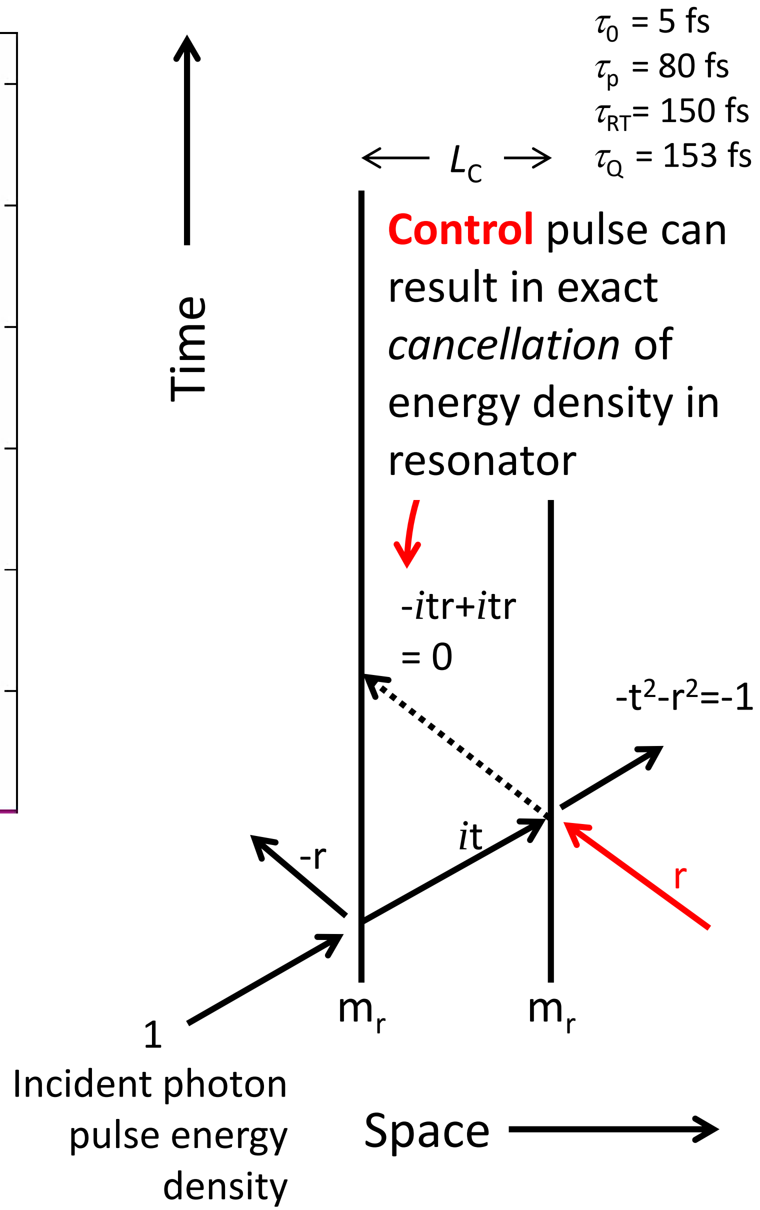

*With* single control pulse




- Coherent control of resonator *short* output pulse using single *short* control pulse
- Short electromagnetic pulse of width $\tau_p$=10 ns < $\tau_{RT}$, $\tau_Q$
- Round-trip time in resonator $\tau_{RT}$=13.7 ns
- Resonator *Q*=633 corresponds to $\tau_Q$=12.5 ns (red curve)
- Measured transmitted electromagnetic signal in time-domain |mV| into 50 Ω

# Coherent control of single-photon resonator output pulse using one backward control pulse



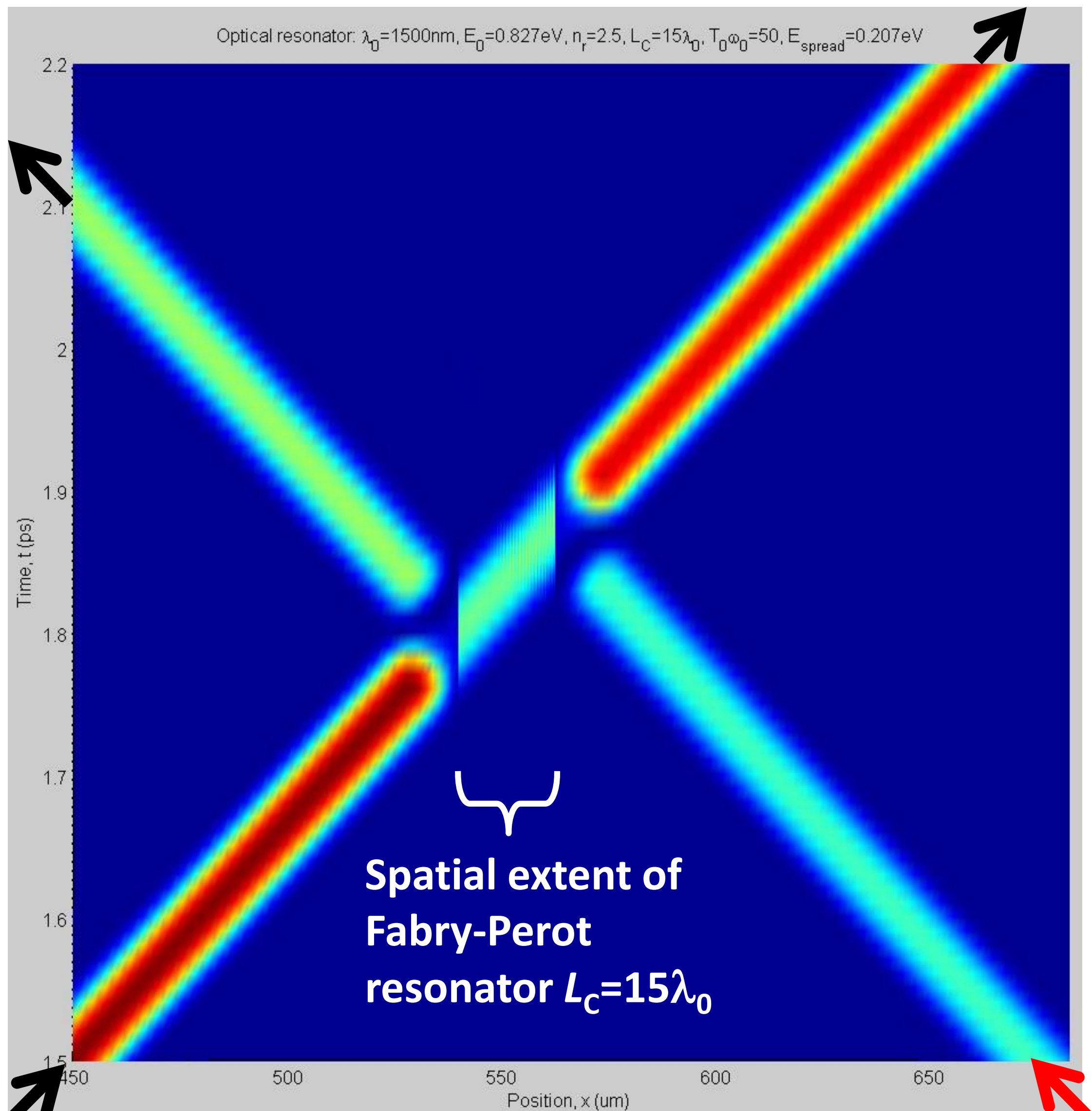

- Lead pulse and *one* backward propagating **control** pulse incident on resonator
- Single pulse transmitted and single pulse reflected with *no* ring-down

# Coherent control of single-photon resonator output pulse using one backward control pulse

Single reflected photon pulse energy density

Transmitted photon energy density as single pulse

Time



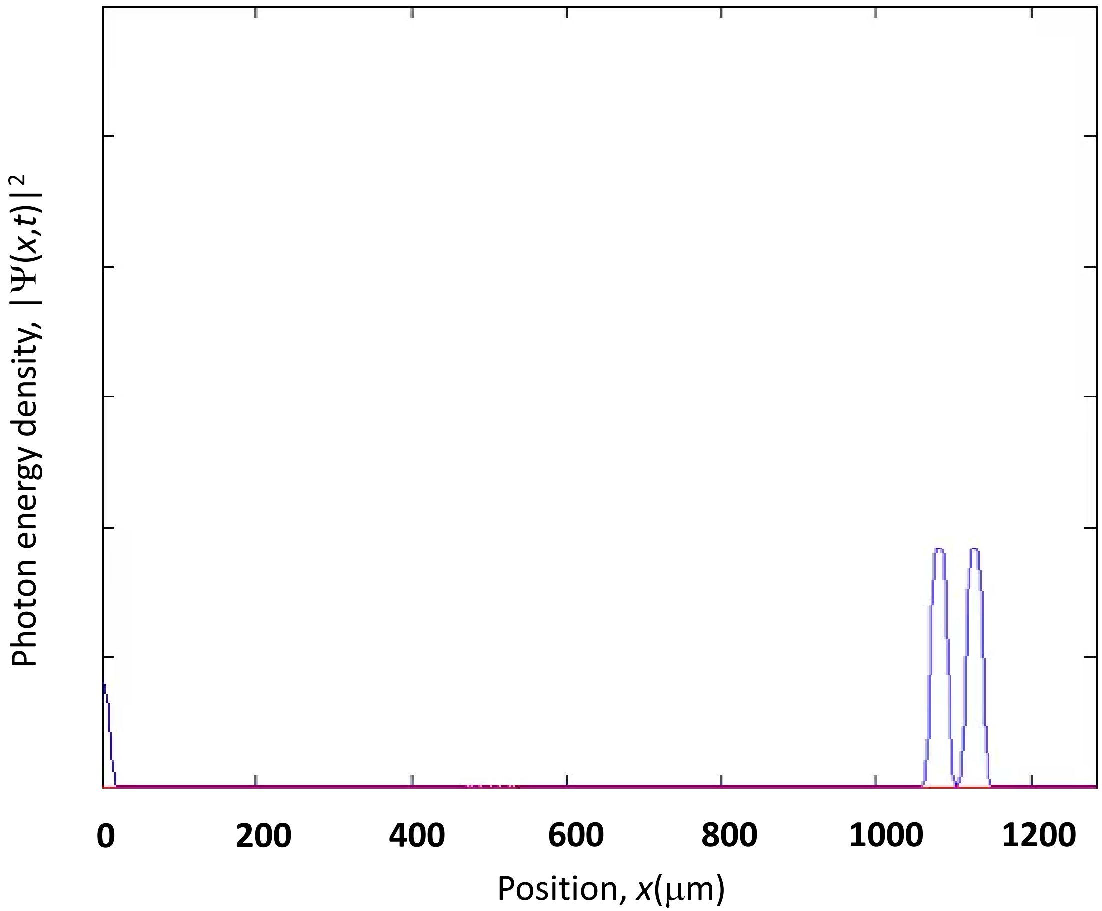

$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

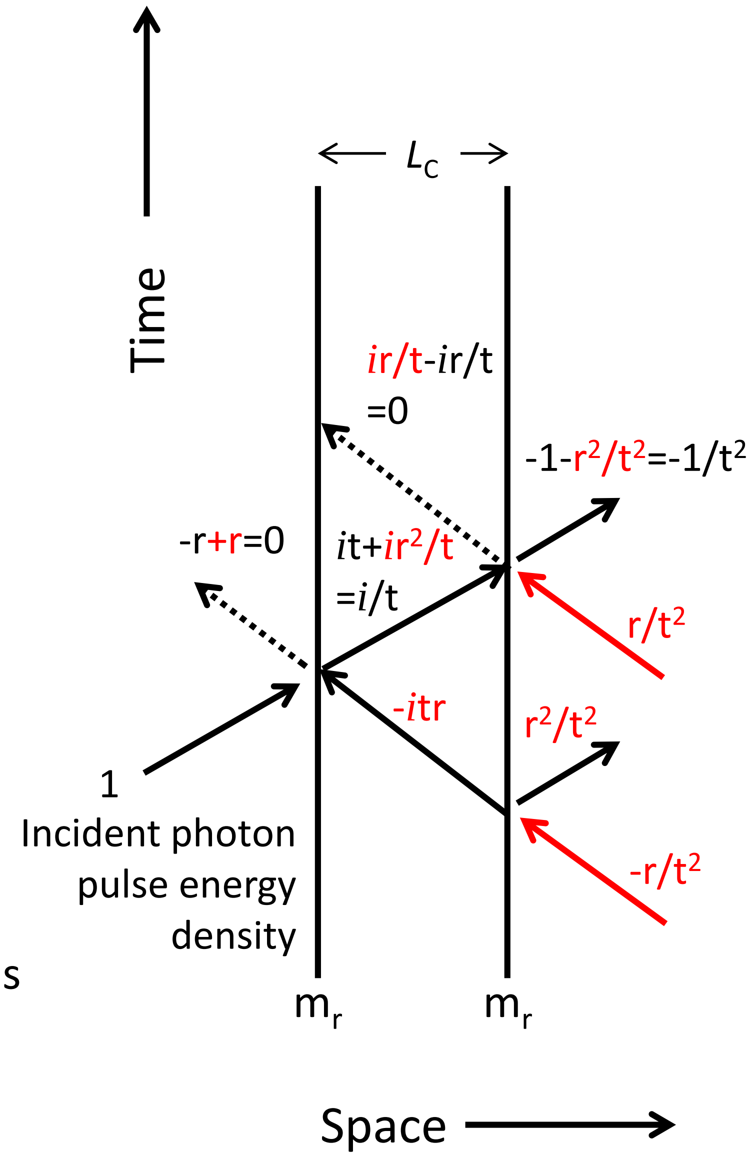
Incident lead photon pulse energy density

Space

Backward propagating control pulse

# Coherent control of single-photon resonator output pulse using two backward control pulses

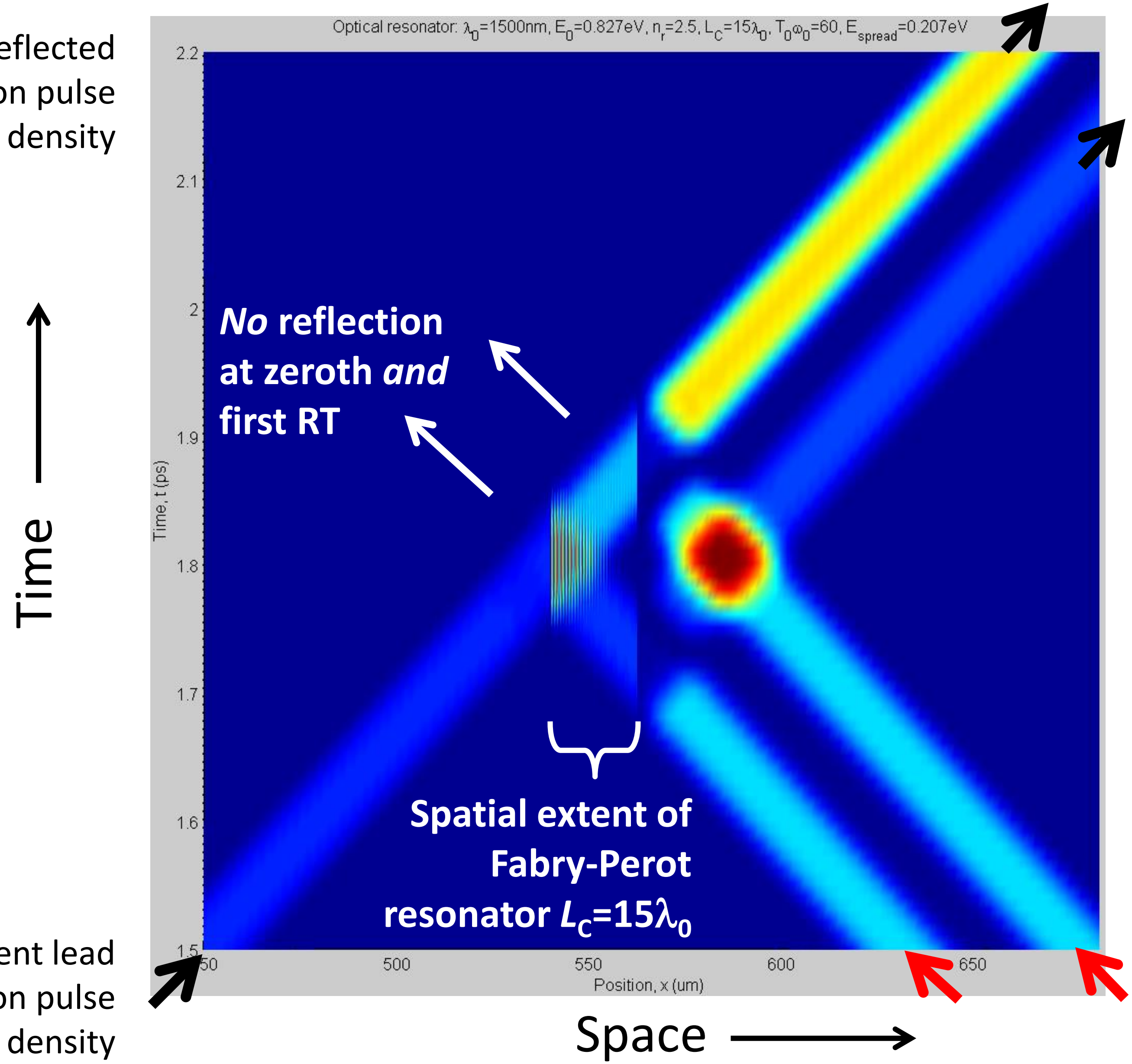



- Lead pulse and *two* backward propagating **control** pulses incident on resonator
- Dual pulse transmitted with *no* ring-down

# Coherent control of single-photon resonator output pulse using two backward control pulses

Single reflected photon pulse energy density



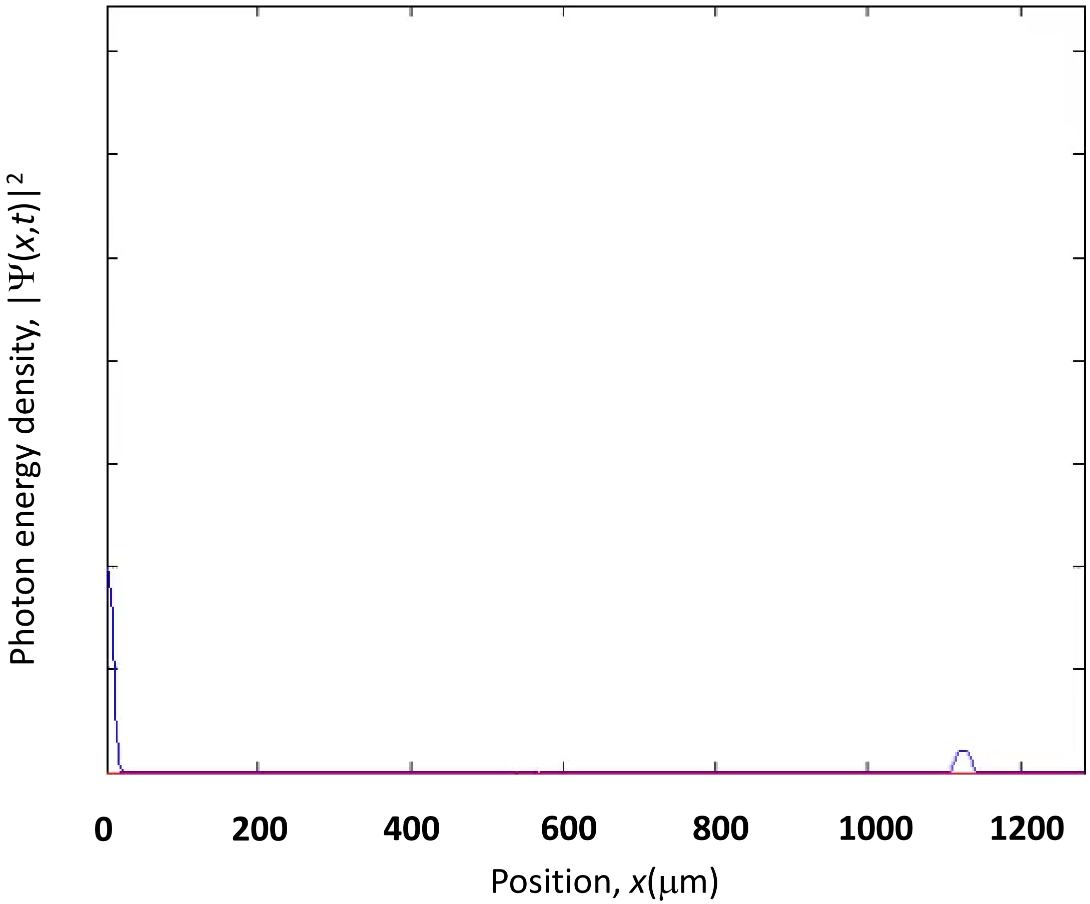

Two transmitted photon energy density pulses

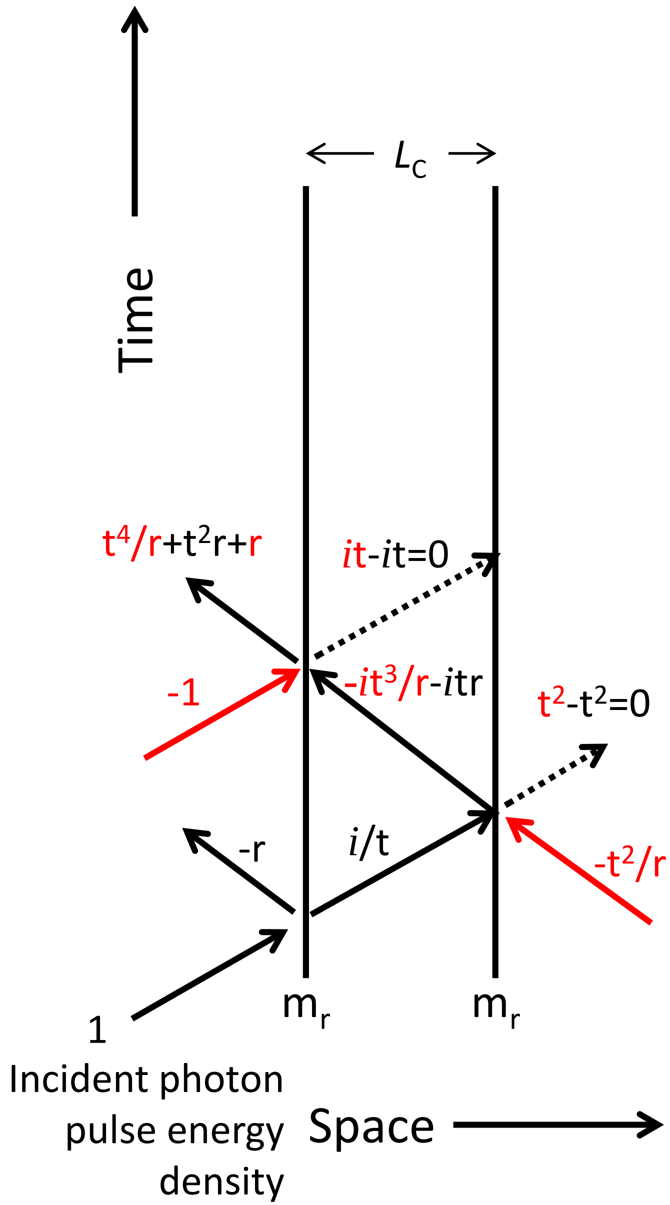
$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

Incident lead photon pulse energy density

Backward propagating control pulses

# Coherent control using one forward and one backward control pulse (or a very small pulse can control two large pulses)




- Lead pulse and *one* forward and *one small* backward propagating **control** pulse incident on resonator
- Two pulses reflected with *no* ring-down
- Note small energy in backward propagating control pulse

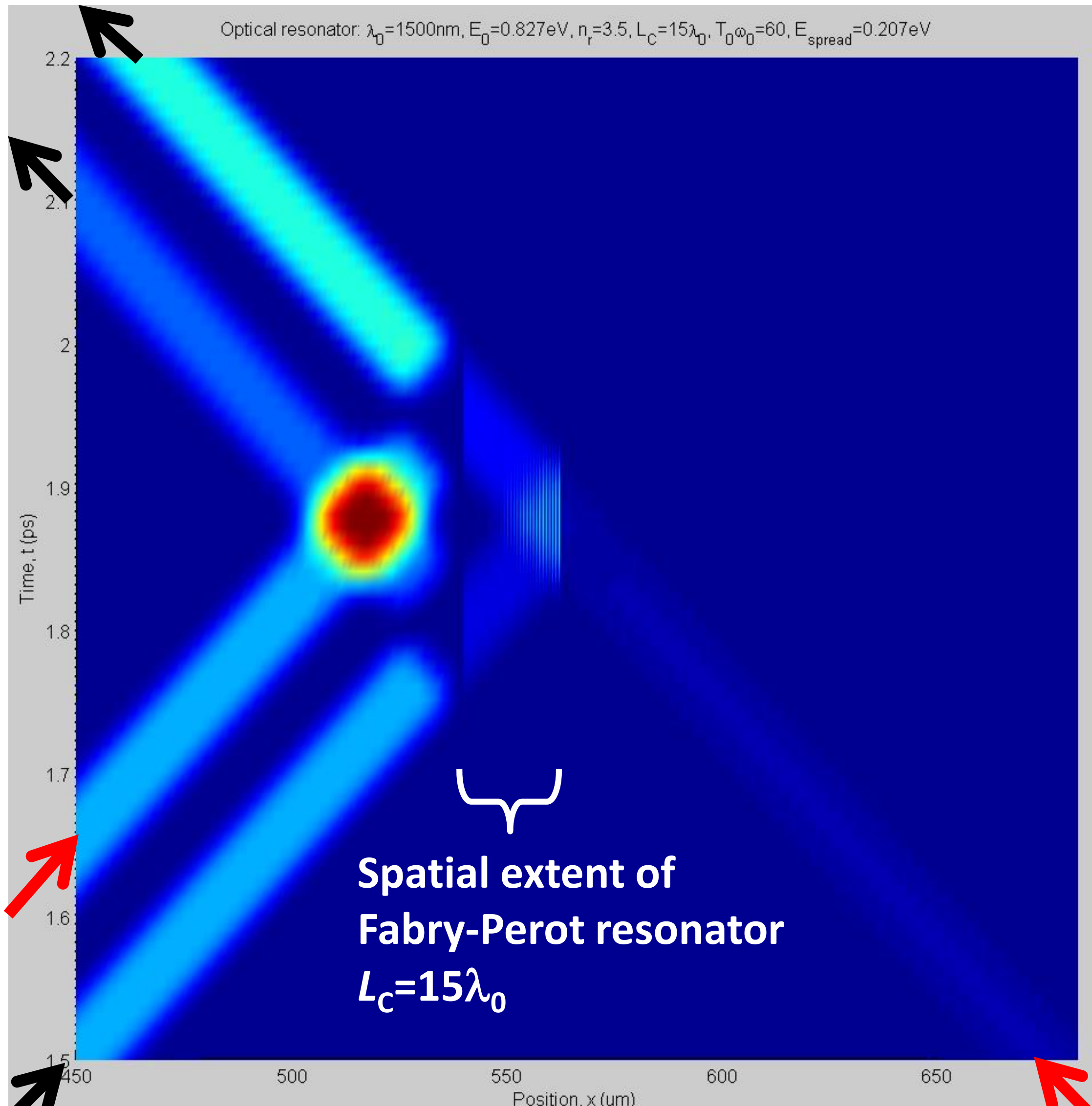
# Coherent control using one forward and one backward control pulse

Reflected photon energy density pulses

Time

Forward propagating control pulse

Incident lead photon pulse energy density



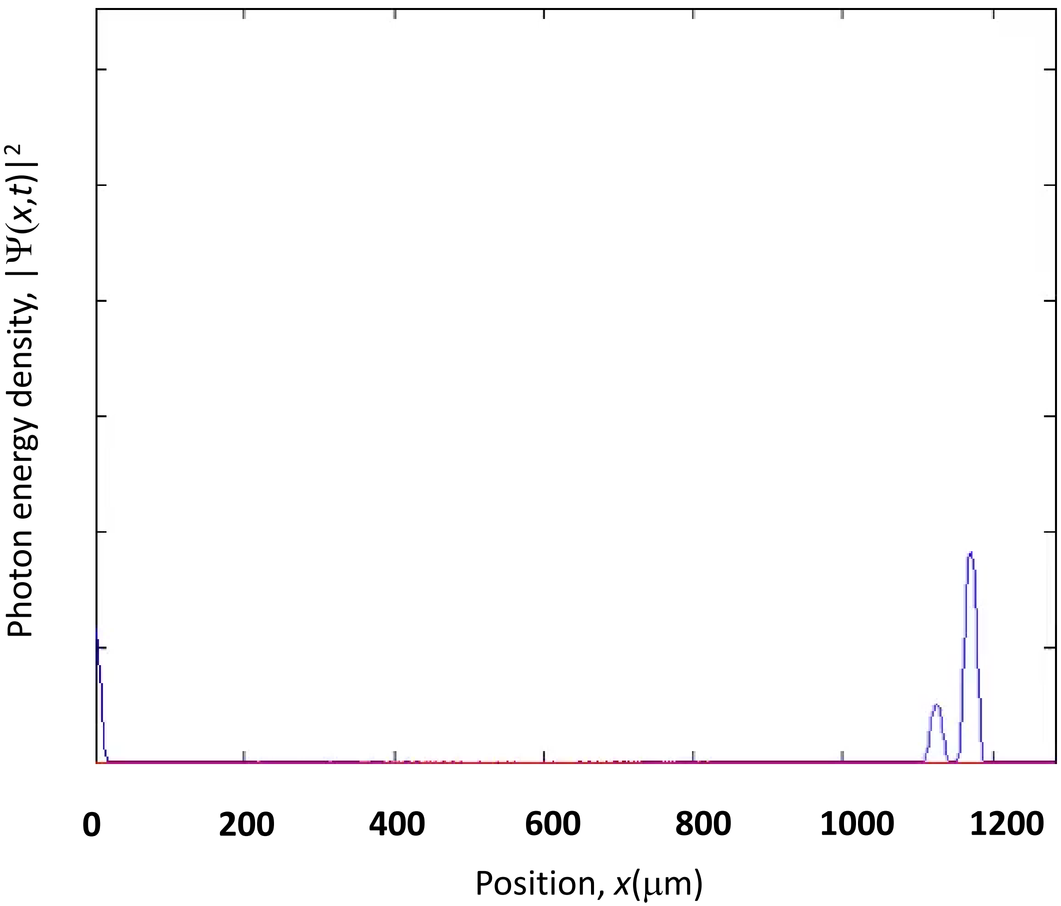

Space

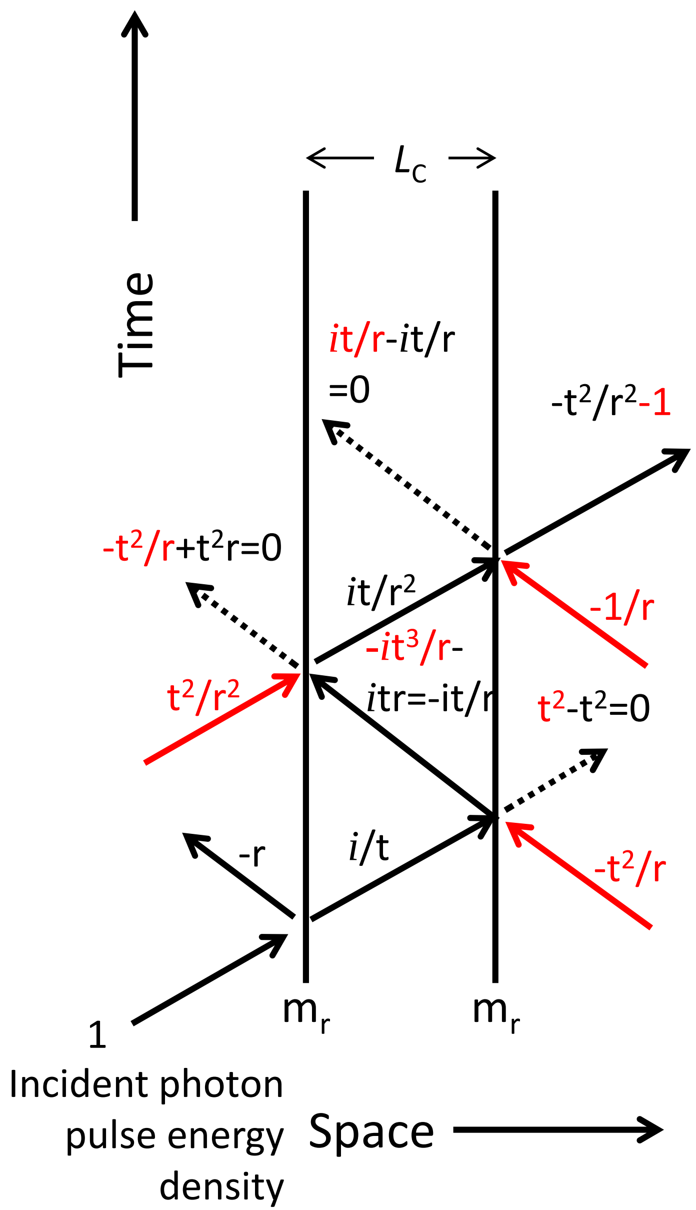
*No* Transmitted photon energy density

$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

Backward propagating control pulse

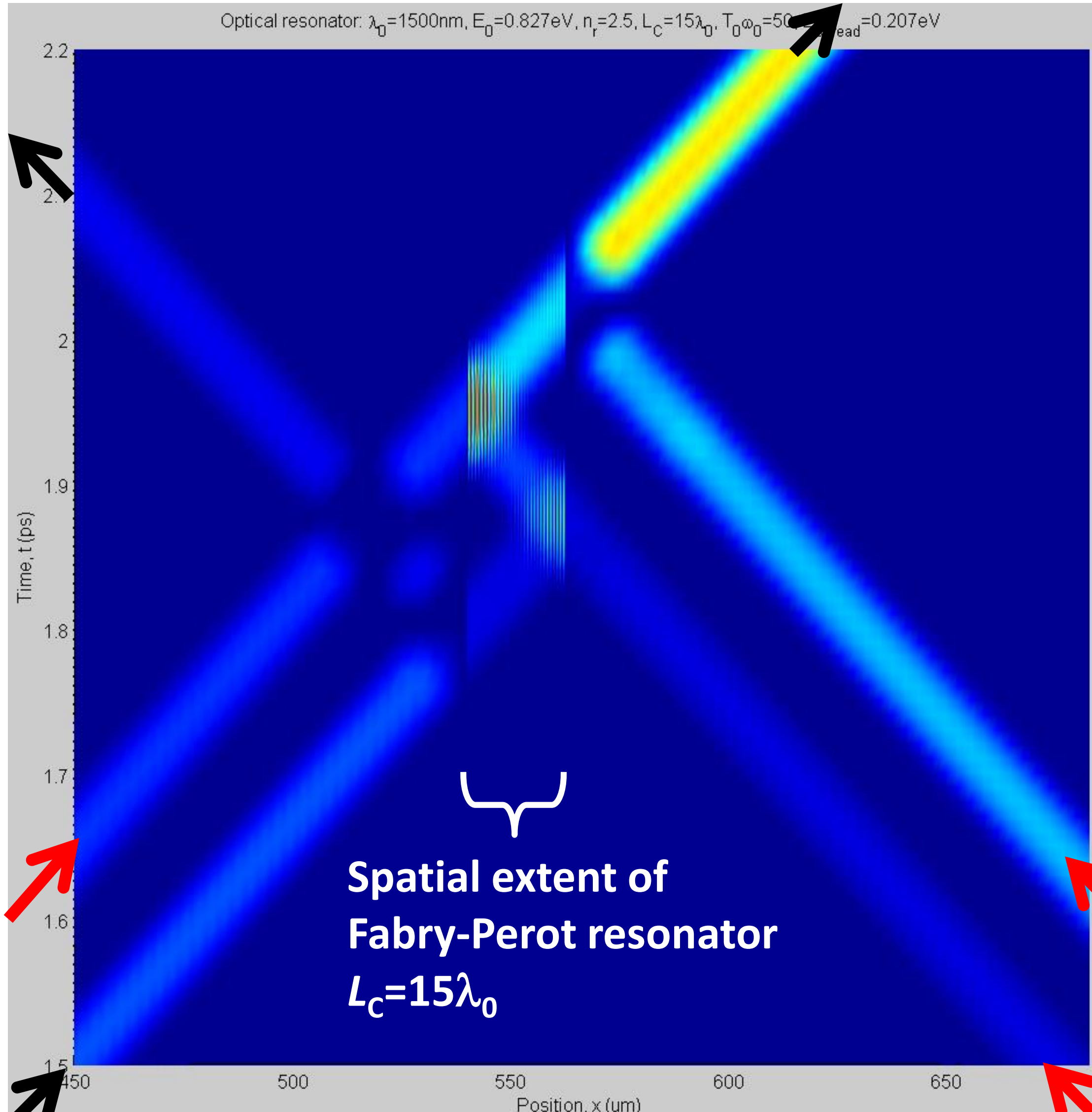
# Coherent control using one forward and two backward control pulses




- Lead pulse and *one* forward and two backward propagating **control** pulses incident on resonator
- Single pulse transmitted and single pulse reflected with *no* ring-down

# Coherent control using one forward and two backward control pulses




Reflected photon energy density pulse

Time

Forward propagating control pulse

Incident lead photon pulse energy density

Transmitted photon energy density

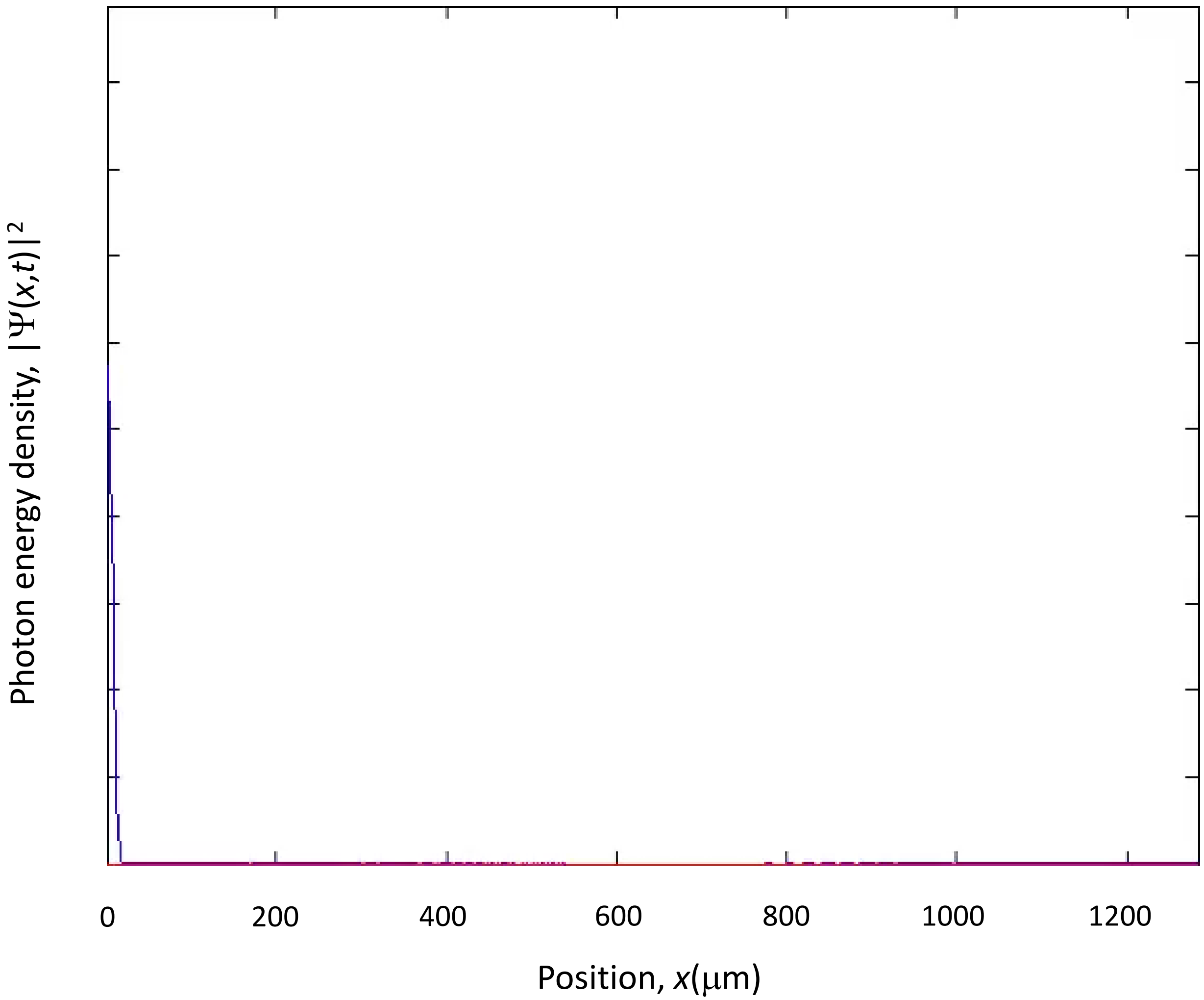
$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$ = 150 fs
$\tau_Q$ = 153 fs

Backward propagating control pulses

Space

# Coherent control of single-photon resonator output pulses using *multiple* control pulses

- Lead pulse and *three* control pulses incident on resonator
- Three identical pulses transmitted and dual pulse reflected with *no* ring-down



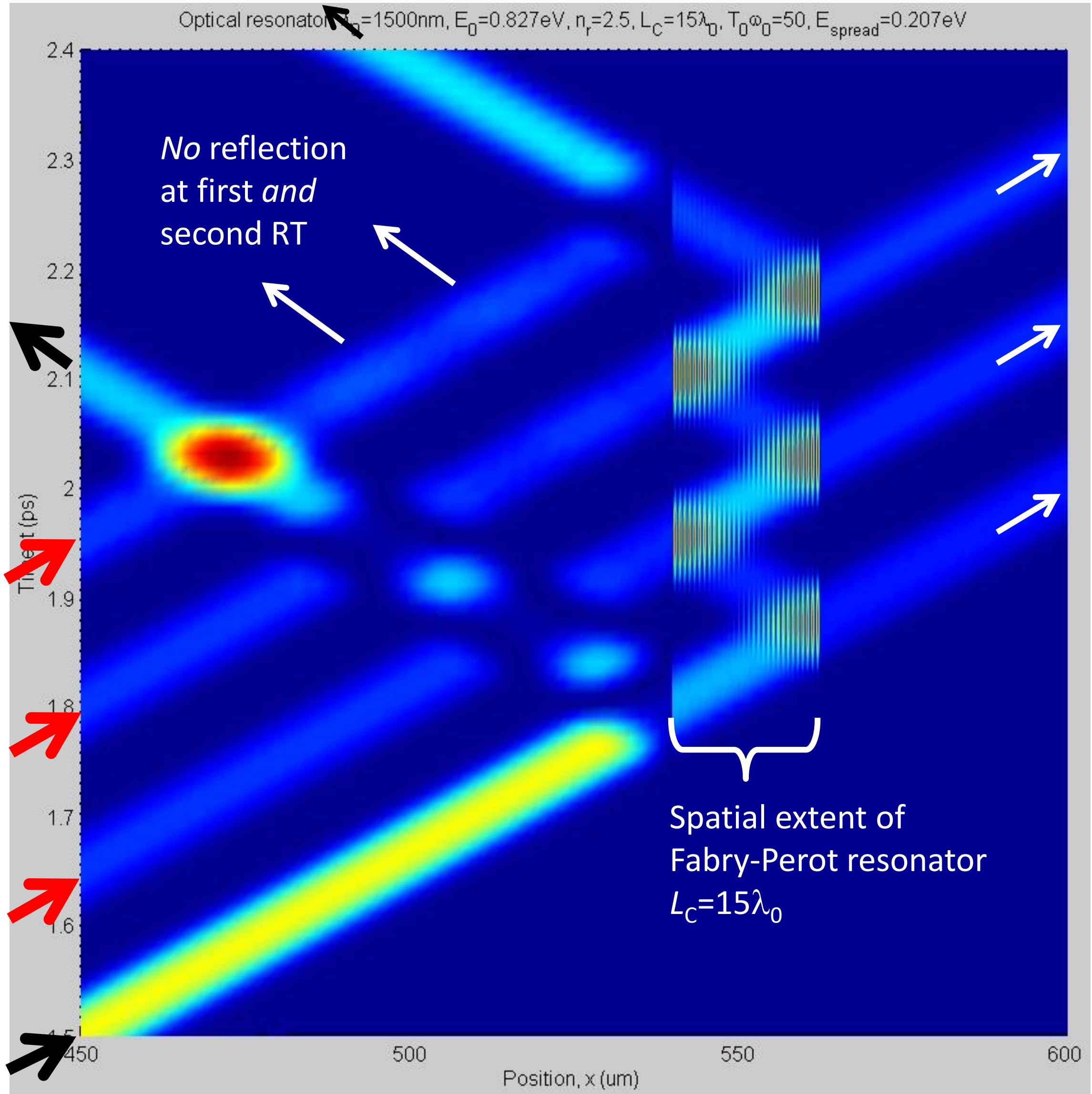

$\tau_0$ =5fs
$\tau_p$ =80fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Coherent control of single-photon resonator output pulse using *three* control pulses

Dual reflected photon pulse energy density

Time

Incident lead photon pulse and multiple control pulse energy density

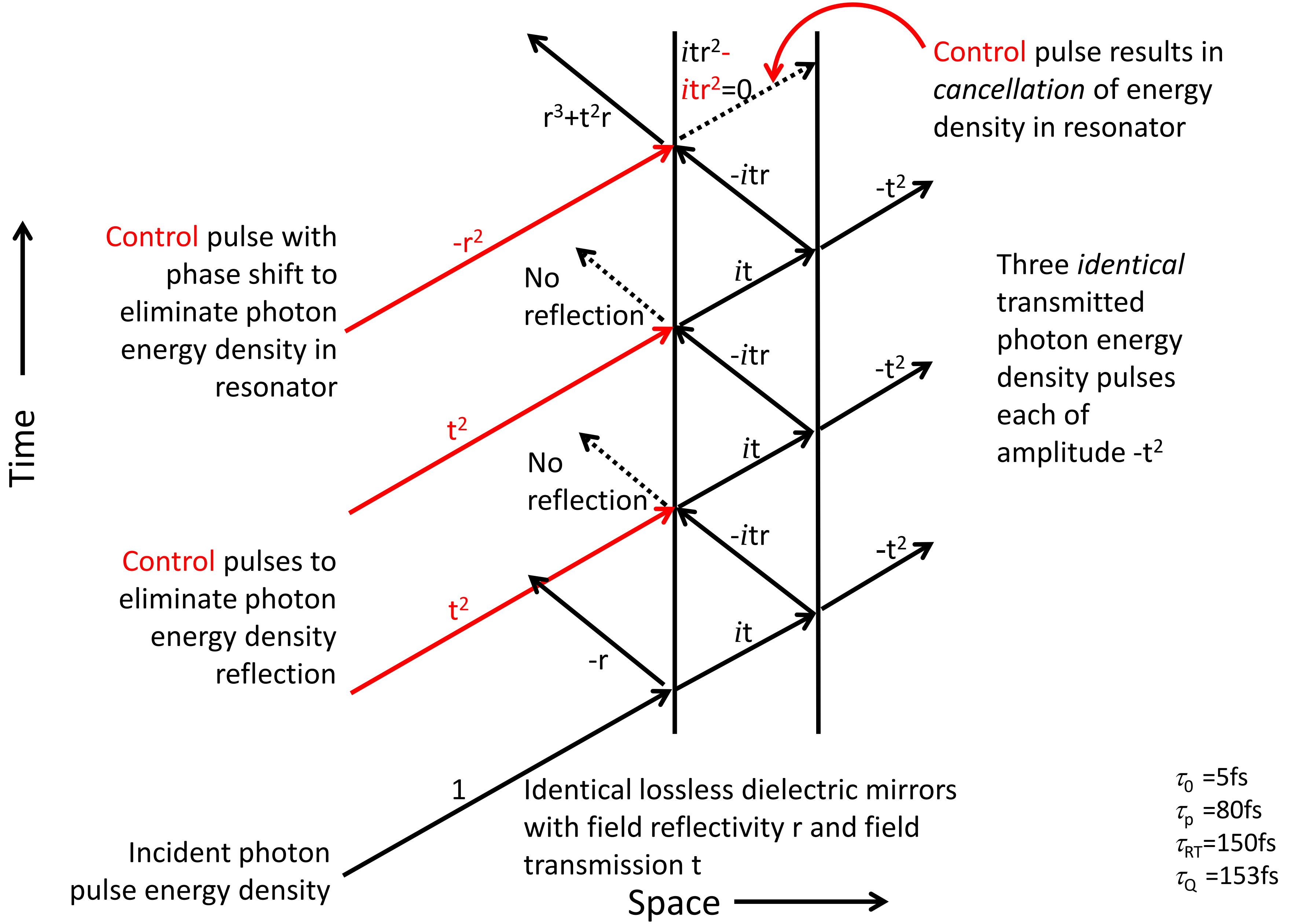



Transmitted photon energy density in three identical pulses

Space

$\tau_0$ =5fs
$\tau_p$ =80fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Coherent control of single-photon resonator output pulse using *three* control pulses




$\tau_0$ =5fs
$\tau_p$ =80fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs

# Geometric series using coherent control pulses to *confine* photon energy density in resonator

Useful relations: $t^2+r^2=1$, $t^2/r^2=1/r^2-1$

$$\sum_{n=0}^{N-1} ax^n = a\,\frac{1-x^N}{1-x}$$

$$x = \frac{e^{i\phi}}{r}$$

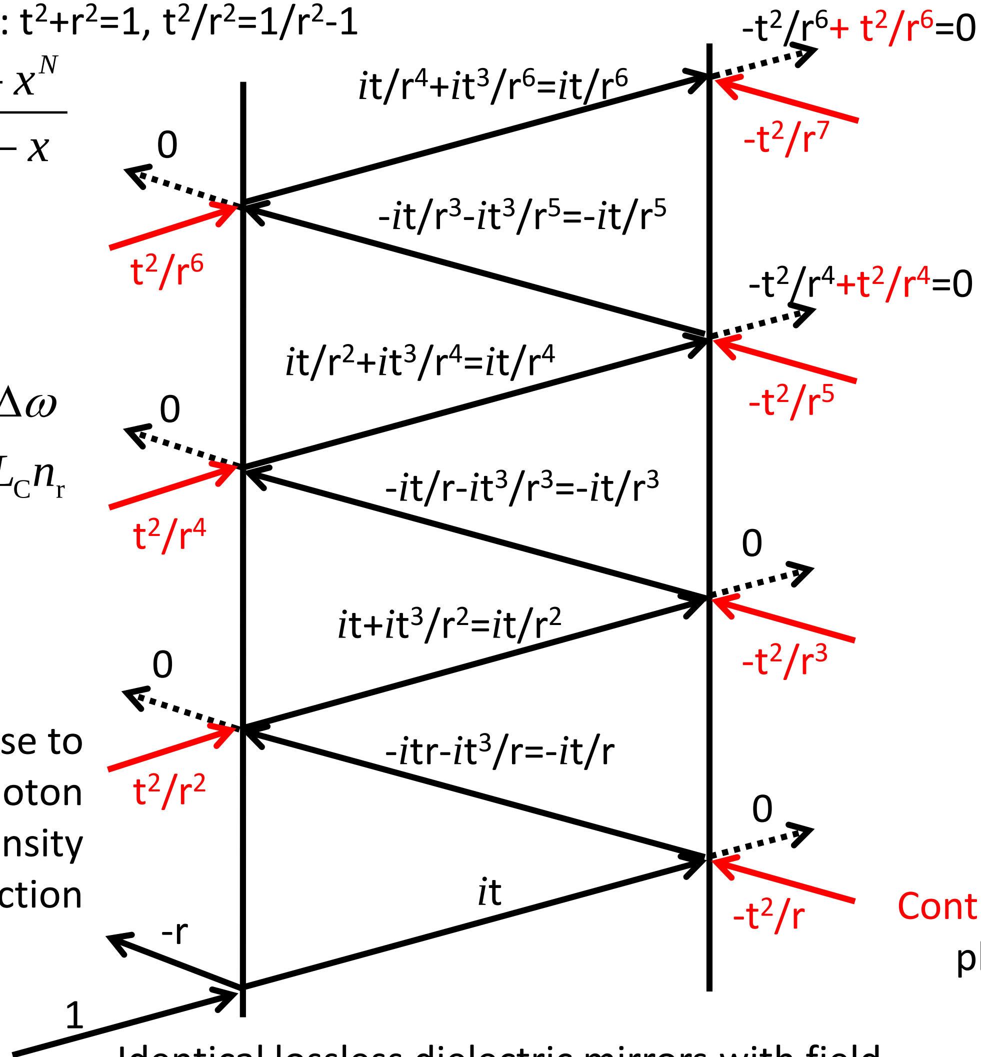
$$a = t$$

$$\phi = \pi\omega / \Delta\omega$$

$$\Delta\omega = \pi c / L_C n_r$$

Time

Control pulse to eliminate photon energy density reflection




Photon field *in* resonator is geometric series in $e^{i\phi}/r$ that sums to the N-1 value as $t(1+e^{i\phi}/r+e^{i2\phi}/r^2+e^{i3\phi}/r^3 + \ldots)= t(1-(e^{i\phi}/r)^N)/(1-(e^{i\phi}/r))$ where phase per round-trip is $2\phi=2\pi\omega/\Delta\omega$ and spacing between resonances is $\Delta\omega=\pi c/L_C n_r$. The series does not converge because $r<1$ and so $|e^{i\phi}/r| >1$.

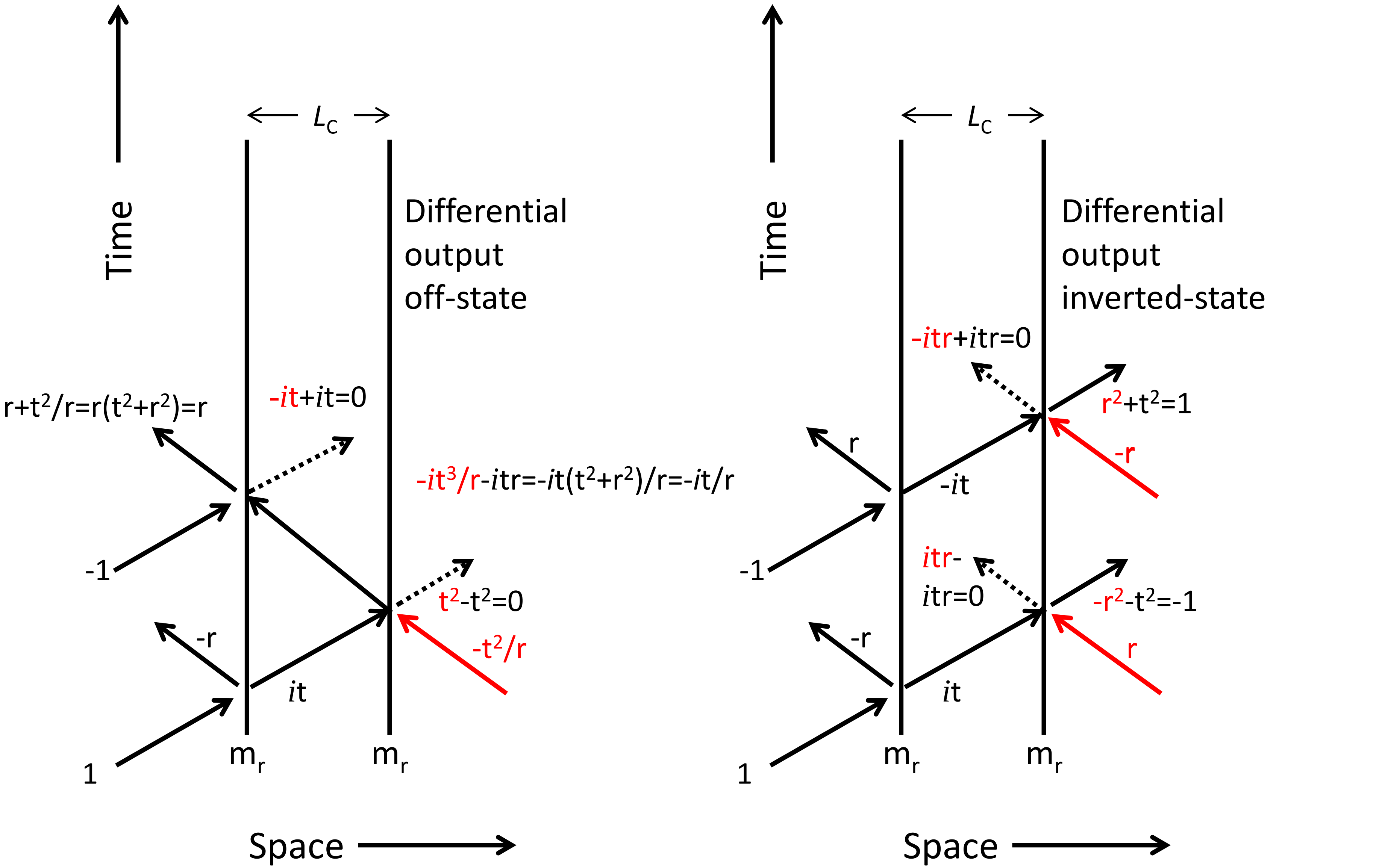
Control pulse to eliminate photon energy density reflection

Incident photon pulse energy density

Identical lossless dielectric mirrors with field reflectivity r and field transmission t

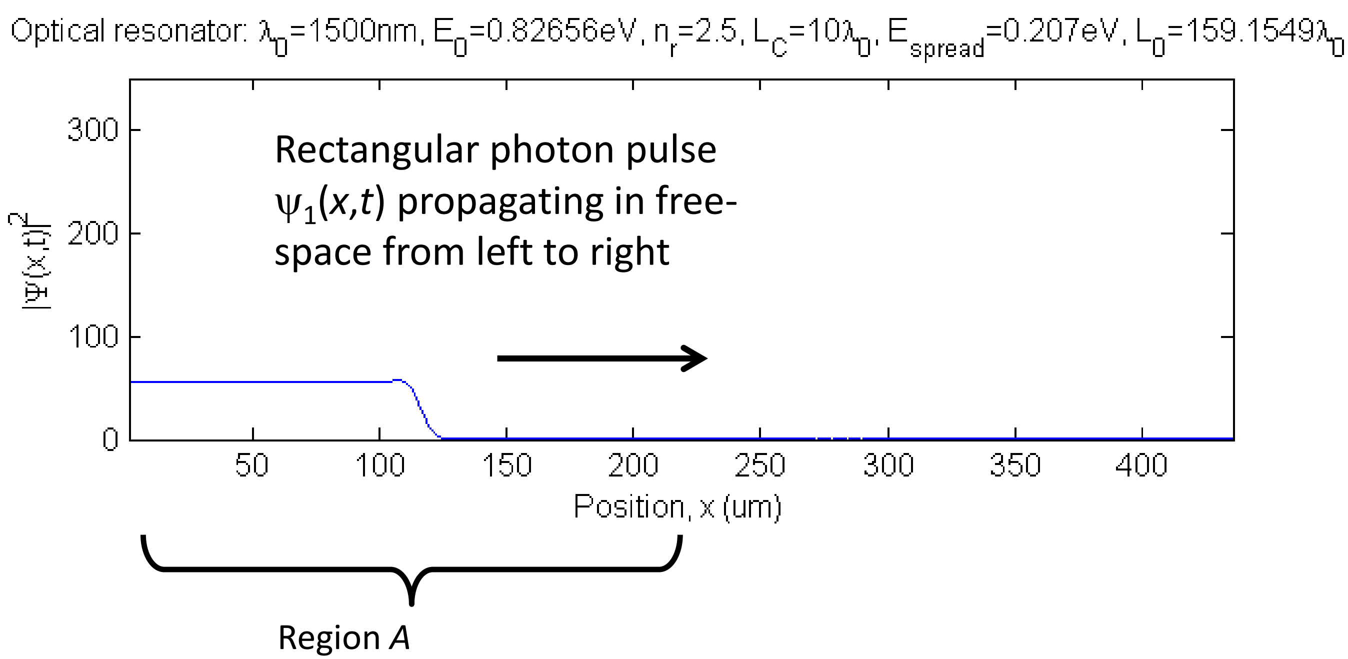
Space

# Coherent control



# Markovianity measure $D(t)$ of single photon

- System (defined as some region of domain) coupled to continuum at $\pm\infty$
- Unitary evolution of initial state eventually dissipates
- Define spatial region *A* in domain and consider freely propagating photon pulse through this region
- Under these conditions one may expect any measure of Markovianity in region $A$ to indicate Markovian behavior
  - *Information leaks* out of region *A* as the photon energy density decays into the continuum



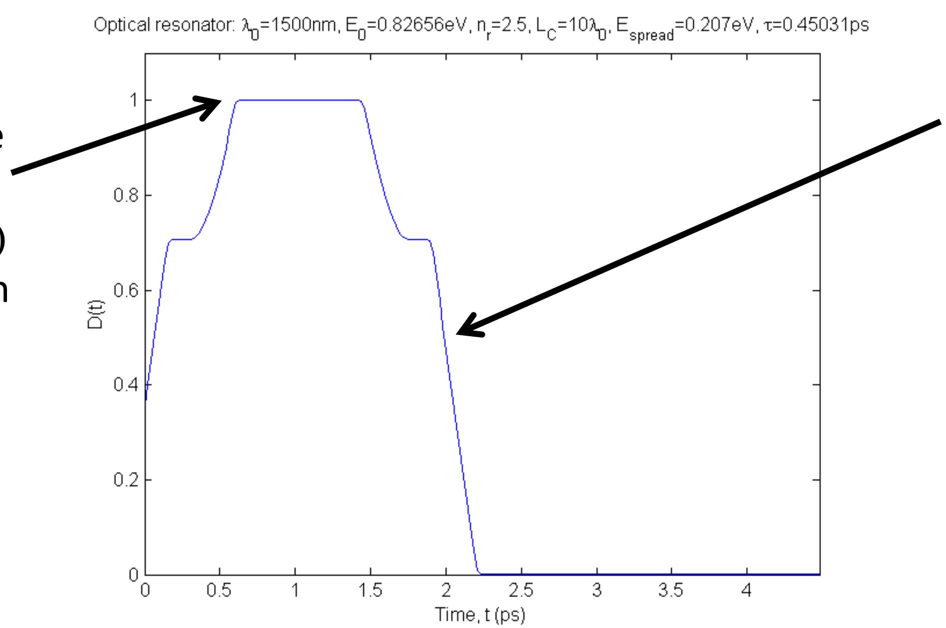
# Hilbert-Schmidt measure $D(t)$ and Markovianity

- Two initially non-interacting (non-overlapping) photon pulses with unitary evolution and initial states such that $\psi_2(x, t) = \psi_1(x, t+\tau_M)$ for fixed delay $\tau_M$ have Hilbert-Schmidt measure in spatial region *A* given by (Lorenzo Campos Venuti)

$$D(t) = \frac{\sqrt{\left(\int_A |\psi_1(x,t)|^2 dx\right)^2 + \left(\int_A |\psi_2(x,t)|^2 dx\right)^2 - 2\left|\int_A \psi_1^*(x,t)\psi_2(x,t)dx\right|^2}}{\sqrt{2}}$$

- The system is considered Markovian if initial states $\psi_1(x, t)$ and $\psi_2(x, t)$ are both in spatial region *A* and $D(t)$ subsequently *decreases monotonically* with time
- Example: non-interacting rectangular photon pulse propagating in free-space

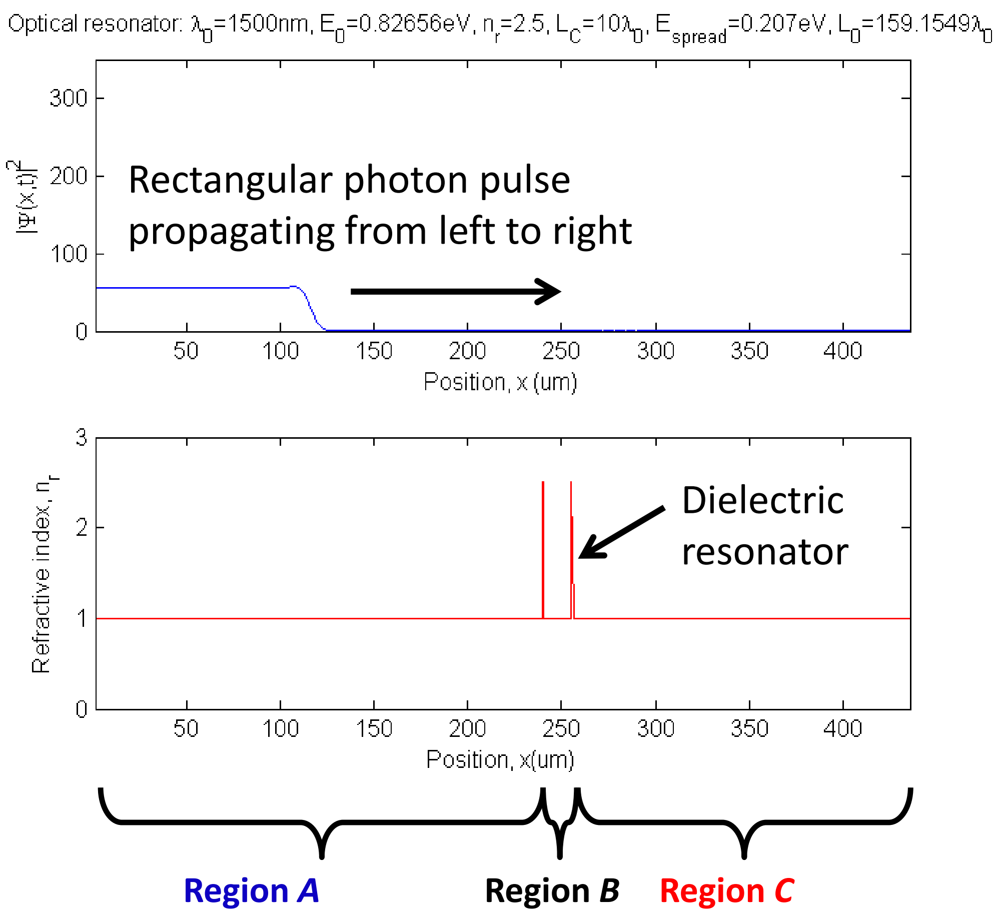
Rectangular photon pulse $\psi_1(x,t)$ and time shifted pulse $\psi_2(x,t) = \psi_1(x,t+\tau_M)$ both freely propagating in region *A* such that normalized measure $D(t)$=1




Monotonic decrease of $D(t)$ as $\psi_1(x,t)$ and $\psi_2(x,t)$ leave and information leaks out of region *A*

# Hilbert-Schmidt measure $D(t)$ of photon interacting with Fabry-Perot dielectric resonator

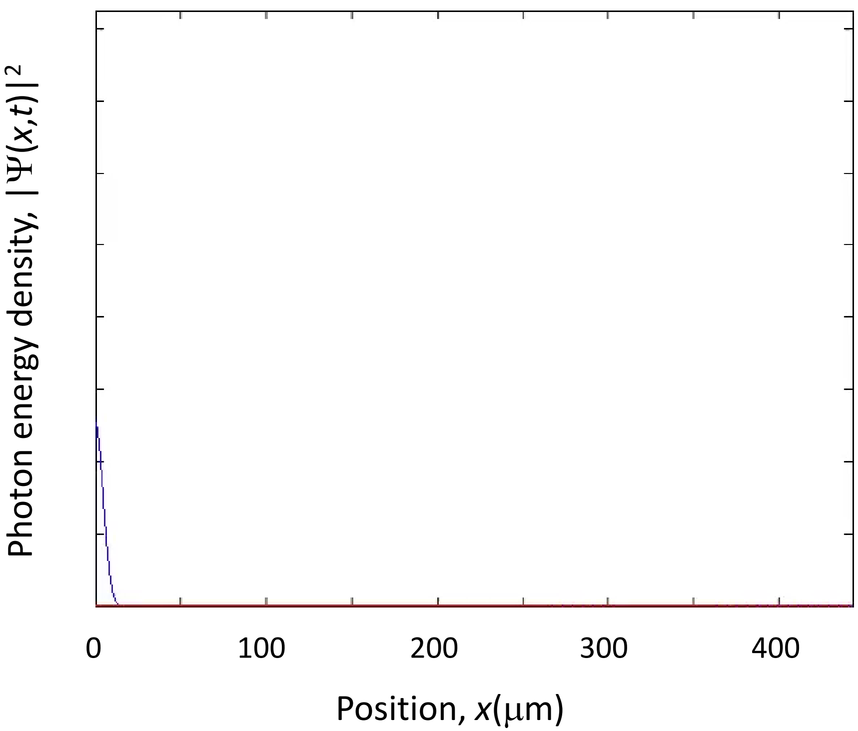
- $A$ (blue curve) left of dielectric resonator with some energy density flow into region
- $B$ (black curve) which is in dielectric resonator with energy density flow into region
- $C$ (red curve) to right of dielectric resonator
- *Note*: Extent of region in domain and definition of system, subsystem, bath, etc., is arbitrary



# Hilbert-Schmidt measure $D(t)$ of photon interacting with Fabry-Perot dielectric resonator

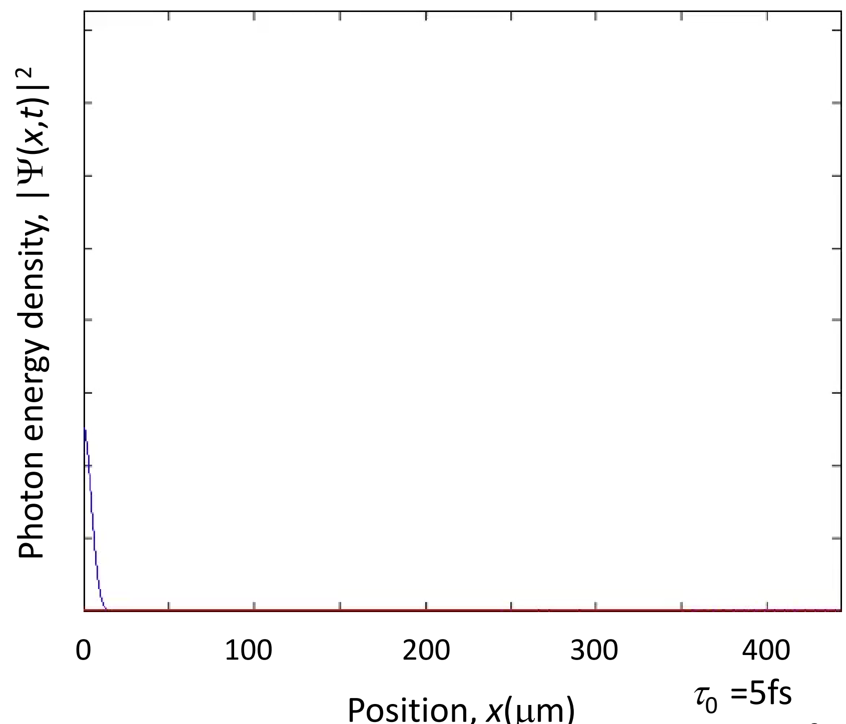
- Incident pulse-width $\tau_p < \tau_{RT}, \tau_Q$
- Single incident pulse produces multiple output pulses (ring-down) spaced at cavity round-trip time and of decreasing energy density as resonator decay $e^{-t/\tau_Q}$

*No* control pulse




↑ Position of FP resonator

*With* single control pulse

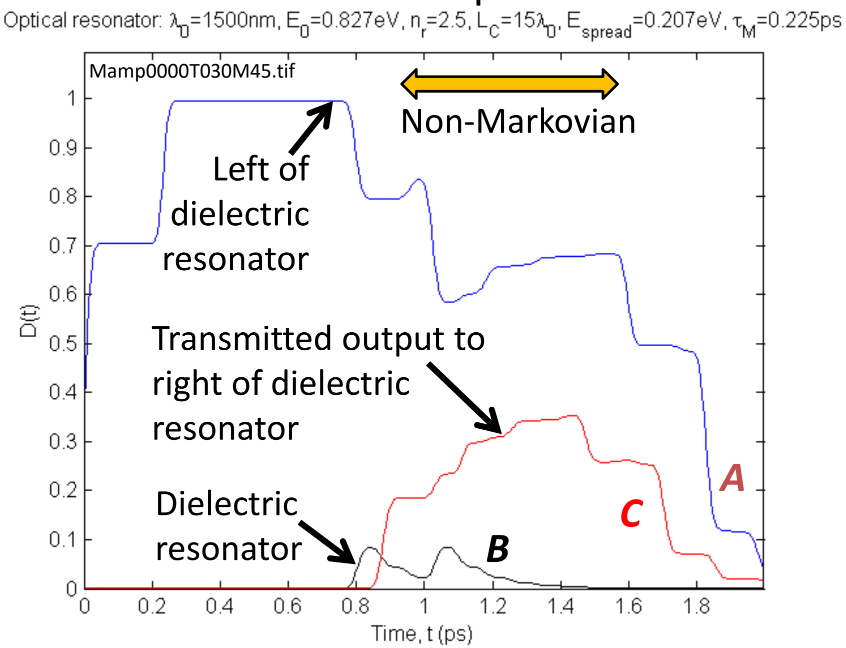



$\tau_0$ =5fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs
$\tau_M$ =225fs

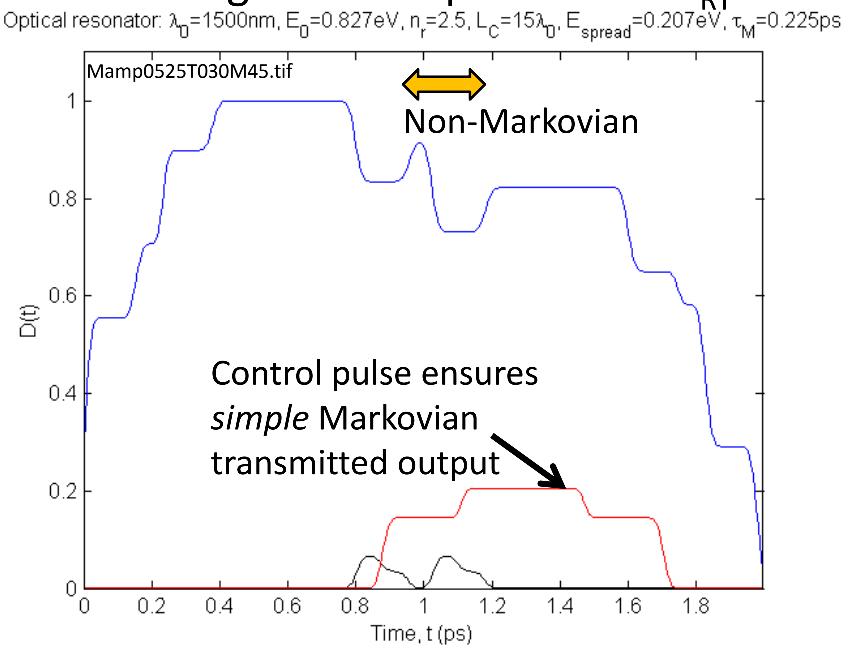
# Hilbert-Schmidt measure $D(t)$ of photon interacting with Fabry-Perot dielectric resonator

- $A$ (blue curve) left of dielectric resonator with some energy density flow into region
- $B$ (black curve) which is in dielectric resonator with energy density flow into region
- $C$ (red curve) to right of dielectric resonator

*No* control pulse




*With* single control pulse at $\tau = \tau_{RT}$



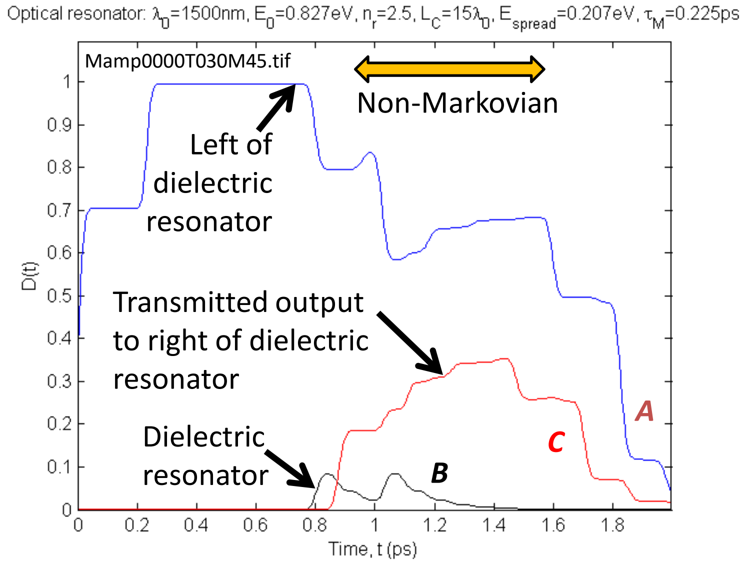

Photon pulse $\psi_1(x,t)$ and time-shifted pulse $\psi_2(x,t) = \psi_1(x,t+\tau_M)$ both initially propagating freely in region *A*

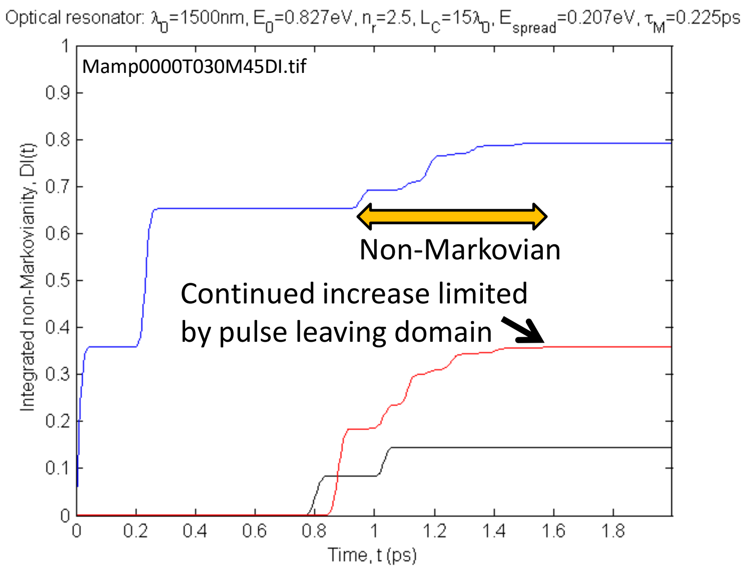
Non-monotonic decrease of *D*(*t*) because energy density is reflected at resonator and energy density is stored and subsequently released from resonant cavity

$\tau_0$ =5fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs
$\tau_M$ =225fs

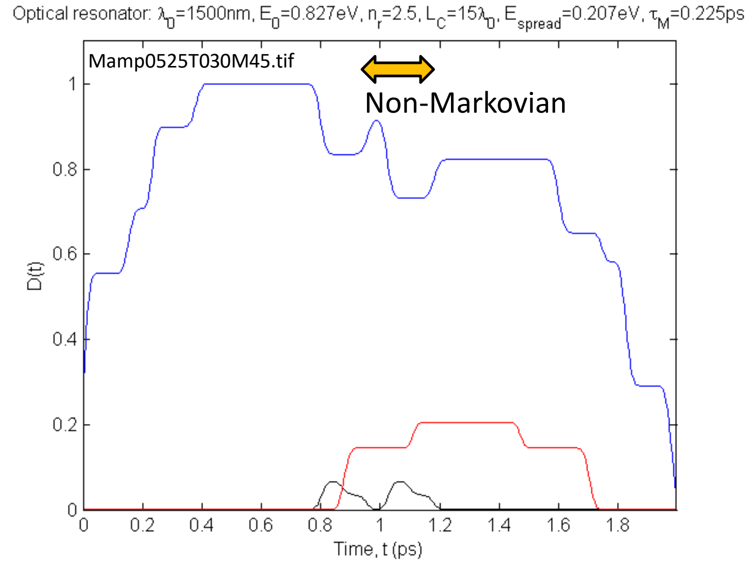
# Integrated non-Markovianity, $DI(t)=\Sigma_i(\Delta D(t_i)|_{positive})$

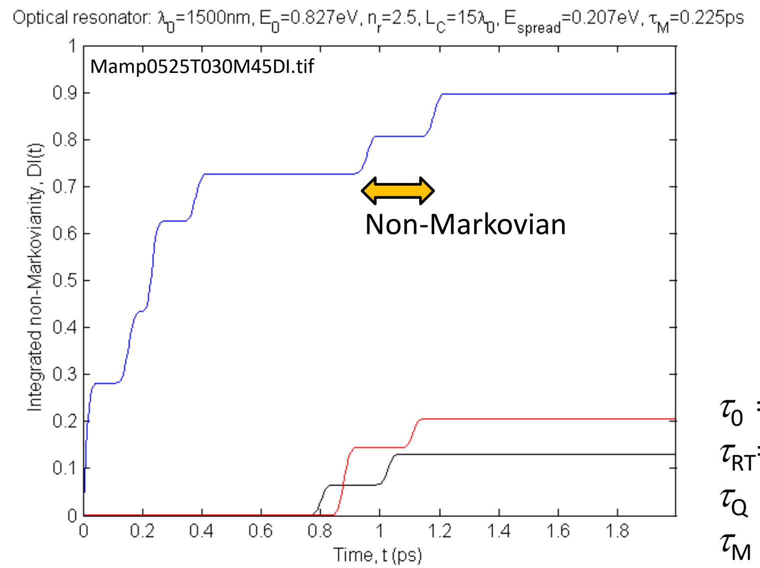
## *No* control pulse




## *With* single control pulse at $\tau = \tau_{RT}$

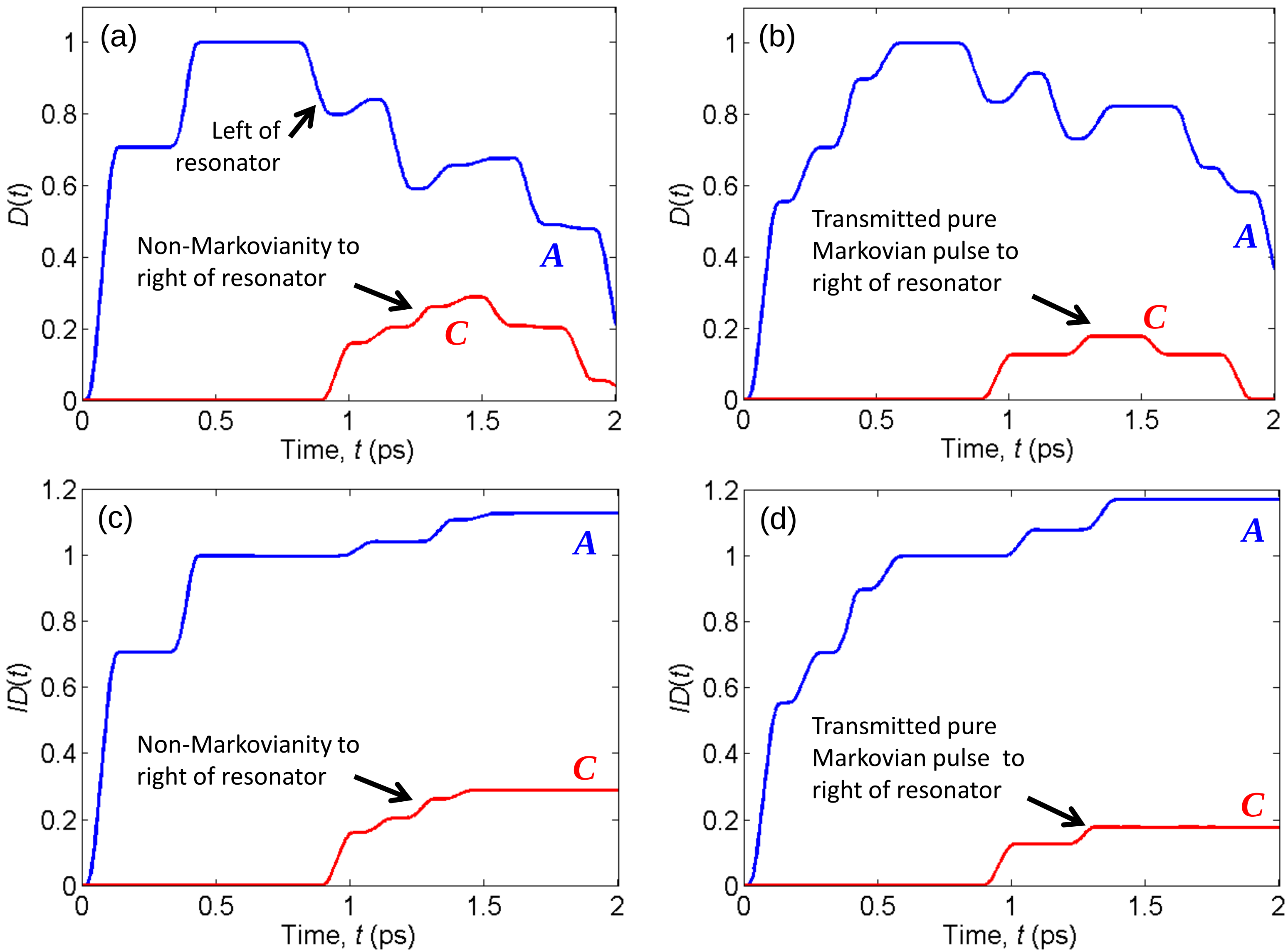



$\tau_0$ =5fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs
$\tau_M$ =225fs

# Integrated non-Markovianity, $DI(t)=\Sigma_i(\Delta D(t_i)|_{\text{positive}})$

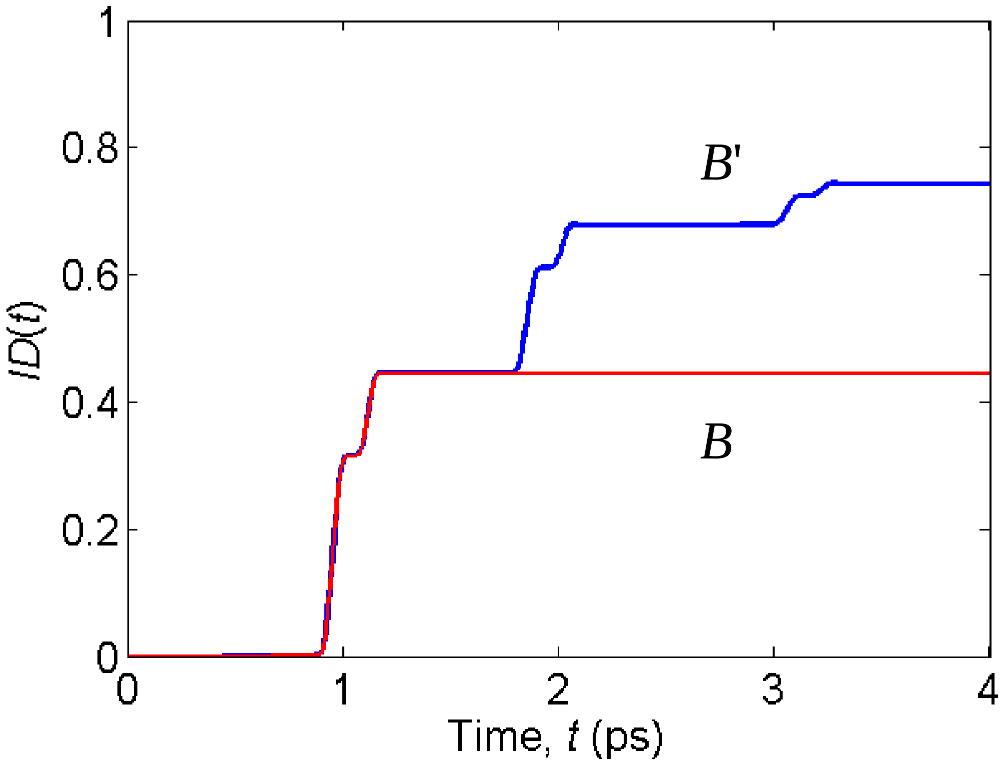
*No* control pulse — *With* single control pulse at $\tau = \tau_{RT}$




$\tau_0$ =5fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs
$\tau_M$ =150fs

# Integrated non-Markovianity, $DI(t)=\Sigma_i(\Delta D(t_i)|_{\text{positive}})$

*No* control pulse
Cavity length $L$=120 x $\lambda_0$
Sub-space B' is left-side half-cavity of length $L/2$




$\tau_0$ =5fs
$\tau_{RT}$=150fs
$\tau_Q$ =153fs
$\tau_M$ =150fs

# Summary: Coherent control of single-photon energy density in a resonator

- Photonic resonator with lossless dielectric mirrors driven by phase-coherent source is open system coupled to continuum that evolves with unitary dynamics
  - Photon wave function, $\Psi(x,t)$, describes single-photon energy density, $U(x,t)=|\Psi(x,t)|^2$
  - Multiple resonator round-trip times, $\tau_{RT}$, required to build-up steady-state behavior
  - Steady-state behavior evolves exponentially during characteristic resonator time, $\tau_Q$
- *Transient behavior* controlled by incident waveform
  - Non-Markovian dynamics because mirror reflections and energy stored in resonator
  - Can eliminate *all* energy density in resonator in less than one round-trip time, $\tau_{RT}$
  - Can control *exact* number of identical transmitted and reflected pulses at multiples of round-trip time, $\tau_{RT}$
  - Can use control to pass long pulses, $\tau_P > \tau_{RT}$, through resonator
  - Control of transient behavior is also control of Markovianity (and hence information flow)
    - **Non-Markovianity** may be viewed **as resource for quantum information processing**
- Natural time scales are $\{\tau_0, \tau_{RT}, \tau_Q\} < \tau_{Coh}$
  - Resource for manipulation of single-photon quantum states
  - Use waveform as sensor probe of resonant structures (inverse problem)

# Coherent control of single-photon transient dynamics in a Fabry-Perot resonator

**A.F.J. Levi, L. Campos Venuti, T. Albash, and S. Haas, "Coherent control of non-Markovian photon resonator dynamics" Phys. Rev. A (2014)**

## OBJECTIVE:

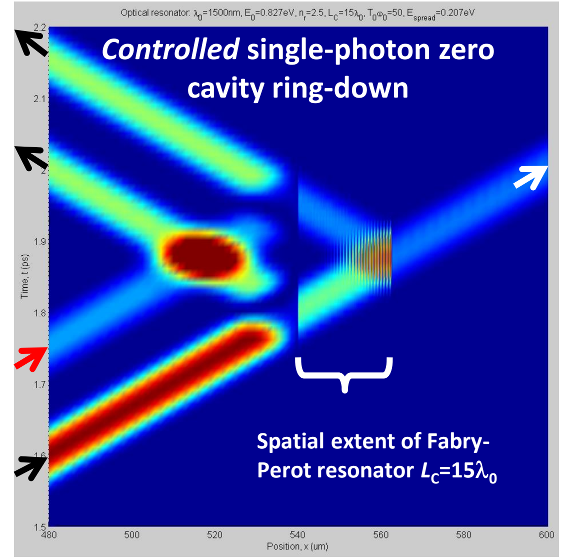
- **Demonstrate coherent quantum control of single-photon dynamics in an optical storage device**
- **Apply techniques developed to demonstrate control of non-Markovianity**

## APPROACH

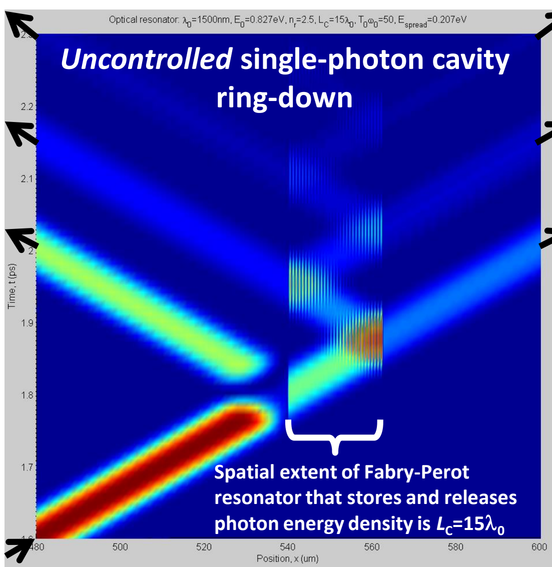
➢ **Use photon pulse injected into Fabry-Perot resonator as model system coupled to continuum and simulate in space-time domain**

➢ **Exert precise control on photon dynamics using coherent control pulses and intuitive resonant control protocol**

➢ **Use L. Campos Venuti's computationally-efficient measure of non-Markovianity: N. Chancellor, C. Petri, L. Campos Venuti, A.F.J. Levi, and S. Haas, Phys. Rev. A (2014)**




$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

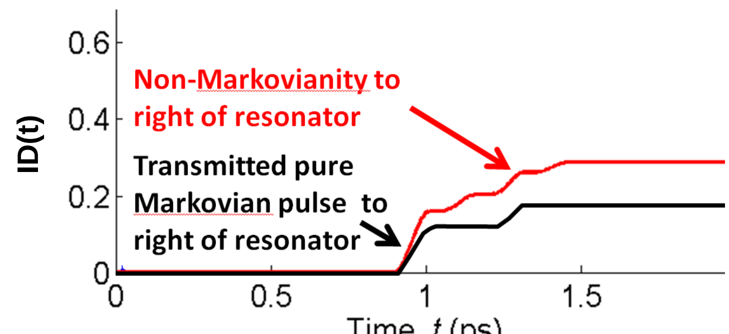



$\tau_0$ = 5 fs
$\tau_p$ = 80 fs
$\tau_{RT}$= 150 fs
$\tau_Q$ = 153 fs

## ACCOMPLISHMENTS: Successfully demonstrated control of single-photon transient dynamics in Fabry-Perot resonator and measure of non-Markovianty

➢ **A first step to exploitation of non-Markovian transient photon dynamics as a resource in coherent quantum systems**

➢ **Established methodology and techniques for further study**



# Coherent control of single-photon transient dynamics for logic

**A. Abouzaid, F. Wang, S. Gupta, and A.F.J. Levi**

**OBJECTIVE:**

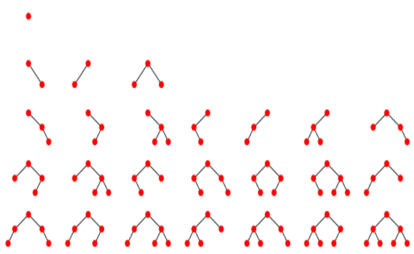
- **Demonstrate coherent quantum control of single-photon dynamics may be applied to boolean logic and perform exhaustive search in minimal linear device design sub-space for all feasible logic operations**

**APPROACH**

- **Basic (minimal) device building block is symmetric 50:50 single-photon beam-splitter**
- **Formally enumerate *all* tree structures up to depth of *k* in which tree-structures have no feedback and no re-convergent fan-out**
- **Combine two phase shifters/Modulators with one beam splitter to reduce the enumeration complexity**
- **Use physical model to validate results**

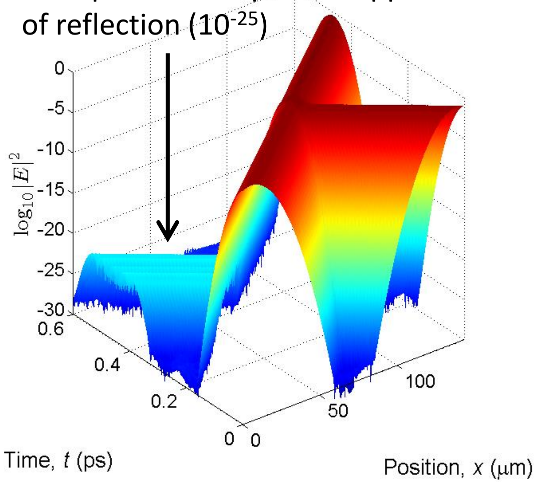
**ACCOMPLISHMENTS: Enumerator discovers all feasible boolean logic tree-structures**

- **High-level simulator checks if feasible solution exists (to depth *k* in tree-structure) for a designated boolean function**
- **If no feasible solution is found by the high-level simulator, then that logic function cannot be implemented using only linear components connected in a tree-structure**
- **For any *n*-input configuration created using only linear components connected in a tree-structure, if a feasible solution exists for a given boolean function in the high level simulation, then the boolean function is implementable in the low-level simulator**



**ACCOMPLISHMENTS: Exact suppression of reflection at beam-splitter using control pulse**

- **Optical pulse contains broad spectrum of frequency components that interact with symmetric 50:50 single-photon beam-splitter**
- **Optimal control pulse to suppress reflection requires search for coherent single-photon phase and amplitude field parameters**




**ACCOMPLISHMENTS: Successfully enumerated all boolean logic using minimal components and constraints**

- **Constrained to single-photon, beam-splitter, amplitude modulator, phase shifter, and tree-structure**
- **Components indicate events, i.e. an interaction between pulses and a particular component at some point in time and space**
- **Successfully demonstrated NAND and so complete for boolean logic**
- **Also, NOT, OR, XOR, XNOR, and multiplexing**
- **AND and NOR are not feasible**
- **Reshaping, retiming, and re-amplifying (3R) output may be achieved for classical light using a saturable absorber, however, the single-photon version of 3R is unknown**

# Acknowledgements

Walter Unglaub

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Stephan Haas

Tameem Albash

Fangzhou Wang

Sandeep Gupta

A.F.J. Levi, L. Campos Venuti, T. Albash, and S. Haas,
“Coherent control of non-Markovian photon resonator dynamics”
Phys. Rev. **A** 90, 022119 (2014)