Coherent control of non-Markovian photon-resonator dynamics

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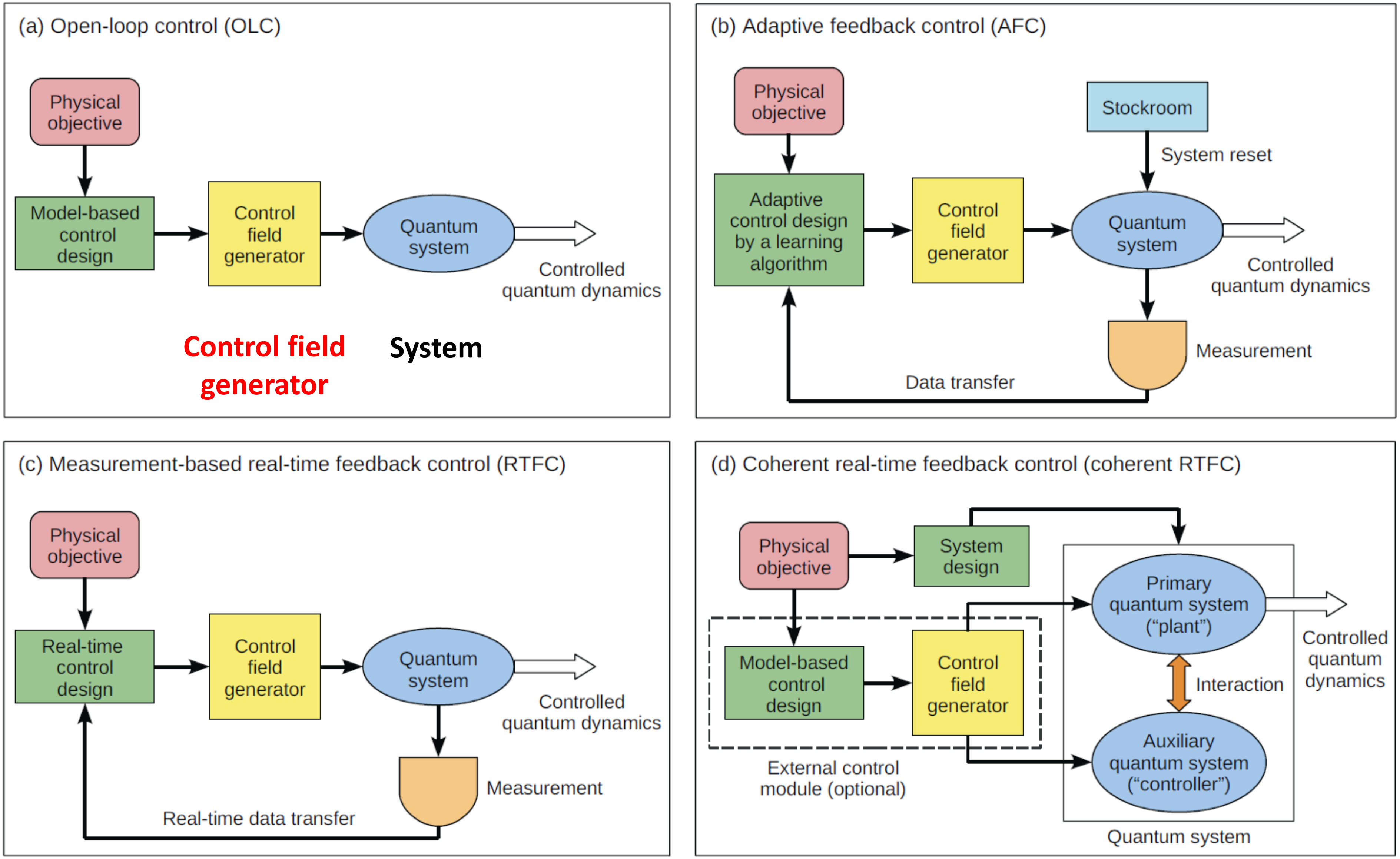
“Coherent control of photons”

- 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 σ 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 ω_n

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

- The lossless dielectric material may be characterized by μ_r and ε_r , and ψ_n satisfies

$$\nabla\times((\mu_0\mu_r)^{-1}\nabla\times\psi_n(x))-\omega_n^2\varepsilon_0\varepsilon_r\psi_n(x)=0$$

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

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

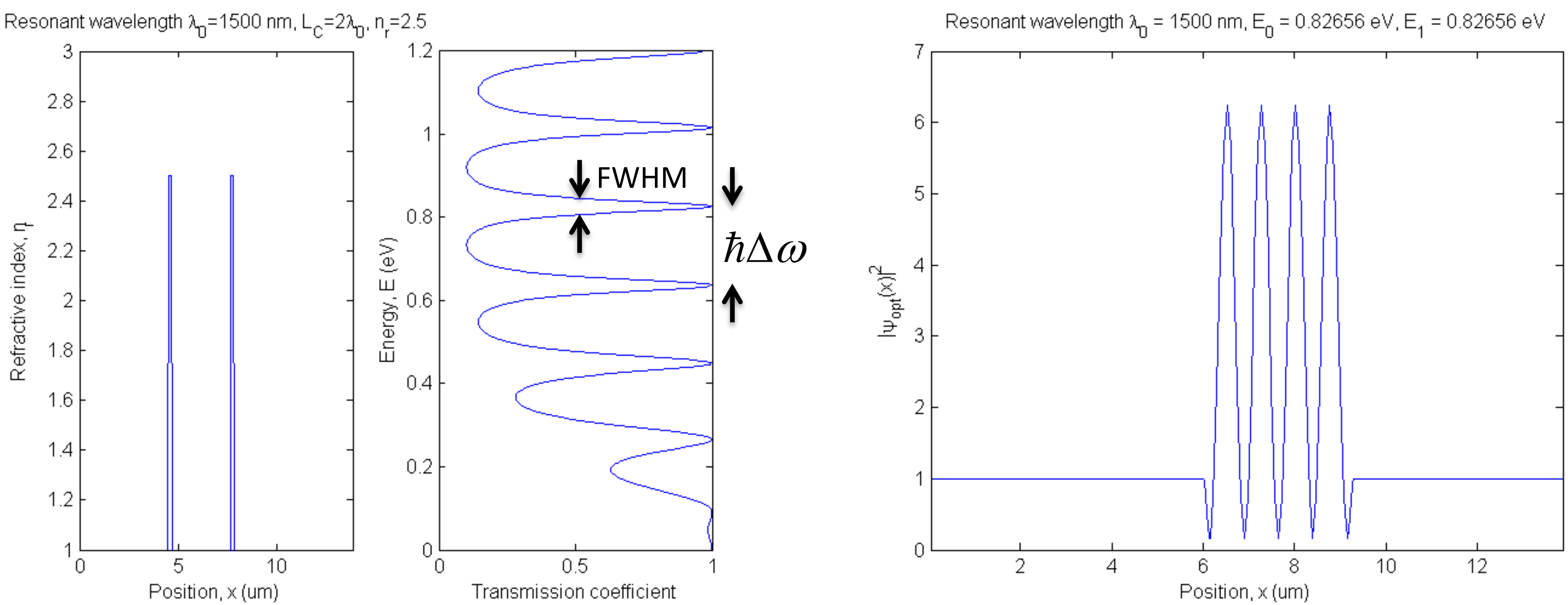
$$\frac{1}{\mu_{r1}}\frac{\partial\psi_n}{\partial x}\bigg|_{x=x_0-\delta}=\frac{1}{\mu_{r2}}\frac{\partial\psi_n}{\partial x}\bigg|_{x=x_0+\delta}$$

and refractive index $n_r=\sqrt{\mu_r}\sqrt{\varepsilon_r}$

- Solve in space and time and assume photon coherence time, τ_{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 =2λ_0 apart creates Fabry-Perot optical *resonator* that is *coupled to the continuum*
- Resonant wavelength λ_0=1500 nm, $\omega_0=2\pi/\tau_0$=2πx200 THz, τ_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/τ_Q} and τ_Q is resonant state lifetime
- Resonator round-trip time defined as $\tau_{RT}=2\pi/\Delta\omega=1/\Delta f$ where Δf 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 λ_0=1500 nm, $\omega_0 = 2\pi/\tau_0 = 2\pi$x200 THz, τ_0=5 fs
- Resonant photon energy E_0=0.826 eV
- Transmission is a *slowly* varying function of photon energy,

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

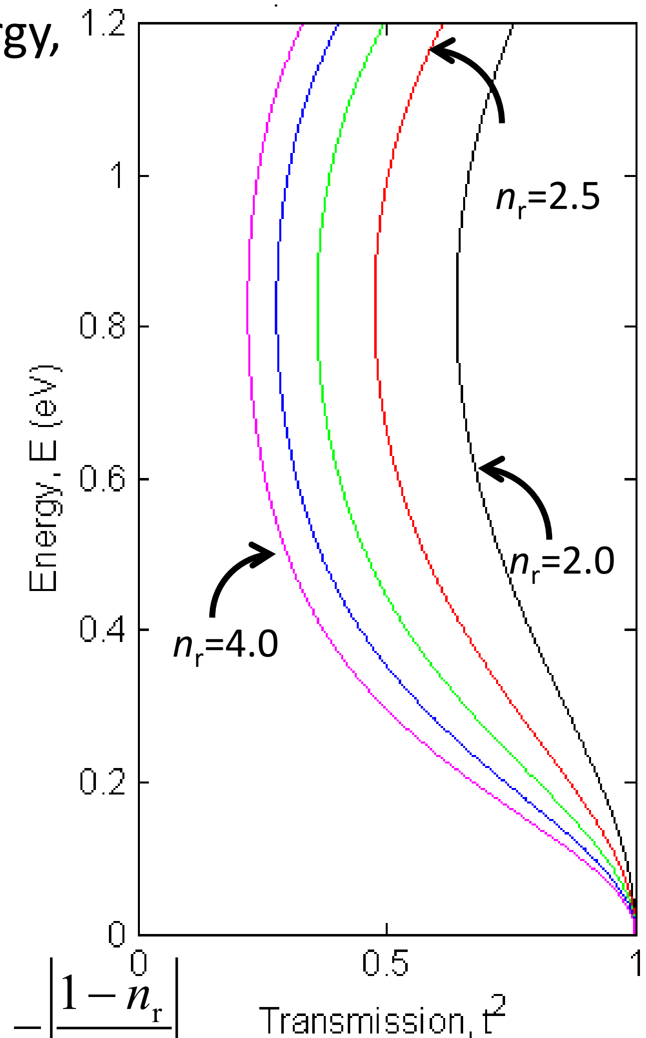
- On resonance $k_1 = \frac{2\pi}{\lambda_0}$, $k_2 = \frac{2\pi n_r}{\lambda_0}$, $L = \frac{\lambda_0}{4n_r}$, so that

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

- 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:

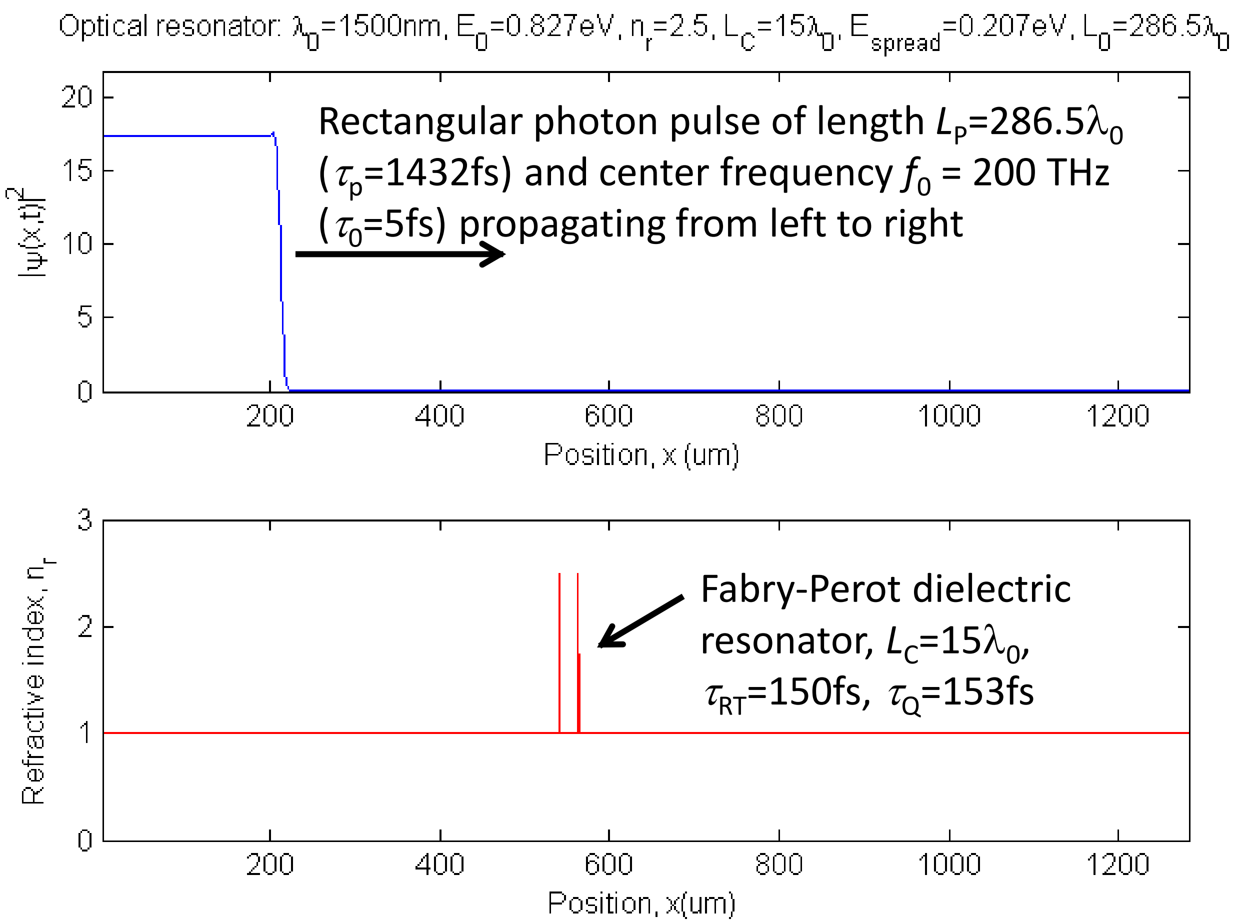
$$n_r \to 1, \quad t^2 \to 1$$
$$n_r \to \infty, \quad t^2 \to 0$$

- π 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

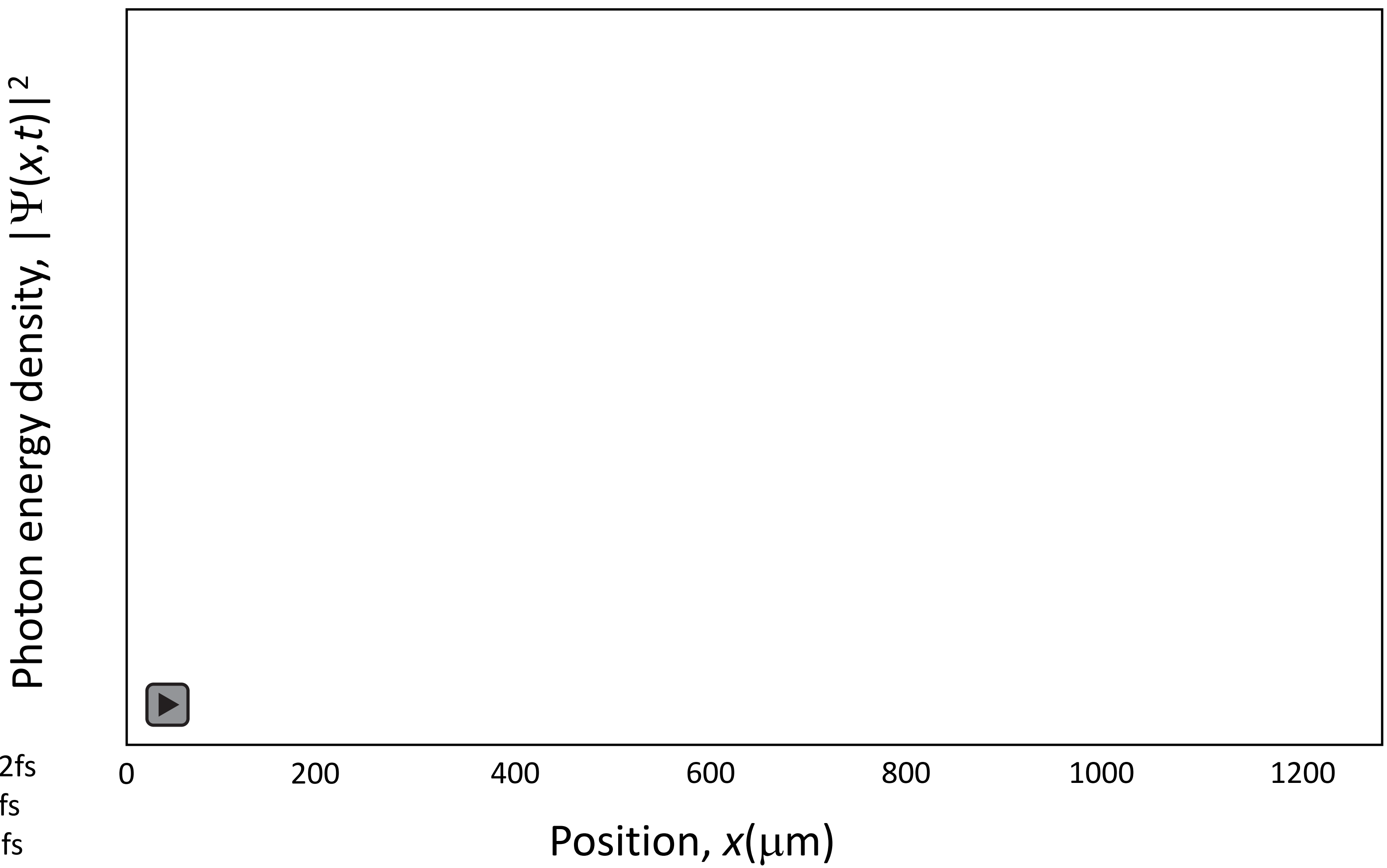
- Rectangular photon pulse with center frequency that is *on resonance at* wavelength λ_0=1500 nm, $\omega_0=2\pi/\tau_0=2\pi\text{x}200$ THz, τ_0=5fs
- Quarter-wave ($\lambda_0/4n_r$) dielectric mirror with n_r=2.5, cavity length $L_C=15\lambda_0$, cavity round-trip time $\tau_{RT}=2\pi/\Delta\omega=30\tau_0$=150fs
- Q=193, $\tau_Q=Q/\omega_0$=153fs



τ_0 =5fs
τ_p =1432fs
τ_{RT}=150fs
τ_Q =153fs

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

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



τ_0 =5fs
τ_p =1432fs
τ_{RT}=150fs
τ_Q =153fs

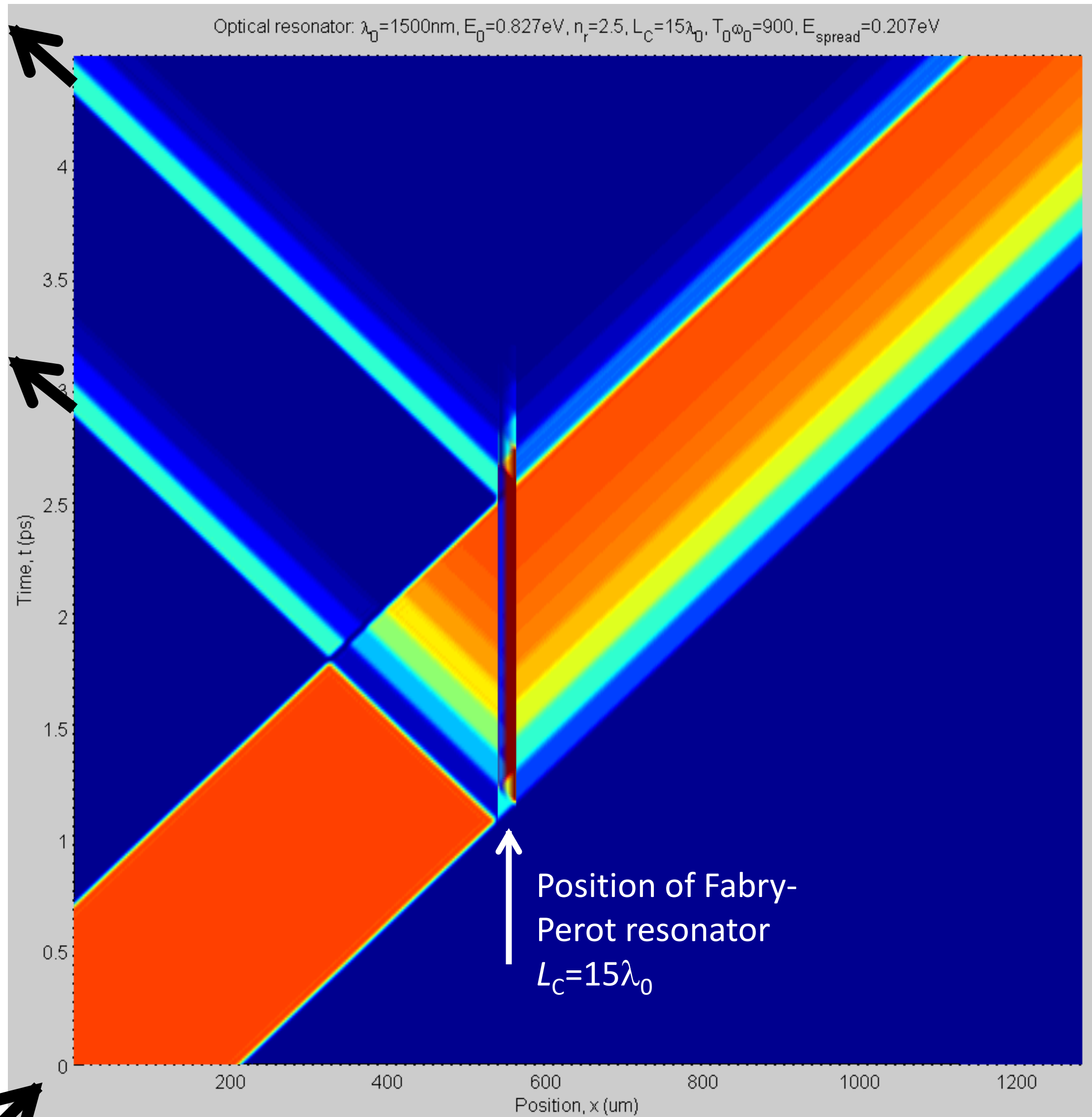
Transient response of single-photon pulse incident on Fabry-Perot cavity at resonance

Reflection from *trailing* edge with step-wise τ_{RT} ring-down and exponential τ_Q envelope

Reflection from *leading* edge with step-wise τ_{RT} ring-down and exponential τ_Q envelope

Time

Incident photon pulse of length L_p=286.5λ_0 in free-space



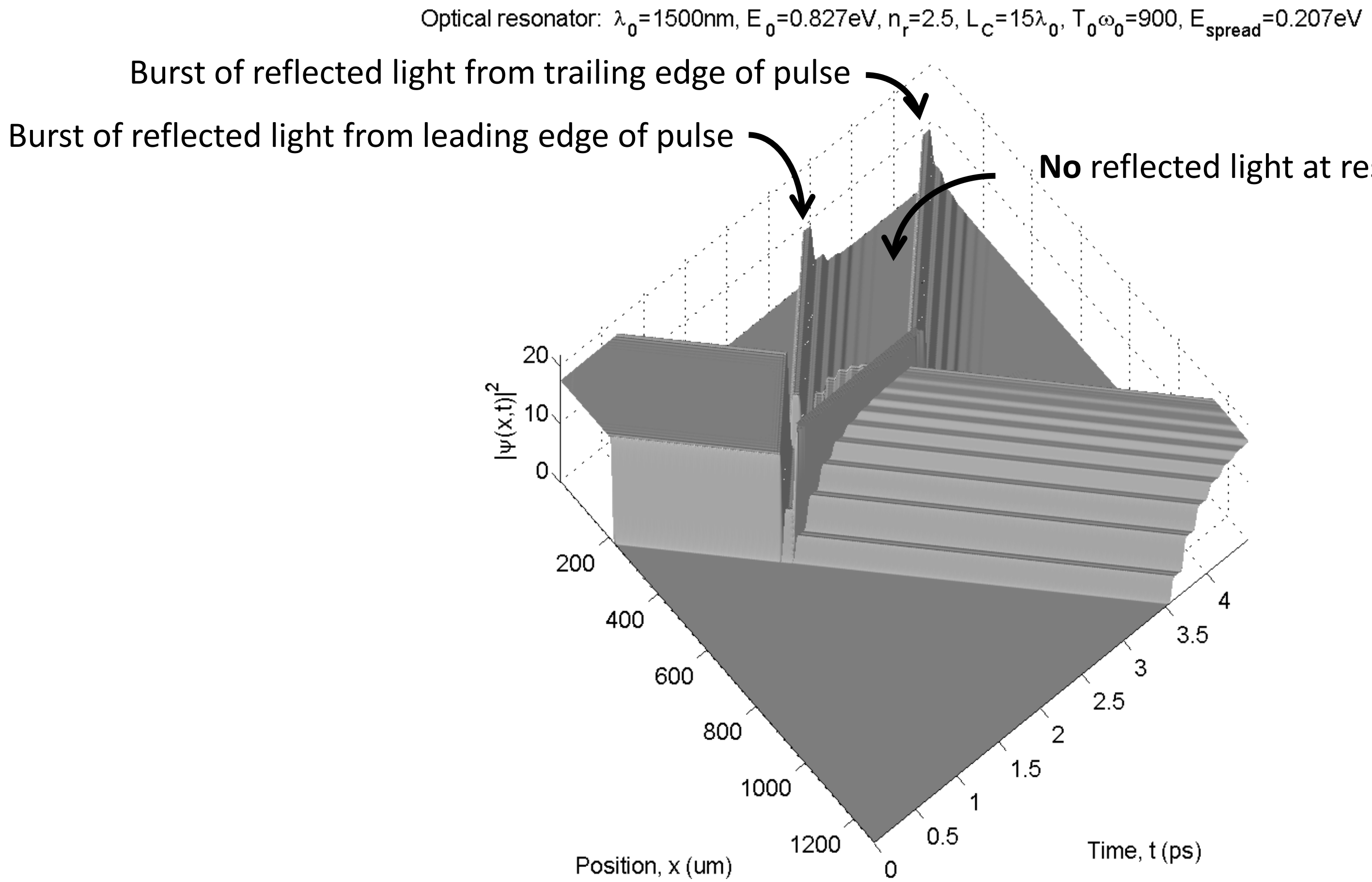
Transmitted photon pulse with step-wise τ_{RT} features and exponential τ_Q envelope

Space

τ_0 =5fs
τ_p =1432fs
τ_{RT}=150fs
τ_Q =153fs

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

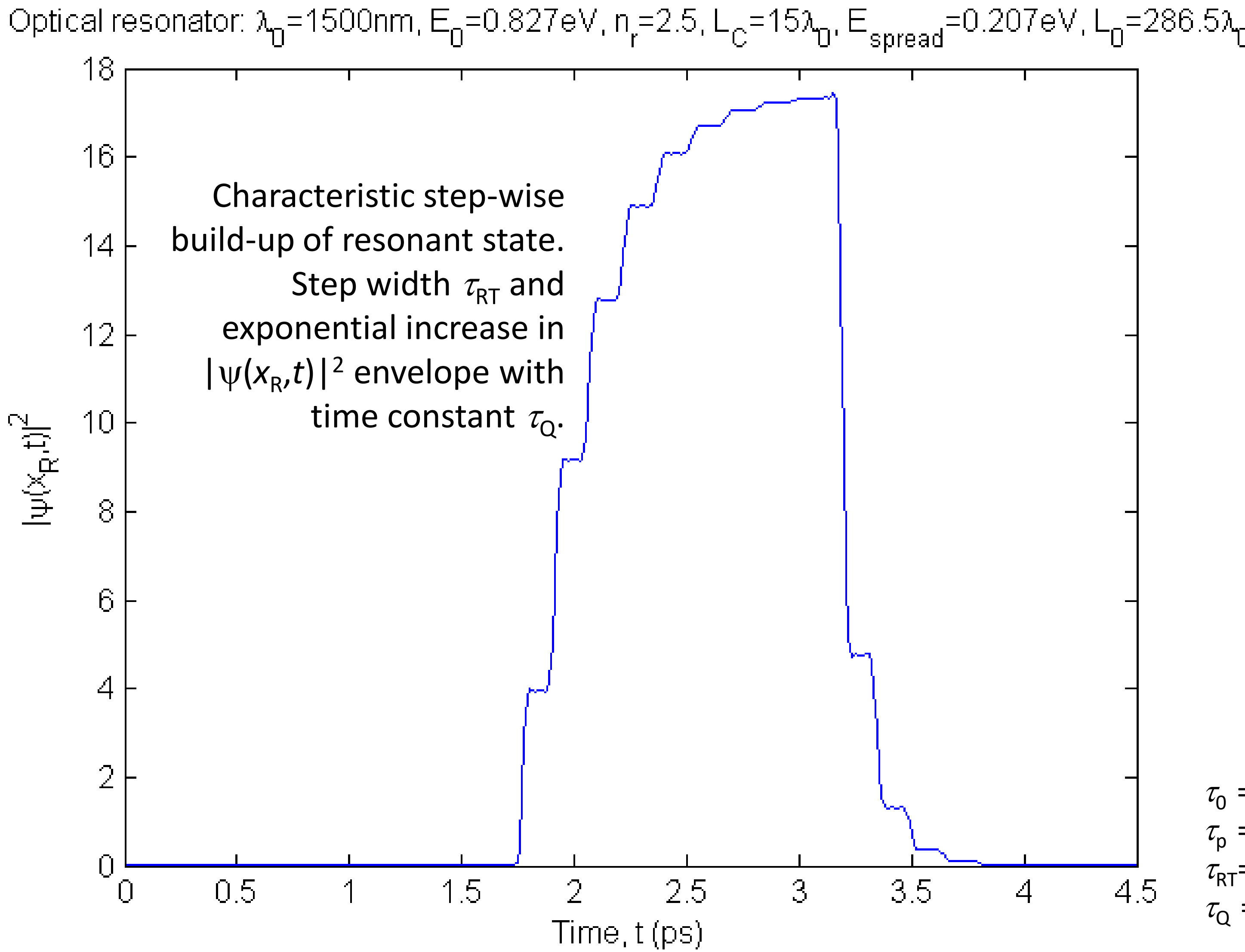
- Multiple cavity round-trip times required to build-up steady-state behavior
- Rectangular photon pulse with center frequency that is on resonance has characteristic transient reflection at leading and trailing edge
  - Reflection depends on frequency components contributing to pulse shape
  - Reflection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



τ_0 =5fs
τ_p =1432fs
τ_{RT}=150fs
τ_Q =153fs

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

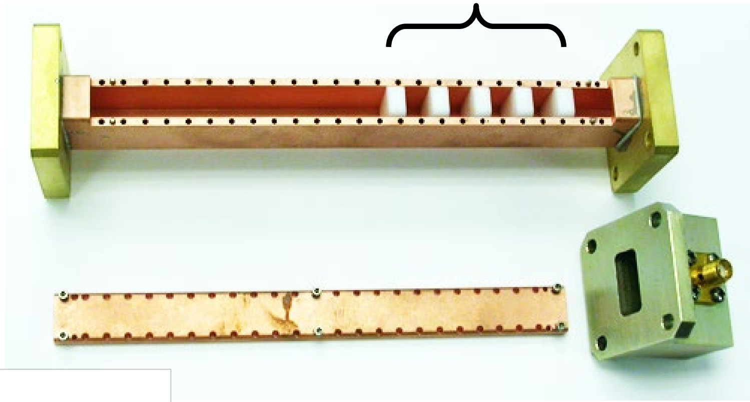
- Calculated transmitted single-photon energy density, $|\psi(x_R, t)|^2$ at x_R=742.8μm

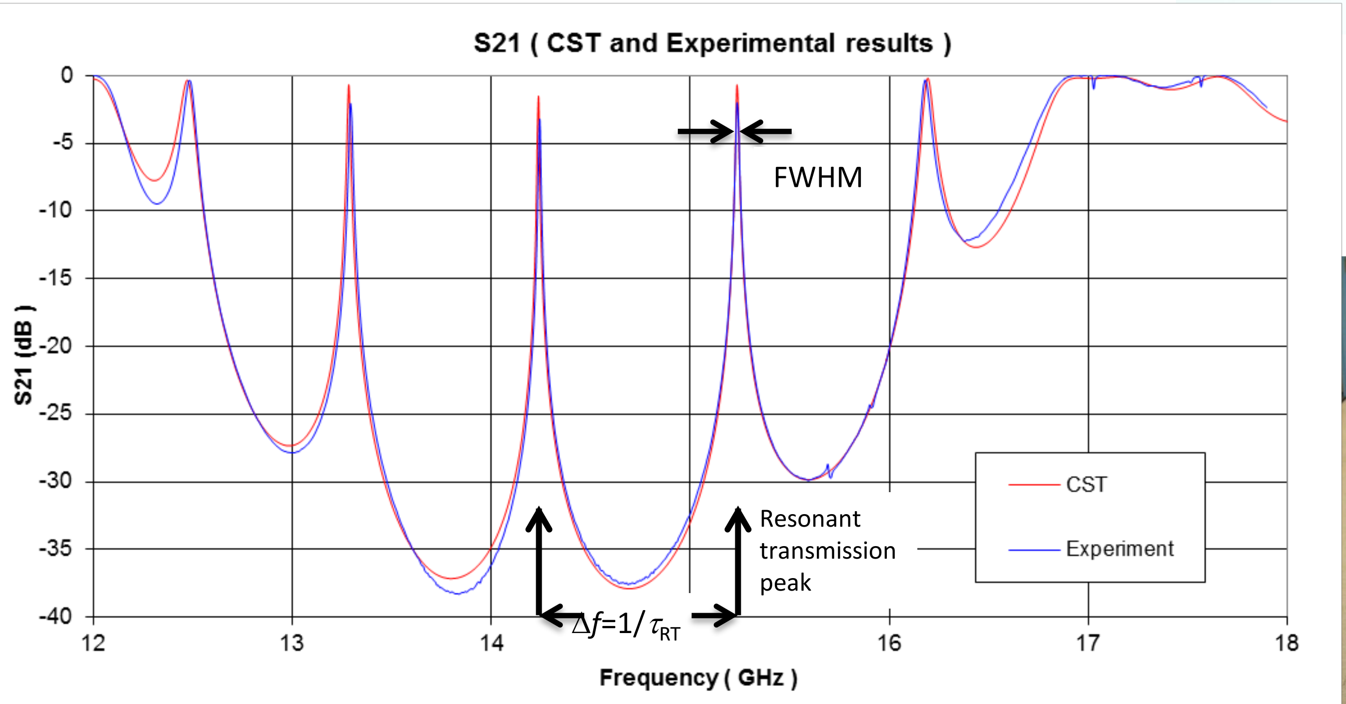


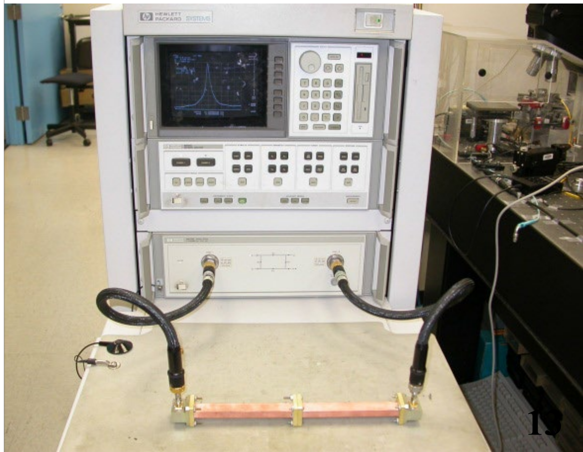
τ_0 =5fs
τ_p =1432fs
τ_{RT}=150fs
τ_Q =153fs

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 μeV)
  - Measured permittivity of teflon, ε_r=2.050
  - Measured loss tangent, δ=0.0005

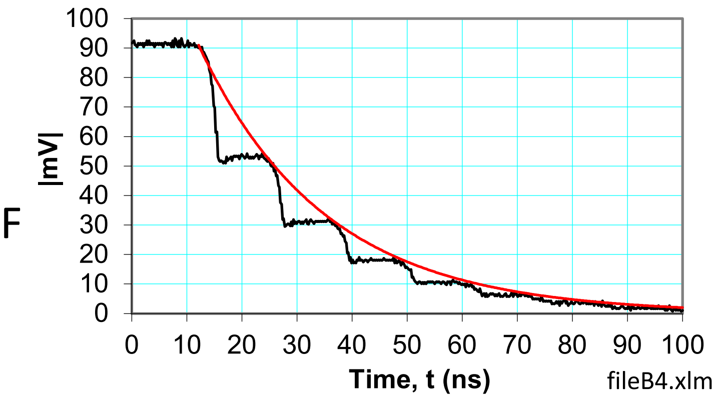


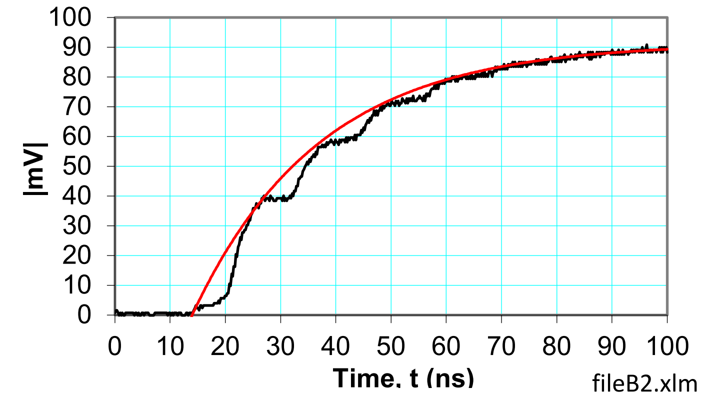


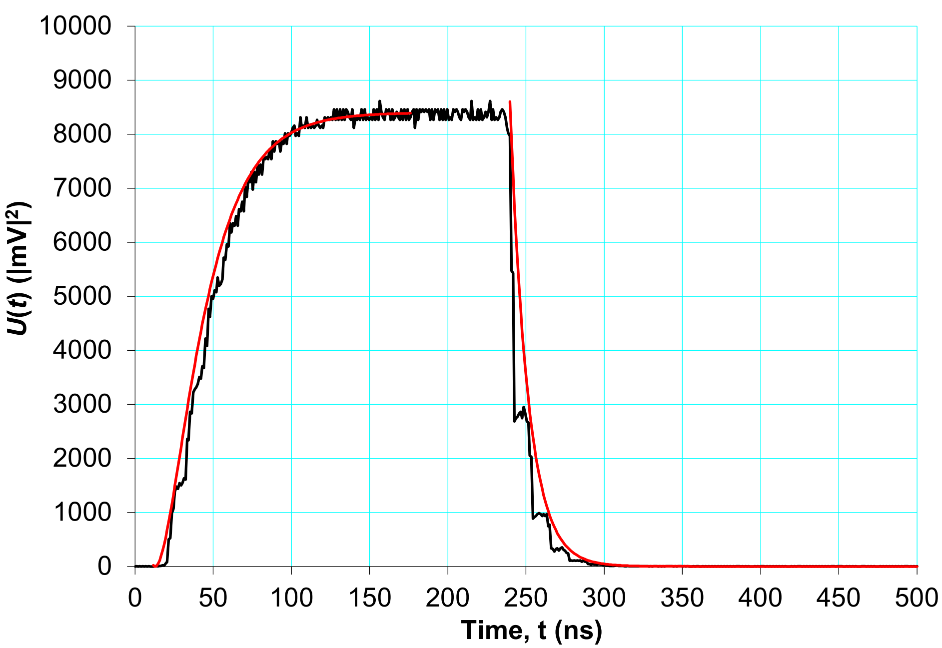


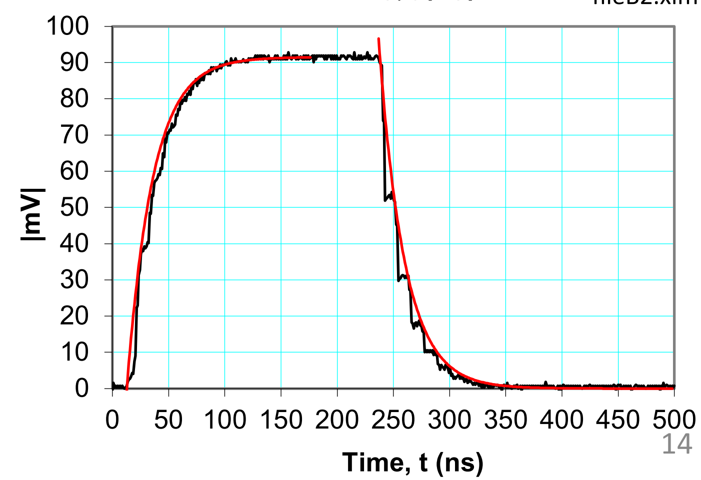
Experimental validation using Fabry-Perot resonator in waveguide

- 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 τ_{RT}=12 ns
- Resonator Q=582 corresponds to τ_Q=11.5 ns (red curve)
- *Long* pulse time τ_p=230ns >> τ_{RT}, τ_Q

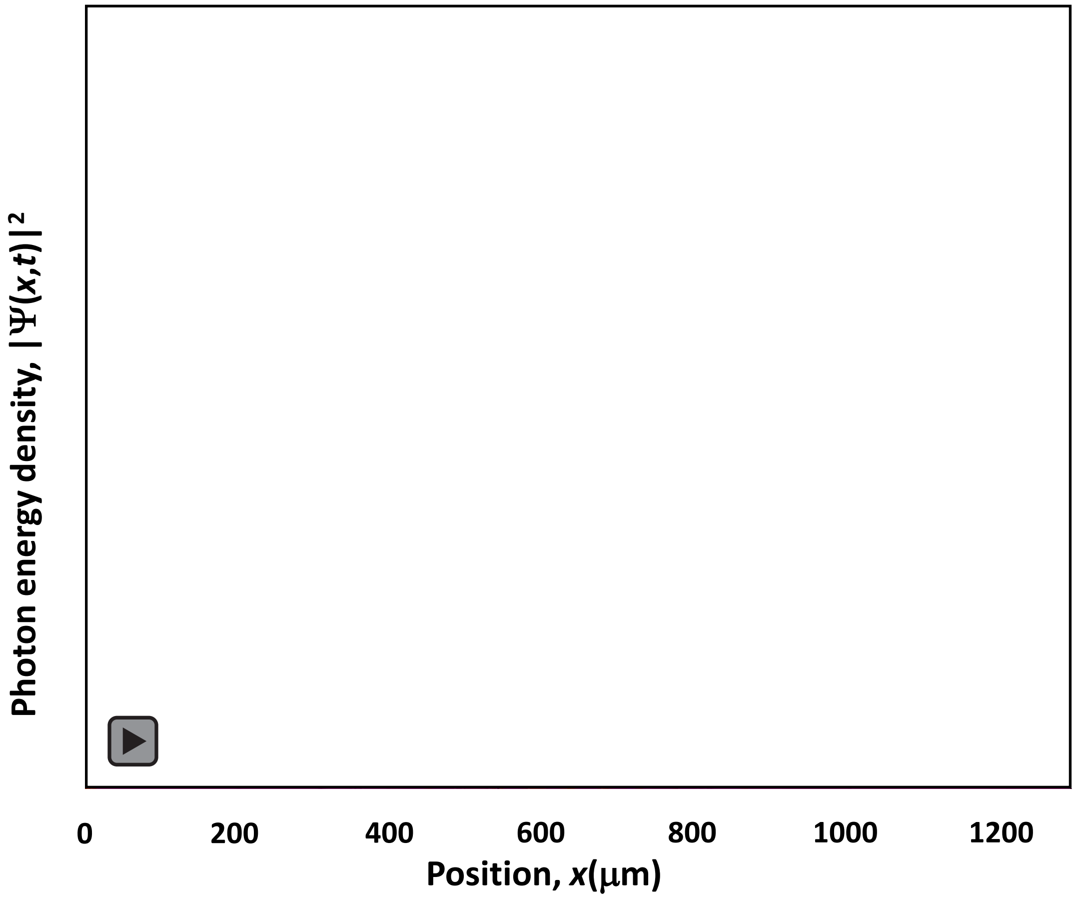


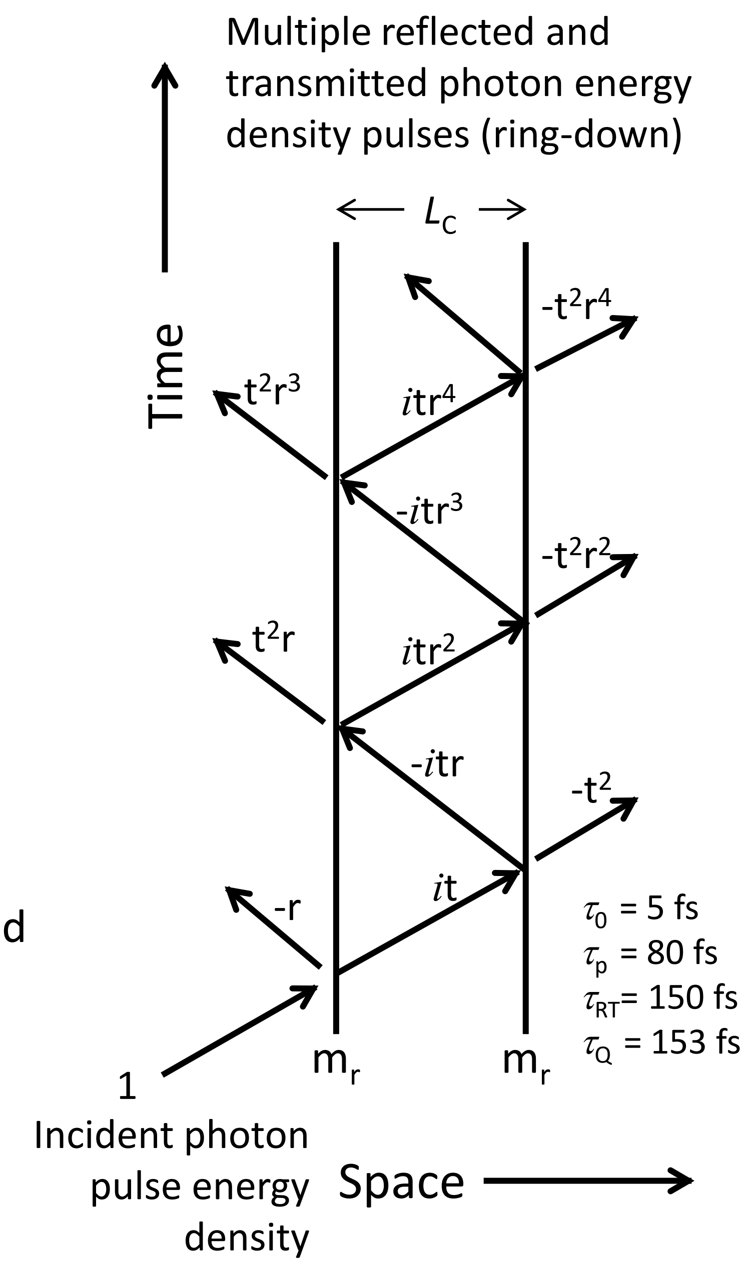






Uncontrolled short single-photon pulse in cavity ring-down



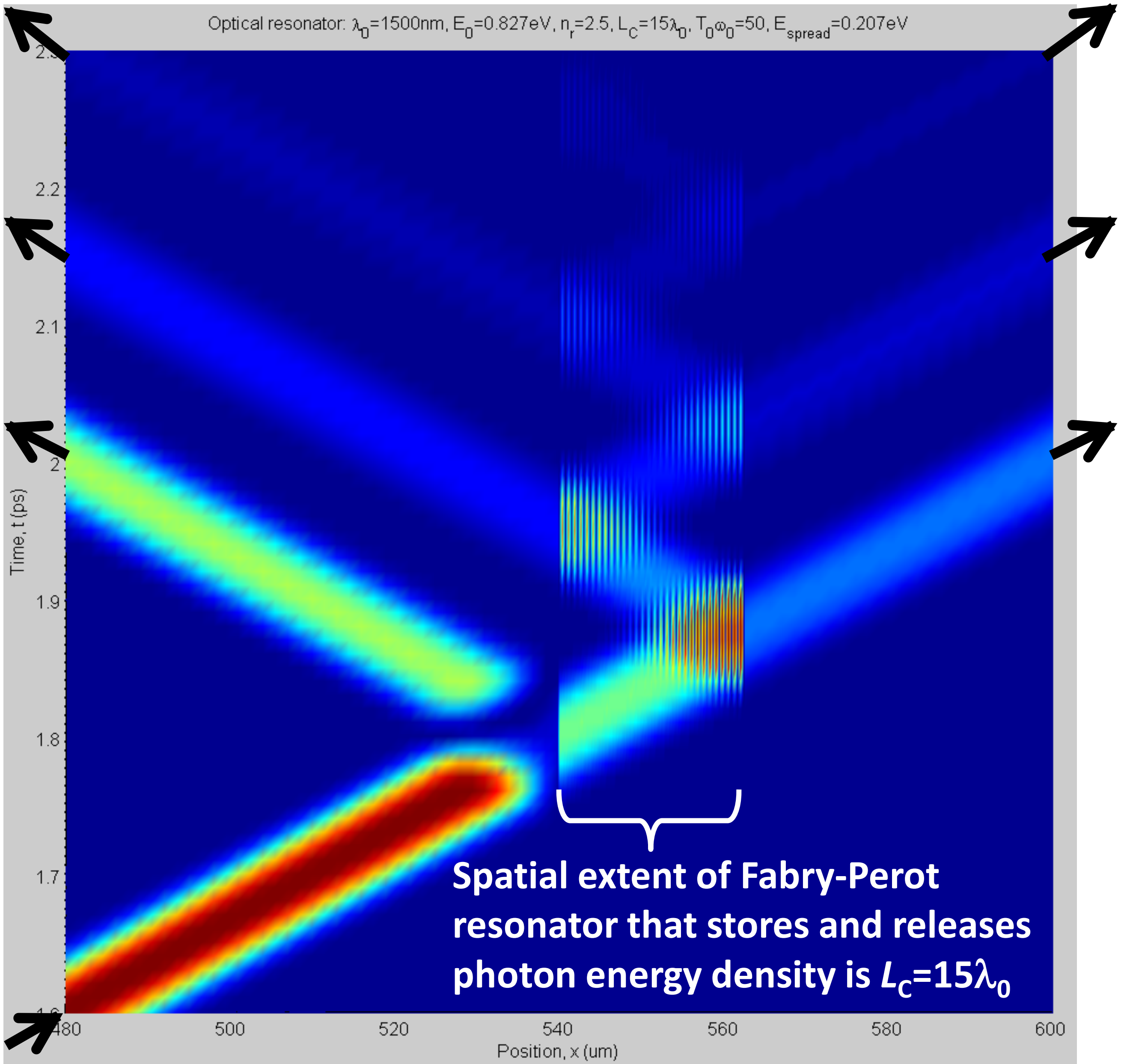


- Identical lossless dielectric mirrors m_r with complex field reflectivity r and transmission t
- π phase shift on reflection of incident field
- Resonant photon field *in* resonator is geometric series $(1+re^{i\phi}+r^2e^{i2\phi}+r^3e^{i3\phi} + \ldots)=1/(1-re^{i\phi})$ where phase per round-trip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

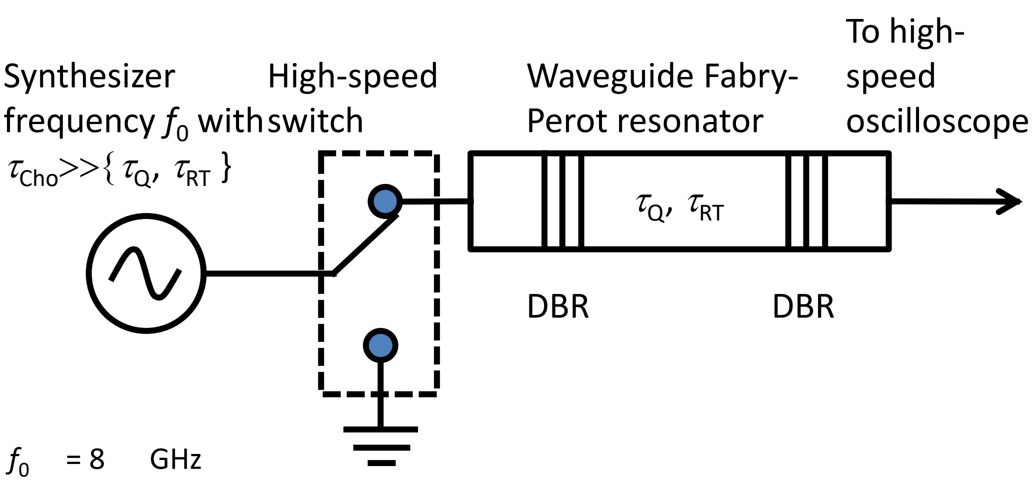
Incident photon pulse energy density

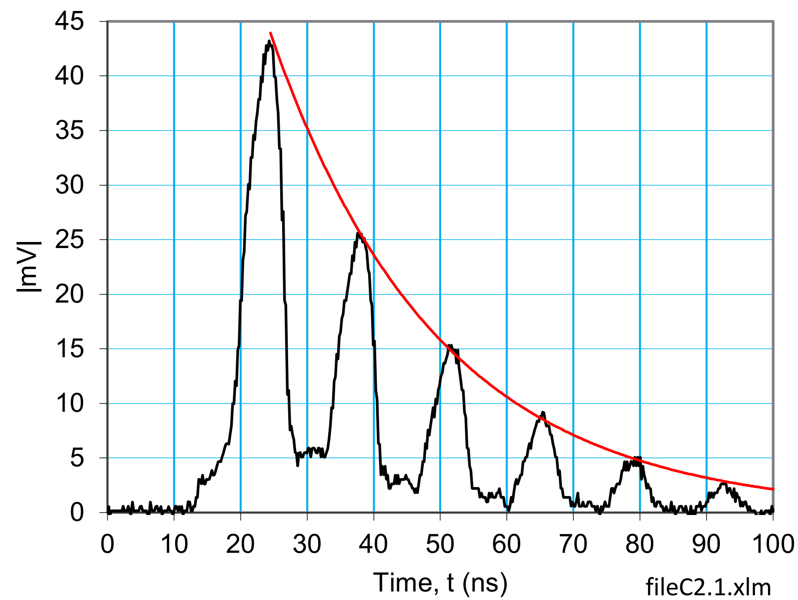
Space

τ_0 = 5 fs
τ_p = 80 fs
τ_{RT}= 150 fs
τ_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 τ_p=7 ns < τ_{RT}, τ_Q
- Round-trip time in resonator τ_{RT}=13.7 ns
- Resonator Q=633 corresponds to τ_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
τ_{Coh} = 1 s
τ_0 = 125 ps
τ_p = 7 ns
τ_{RT} = 13.7 ns
τ_Q = 12.5 ns

Coherent control of *transient dynamics*

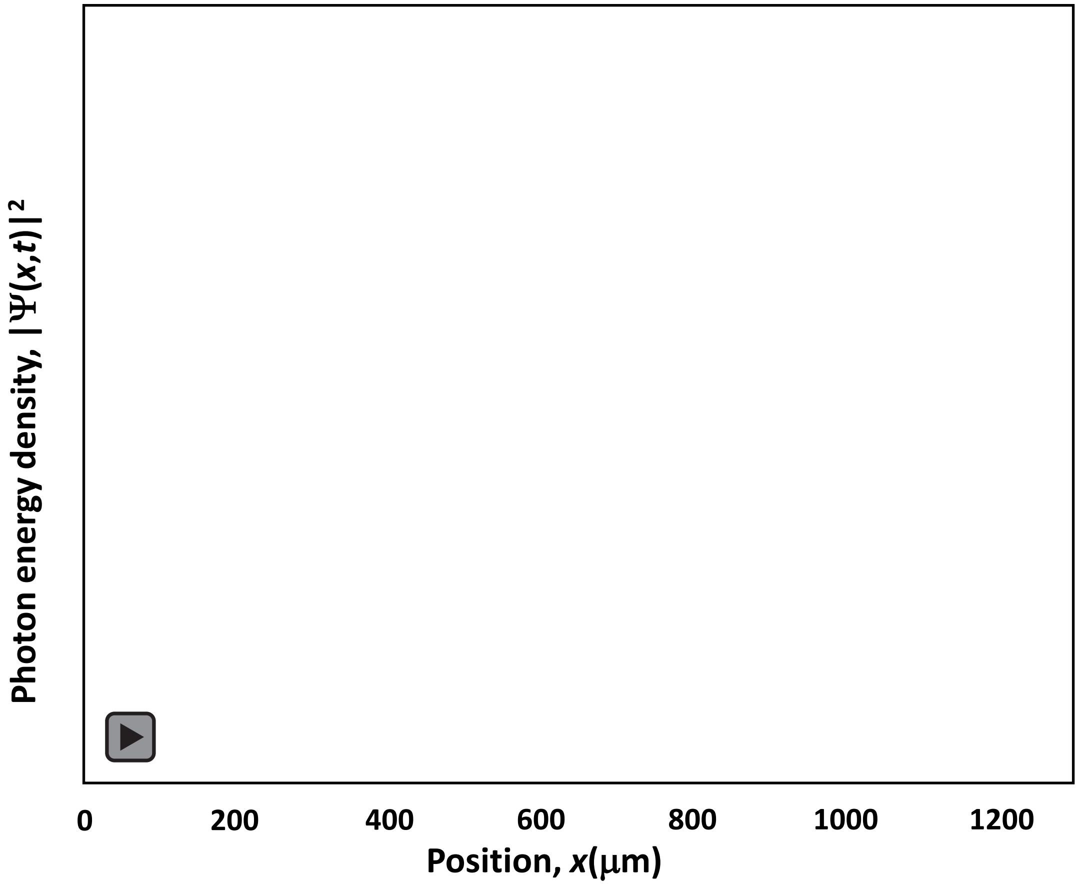
- Zero-energy ground-state is a *guaranteed* control point
- Question: How do you *stop* a bell ringing ?
  - The "ringing bell" could be *excitations* of a molecule, a crystal, a device, …

Coherent control of *transient dynamics*

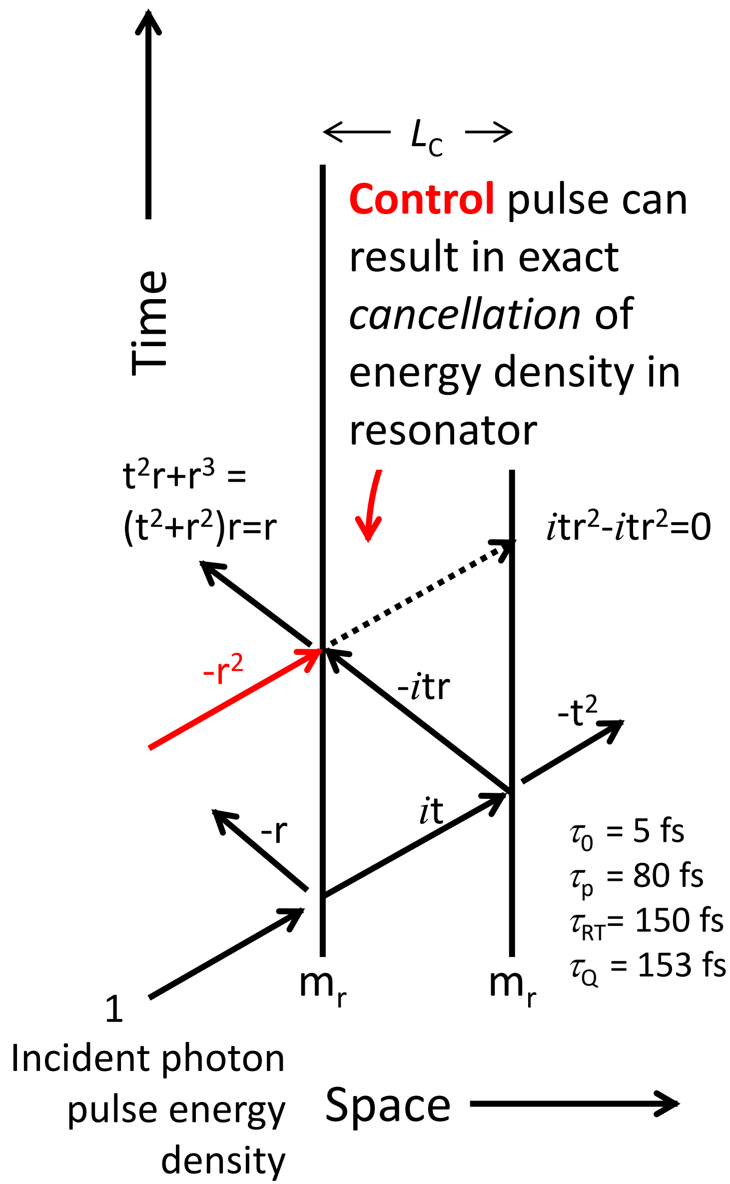
- Question: How do you *stop* a bell ringing ?
- Answer: You hit it ! (… in a *very* controlled and precise way)

Control field generator **System**

Controlled single-photon zero cavity ring-down



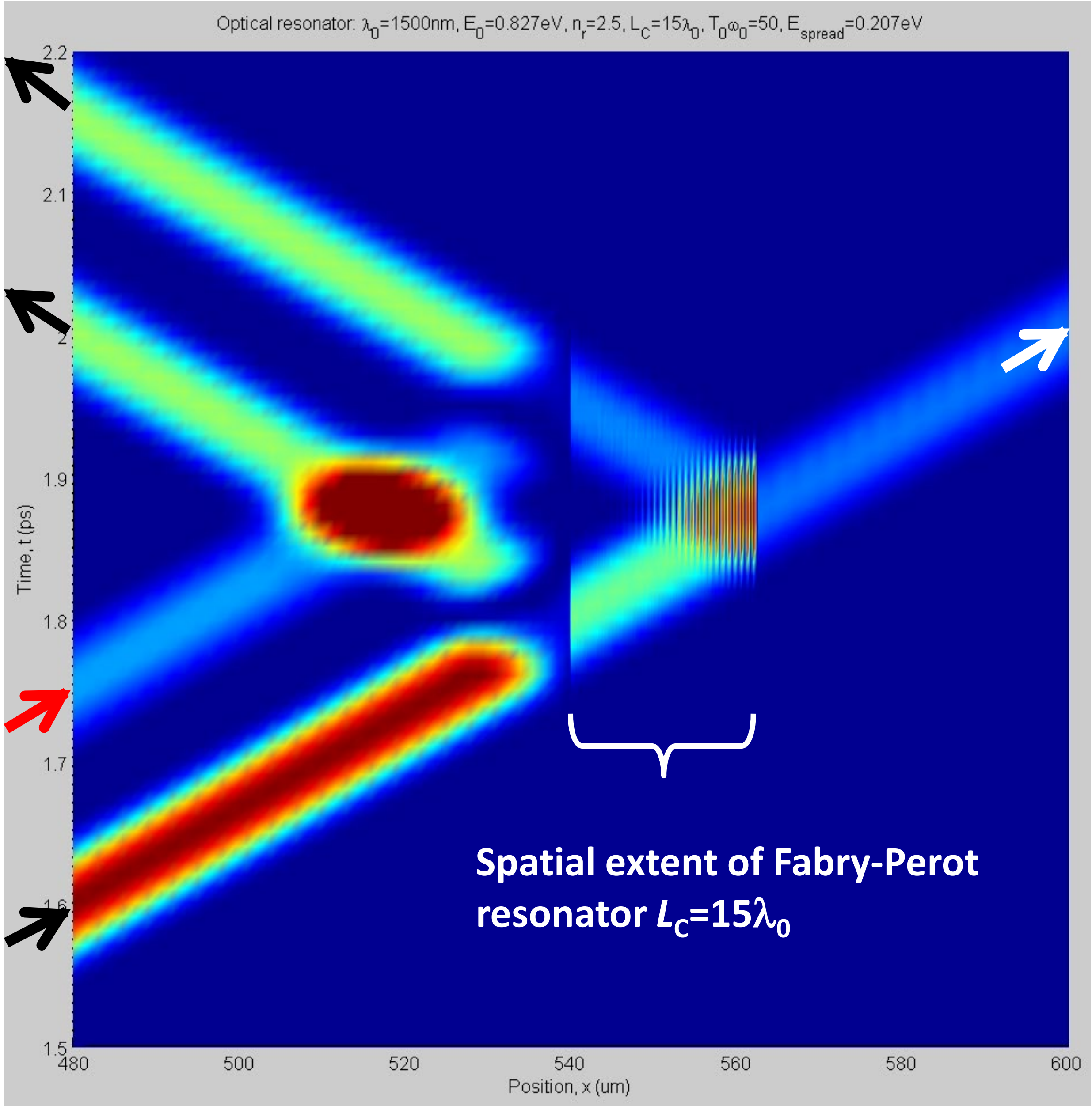
- Identical lossless dielectric mirrors m_r with field reflectivity r and field transmission t
- **Control** pulse with optimal amplitude and phase shift to eliminate photon energy density in resonator
- Formal control methods replaced by *intuitive* ray-tracing of *resonant* part of photon field



Controlled single-photon zero cavity ring-down

Dual reflected photon pulse energy density

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



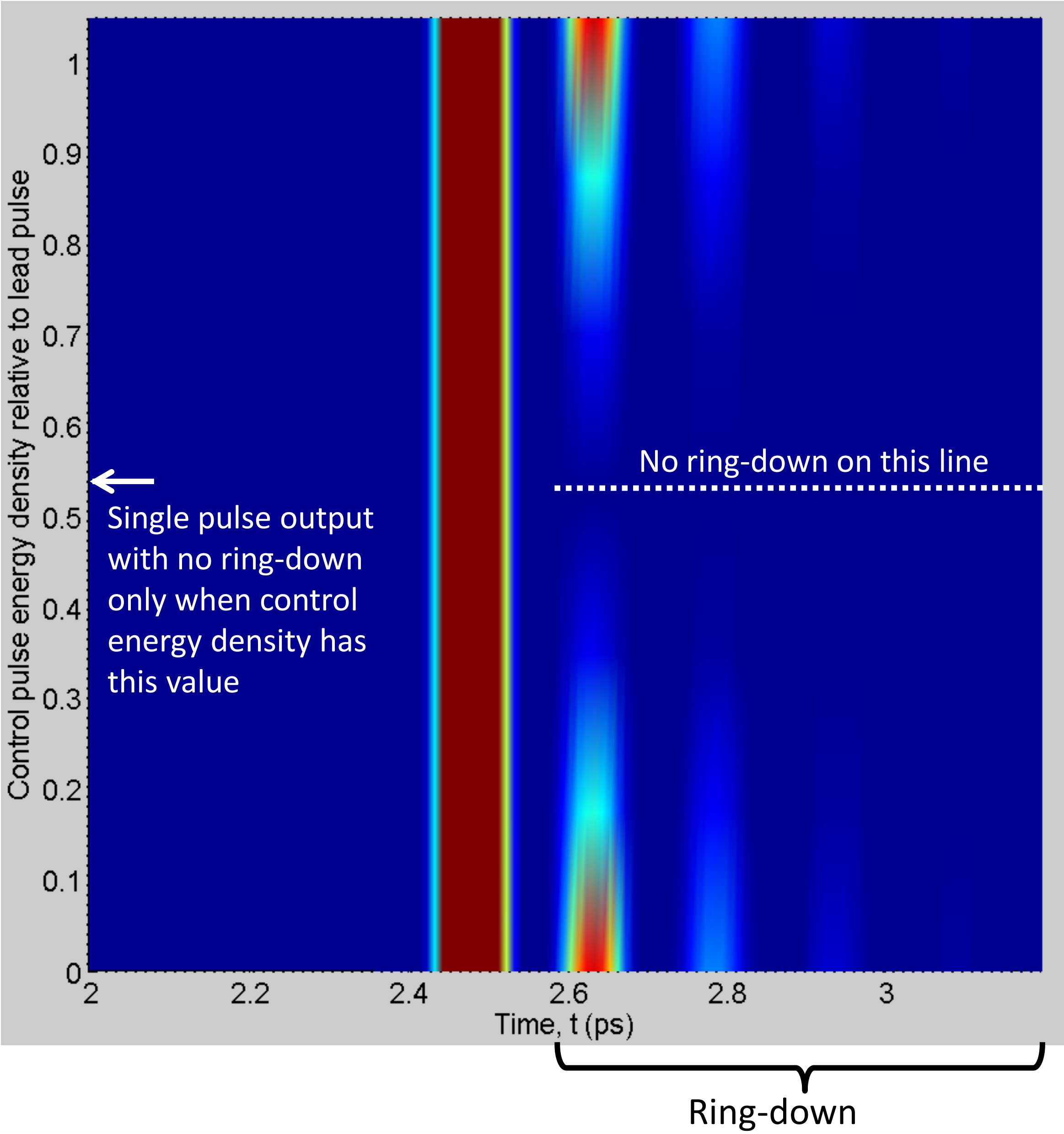
Time

Space

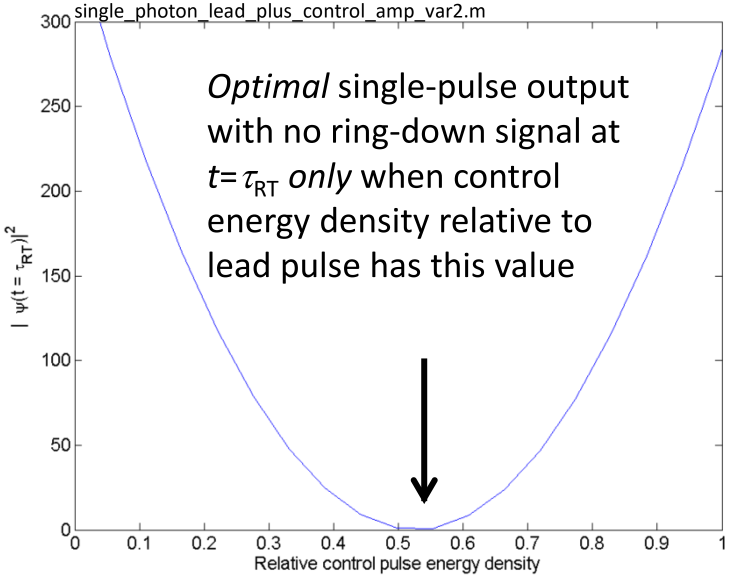
Incident control photon pulse and lead pulse energy density

τ_0 = 5 fs
τ_p = 80 fs
τ_{RT} = 150 fs
τ_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

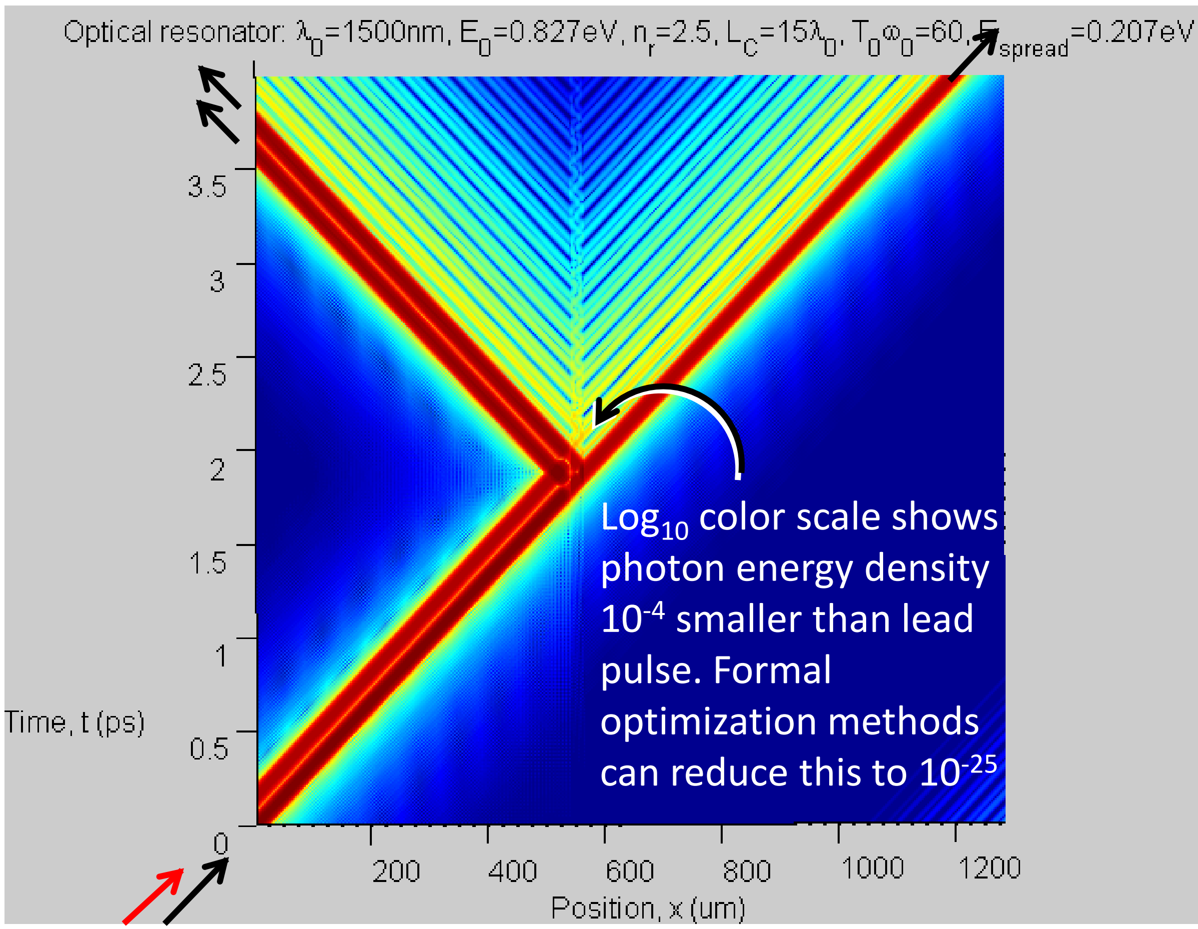


τ_0 =5fs
τ_p =80fs
τ_{RT}=150fs
τ_Q =153fs

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

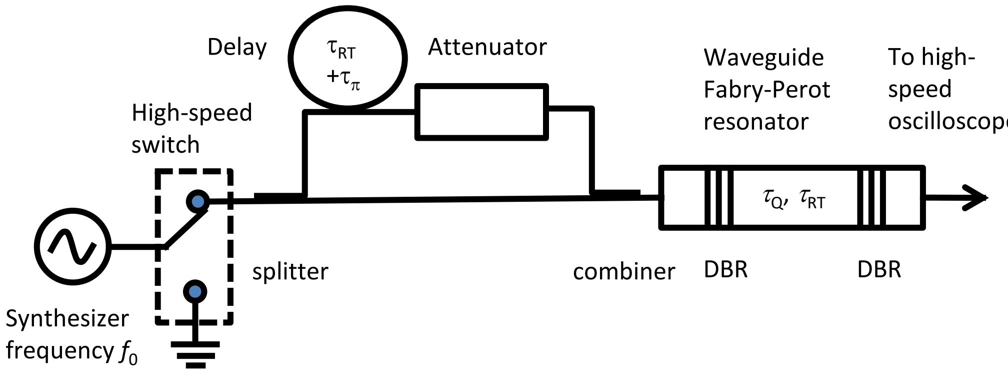


Single transmitted photon energy density pulse amplitude t^2

Incident lead photon pulse and control pulse energy density

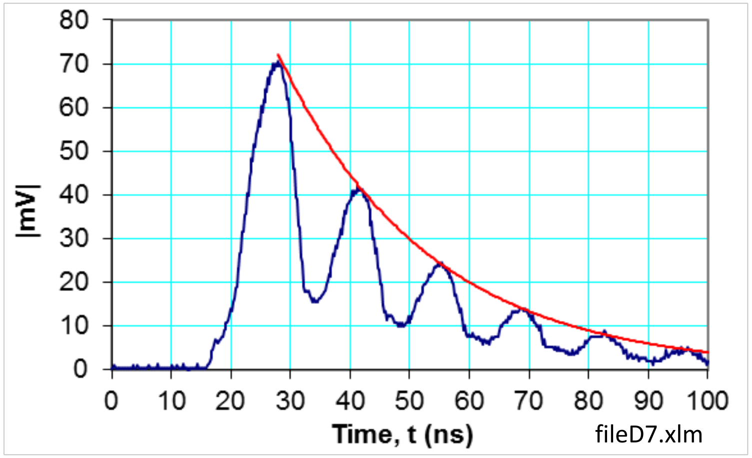
τ_0 =5fs
τ_p =80fs
τ_{RT}=150fs
τ_Q =153fs

Experimental validation using Fabry-Perot resonator in waveguide

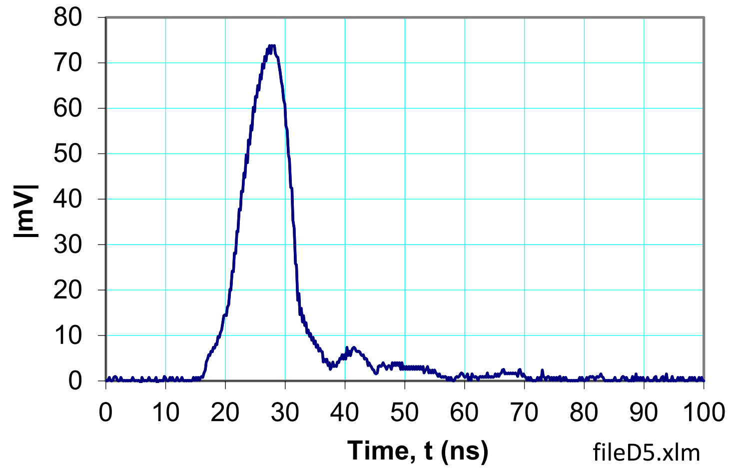


f_0 = 8 GHz, τ_{Coh} = 1 s, τ_0 = 125 ps, τ_p = 7 ns, τ_{RT} = 13.7 ns, τ_Q = 12.5 ns

No control pulse

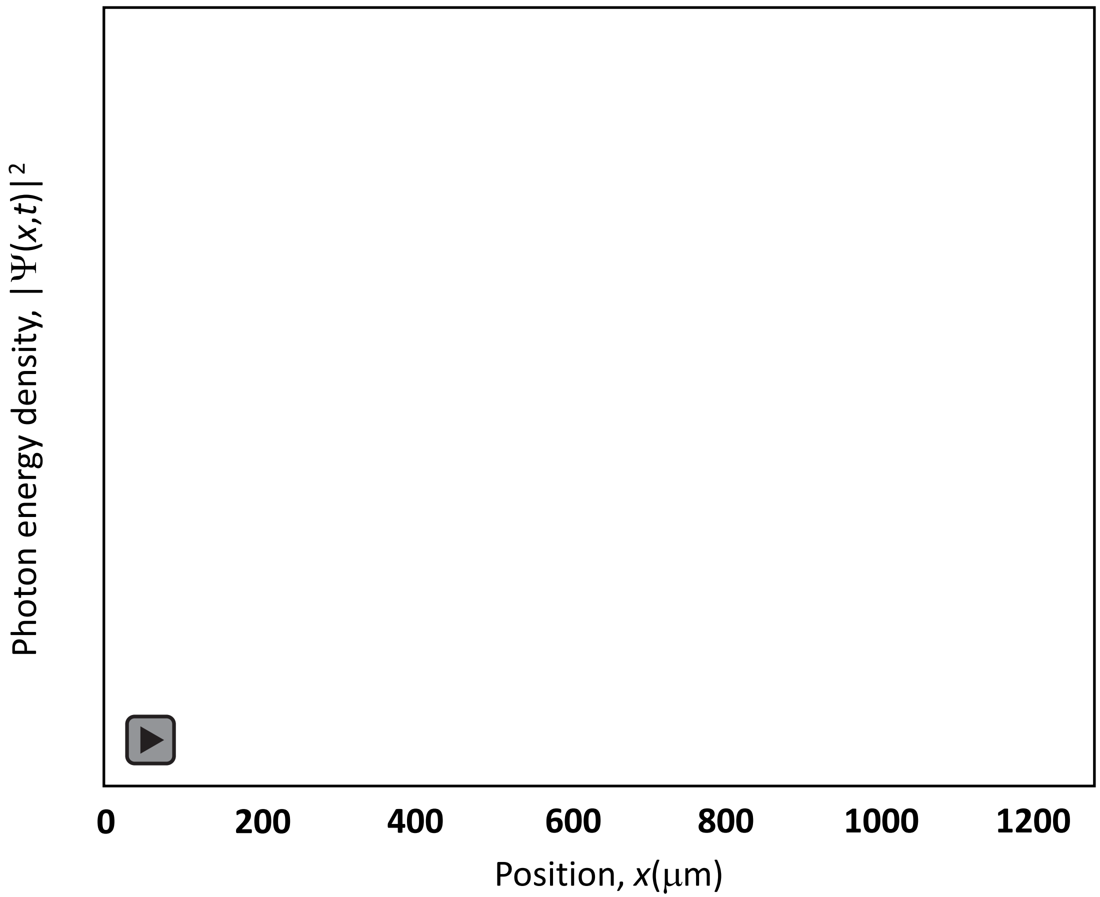


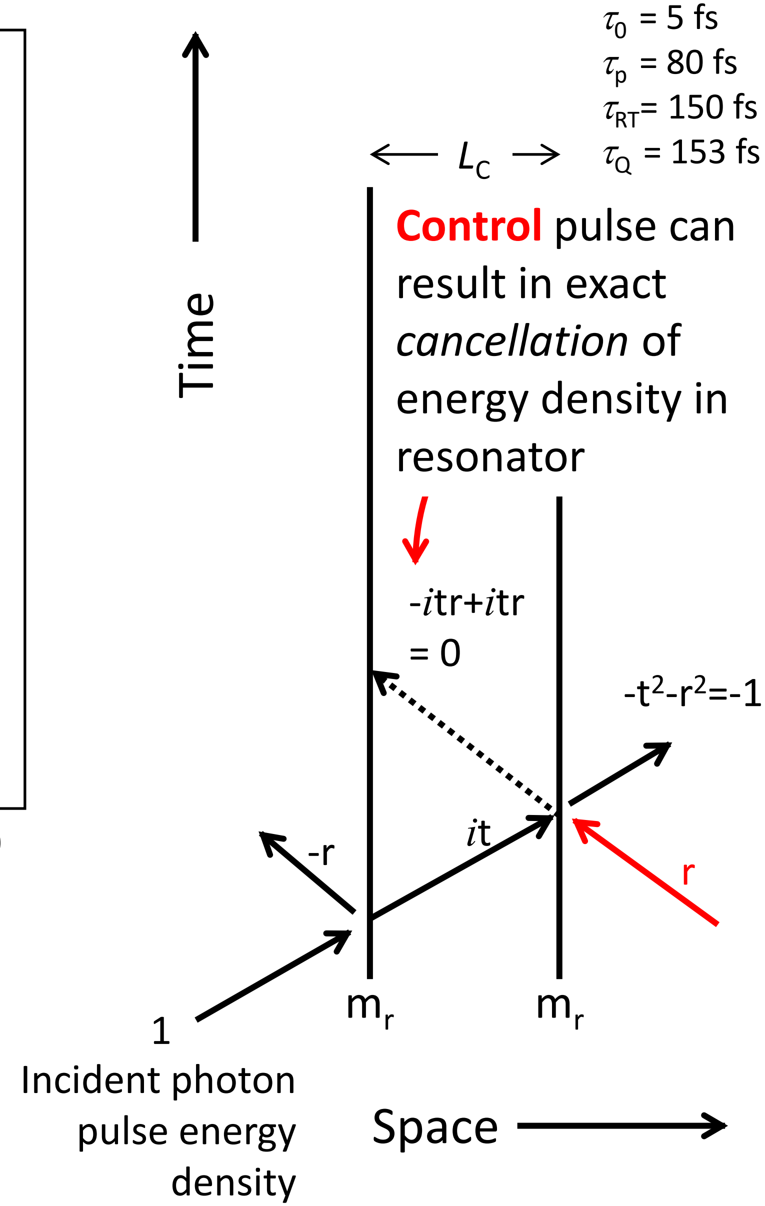
With single control pulse



- Coherent control of resonator *short* output pulse using single *short* control pulse
- Short electromagnetic pulse of width τ_p=10 ns < τ_{RT}, τ_Q
- Round-trip time in resonator τ_{RT}=13.7 ns
- Resonator *Q*=633 corresponds to τ_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





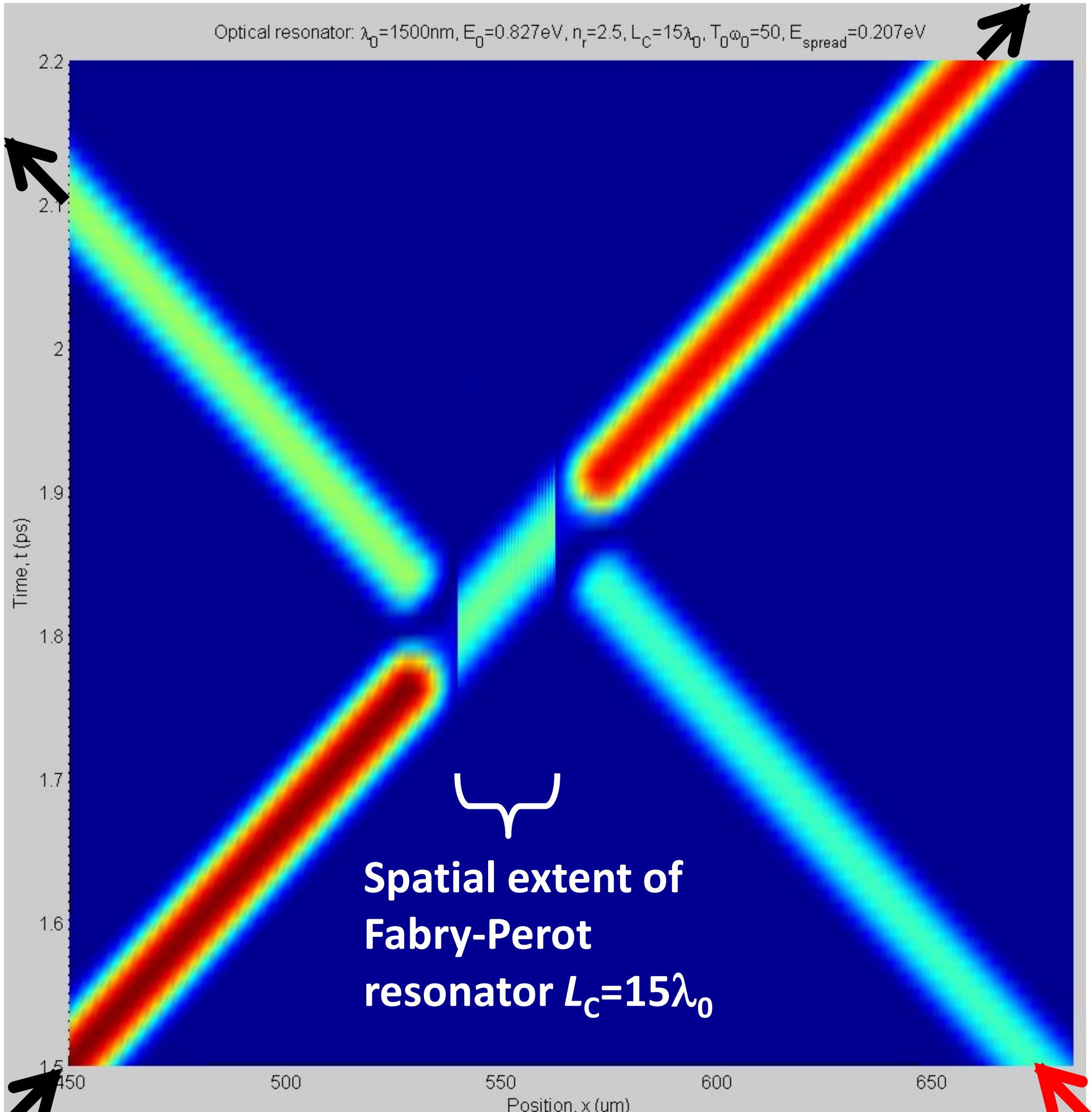
- Lead pulse and *one* backward propagating **control** pulse incident on resonator
- Single pulse transmitted and single pulse reflected with *no* ring-down

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

Single reflected photon pulse energy density

Time

Incident lead photon pulse energy density



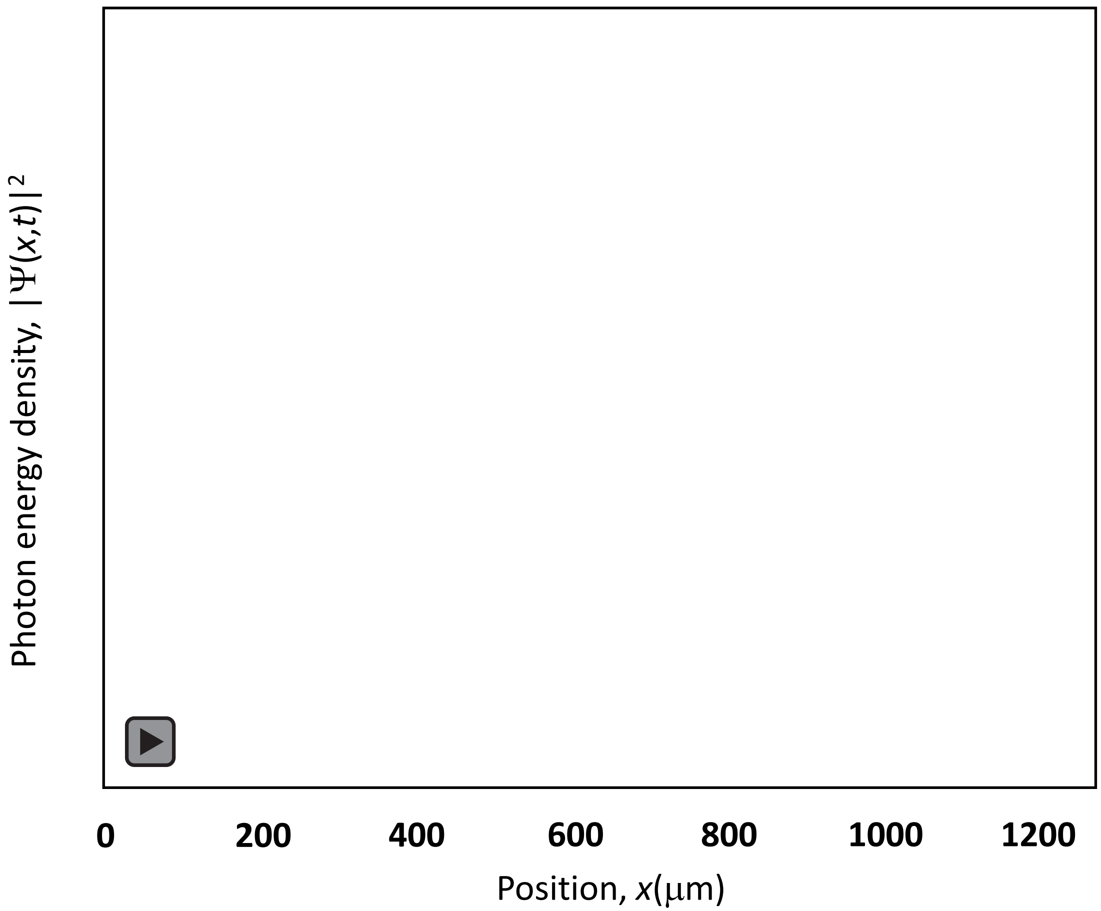
Space

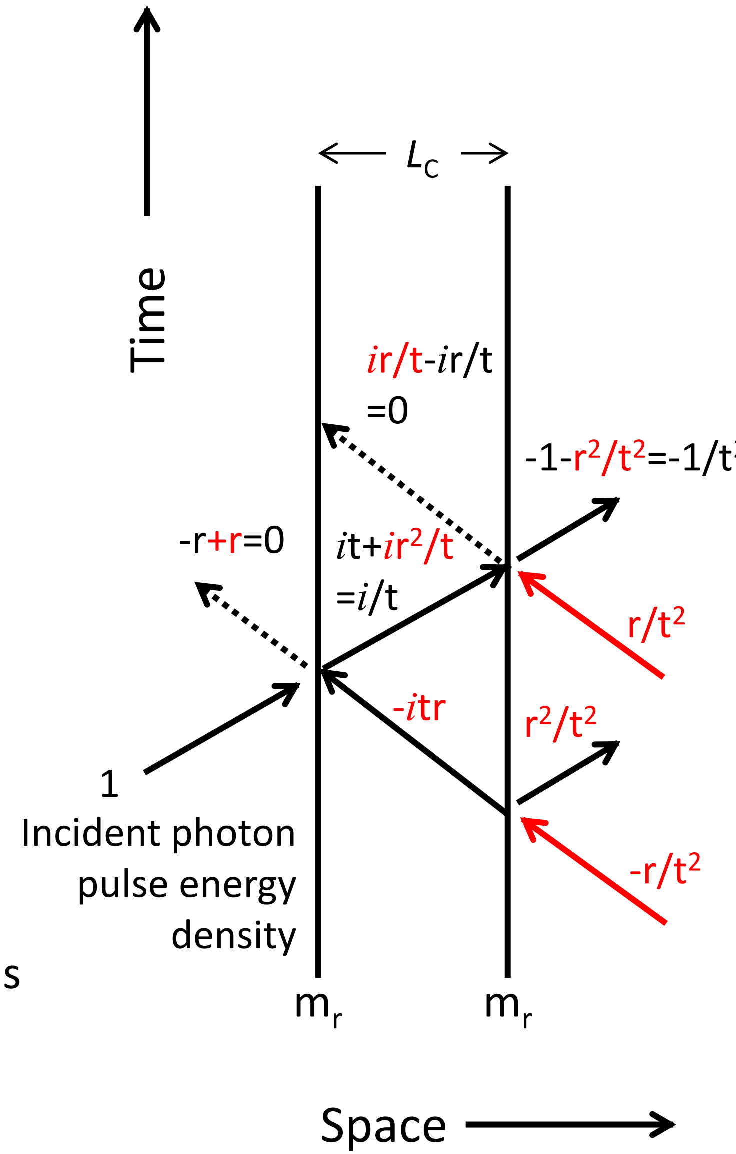
Transmitted photon energy density as single pulse

τ_0 = 5 fs
τ_p = 80 fs
τ_{RT}= 150 fs
τ_Q = 153 fs

Backward propagating control pulse

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



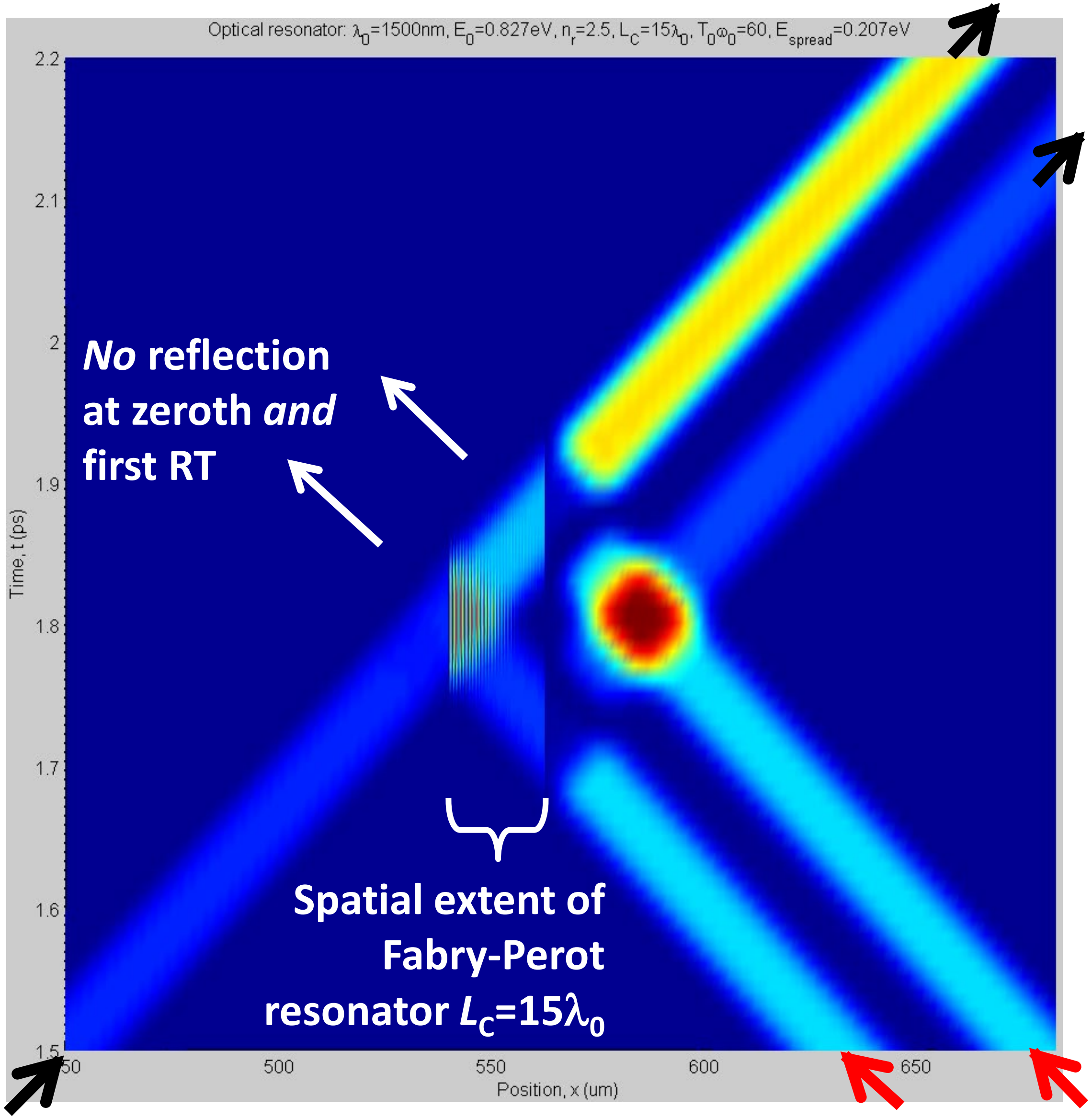


- Lead pulse and *two* backward propagating **control** pulses incident on resonator
- Dual pulse transmitted with *no* ring-down

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

Single reflected photon pulse energy density

Time



Two transmitted photon energy density pulses

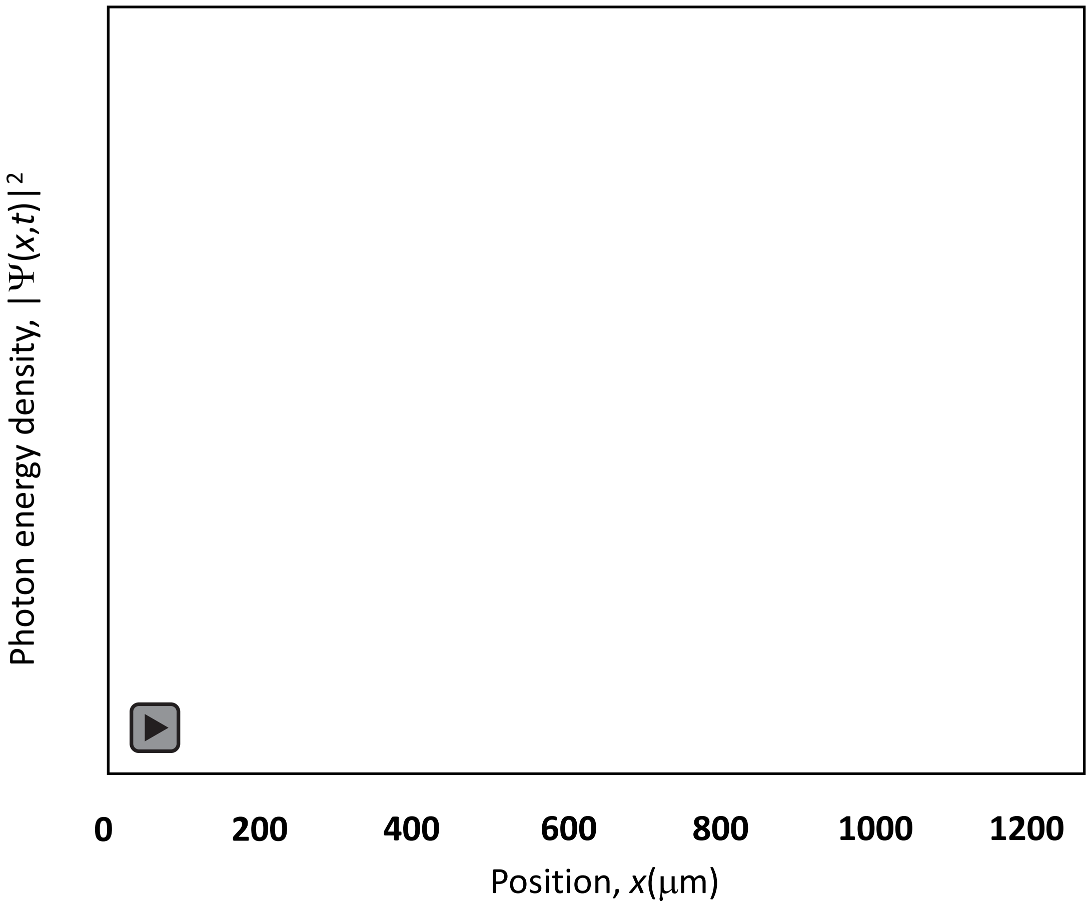
τ_0 = 5 fs
τ_p = 80 fs
τ_{RT}= 150 fs
τ_Q = 153 fs

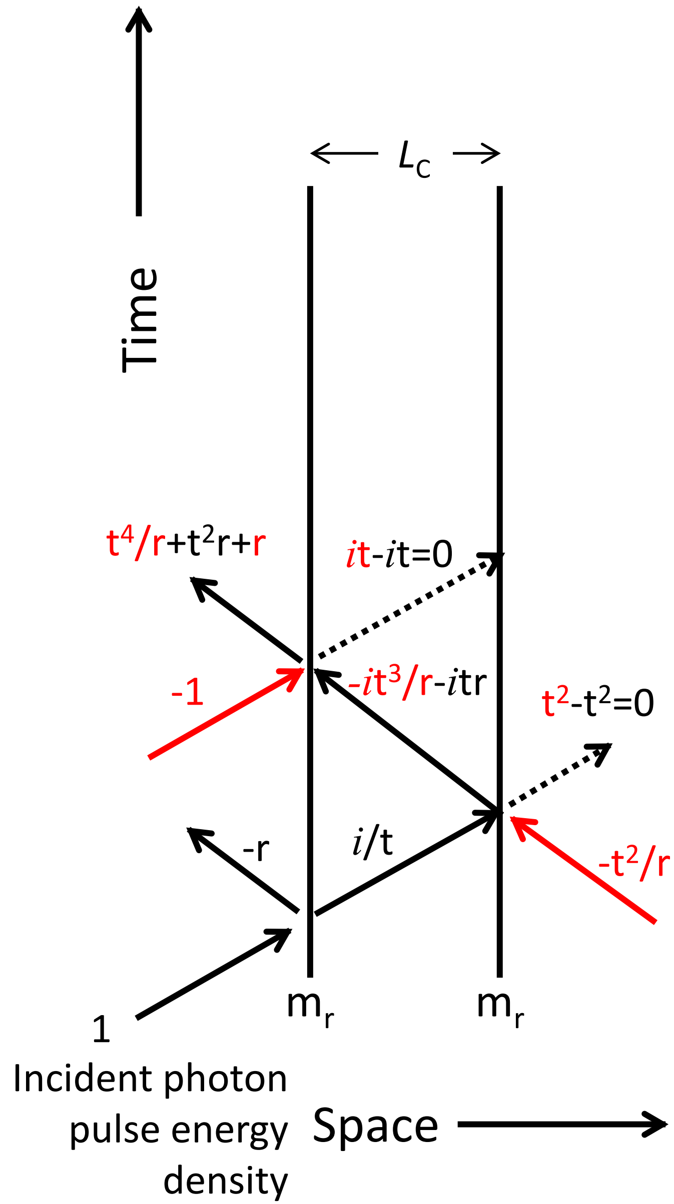
Incident lead photon pulse energy density

Space

Backward propagating control pulses

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





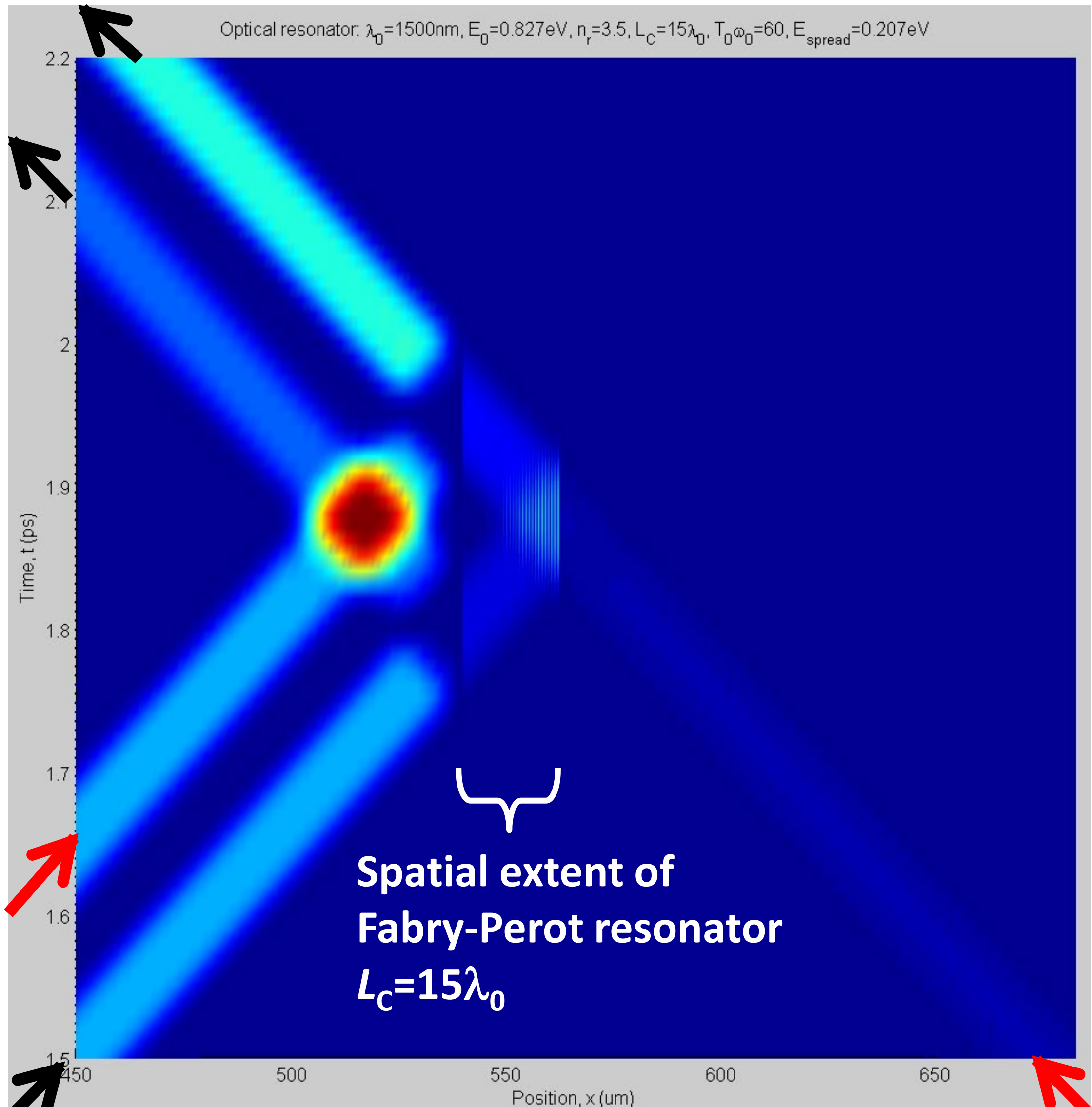
- Lead pulse and *one* forward and *one small* backward propagating **control** pulse incident on resonator
- Two pulses reflected with *no* ring-down
- Note small energy in backward propagating control pulse

Coherent control using one forward and one backward control pulse

Reflected photon energy density pulses

No Transmitted photon energy density

Time



τ_0 = 5 fs
τ_p = 80 fs
τ_{RT}= 150 fs
τ_Q = 153 fs

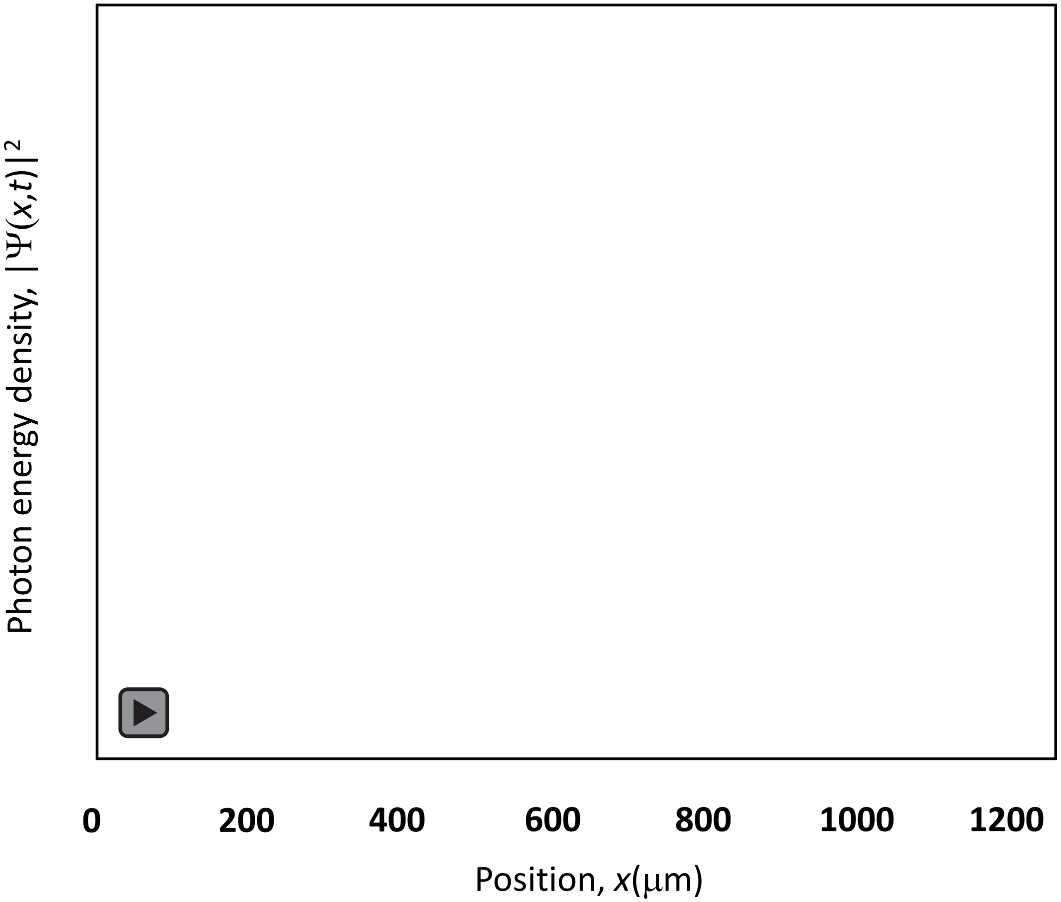
Forward propagating control pulse

Incident lead photon pulse energy density

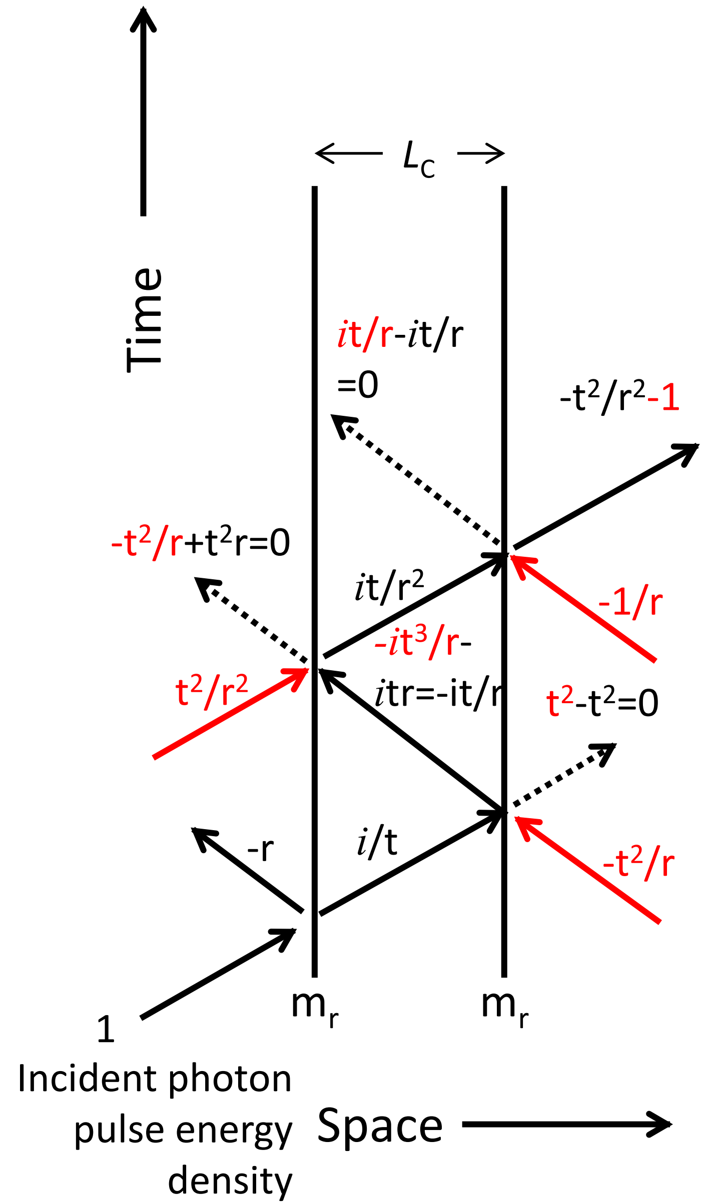
Space

Backward propagating control pulse

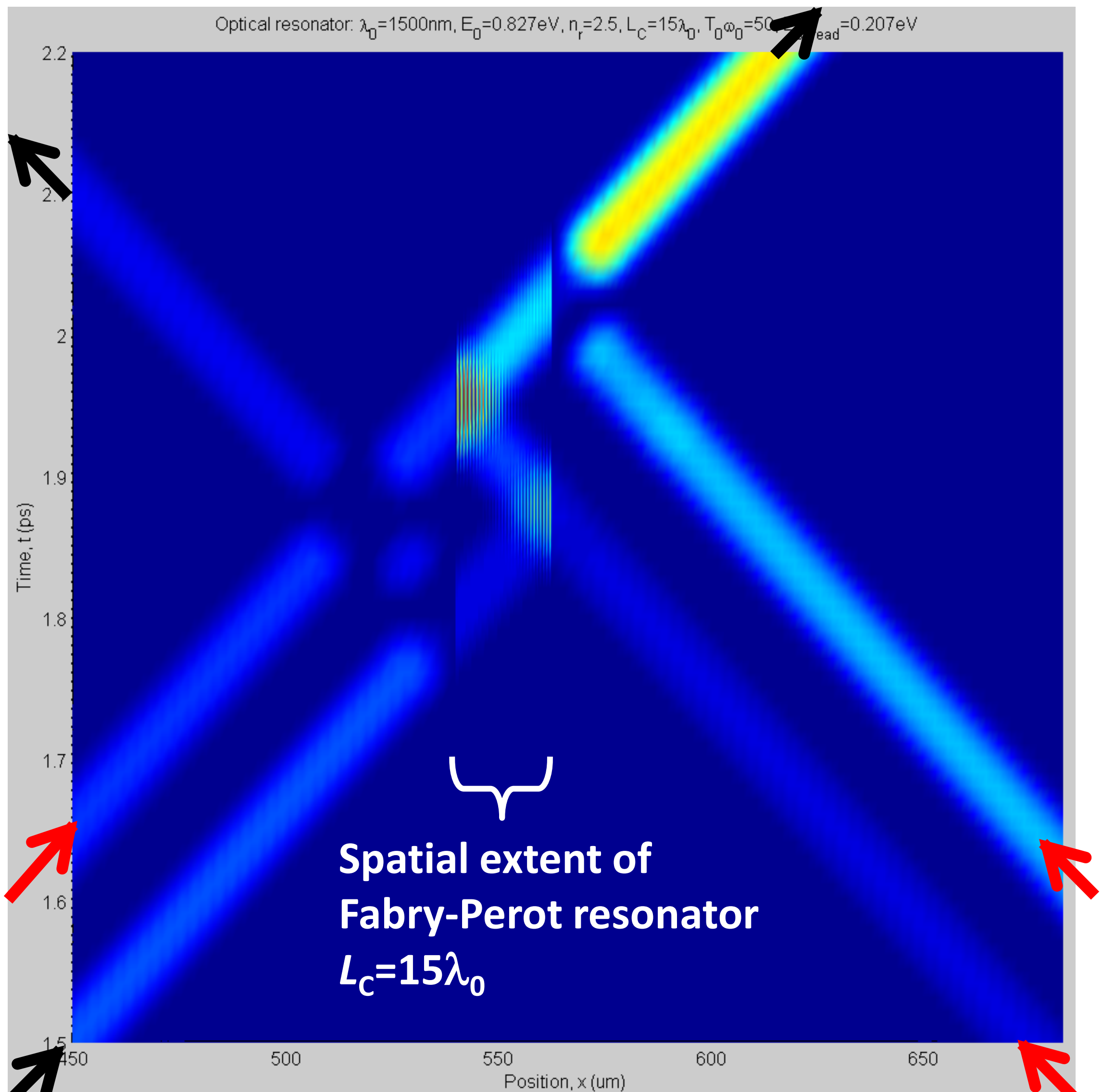
Coherent control using one forward and two backward control pulses



- 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

Space

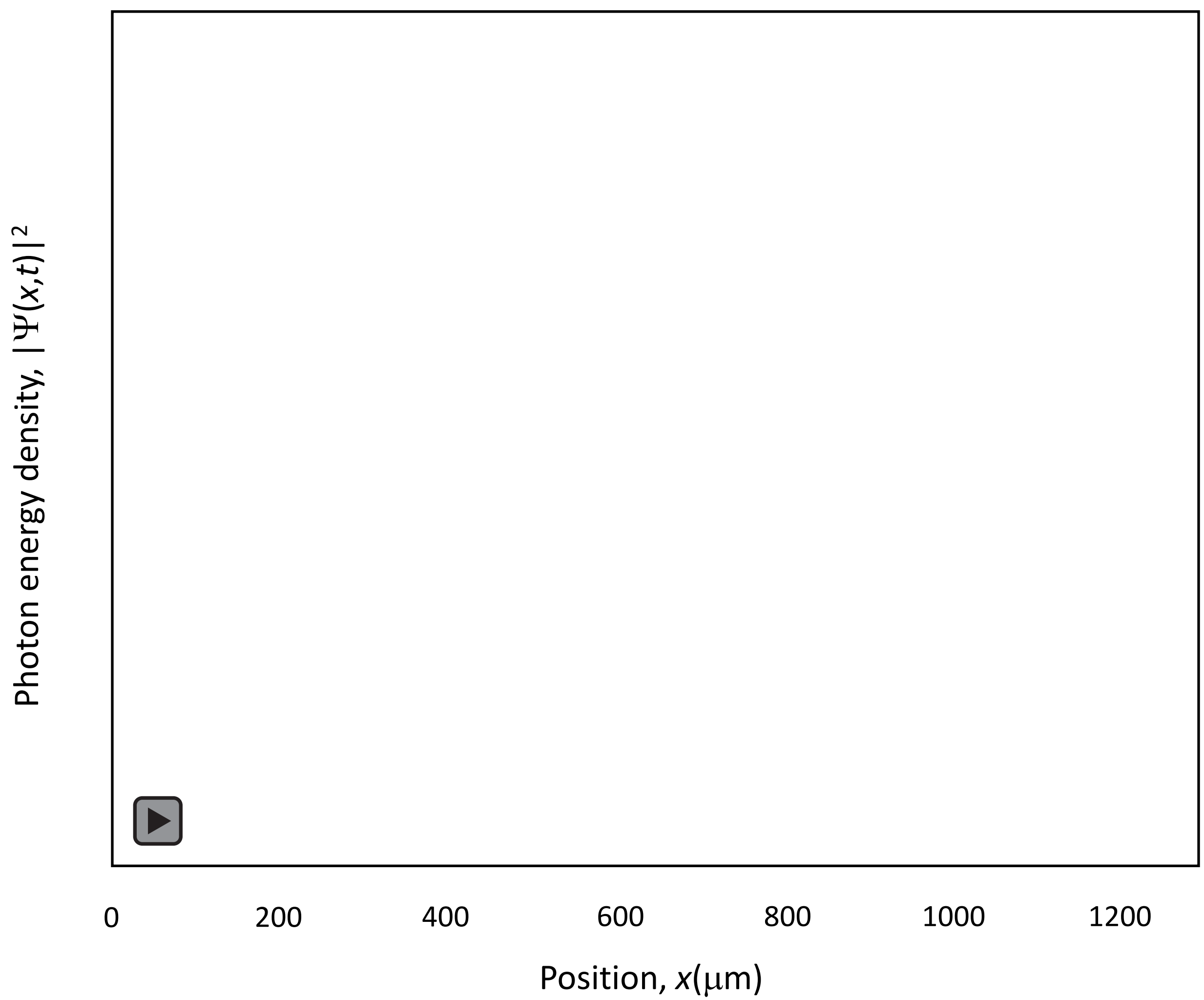
Transmitted photon energy density

τ_0 = 5 fs
τ_p = 80 fs
τ_{RT}= 150 fs
τ_Q = 153 fs

Backward propagating control pulses

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

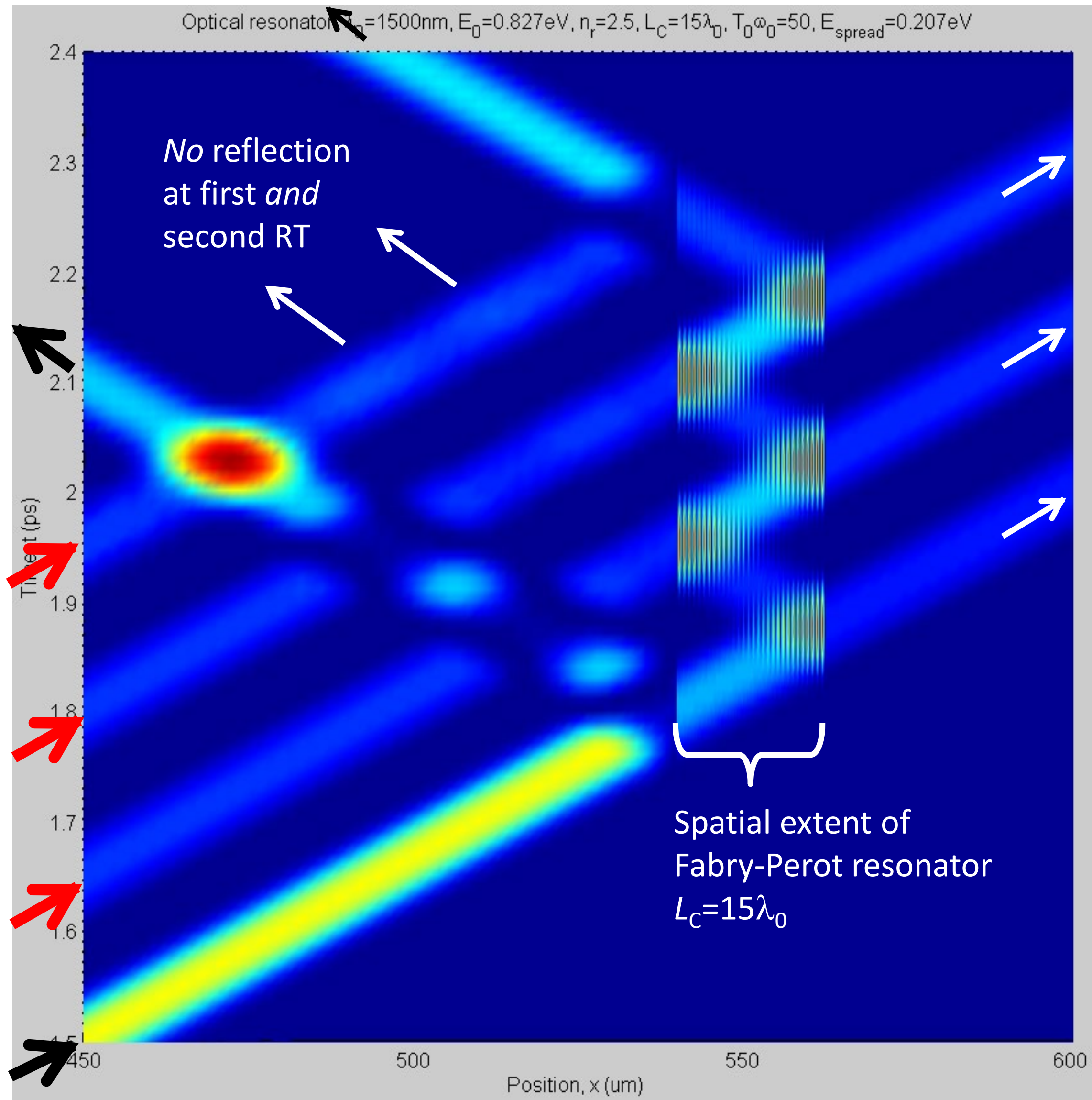


τ_0 =5fs
τ_p =80fs
τ_{RT}=150fs
τ_Q =153fs

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

Dual reflected photon pulse energy density

Time



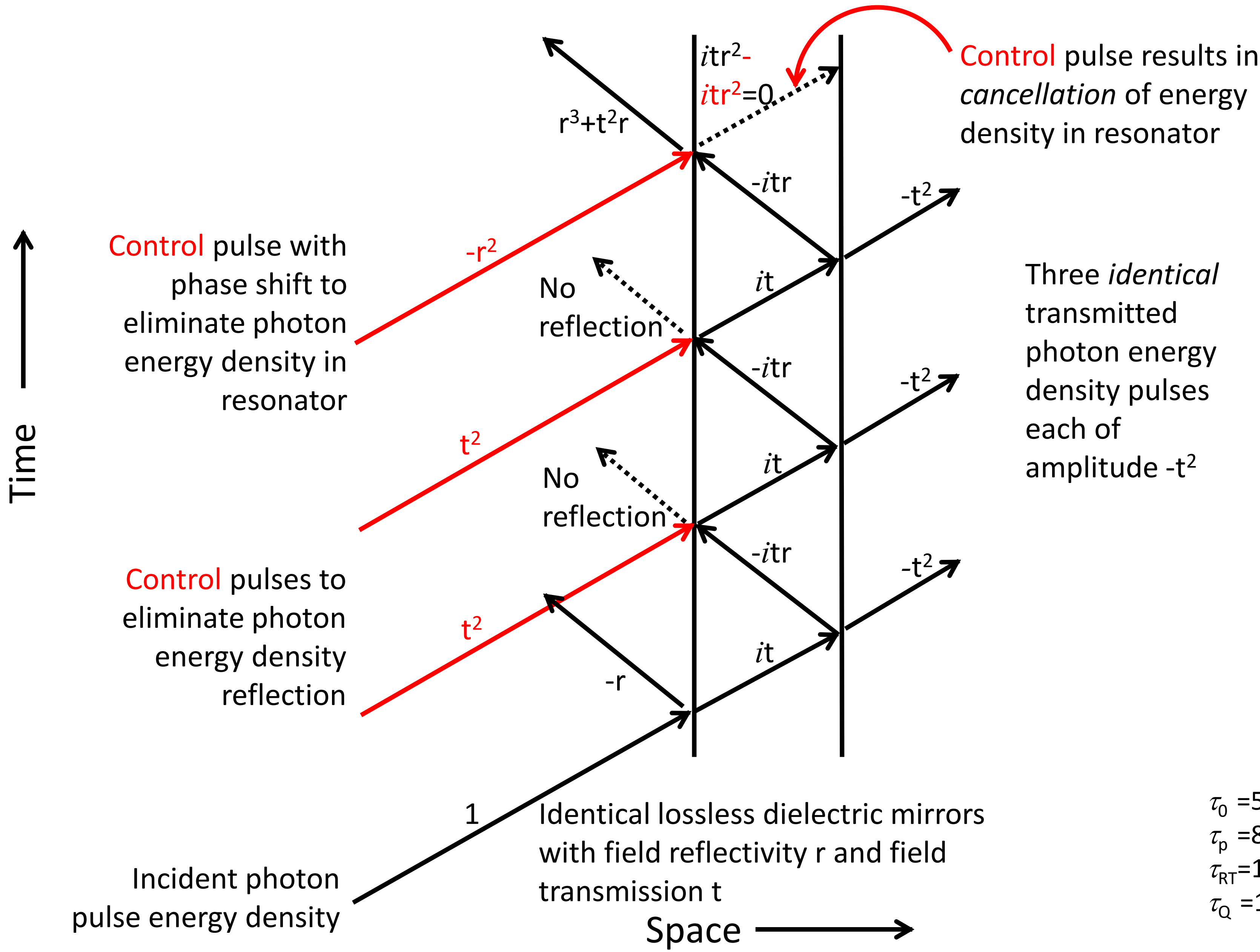
Incident lead photon pulse and multiple control pulse energy density

Transmitted photon energy density in three identical pulses

Space

τ_0 =5fs
τ_p =80fs
τ_{RT}=150fs
τ_Q =153fs

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



τ_0 =5fs
τ_p =80fs
τ_{RT}=150fs
τ_Q =153fs

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

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

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

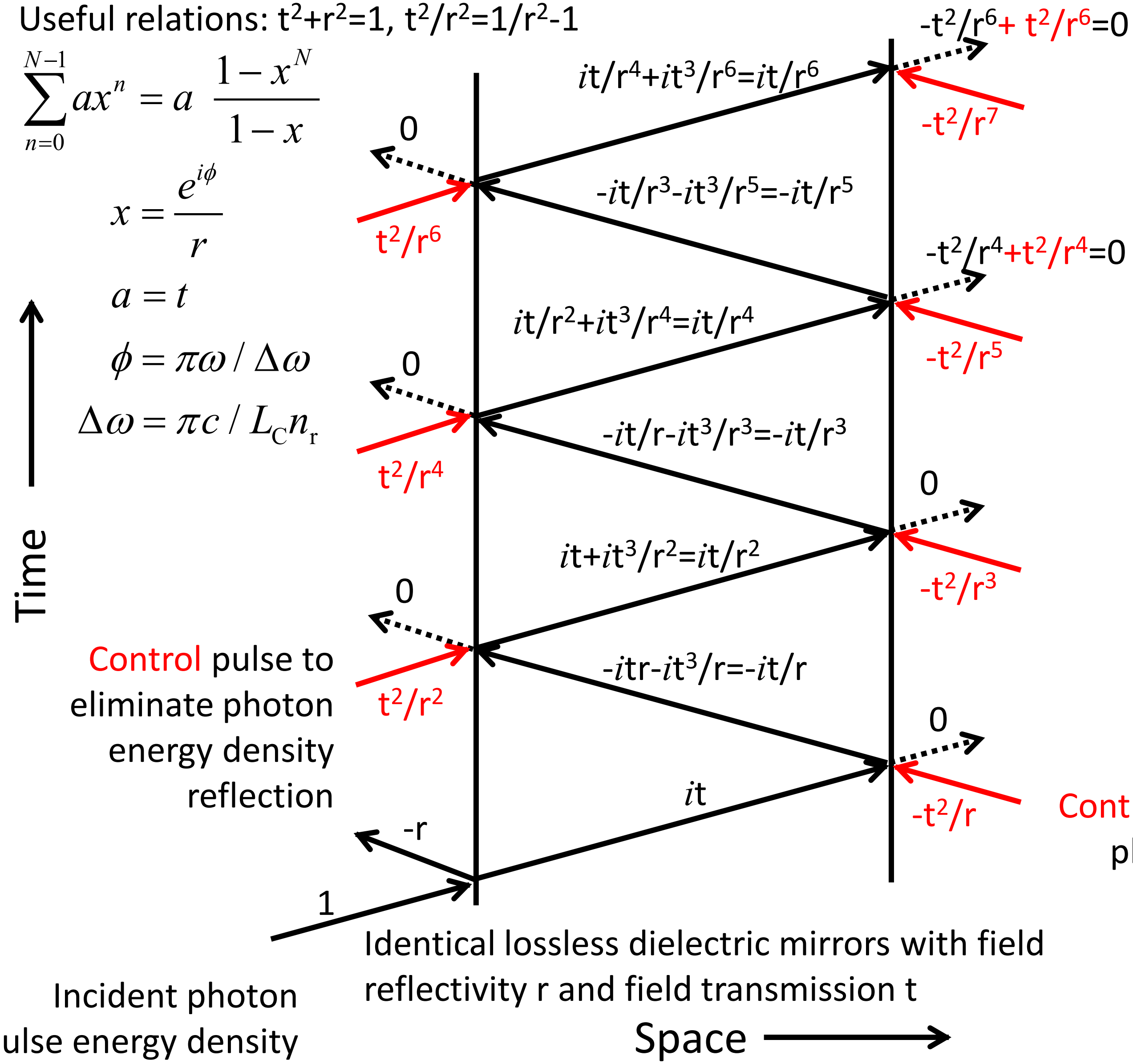
$$x=\frac{e^{i\phi}}{r}$$

$$a=t$$

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

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

Control pulse to eliminate photon energy density reflection



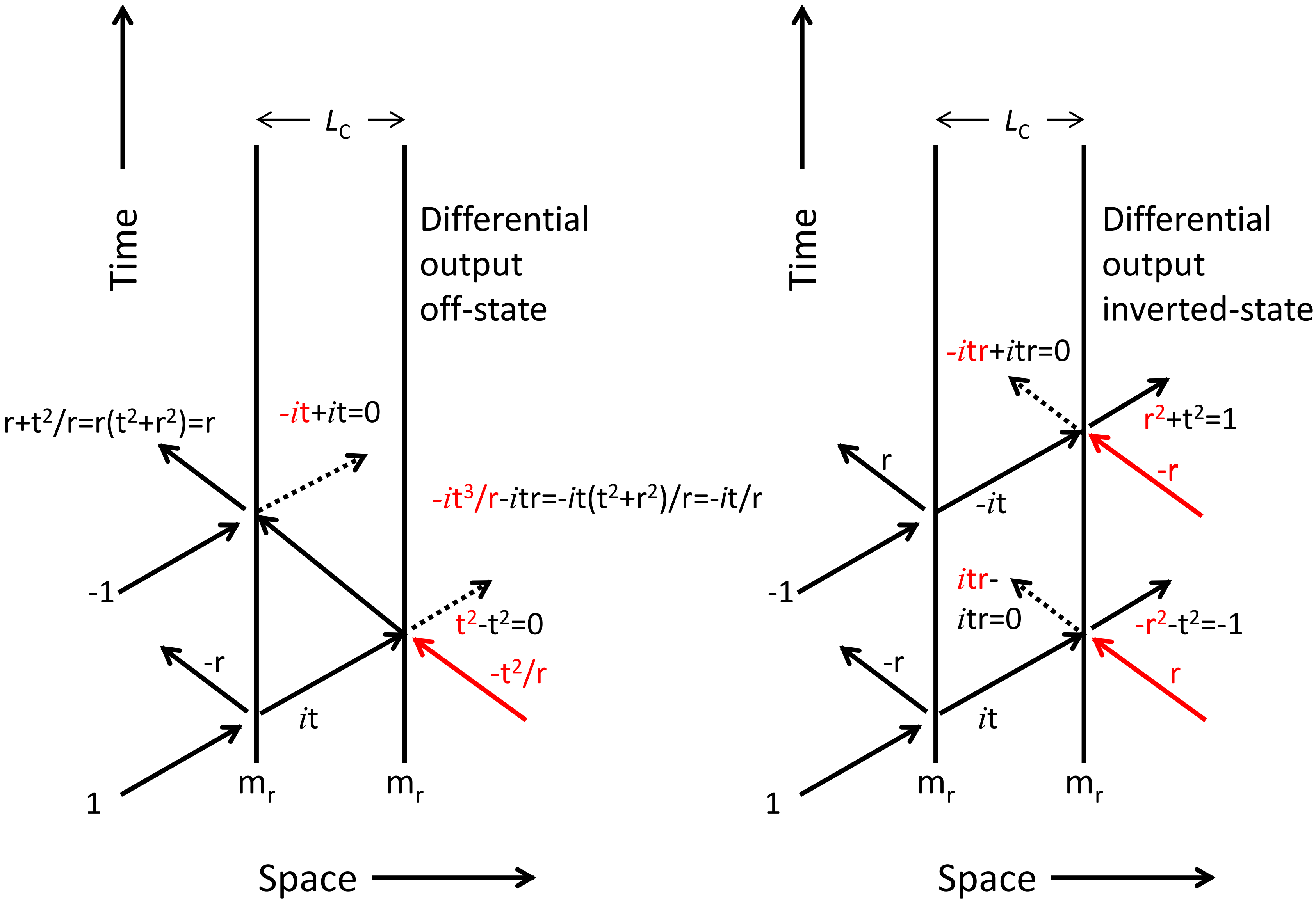
Photon field *in* resonator is geometric series in $e^{i\phi}/r$ that sums to the N-1 value as $t(1+e^{i\phi}/r+e^{i2\phi}/r^2+e^{i3\phi}/r^3+\ldots)=t(1-(e^{i\phi}/r)^N)/(1-(e^{i\phi}/r))$ where phase per round-trip is $2\phi=2\pi\omega/\Delta\omega$ and spacing between resonances is $\Delta\omega=\pi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

Control pulse to eliminate photon energy density reflection

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

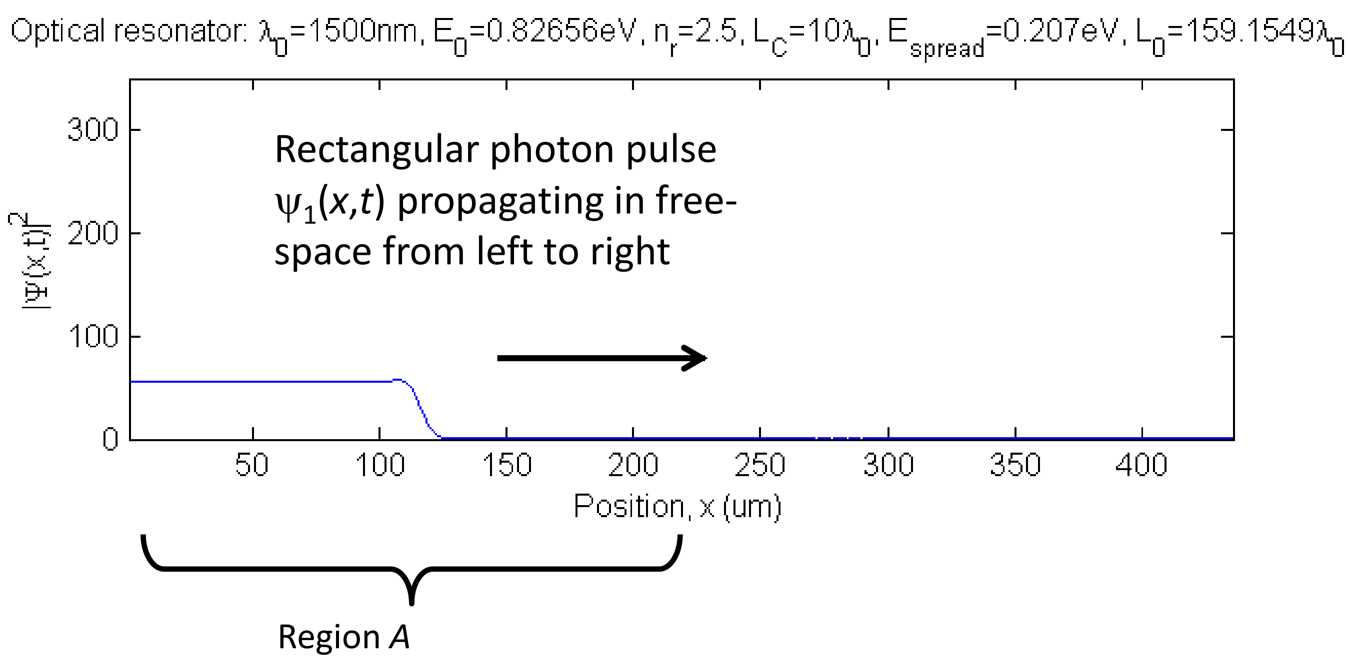
Incident photon pulse energy density

Coherent control



Markoviantiy 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



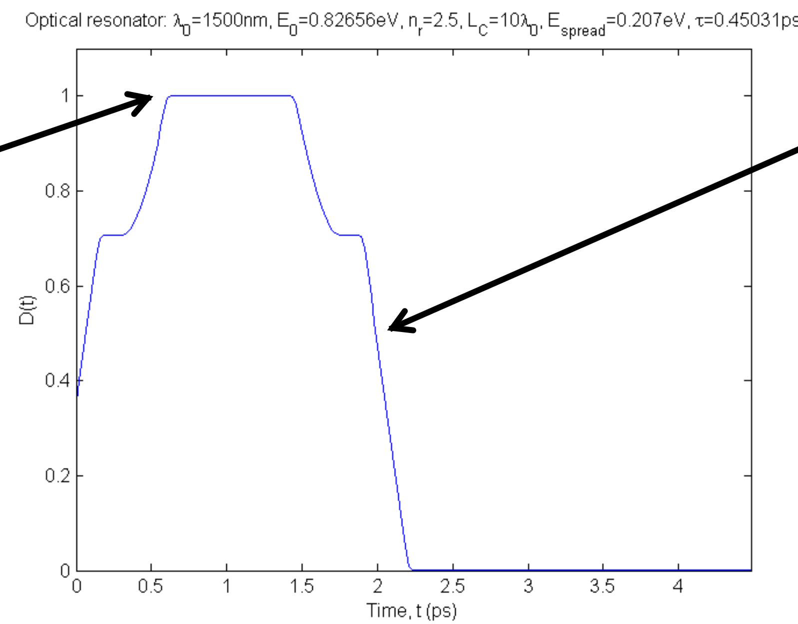
Hilbert-Schmidt measure $D(t)$ and Markovianity

- 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 τ_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

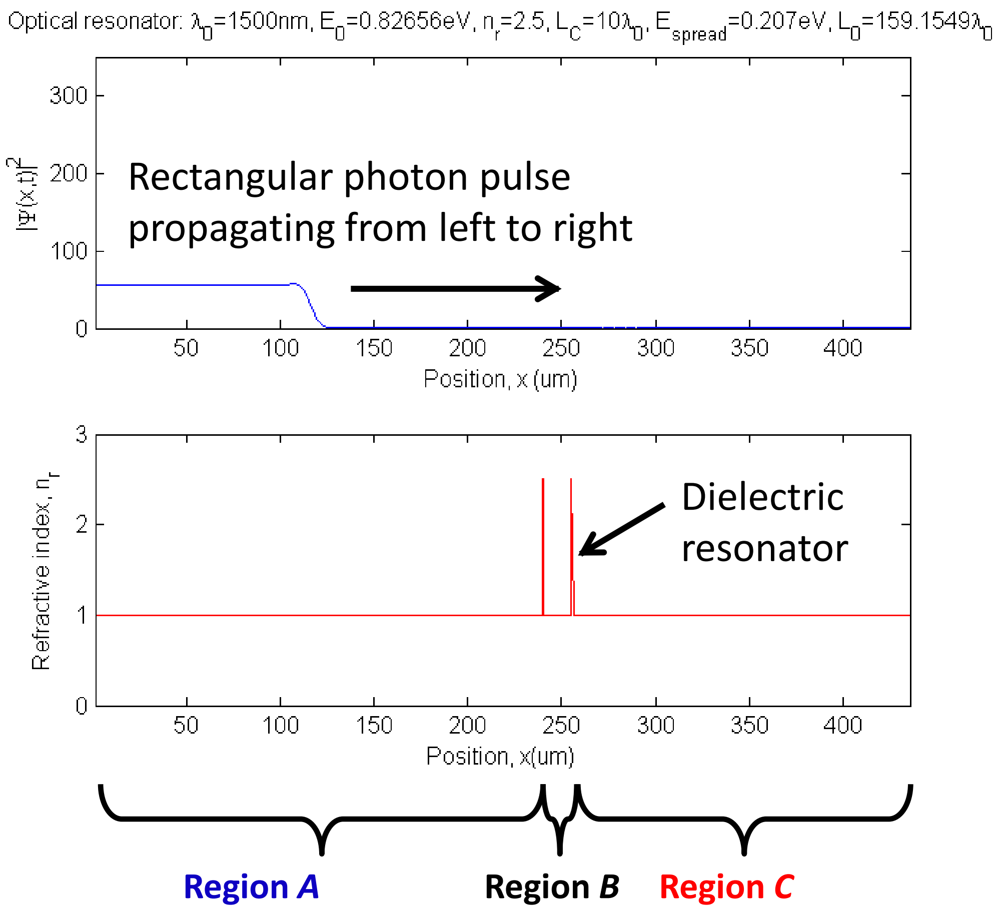
Rectangular photon pulse $\psi_1(x,t)$ and time shifted pulse $\psi_2(x,t) = \psi_1(x,t+\tau_M)$ both freely propagating in region *A* such that normalized measure *D*(*t*)=1



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

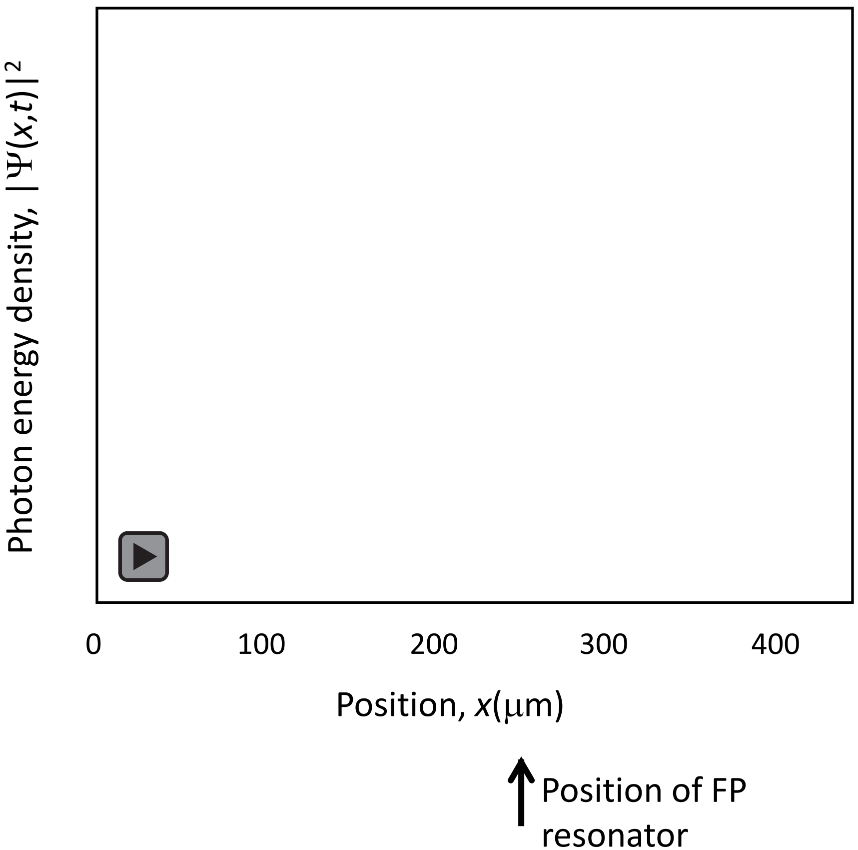
- A (blue curve) left of dielectric resonator with some energy density flow into region
- B (black curve) which is in dielectric resonator with energy density flow into region
- C (red curve) to right of dielectric resonator
- *Note*: Extent of region in domain and definition of system, subsystem, bath,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



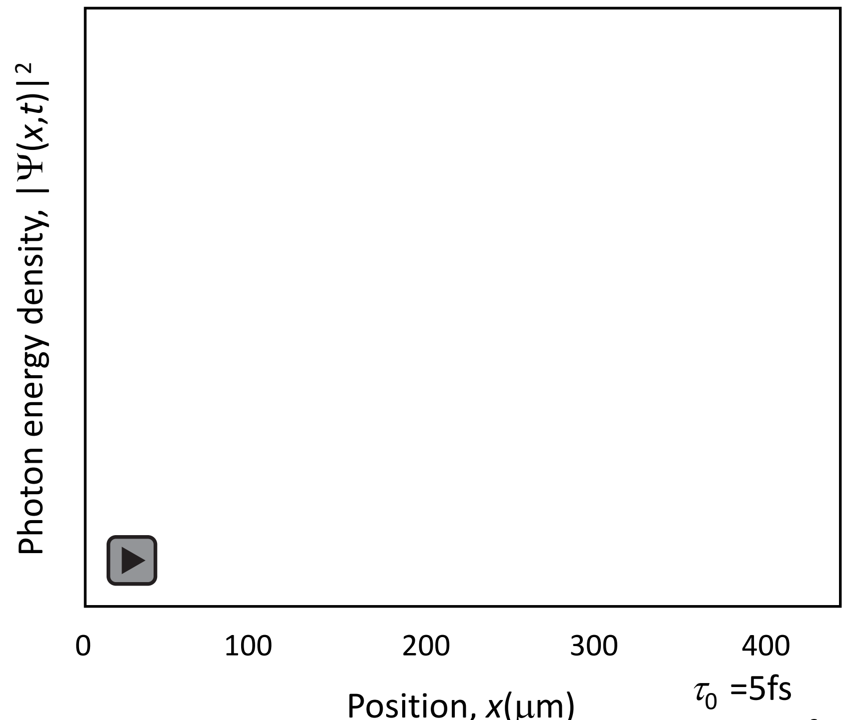
Hilbert-Schmidt measure $D(t)$ of photon interacting with Fabry-Perot dielectric resonator

- 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/τ_Q}

No control pulse



With single control pulse

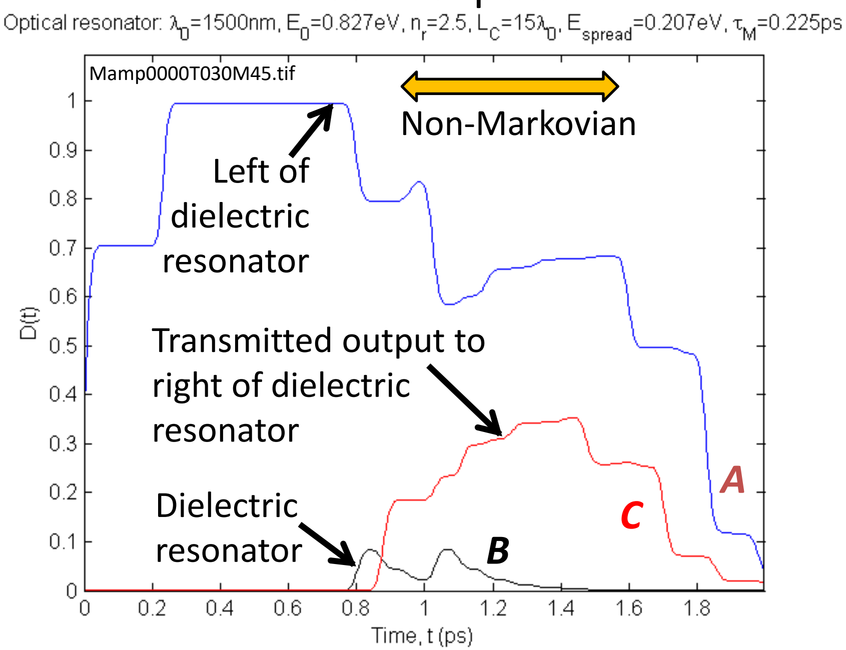


τ_0 =5fs
τ_{RT}=150fs
τ_Q =153fs
τ_M =225fs

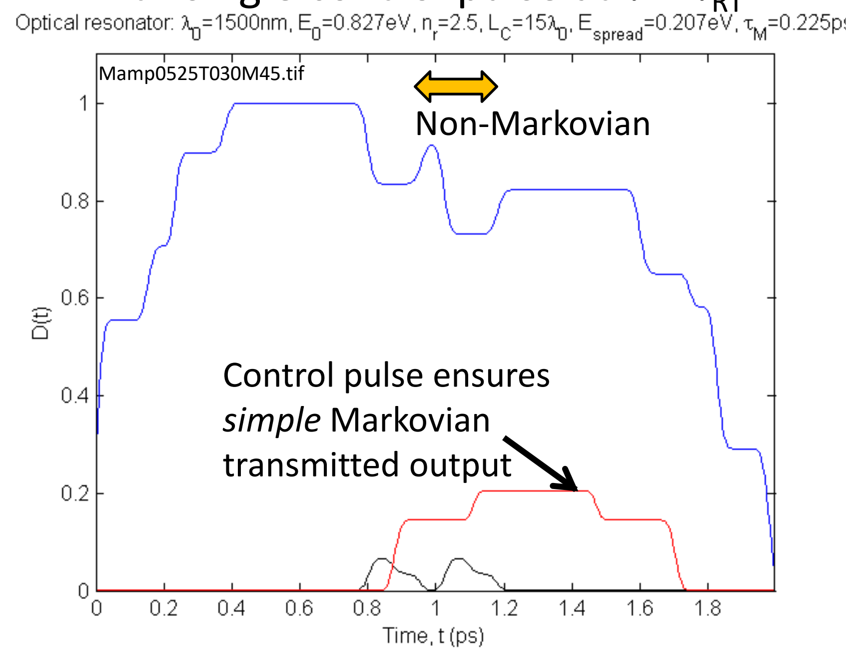
Hilbert-Schmidt measure $D(t)$ of photon interacting with Fabry-Perot dielectric resonator

- 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 $\tau = \tau_{RT}$



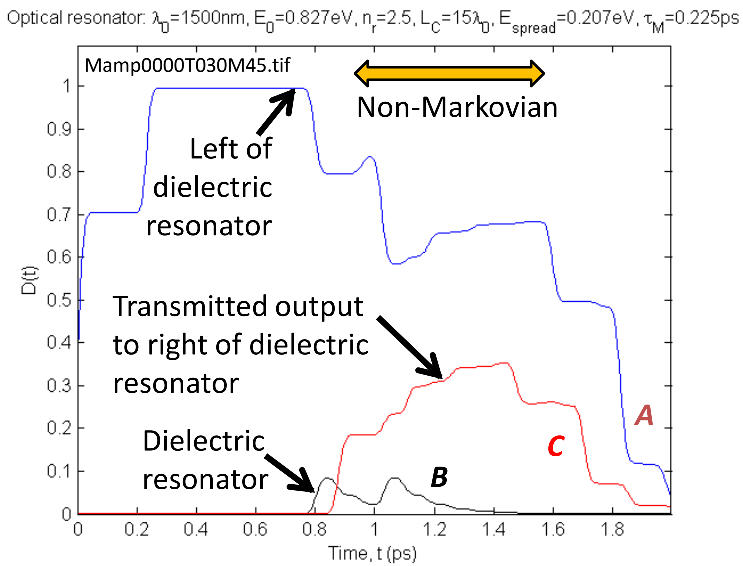
Photon pulse $\psi_1(x,t)$ and time-shifted pulse $\psi_2(x,t) = \psi_1(x,t+\tau_M)$ both initially propagating freely in region *A*

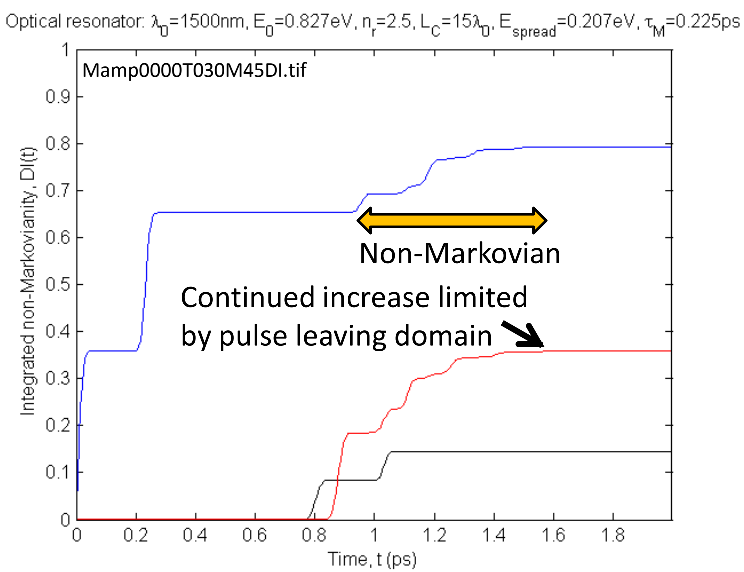
Non-monotonic decrease of *D*(*t*) because energy density is reflected at resonator and energy density is stored and subsequently released from resonant cavity

τ_0 =5fs
τ_{RT}=150fs
τ_Q =153fs
τ_M =225fs

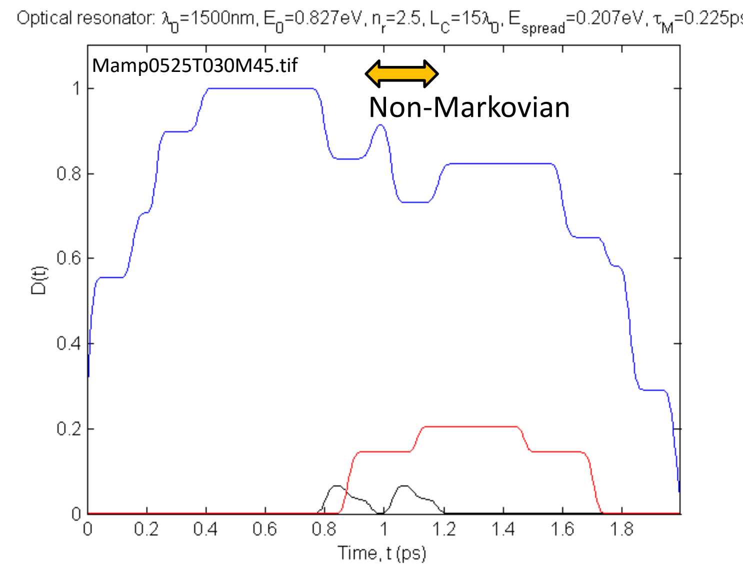
Integrated non-Markovianity, $DI(t)=\Sigma_i(\Delta D(t_i)|_{\text{positive}})$

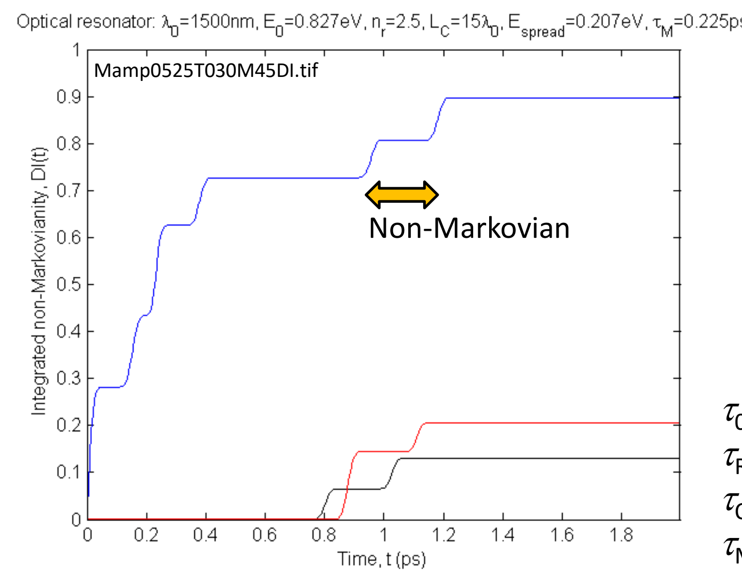
No control pulse





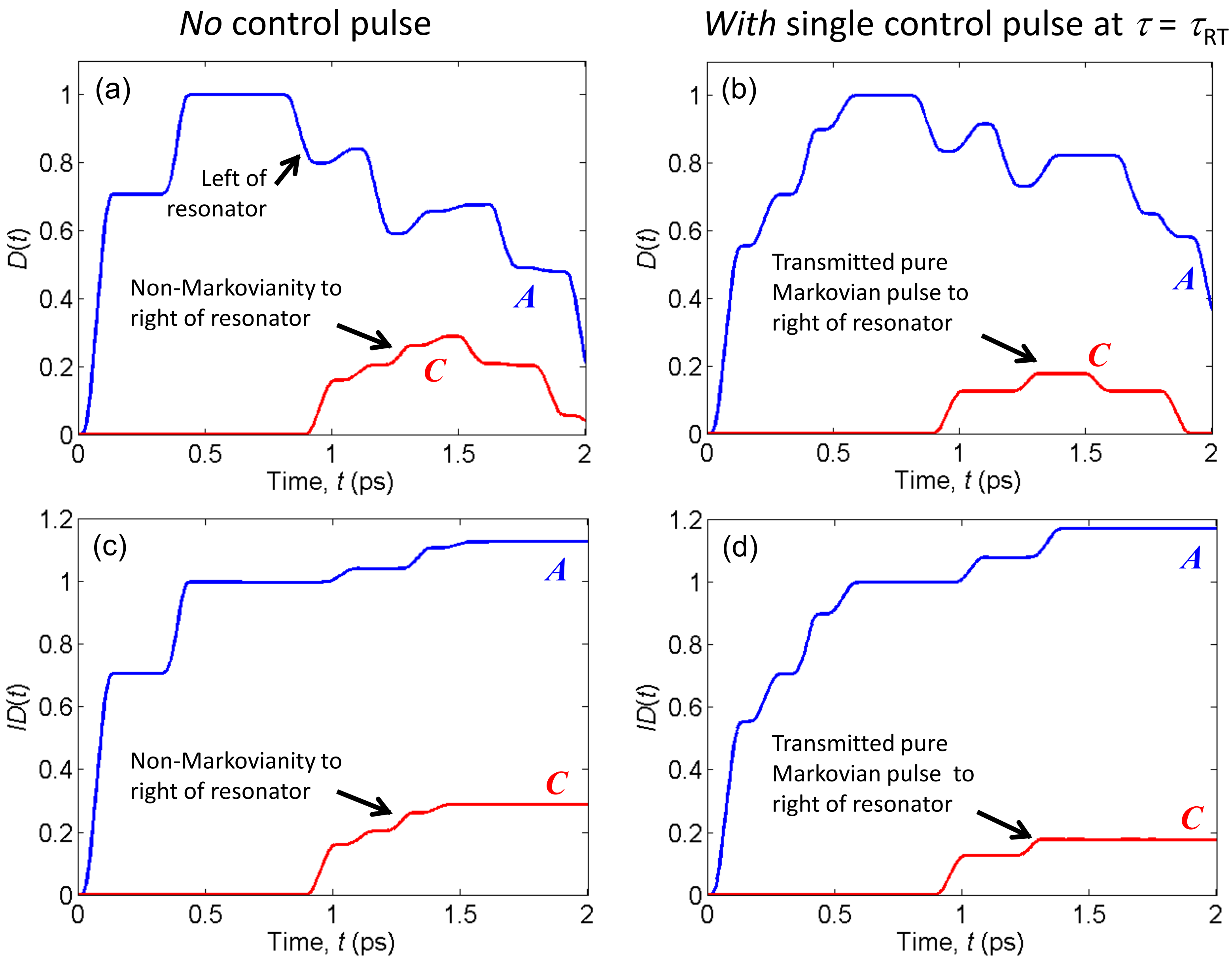
With single control pulse at $\tau = \tau_{RT}$





τ_0 =5fs
τ_{RT}=150fs
τ_Q =153fs
τ_M =225fs

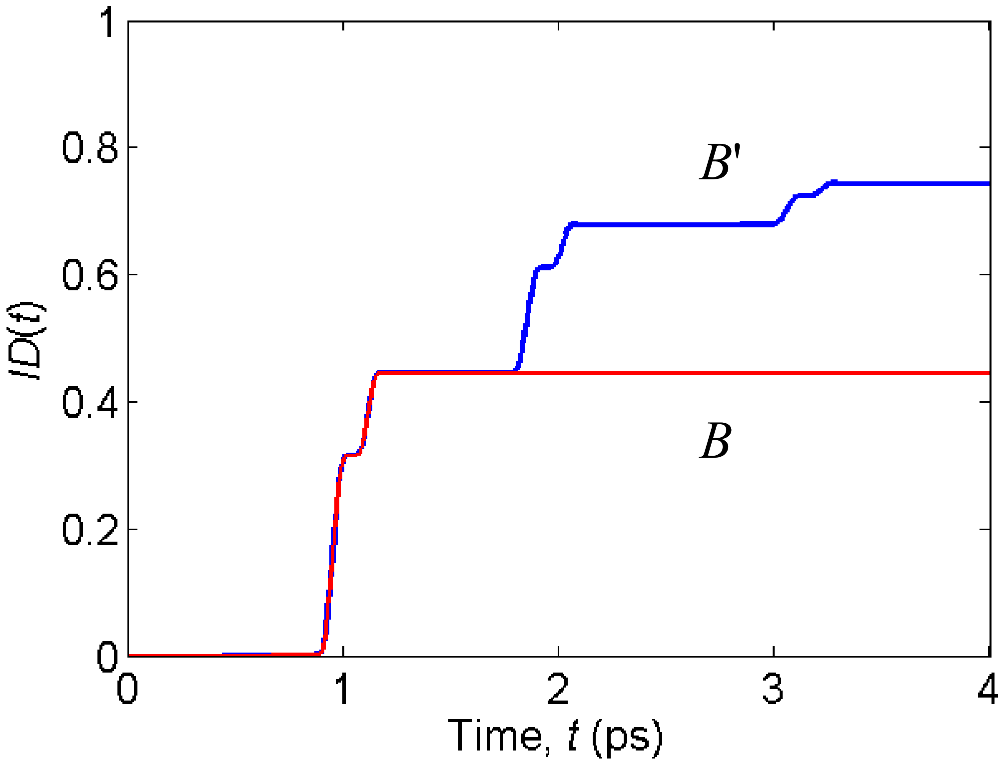
Integrated non-Markovianity, $DI(t)=\Sigma_i(\Delta D(t_i)|_{\text{positive}})$



τ_0 =5fs
τ_{RT}=150fs
τ_Q =153fs
τ_M =150fs

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

No control pulse
Cavity length L=120 x λ_0
Sub-space B' is left-side half-cavity of length $L/2$



τ_0 =5fs
τ_{RT}=150fs
τ_Q =153fs
τ_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, τ_{RT}, required to build-up steady-state behavior
  - Steady-state behavior evolves exponentially during characteristic resonator time, τ_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, τ_{RT}
  - Can control *exact* number of identical transmitted and reflected pulses at multiples of round-trip time, τ_{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:

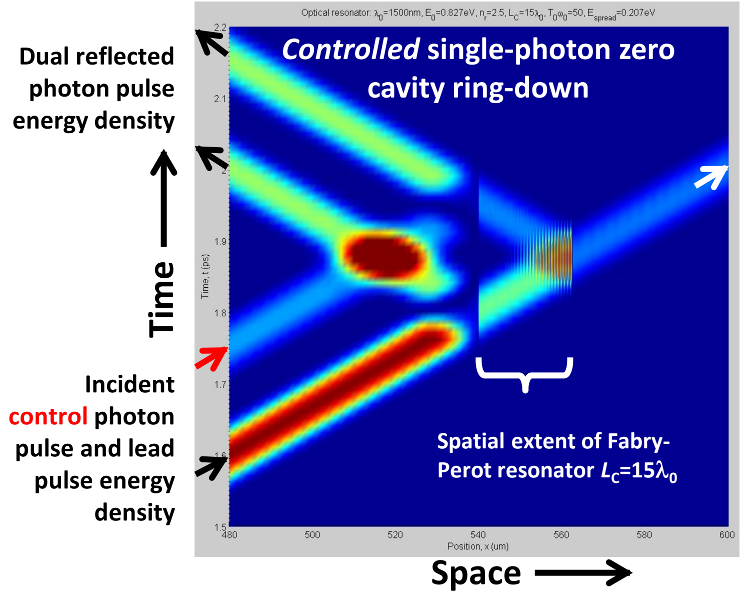
- **Demonstrate coherent quantum control of single-photon dynamics in an optical storage device**
- **Apply techniques developed to demonstrate control of non-Markovianity**

APPROACH

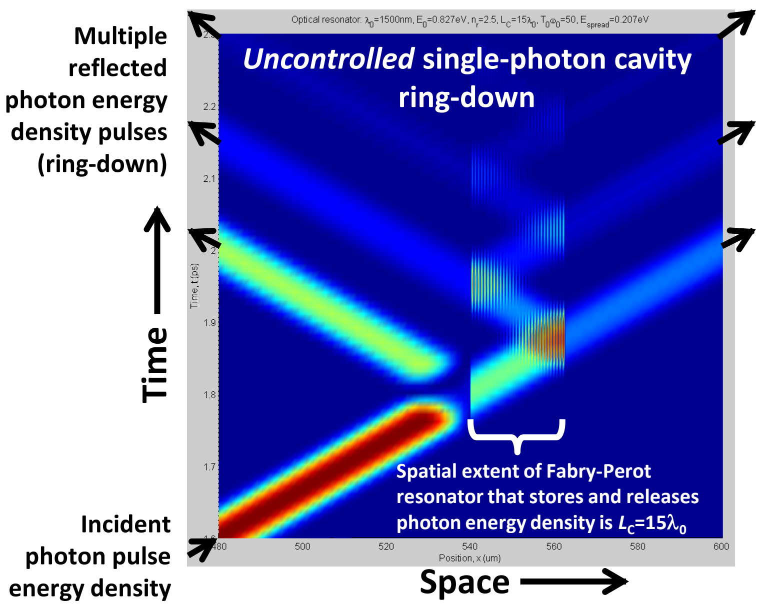
➢ **Use photon pulse injected into Fabry-Perot resonator as model system coupled to continuum and simulate in space-time domain**

➢ **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)**



τ_0 = 5 fs
τ_p = 80 fs
τ_{RT} = 150 fs
τ_Q = 153 fs

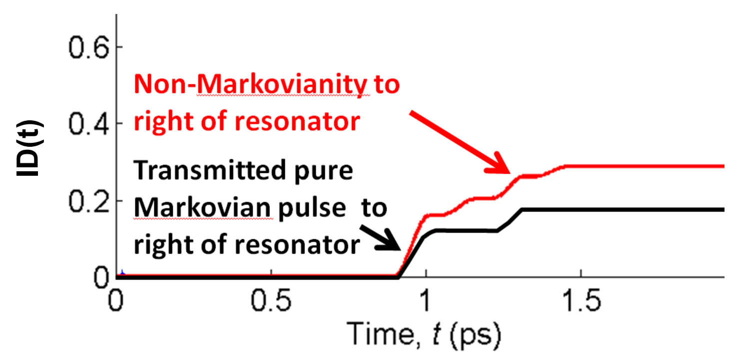


τ_0 = 5 fs
τ_p = 80 fs
τ_{RT} = 150 fs
τ_Q = 153 fs

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:

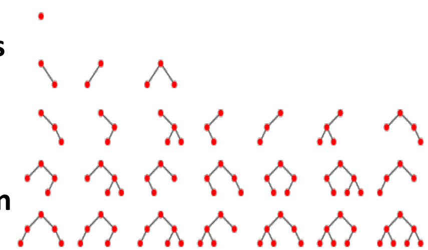
- **Demonstrate coherent quantum control of single-photon dynamics may be applied to boolean logic and perform exhaustive search in minimal linear device design sub-space for all feasible logic operations**

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

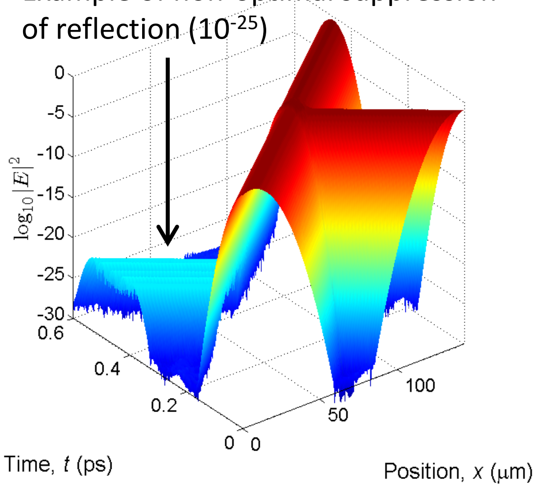
- **High-level simulator checks if feasible solution exists (to depth *k* in tree-structure) for a designated boolean function**
- **If no feasible solution is found by the high-level simulator, then that logic function cannot be implemented using only linear components connected in a tree-structure**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

Example of non-optimal suppression of reflection (10^{-25})



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

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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)