Suppressing Polarization Mode Dispersion with the Quantum Zeno Effect

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Introduction

The Quantum Zeno Effect

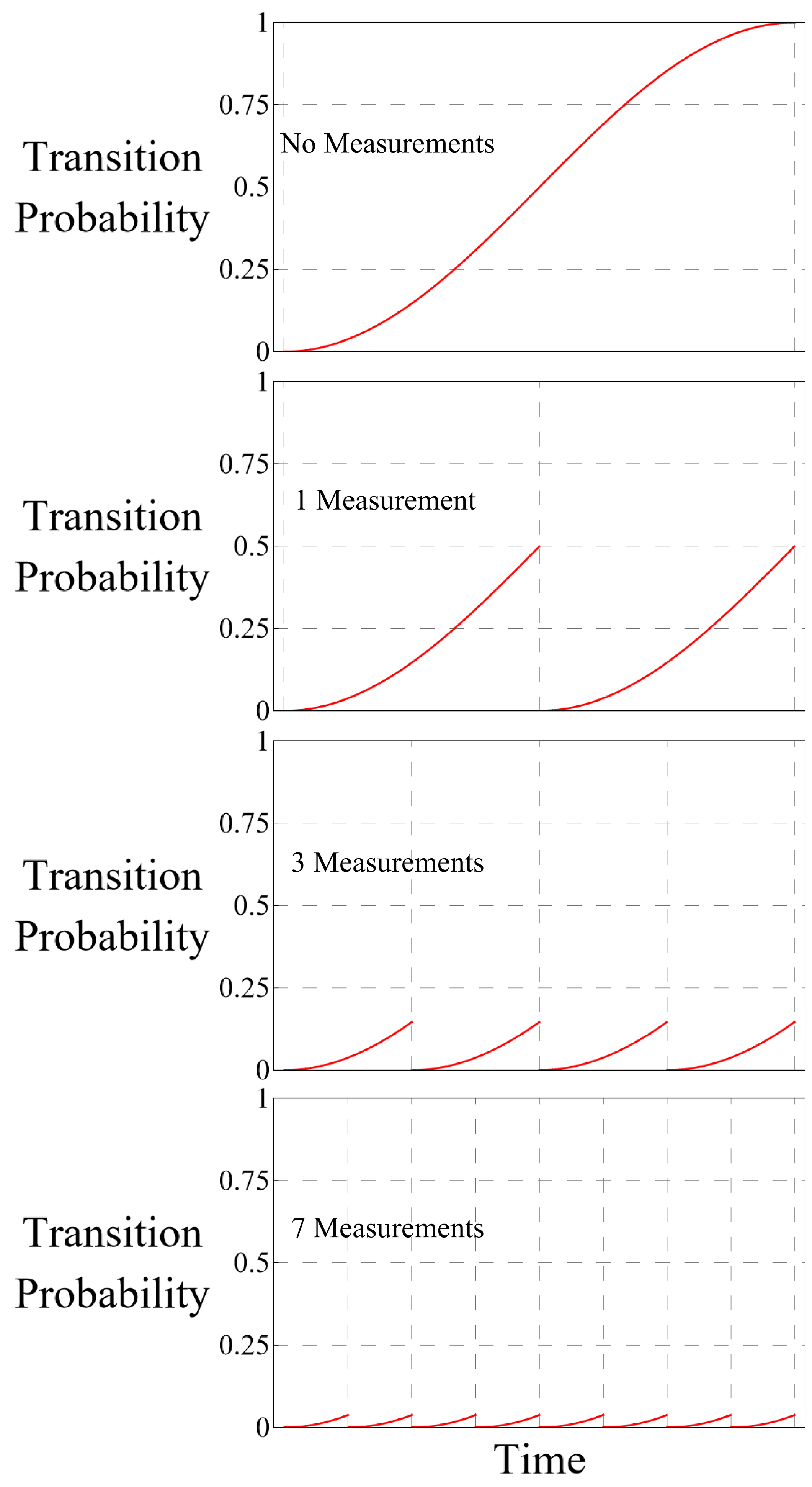
- Frequent measurements on a quantum system will suppress its evolution [1].
  - Essentially an applied wave-function collapse.
- Greater frequency of measurements means lower overall probability to transition.
  - (See figures at the right.)
- While it restricts transitions, it does not necessarily block them all.
  - Can be tailored to permit certain otherwise impossible transformations [2-4].
- A "measurement" in a practical sense is any interaction with another (usually quantum) system.

Polarization Mode Dispersion (PMD)

- Optical fiber tend to have variations in core shape.
  - Refractive index is dependent on polarization (vertical "V" and horizontal "H", etc.), and consequently the propagation constant:

$$k_H(\omega) \approx k_{0,H} + \alpha_H(\omega-\omega_0) + \beta_H(\omega-\omega_0)^2$$
$$k_V(\omega) \approx k_{0,V} + \underbrace{\alpha_V(\omega-\omega_0)}_{\text{Group Velocity}} + \underbrace{\beta_V(\omega-\omega_0)^2}_{\text{Dispersion}} \quad (1)$$

  - Causes polarization to change over time [5]



Theory

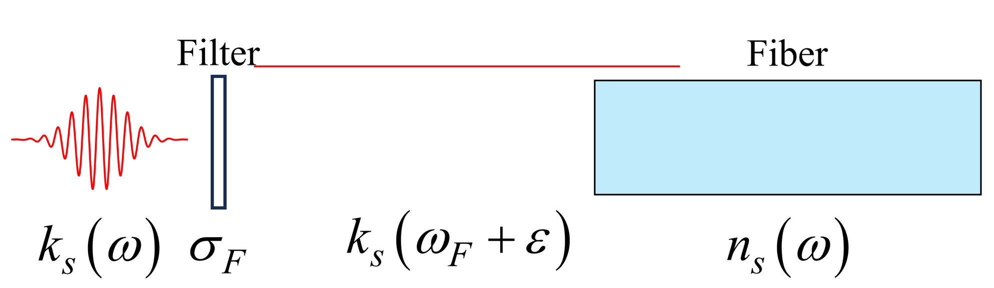
- The electric-field operator (s is polarization):

$$\hat{E}_i^+(z_i,t_i) = i\sum_{\omega_i,s}\sqrt{\frac{2\pi\hbar\omega_i}{V}}e^{i(k_i z_i-\omega_i t_i)}\hat{a}_{k_i,s}\hat{e}_s \quad (2)$$

- General single-photon state at $t = 0$:

$$|\psi(0)\rangle = c_N\int d\omega\, g(\omega)\hat{a}^\dagger_{k,s}|0\rangle \quad (3)$$

- Assume the photon has a narrow bandwidth, as if it passed through a filter (see figure)



- Assume right circular polarization:

$$|R\rangle = \tfrac{1}{\sqrt{2}}(\hat{e}_H - i\hat{e}_V) = \tfrac{1}{\sqrt{2}}(|H\rangle - i|V\rangle) \quad (4)$$

- Applying E-field to single-photon state:

$$\hat{E}_i|\psi\rangle = \tfrac{c_N}{\sqrt{2}}\int d\omega\begin{bmatrix} e^{-(\omega-\omega_F)^2/2\sigma_F^2}e^{-i\omega t} \\ \times\left(e^{ik_H x}|H\rangle - ie^{ik_V x}|V\rangle\right)\end{bmatrix} \quad (5)$$

- Evaluating the integral:

$$|\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\left(e^{-i\phi_H t}|H\rangle - ie^{-i\phi_V t}|V\rangle\right)$$
$$|\psi(0)\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle - i|V\rangle\right) = |R\rangle \quad (6)$$

- The phase factors are:

$$\phi_s = \frac{\sigma_F^2 n_s}{2\pi\beta_s c}\left(\alpha_s\frac{c}{n_s} - 1\right)^2 \quad (7)$$

- The time-evolution operator:

$$\hat{U}(t) = e^{i\hat{\Phi}/\hbar\, t} = \begin{bmatrix} e^{-i\phi_H t} & 0 \\ 0 & e^{-i\phi_V t}\end{bmatrix} \quad (8)$$

- Project onto $|R\rangle$ infinite times over finite time period T gives effective time-evolution [1]:

$$\hat{V}(T) = e^{i(\phi_H+\phi_V)T}|R\rangle\langle R| \quad (9)$$

- And the time-evolved state:

$$|\psi(T)\rangle = \hat{V}(T)|\psi(0)\rangle = e^{i(\phi_H+\phi_V)T}|R\rangle \quad (10)$$

Simulation

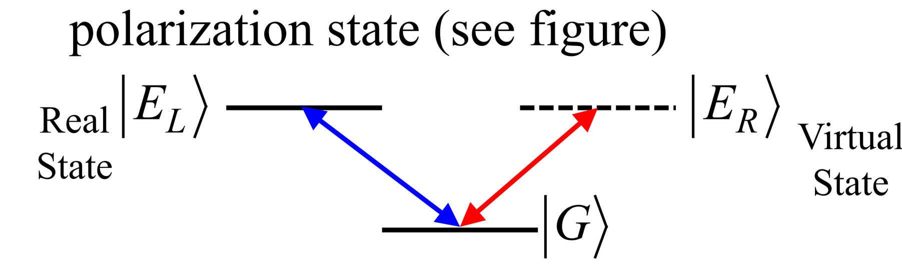
- Simulation performed in Mathematica.
- Solved the Schrödinger Equation numerically:

$$i\hbar\frac{d}{dt}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle \quad (11)$$

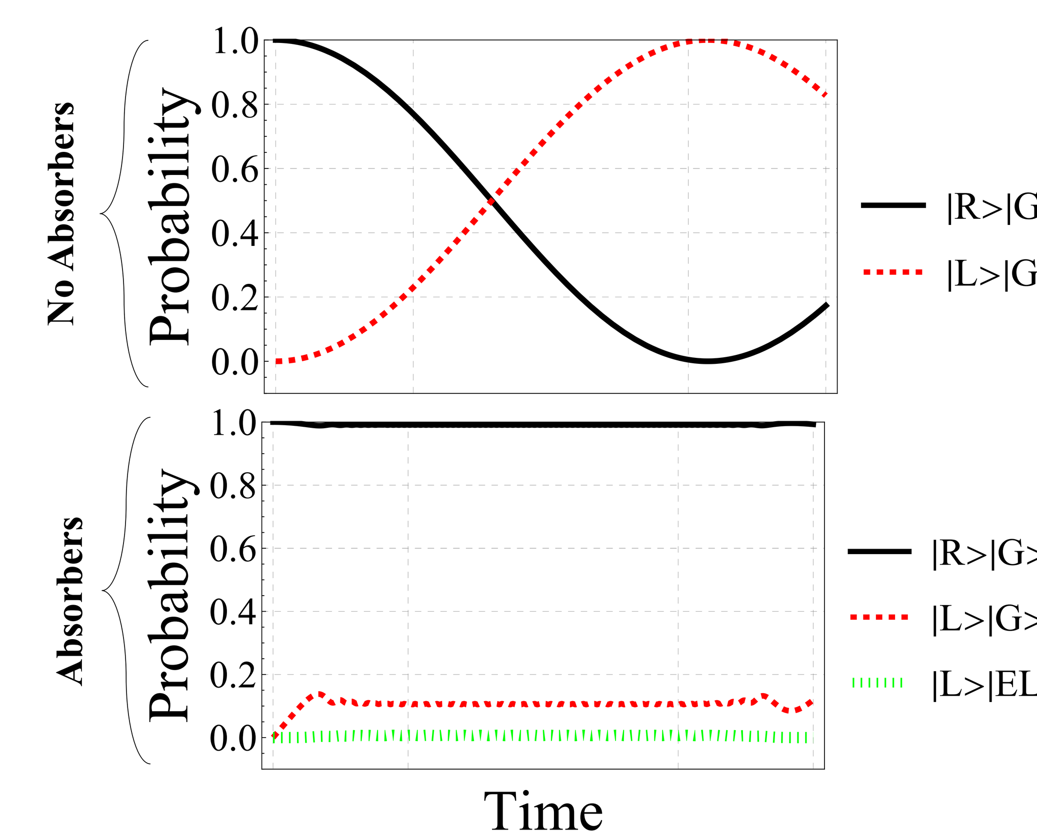
- In this system:

$$\hat{H} = \hbar\omega\left(\hat{a}_R^\dagger\hat{a}_R + \hat{a}_L^\dagger\hat{a}_L + 1\right) + \frac{1}{2}\hbar\omega\hat{\sigma}_z + \hbar\hat{\Phi} + \hbar\lambda\left(\hat{a}_L^\dagger\hat{\sigma}_- + \hat{a}_L\hat{\sigma}_+\right) \quad (12)$$

- The final term represents two-level atoms which are resonant with left-photons
  - Destroys left-photons, projecting onto right-polarization state (see figure)



- Evolution with/without absorbers shown below:



Conclusions

- The quantum Zeno effect offers a novel strategy for suppressing the effects of PMD
- Produces a quantum phase shift, sum of the shifts of two orthogonal polarization states
- Consideration: As described, the atoms present in the fiber will not allow the opposing polarization to travel.

References

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