Improved entanglement sources through incoherent nonlinear optics

POLYTECHNIQUE MONTRÉAL
LE GÉNIE EN PREMIÈRE CLASSE

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CAP Congress

Objectives

- Context.
- Nonlinear optics for entanglement sources.
- Benefits of an incoherent pump in fibers.

Context

Photons as qubits

Photons are poor processing qubits, but good passive flying qubits.

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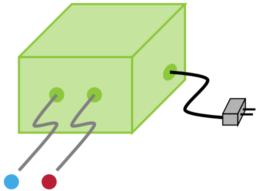
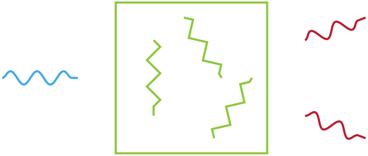


$$\frac{|HH\rangle + |VV\rangle}{\sqrt{2}}$$

Nonlinear optics

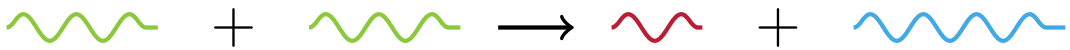
Nonlinear optics



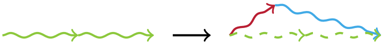
Parametric processes

Conservations

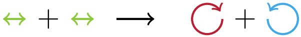
1. Energy :



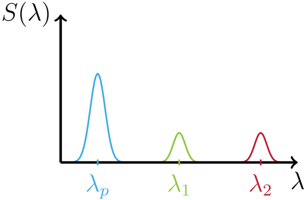
2. Momentum :

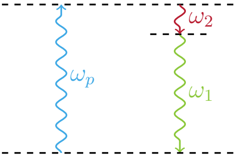


3. Angular momentum (helicity) :

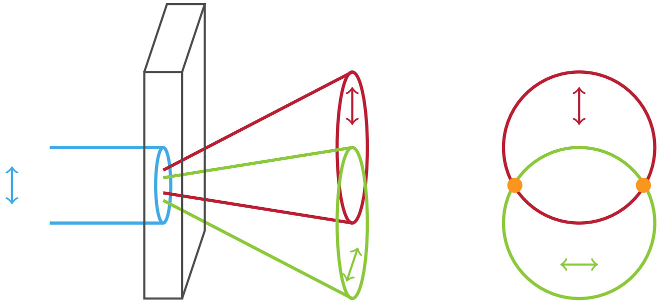


Parametric down conversion





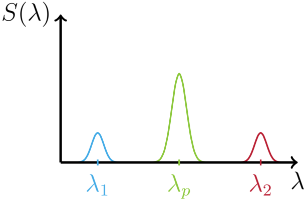
Type II phasematch

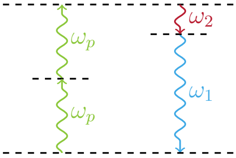


$$\frac{|HV\rangle + |VH\rangle}{\sqrt{2}}$$

Kwiat *et al.*, PRL **75**, 4337 (1995)

Modulation instabilities





Phasematching in fibers

Fibres $\rightarrow$ copropagating modes

Phasematch : $2\,n(\omega_p)\,\omega_p = n(\omega_1)\,\omega_1 + n(\omega_2)\,\omega_2.$

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Fibres → copropagating modes

Phasematch : $2\,n(\omega_p)\,\omega_p = n(\omega_1)\,\omega_1 + n(\omega_2)\,\omega_2.$

Birefringence plays a fundamental role

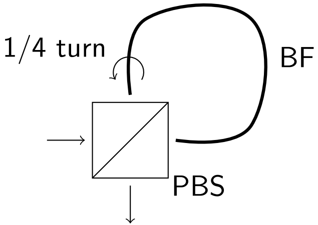
Type C Copolarized photons
HH → HH

Type O Signals orthogonal to pump
HH → VV

Type M Mixed
HV → VH

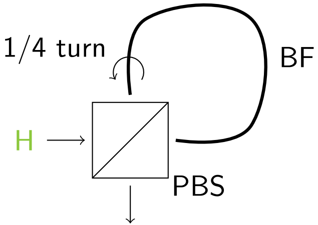
Source of entangled photons
Type O VMI

Type O : HH → VV



Source of entangled photons
Type 0 VMI

Type 0 : HH → VV



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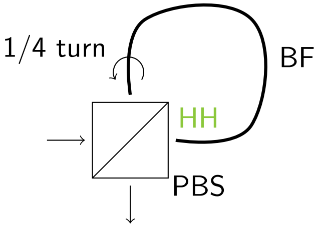

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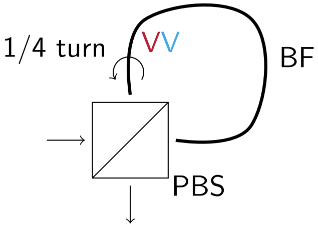

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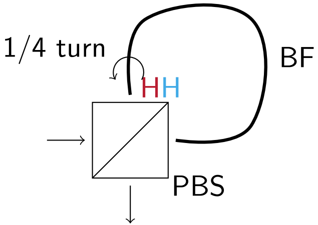

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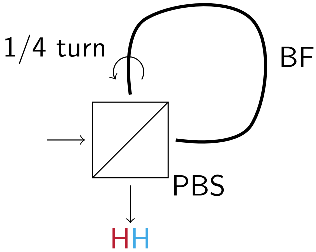

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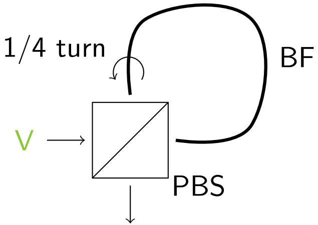

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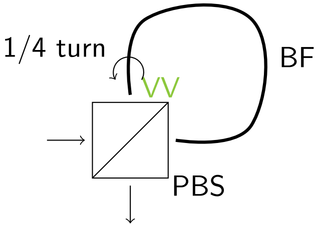

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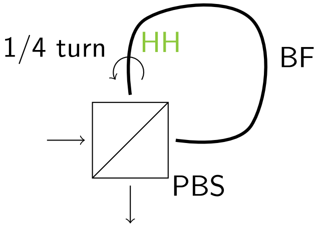

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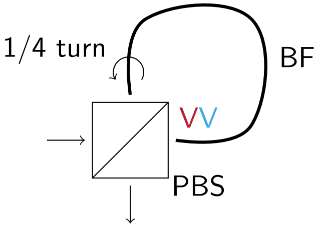

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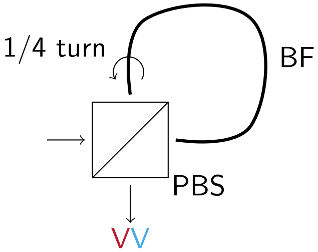

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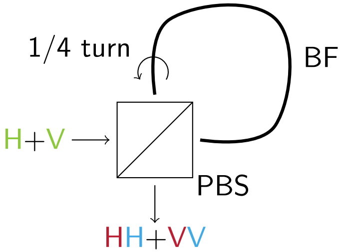

Coherence

Coherence

$$a(t) = \sqrt{P(t)}\, e^{i\varphi(t)}$$

- Coherent case : φ is well defined.
  - Phase relationships between $\{a(t_1), a(t_2), \cdots\}$ are fixed.
- Incoherent case : φ is not well defined.
  - Phase relationships between $\{a(t_1), a(t_2), \cdots\}$ are random.

Density matrix

Basics

Quantum state

- Pure sate : $|\Psi\rangle = \sum_i a_i |\phi_i\rangle$ $\Psi \equiv \{a_1, a_2, \cdots\}$

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- Mixed state : random distribution of $\Psi_\ell \equiv \{a_{\ell,1}, a_{\ell,2}, \cdots\}$

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Pure state (coherent)

$$\rho_{i,j} = a_i \; a_j^*$$

$$\hat{\rho} = \begin{bmatrix} |a_1|^2 & \cdots & a_1 a_i^* & \cdots \\ \vdots & \ddots & \vdots & \vdots \\ a_1^* a_i & \cdots & |a_i|^2 & \vdots \\ \vdots & \cdots & \cdots & \ddots \end{bmatrix}$$

Quantum state

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Mixed state (incoherent)

$$\rho_{i,j} = \left\langle a_{\ell,i} \; a_{\ell,j}^* \right\rangle_\ell$$

$$\hat{\rho} = \begin{bmatrix} |a_1|^2 & \cdots & 0 & \cdots \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & |a_i|^2 & \vdots \\ \vdots & \cdots & \cdots & \ddots \end{bmatrix}$$

Density matrix
Continuous indices

Coherent state

$$\rho(t_1, t_2) \equiv a(t_1)\, a^*(-t_2)$$

Density matrix
Continuous indices

Coherent state

$$\rho(t_1, t_2) \equiv a(t_1)\ a^*(-t_2)$$

Incoherent state

$$\rho(t_1, t_2) \equiv \langle a(t_1)\ a^*(-t_2)\rangle$$

Density matrix

Continuous indices

Coherent state

$$\rho(t_1, t_2) \equiv a(t_1)\; a^*(-t_2)$$

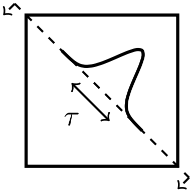
Incoherent state

$$\rho(t_1, t_2) \propto$$

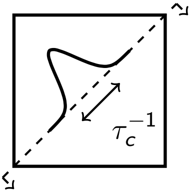
$$P\left(\frac{t_1 - t_2}{2}\right)\; S\left(t_1 + t_2\right)$$

Density matrix
Properties

$$P(t) = \rho(t, -t)$$



$$\mathcal{S}(\omega) = \rho(\omega, \omega)$$



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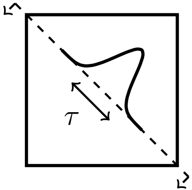

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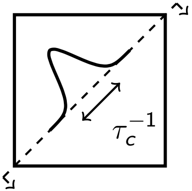

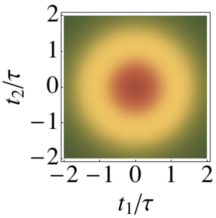

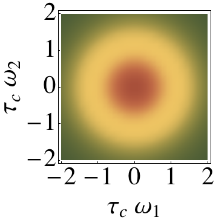

Density matrix
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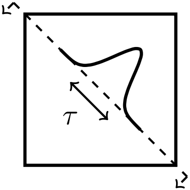

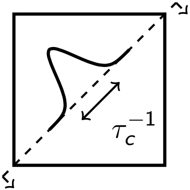

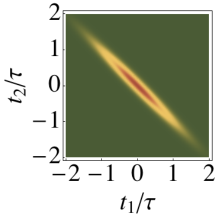

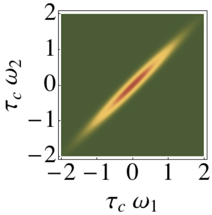

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Split-step Fourier method

Split-step Fourier method

Nonlinear effects in the time domain

$$\frac{\partial a(t)}{\partial z} = i\gamma \left|a(t)\right|^2 \, a(t) \equiv i\gamma P(t) \, a(t)$$

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Nonlinear effects in the time domain

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Dispersion effects in the frequency domain

$$\frac{\partial a(\omega)}{\partial z} = i\beta(\omega)\; a(\omega)$$

Split-step Fourier method

Nonlinear effects in the time domain

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Dispersion effects in the frequency domain

$$\frac{\partial a(\omega)}{\partial z} = i\beta(\omega)\ a(\omega)$$

Split-step Fourier method :

$$\dashrightarrow \boxed{a(t,z)} \longrightarrow \boxed{i\gamma P(t)} \xrightarrow{\text{FT}} \boxed{i\beta(\omega)} \xrightarrow{\text{IFT}} \boxed{a(t, z+\delta z)} \dashrightarrow$$

Generalized split-step Fourier method

Time step

$$\frac{\partial a(t)}{\partial z} = i\gamma P(t)\, a(t)$$

Frequency step

$$\frac{\partial a(\omega)}{\partial z} = i\beta(\omega)\, a(\omega)$$

Generalized split-step Fourier method

Time step

$$\frac{\partial a(t)}{\partial z} = i\gamma P(t)\ a(t)$$

$$\frac{\partial \rho(t_1, t_2)}{\partial z} = i\gamma\ [\rho(t_1, -t_1) - \rho(-t_2, t_2)]\ \rho(t_1, t_2)$$

Frequency step

$$\frac{\partial a(\omega)}{\partial z} = i\beta(\omega)\ a(\omega)$$

$$\frac{\partial \rho(\omega_1, \omega_2)}{\partial z} = i\,[\beta(\omega_1) - \beta^*(\omega_2)]\ \rho(\omega_1, \omega_2)$$

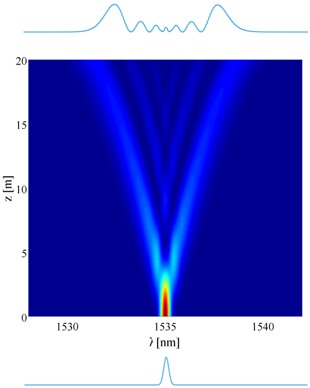
Model

Initial conditions

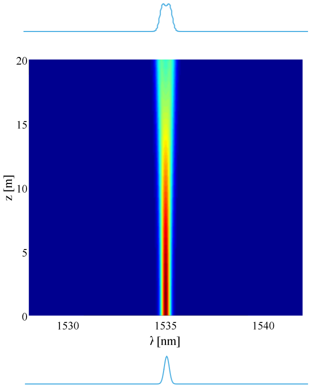
- Same spectral width (defining the coherence time τ_c).
- Same peak power.
- Same fiber properties and propagation length.
- Only difference : pulse length.
  - Coherent case : $\tau = \tau_c$.
  - Incoherent case : $\tau = 10\ \tau_c$.

Propagated spectra

$\tau = \tau_c$



$\tau = 10\ \tau_c$



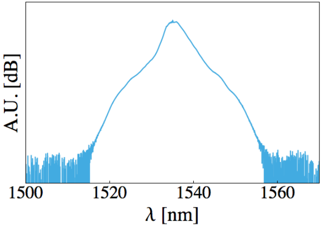
Experimental results

Experimental conditions

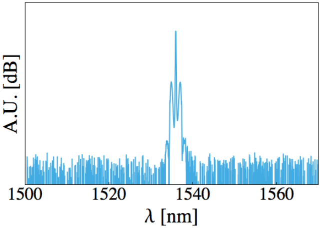
- Same spectral width (filtered at input).
- Same peak power.
- Same fiber properties and propagation length.
- Only difference : pulse length.
  - Coherent case : $\tau \simeq \tau_c$.
  - Incoherent case : $\tau \simeq 250\ \tau_c$.

Experimental data

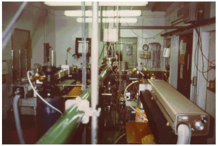
$\tau = 20$ ps



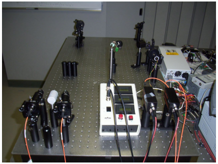
$\tau = 5$ ns



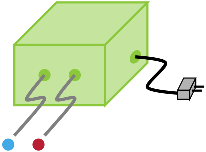
Conclusion



Aspect Lab c. 1982

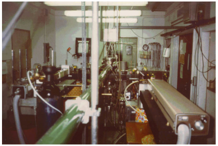


Undergrad Exp. c. 2010



The future

Conclusion



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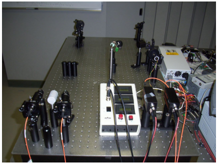

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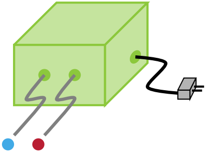

The future

Thank you.

INTRIQ
Fonds de recherche Nature et technologies Québec
CRSNG NSERC

Filtering

A difficult task