Single-photon source heralding efficiency and detection efficiency metrology at 1550 nm using periodically poled lithium niobate

S. Castelletto, I.P. Degiovanni, V. Schettini

Istituto Elettrotecnico Nazionale GALILEO FERRARIS

A. Migdall

Physics Laboratory
Optical Technology Division
NIST National Institute of Standards and Technology

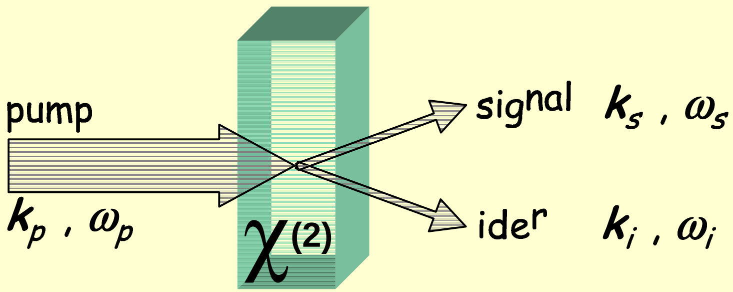
NEWRAD 2005

Introduction

Parametric Down Conversion

→ Quantum Metrology

→ Quantum Information



Phase-matching $\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$

Energy-matching $\omega_p = \omega_s + \omega_i$

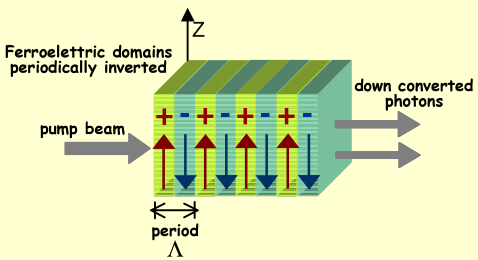
This two-photon light allows one photon to indicate or to *herald* the existence of its twin, the so called *heralded* photon, permitting to create a

SINGLE PHOTON SOURCE

To realize a SINGLE PHOTON SOURCE we consider two key issues:

•EFFICIENT PHOTON PAIR PRODUCTION

Use of **periodically poled** crystals:
Not yet tested for metrology applications



* T tunable QPM
* access to d_{33}

•Advantage of high pump conversion efficiency

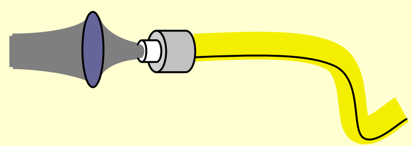
•What about the other characteristics?

• Background fluorescence can limit the uncertainty achievable

•COLLECTION OF THE HERALDED PHOTON IN A SINGLE-MODE FIBER

•understanding and modelling the two-photon process

•detection of one photon of a PDC pair in a well defined **spatial** and **spectral mode**



and for commercial applications the SINGLE PHOTON SOURCE has to be

@ TELECOM wavelengths

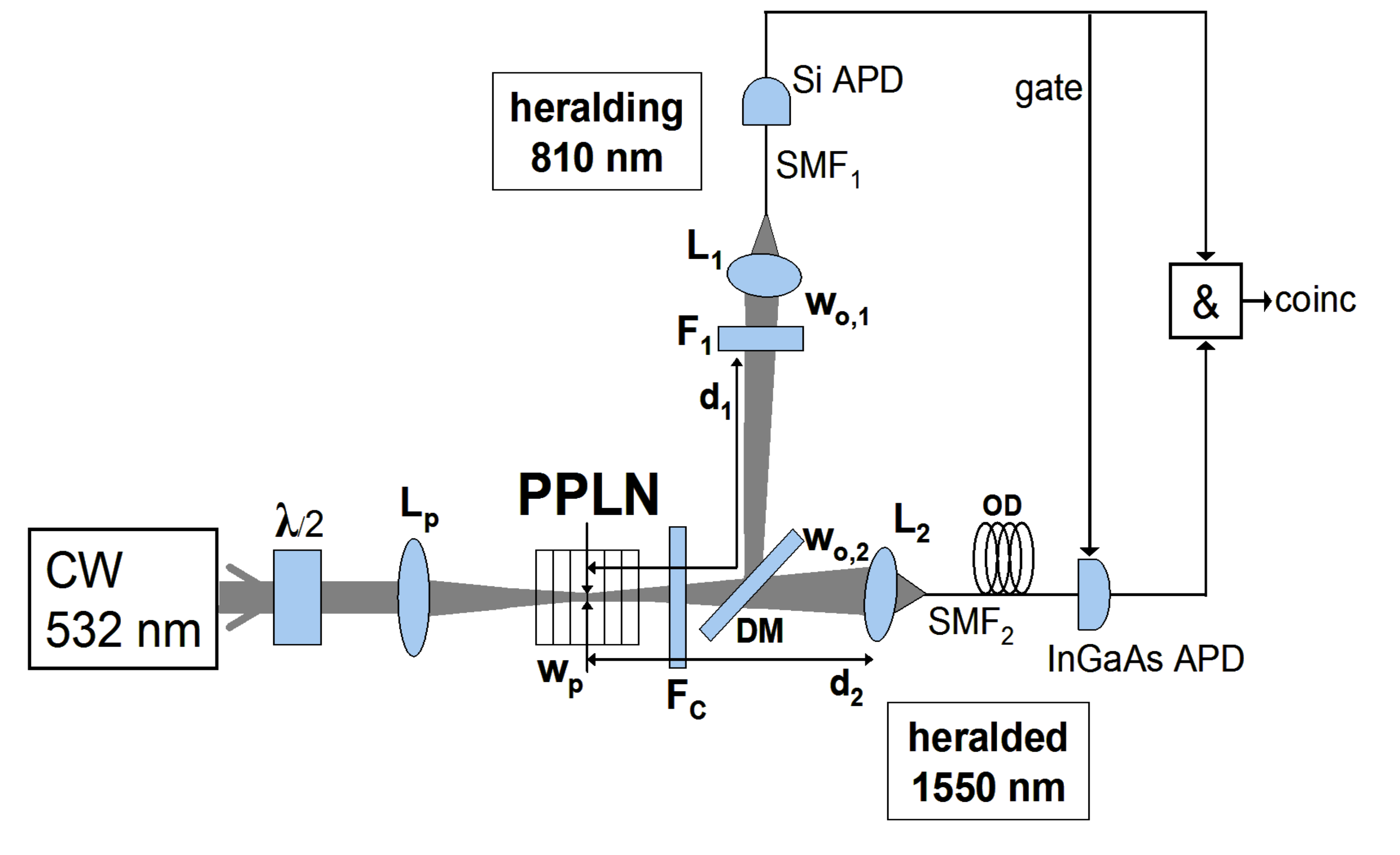
Outline

- description of the implemented PDC source
- description of the used measurement technique
- presentation of theoretical and experimental characterization of the photon collection

. . .

Experimental configuration

setup to herald single photons from CW PDC source from a PPLN crystal operating in a slightly noncollinear geometry

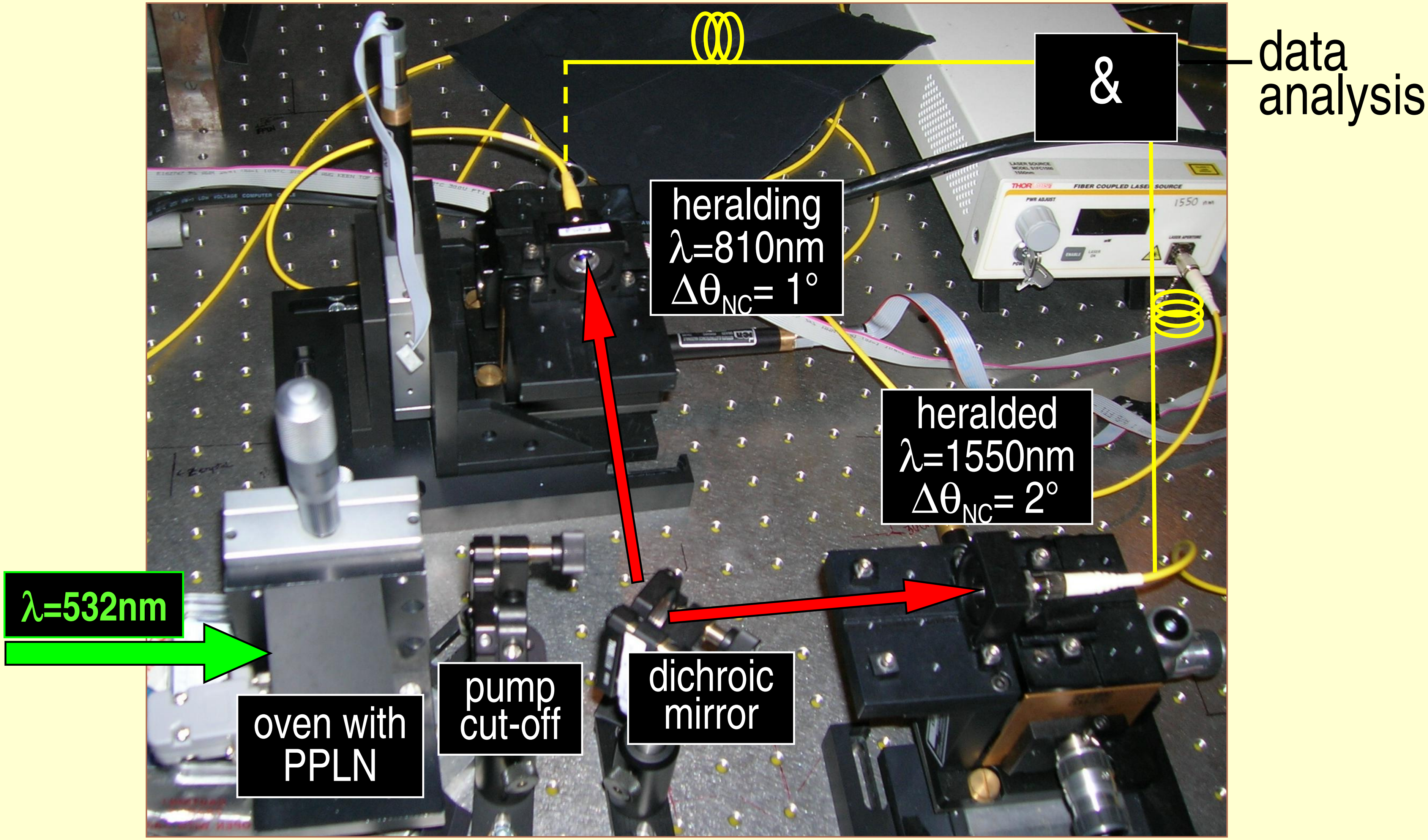


some details:

Laser source: CW Coherent VERDI
Pump Beam Power at crystal = 350mW
L_p with f=1m
w_p =144mm

PPLN (MgO 5%)grating used=7.36μm
T_{OVEN}=131°C
F_1 centered @ 810nm with FWHM=10nm
L_1 and L_2 with f=8mm

Zoom on experimental set-up



Measurement technique

The detector efficiency is given by

$$\eta_{det} = (\chi_P \cdot \tau_{opt} \cdot \tau_{SMF-lens})^{-1} \cdot \chi_D$$

χ_P	single-mode preparation efficiency
τ_{opt}	optical transmittance of PPLN + F_1 + DM
$\tau_{SMF-lens}$	optical transmittance of L_2 + SMF_2

The raw detector efficiency is directly measured according to

$$\chi_D = \frac{P_{coinc} - P_{uncorr}}{(1 - P_{uncorr})(1 - P_{backgnd}^{heralding})}$$

probability per gate of

P_{coinc}	coincidence counts	
P_{uncorr}	uncorrelated or accidental coincidences counts	changing the heralding delay
$P_{backgnd}^{heralding}$	uncorrelated photons and dark counts on the heralding arm	changing the polarization of pump beam

Estimate and uncertainty model

Considering the terms P_{coinc}, P_{uncorr} and $P^{heralding}_{backgnd}$ all indipendent variables, the estimate of the **raw detection efficiency** is

$$\langle \chi_D \rangle = \langle \frac{1}{1 - P^{heralding}_{backgnd}} \rangle \times [1 - \langle \frac{1}{1 - P_{uncorr}} \rangle (1 - \langle P_{coinc} \rangle)]$$

We apply the **maximum likelihood** model estimator to the variables P_{coinc} and P_{uncorr}
The probability of M_C coincidence counts given $M_{heralding}$ heralding counts is

$$P(M_c|M_{heralding}, p) = \frac{M_{heralding}!}{M_c!(M_{heralding} - M_c)!} \times p^{M_c}(1-p)^{M_{heralding} - M_c}$$

where **p** is the parameter to estimate

maximum likelihood functions:

P_{coinc} ⇒ $$L(M_c, M_{heralding}|p) = P(M_c|M_{heralding}, p) \times P(M_{heralding})$$

P_{uncorr} ⇒ $$L(M_{uncorr}, M^{delayed}_{heralding}|p') = P(M_{uncorr}|M^{delayed}_{heralding}, p) \times P(M^{delayed}_{heralding})$$

$$p = (p' - 1)/p'$$

$P^{heralding}_{backgnd}$ ⇒ $$\langle P^{heralding}_{backgnd} \rangle \approx \langle M_{backgnd} \rangle / \langle M_{heralding} \rangle$$

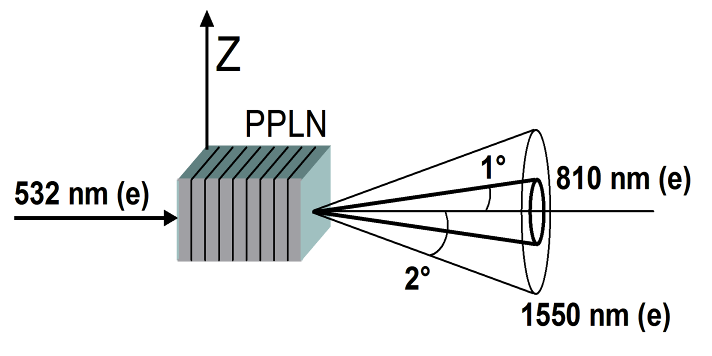
Finally we estimate:

$$\langle \chi_D \rangle = \frac{1}{1 - \frac{\langle M_{backgnd} \rangle}{\langle M_{heralding} \rangle}} \times \left[\left(1 - \left\langle \frac{M^{delayed}_{heralding}}{M^{delayed}_{heralding} - M_{uncorr}} \right\rangle \right) \left(1 - \left\langle \frac{M_{coinc}}{M_{heralding}} \right\rangle \right) \right]$$

uncertainty given by the gaussian uncertainty propagation for each variable indipendent

N E W R A D 2 0 0 5

Spectral bandwidths



PDC phase matching function

$$\Phi(\omega_s, \theta_i, \theta_s) = \exp\left(-\frac{w_p^2(\Delta k_x^2 + \Delta k_y^2)}{4}\right) \times \left(\frac{\sin \Delta k_z L}{\Delta k_z L}\right)^2$$

in the case of PPLN

$$\Delta k_z = \frac{n(\omega_p)\omega_p}{c} - \frac{n(\omega_s)\omega_s}{c}\cos\theta_s - \frac{n(\omega_i)\omega_i}{c}\cos\theta_i - \frac{2\pi}{\Lambda}$$

$$\Delta k_{x,y} = \frac{n(\omega_s)\omega_s}{c}\sin\theta_s + \frac{n(\omega_i)\omega_i}{c}\sin\theta_i$$

POLING PERIOD (Λ)

$$\chi_P = \frac{4\; w_p^2 w_{o,1}^2 w_{o,2}^2 (w_{o,1}^2 + w_p^2)}{(w_{o,2}^2 w_p^2 + w_{o,1}^2\;(w_{o,2}^2 + w_p^2))^2} \times \frac{\Delta_2}{(\Delta_1^2 + \Delta_2^2)^{\frac{1}{2}}} \frac{f(c_1, c_2)}{f(s_1, s_2)}$$

$\Delta_{1,2}$ are the FWHM spectral distribution selected geometrically by the SMFs

Inserting a **monochromator** on the heralding channel we directly measured the bandwidth: we spectrally scanned the **heralding single counts** at three different values of $\mathbf{w_{0,1}}$

Table 1: Measured and estimated Δ_1

d_1 (mm)	$w_{0,1}$ (μm)	Δ_1 measured (nm)	Δ_1 estimated (nm)
270	82	2.05	2.6
400	105	1.87	2.3
520	132	1.64	2.1

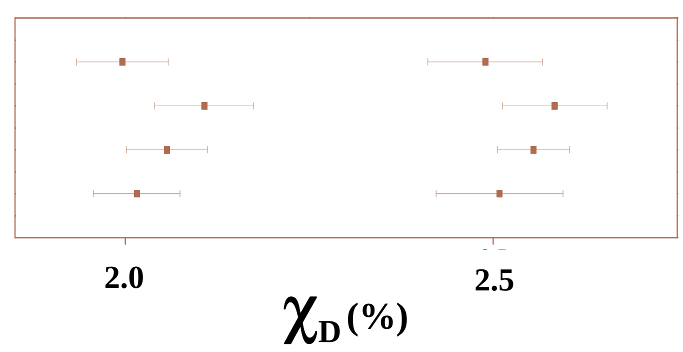
reasons for discrepancy:

- use of Sellmeier's equations for undoped PPLN
- no precise knowledge of the crystal poling length

Experimental results

χ_D measured with $\mathbf{W_{0,1}}$=82μm for 2 different positions of the heralded arm

$w_{o,2}$ =158 μm			$w_{o,2}$ =197 μm		
χ_D (%)	σ_{ML} (%)	σ_{stat} (%)	χ_D (%)	σ_{ML} (%)	σ_{stat} (%)
2.508	0.044	0.040	2.015	0.030	0.028
2.555	0.025	0.019	2.056	0.028	0.035
2.584	0.036	0.031	2.107	0.034	0.028
2.489	0.039	0.037	1.996	0.032	0.026



- For each setup we tested the repeatability applying the alignment procedure over several days
- Repeatability of our measurements is in agreement with the estimated uncertainty at $2\sigma_{ML}$ level

$\tau_{SMF-lens}$=83%

τ_{opt}=65%

⇒

$\chi_p = 48\%, 37\%$

$\chi_p^{teo} = 20\%, 13\%$

The model can only be considered **qualitative**

...? The approximation adopted in our theoretical model for χ_p, sensitive mostly to the measurements of the beam waists and bandwidth estimates, is acceptable for the degenarate case but inaccurate in a non degenerate condition.

Conclusions:

We have shown the feasibility of using **PPLN** for the calibration of single photon detectors operating **@1550 nm** as well as single photon source in a single mode fiber, and we highlight:

- the need of maintaining **low dark counts** in the heralding arm
- the paramount importance to have a proper **spatial** mode matching and **spectral** mode selection

@810 nm

@1550 nm

non degenerate case

WORK IN PROGRESS ON...

@1550 nm

@1550 nm

degenerate case

Brief bibliography

- A. Migdall, S. Castelletto, I. P. Degiovanni, M. L. Rastello, Appl.Opt., **41**, 2915 (2002).
- S. Castelletto, I. P. Degiovanni, M. L. Rastello, J. Opt. Soc. Am. B, **19**, 1247 (2002).
- S. Castelletto, I. P. Degiovanni, V. Schettini, M. Ware, A. Migdall, SPIE proc. **5551**, 60 (2004).
- S. Castelletto, I. P. Degiovanni, V Schettini, A. Migdall, Opt. Exp. **13**, 6709 (2005).

Raw detection efficiency model

The total coincidence probability is

$$P_{coinc} = P_{coinc}^{heralded} + P_{uncorr}$$

$$P_{coinc}^{heralded} = \chi_D \cdot P_{PDC}^{heralding} \cdot p_{T/2}^{0}$$

$$\begin{aligned} P_{uncorr} &= (1-p_T^0)P_{backgnd}^{heralding} + (1-p_{T/2}^0)P_{PDC}^{heralding} \\ &\quad + p_{T/2}^0(1-\chi_D)(1-p_{T/2}^0)P_{PDC}^{heralding} \end{aligned}$$

Where we have considered that $P_{PDC}^{heralding} + P_{backgnd}^{heralding} = 1$

p_T^0 is the probability of the heralded detector of not firing during the time T

and we assume that the events that makes the heralded detector fires
have a **poissonian distribution –uniform in time-**

$$\chi_D = \frac{P_{coinc} - P_{uncorr}}{(1-P_{uncorr})(1-P_{backgnd}^{heralding})}$$