Heralded single photon sources based on intermodal four wave mixing

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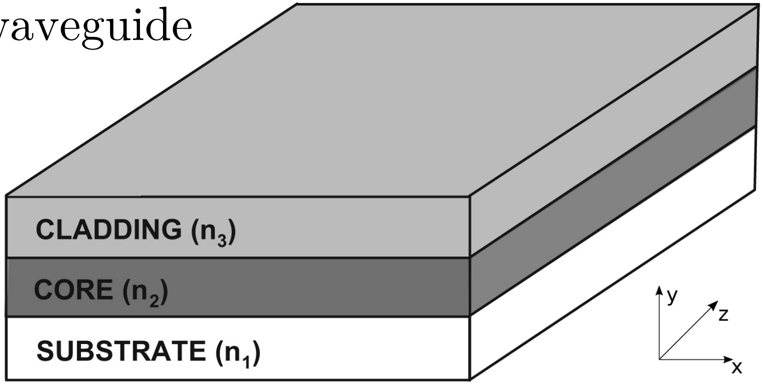
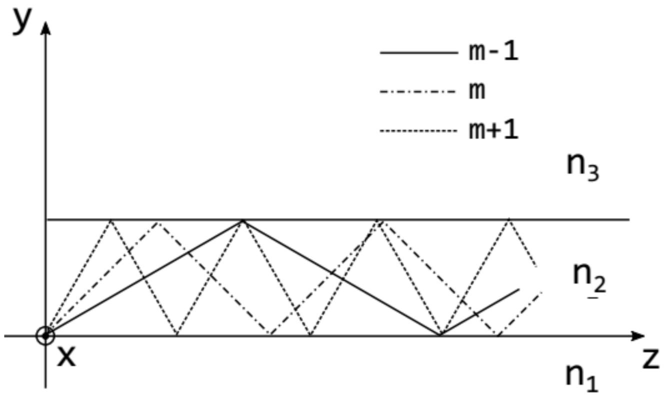
Waveguide modes

Planar waveguide



Source reference [1].



Source reference [2].

1) $\mathbf{E}_m(\mathbf{r},t) = \mathscr{E}_m(x,y)\exp(i\beta_m z - i\omega t)$

2) $\mathbf{H}_m(\mathbf{r},t) = \mathscr{H}_m(x,y)\exp(i\beta_m z - i\omega t)$

- $\beta_m = \frac{\omega}{v} = \frac{\omega}{c} n_m^{\mathrm{eff}}$
- $\beta_m(\omega) = \sum_k \frac{1}{k!}\beta_m^{(k)}(\omega-\omega_0)^k$

Nonlinear optical processes

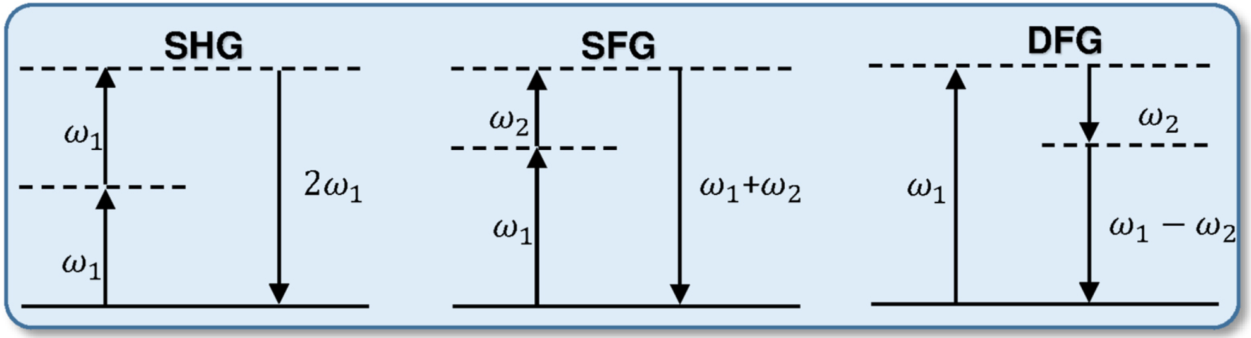
For linear media:

$$\mathbf{P} = \varepsilon_0 \chi^{(1)} \mathbf{E}$$

Nonlinear media contribution:

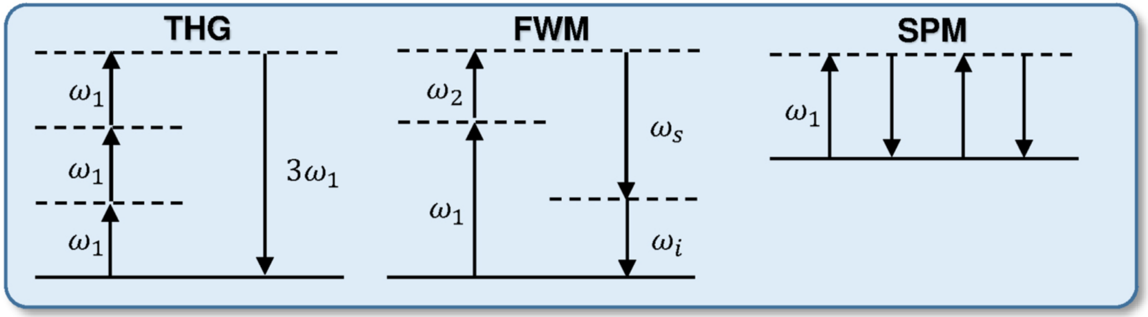
$$\mathbf{P}_{NL} = \mathbf{P}^{(2)} + \mathbf{P}^{(3)} + \cdots = \varepsilon_0 \left[\chi^{(2)} : \mathbf{EE} + \chi^{(3)} \vdots \, \mathbf{EEE} + \cdots \right]$$

Schematization of some second order nonlinear processes:



Source reference [3].

Some third order nonlinear processes:



Source reference [3].

- Energy conservation:

$$\hbar\omega_{p1} + \hbar\omega_{p2} = \hbar\omega_s + \hbar\omega_i$$

- Phase matching condition:

$$k_{p1} + k_{p2} = k_s + k_i$$

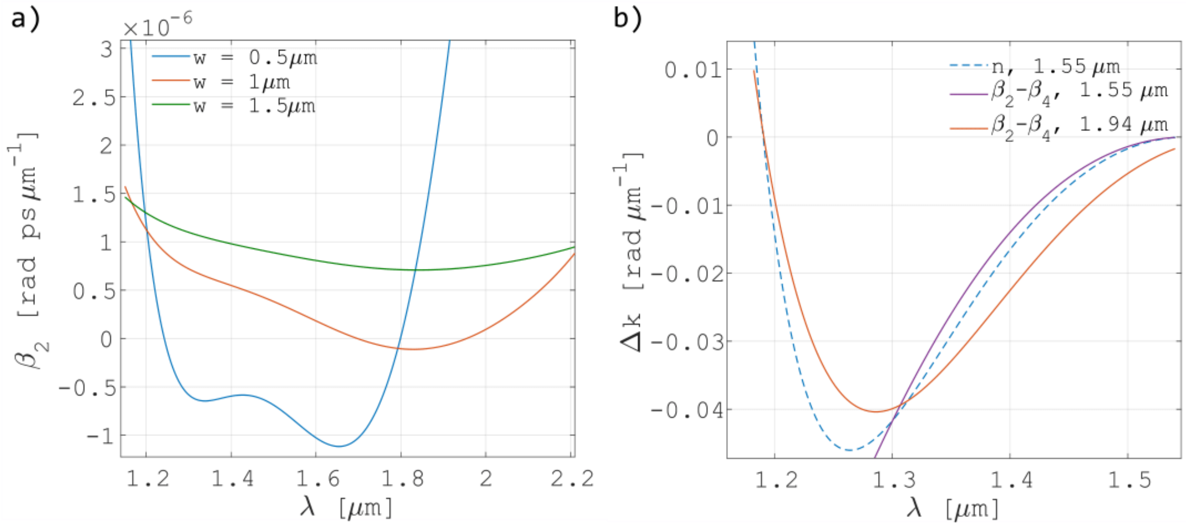
The most common third order process:

Nonlinear optical processes

Phase mismatch:

$$\Delta k = k_{p1} + k_{p2} - k_s - k_i \xrightarrow{\text{for DFWM}} \Delta\beta = 2\beta(\omega_p) - \beta(\omega_s) - \beta(\omega_i)$$

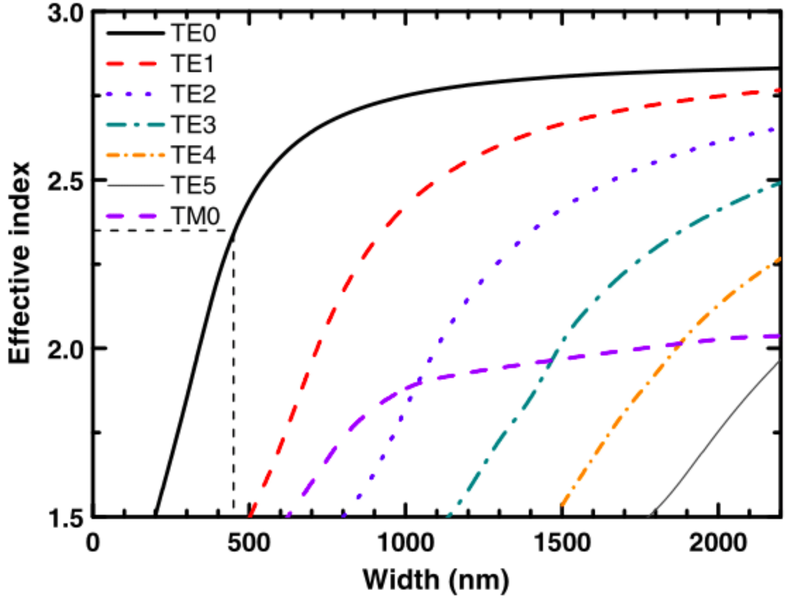
$$\Delta\beta = -\beta_2(\omega_p)\Delta\omega^2 - \frac{1}{12}\beta_4(\omega_p)\Delta\omega^4 - \dots$$



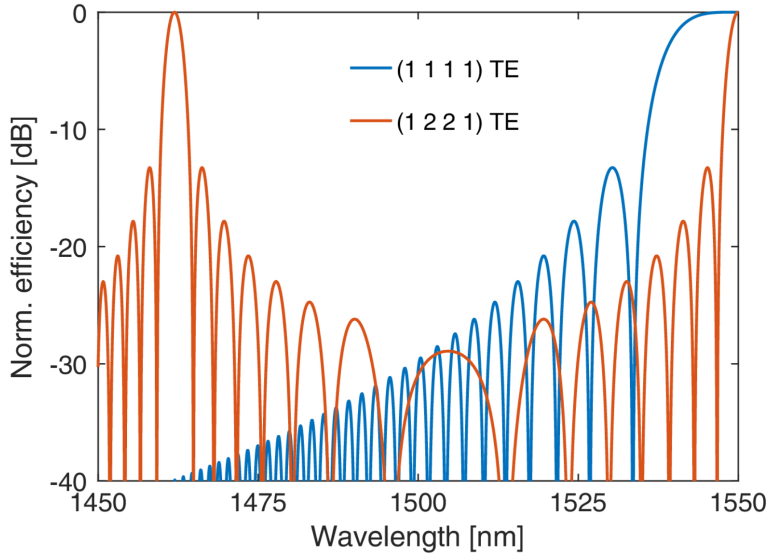
Source reference [2].

Intermodal four wave mixing

$$\Delta k = \frac{\omega_p}{c} n_{\text{eff}}^{p_1}(\omega_p) + \frac{\omega_p}{c} n_{\text{eff}}^{p_2}(\omega_p) - \frac{\omega_s}{c} n_{\text{eff}}^{s}(\omega_s) - \frac{\omega_i}{c} n_{\text{eff}}^{i}(\omega_i)$$



Source reference [4].



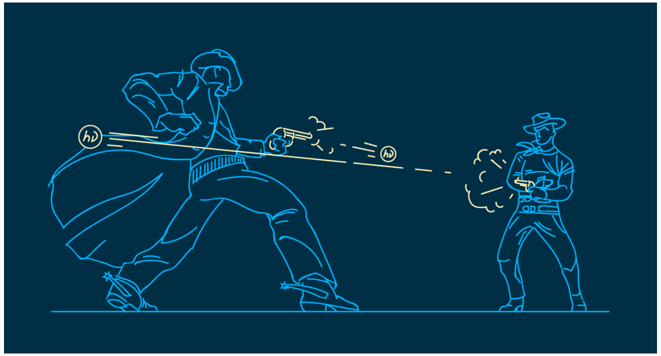
Source reference [5].

Single photon sources

Ideal single photon source

- 100% single emission probability
- 0% multi-photon emission
- Indistinguishable subsequently emitted photons

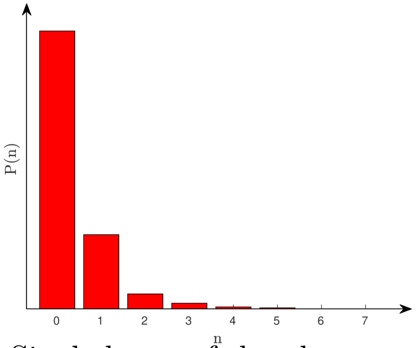
The ideal photon gun



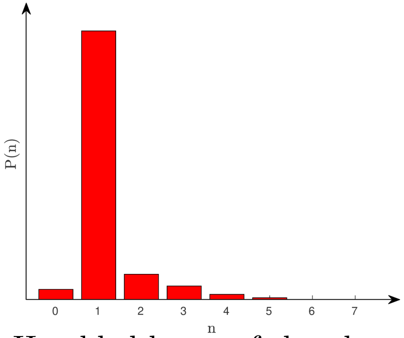
➔ Deterministic sources (on-demand emission)

➔ Probabilistic sources (heralded)

- Photon number distribution: $P(n)$ is the probability to detect n photons in the output beam



Single beam of the photon pair source



Heralded beam of the photon pair source

Heralded single photon sources

- Second order coherence $g^{(2)}(\Delta t)$: spatial and temporal correlation function between emitted photons

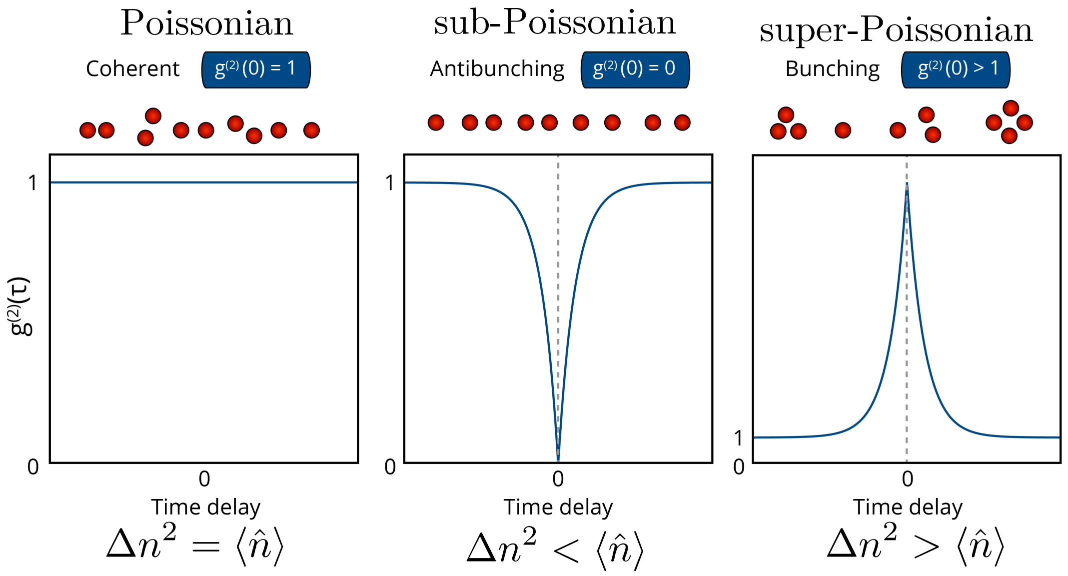
→ $$g^{(2)}(0) = \frac{\langle \hat{n}(\hat{n}-1)\rangle}{\langle \hat{n}\rangle^2} = \frac{\langle \hat{n}^2\rangle - \langle \hat{n}\rangle}{\langle \hat{n}\rangle^2}$$

for $n = 1$ → $g^{(2)}(0) = 0$

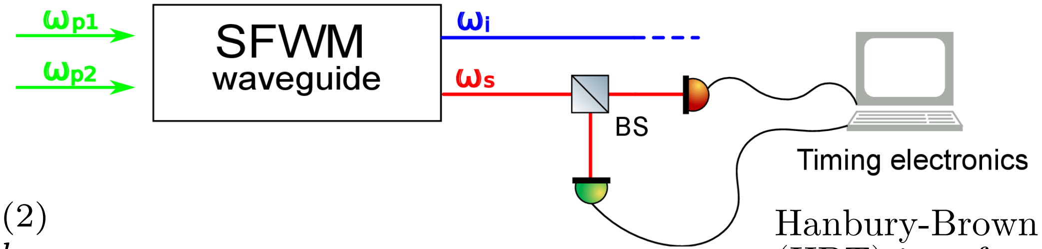
for $n = 2$ → $g^{(2)}(0) = 0.5$

→ $$g^{(2)}(0) = 1 + \frac{\Delta n^2 - \langle \hat{n}\rangle}{\langle \hat{n}\rangle^2}$$

with $\Delta n^2 = \langle \hat{n}^2\rangle - \langle \hat{n}\rangle^2$

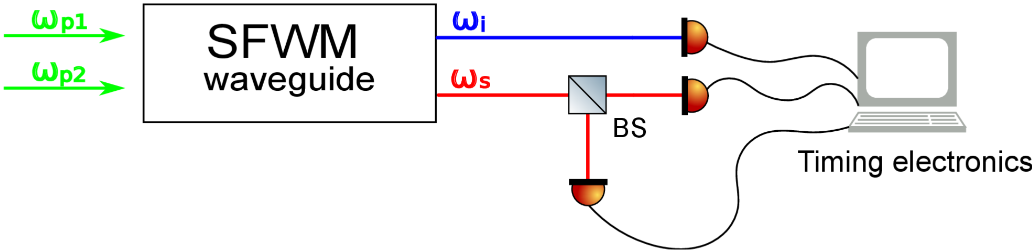


- Purity: measurement of the single mode emission character $\implies P = g^{(2)}(0) - 1$



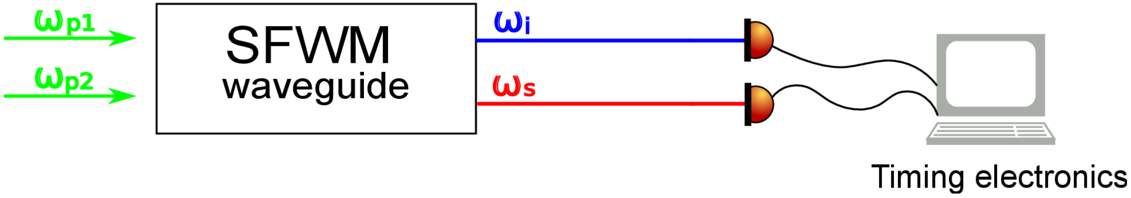
Hanbury-Brown and Twiss (HBT) interferometer

- Antibunching Dip - heralded $g_h^{(2)}$



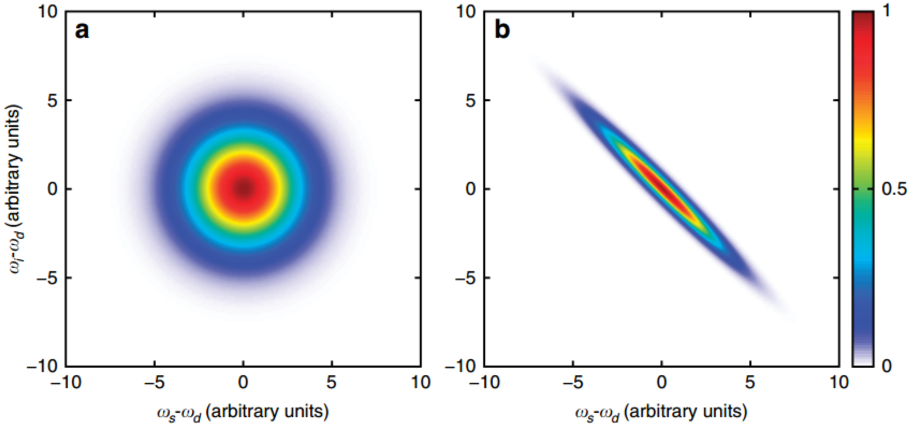
- Coincidence to accidental ratio

$$CAR = \frac{R_{si} - R_{acc}}{R_{acc}}$$



Other parameters

- Joint spectral intensity (JSI): correlations between signal and idler photons



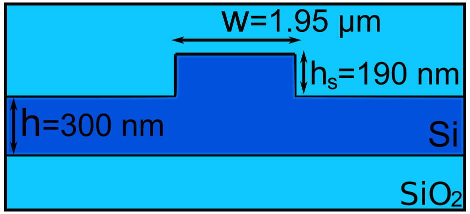
Source reference [6].

- Heralding efficiency: probability to detect the heralded photon, given the detection of the herald

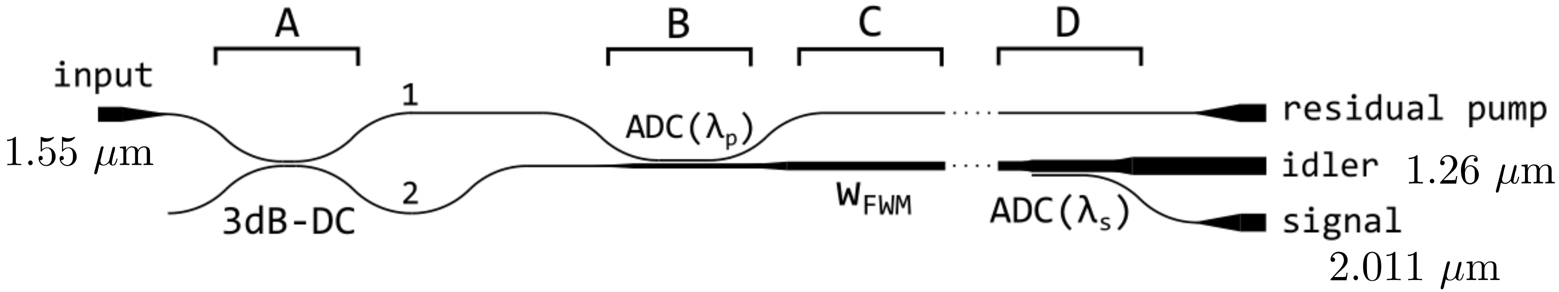
- Brightness, indistinguishability, quantum interference, ...

Chip and experimental setup

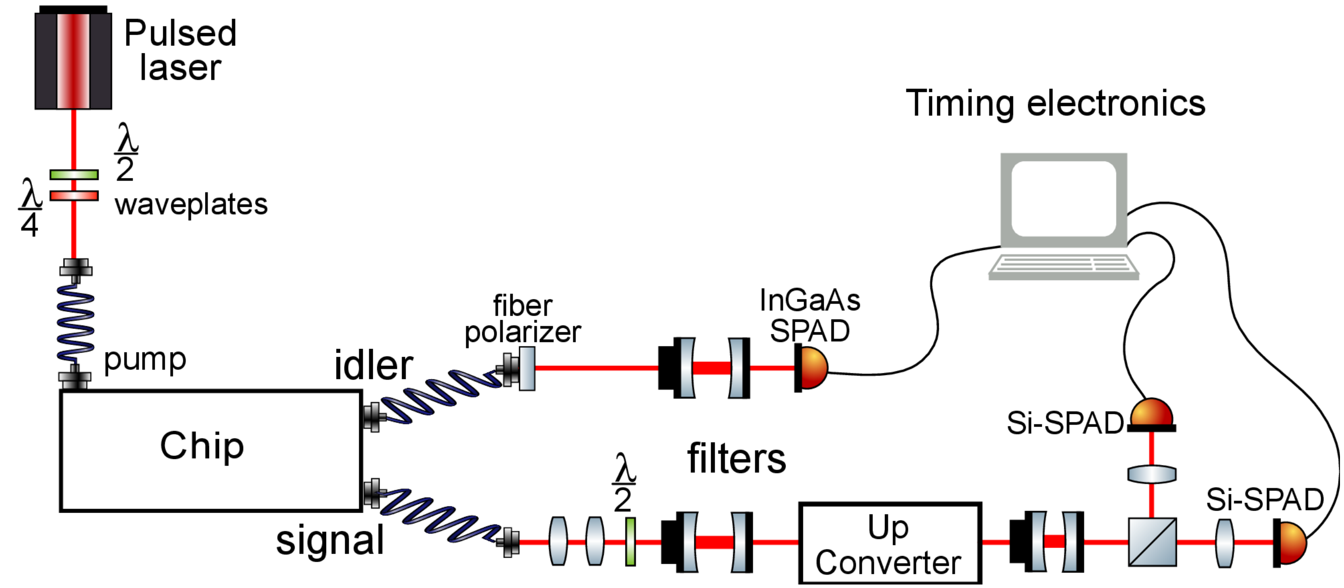
Waveguide cross-section:



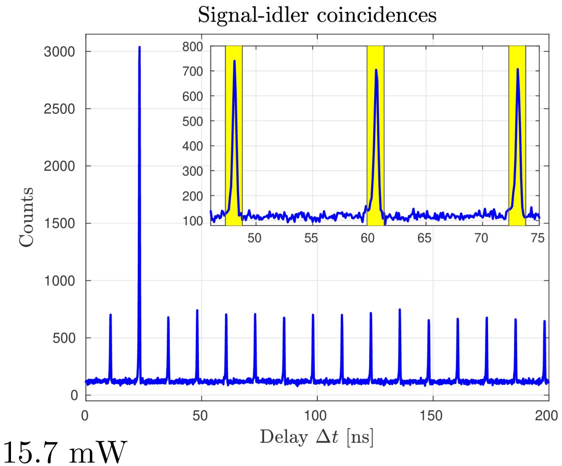
Chip design (fabricated by FBK-CMM):



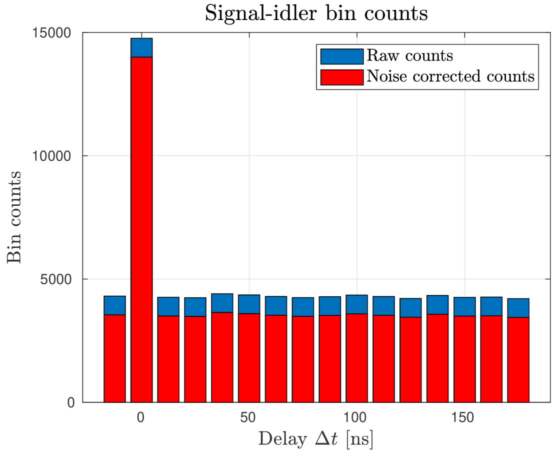
Experimental setup
(in the Nanoscience Laboratory
- University of Trento):

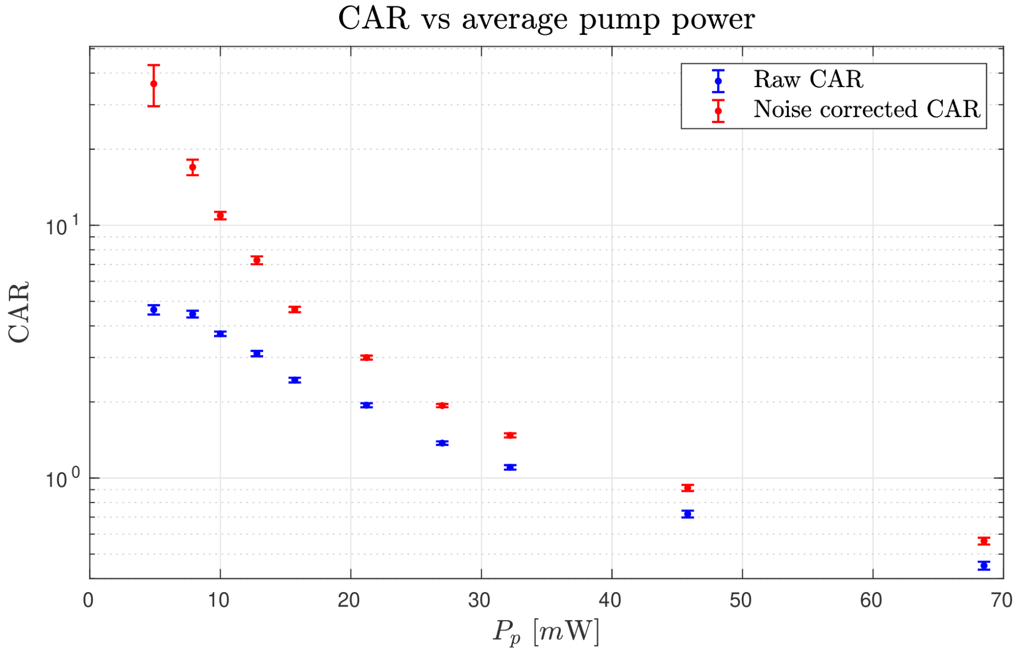


CAR measurement:



$P_p = 15.7$ mW

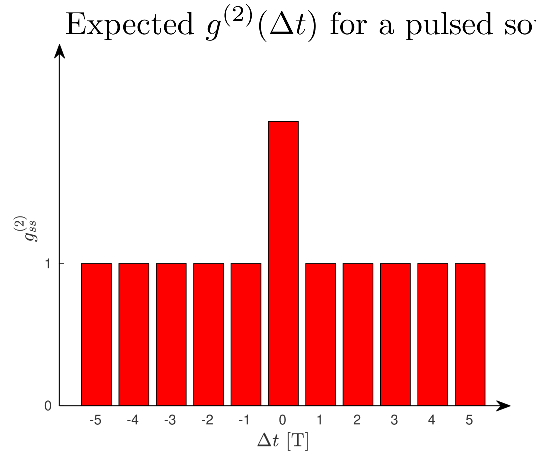


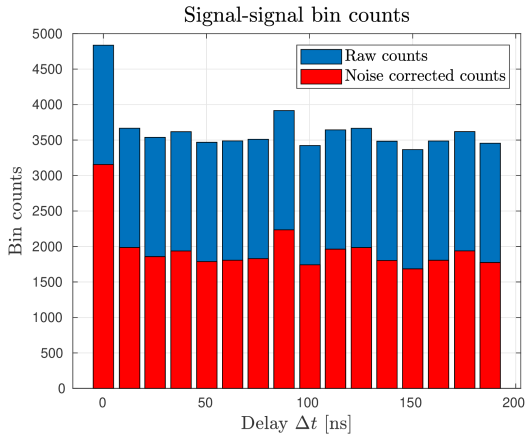


Maximum CAR: 36(5)

Heralded single photon source in the MIR

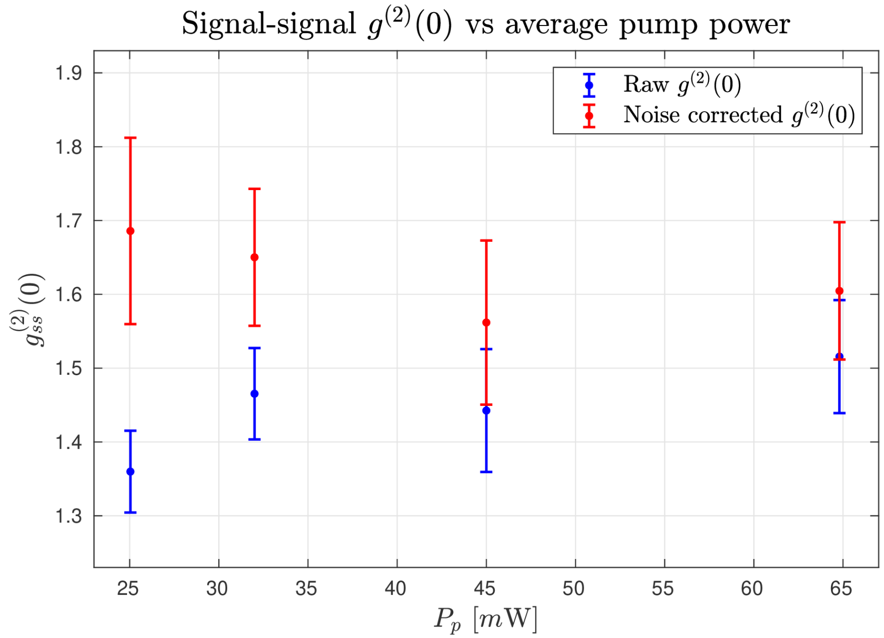
Purity measurement:





$P_p = 25.04$ mW

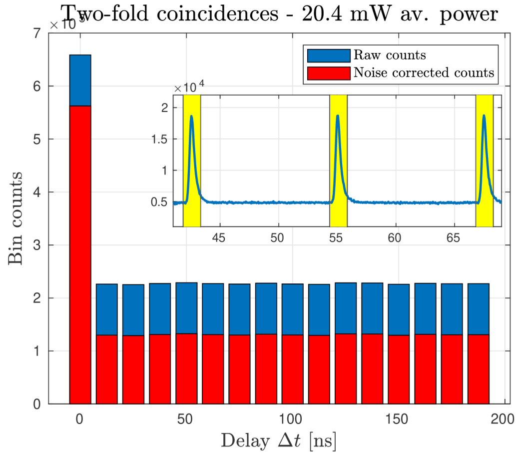
$$g^{(2)}(0) = \frac{P_{ss}(0)}{P_{ss}(\Delta t > 0)} = \frac{N_{ss}(0)}{N_{ss}(\Delta t > 0)}$$

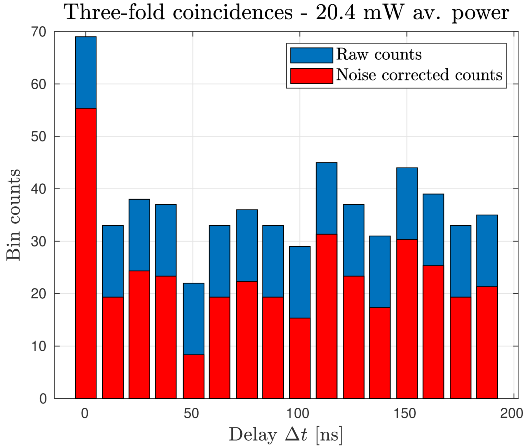


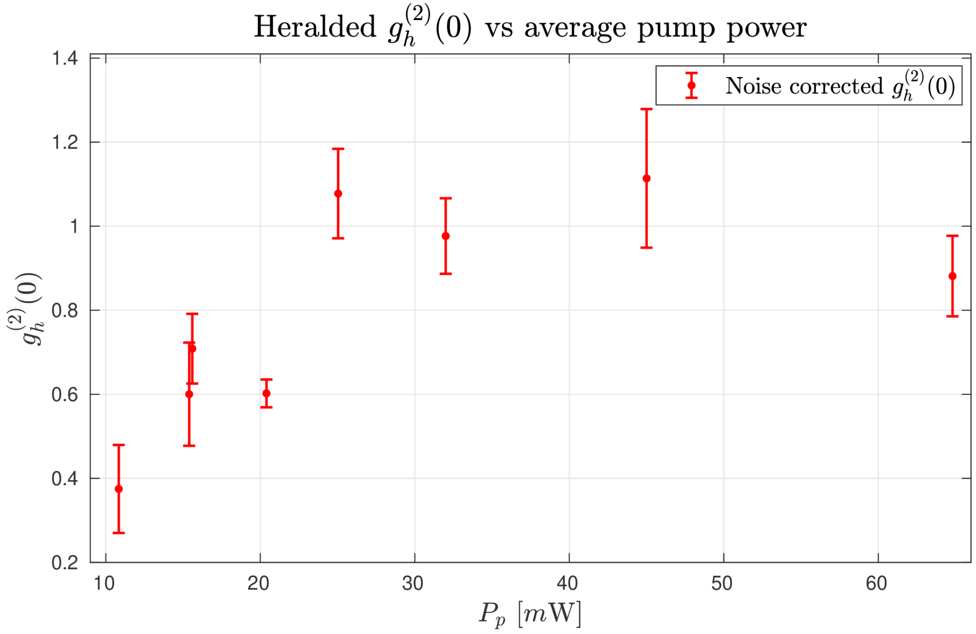
Maximum purity: $P = g^{(2)}(0) - 1 = 0.68(13)$

Antibunching measurement:

$$g_h^{(2)}(0) = \frac{N_{12i}(0)}{N_{2i}(0)} \frac{N_{2i}(\Delta t > 0)}{N_{12i}(\Delta t > 0)}$$







Minimum $g_h^{(2)}$: 0.37(9) → Single photon emission in the MIR

Figure references

[1] C. Grivas, "*Optically pumped planar waveguide lasers, part i: Fundamentals and fabrication techniques*", Progress in Quantum Electronics, vol. 35, 2011.

[2] S. Signorini, "*Intermodal four wave mixing for heralded single photon sources in silicon*", Phd Thesis. University of Trento, 2019.

[3] M. Borghi et al., "*Nonlinear silicon photonics*", Journal of Optics (IOP science), 06 2017.

[4] I. Cerutti et al., "*Engineering of closely packed silicon-on-isolator waveguide arrays for mode division multiplexing applications*", Journal of the Optical Society of America B, vol. 34, 02 2017.

[5] S. Signorini et al., "*Intermodal four-wave mixing in silicon waveguides*", Photonics Research, vol. 6, 08 2018.

[6] L. Caspani et al., "*Integrated sources of photon quantum states based on nonlinear optics*", Light: Science and Applications, vol. 6, 11 2017.