Chapter 4

Generating Single Photons

The development of single photon sources has been an active field of research for several decades. First demonstrations were done with atoms and molecules, intense efforts have followed with solid state based devices. A key element was the technological development that made it possible to detect the light emitted by a single photon emitter: the charge coupled device (CCD camera), the photomultiplier tube and the avalanche photodiode made it possible in the 1980s and 1990s to observe a single molecule.

An ideal single photon source should combine a wide range of properties: narrow emission spectrum, high brightness, repetition rate, polarization control, tunability, purity, room temperature operation are some elements one could wish for.

How can a single photon source be made? Because photons are bosons, there is no easy way to use interactions among photons to 'select' one single photon from a beam of light. Instead, what can be done is to isolate a single electron which is possible because of its charge and its fermionic nature and then use this electron to undergo a radiative transition. One single electron will undergo only one transition at a time and hence emit only one photon at a time. This can be done in a quantum dot, an 'artifical atom' or a 'quantum box' with nm sizes in all directions.

Practical devices can be made with solid state single photon sources based on semiconductor quantum dots, single molecules, single defects, single ions and atoms. Intense research has been carried out and there are now commercial devices made by companies such as Sparrow Quantum and Quandela.

There are important remaining challenges: - the light extraction efficiency: semiconductors have large refractive indexes, light emitted inside a high refractive index material tends to stay trapped in the material because of total internal reflection. - electrical vs optical excitation: the easiest implementation is to excite the single photon emitter with a laser pulse. But a small, compact practical device should be electrically pumped, this is not easy. - higher operation temperature: because the confinement energy is usually limited and because competing processes have some activation energy, single photon sources tend to only operate at low temperatures and often at very low temperatures, at some Kelvins only. This requires the use of cryostats, high-performance fridges that add complexity, costs and power consumption to single photon sources. - operation at telecom wavelengths: the emission wavelength is crucial and most applications for single photon sources would be in the field of quantum communication, if one were to use optical fibers, one would require emission at telecom frequencies: around 1300 or 1550 nm. - Energy efficiency: the generation of single photons might well be the most inefficient thing ever done by man: to generate a stream of single photons containing only femto Watts of optical power, we operate cryostats and laser system consuming kilo Watts.

The first demonstration of single photon generation was performed with sodium atoms in 1977. This experiment was crucial in demonstrating the quantum nature of the photon.

Heralded single photons: By shining light on a non-linear crystal, we can have a down conversion process: each blue photon is turned into two red photons. When we detect one red photon in one output, we know that there is another photon in the other arm, that photon is 'heralded'. While the statistics of the light is the same as that of the incoming laser (Poissonian), we can use this approach to work with single photons. This has its limits as Poissonian statistics implies that two photons could very well be simultaneous.

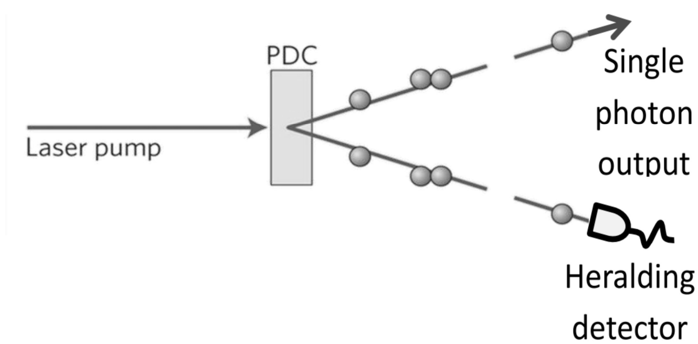

Figure 4.1: Parametric down conversion.

The Hanbury Brown Twiss interferometer

How do we measure photon statistics? We use a Hanbury-Brown Twiss interferometer and measure time intervals between detection events on each detector. After acquiring a long list of events, we build a histogram of the time intervals.

we want to measure the g(2) function to see what type of light statistics we have, the second order correlation function is defined as:

$$g^{(2)}(\tau) = \frac{\langle : \hat{n}(t)\hat{n}(t+\tau) : \rangle}{\langle \hat{n} \rangle^2}$$

- $g^{(2)}(0)=1$ – **random**, no correlation
- $g^{(2)}(0)>1$ – **bunching**, photons arrive together
- $g^{(2)}(0)<1$ – **anti-bunching**, photons "repel"
- $g^{(2)}(\tau) \rightarrow 1$ at long times for all fields

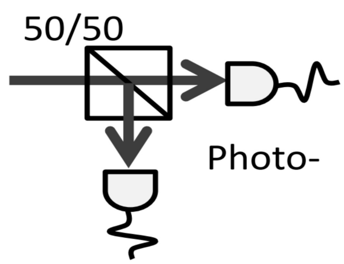

Figure 4.2: Hanbury Brown Twiss interferometer.

The term antibunched light applies to the case where there is always a minimum time interval between photons.

We can go beyond the g(2) function and measure g(n) which are correlations among n detectors. While this is possible, it still lacks a use and implies longer measurements.

Trick question: why not use only one single photon detector? This has to do with deadtime, after a detection event a detector is not able to detect another photon for a certain time. We need to rely on another detector during that time.