# Photon pair generation in silicon microring resonators on a chip

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**Abstract**

One of the main challenges in the development of quantum information processing technologies is high quality single or entangled photon sources on chip. The focus of this paper is to provide a theoretical background of entangle photons generation through spontaneous four wave mixing process. Additionally, the latest developments in the generation of these photon sources as quantum states of light in integrated circuits compatible with the semiconductor industry processes and its current infrastructure, are shown.

## 1. Introduction

Quantum mechanics has played a crucial role in the technology since its introduction at the beginning of the 20th century. It defines the behavior of nature at fundamental level through probability. The two most remarkable characteristics of quantum mechanics are superposition and entanglement. Superposition occurs when an object can be in two places at once or can follow more than one path, and entanglement occurs when two objects can interact immediately, even if a very long distance are separating them. The experiments show the accuracy of quantum mechanics predictions, making this theory the most successful so far.

Quantum Information Processing (QIP) is the use of QM systems (i.e. individual atoms, ions, photons) to solve information processing tasks, such computation and communication, by taking advantage of superposition in a two states quantum system called qubit. One of the most promising approaches to developing QIP technologies is the use of integrated quantum photonic devices, due to its ability to take advantage of current semiconductor manufacturing technics and infrastructure. However, to complete this landscape is also required to generate quantum states of light on a chip.

This article focuses specifically on the creation of entangled or quantum correlated photon sources, usually called biphotons, in silicon chips. This process is based on $\chi^{(3)}$ nonlinearity of silicon that leads to phenomena called spontaneous four wave mixing (SFWM) explained in section 2. Biphoton generation on chip has been studied using several photonic structures: waveguides [2][3][4][5], microring resonators [4][11][18][20], photonic crystal waveguides [7], microdisk resonators [12], coupled photonic wire nanocavities (PhC/PhW) [16] and coupled resonators optical waveguide (CROW) [10][17]. However, in this report the analysis is restricted to structures based on microring resonators, because they have a good balance between simplicity and excellent performance [18].

## 2. Theory of Spontaneous Four Wave Mixing

In order to analyze the quantum theory background of the spontaneous four wave mixing process, I will follow the nomenclature and treatment given by [6]. The starting point for a quantum analysis of the biphoton generation is a Hamiltonian that can describe the energy interactions of our system

$$\mathcal{H} = \mathcal{H}^{ch} + \mathcal{H}^{cp} + \mathcal{H}^{R}$$

where $\mathcal{H}^{ch}$ is the channel Hamiltonian with a related waveguide operator $\hat{\psi}_{\mu}$, $\mathcal{H}^{R}$ is the ring Hamiltonian with a related ring operator $\hat{b}_{\mu}$, and $\mathcal{H}^{cp}$ is the coupling Hamiltonian that contains the interaction between the waveguide and the ring. The subscript $\mu$ has two terms $(m, N)$ where $m$ is the transverse propagation mode and $N$ is the cavity resonant mode number of the ring.

The input is defined as a coherent state in the channel at the coupling point described by

$$|\psi_{\text{in}}\rangle = \exp\left(\alpha \hat{A}^{\dagger}_{\mu_P} - \text{h.c.}\right)|\text{vac}\rangle$$

$$\hat{A}^{\dagger}_{\mu_P} = \int dk\, \phi_P(k)\, \hat{a}^{\dagger}_{\mu_P}(k)$$

$$\hat{a}^{\dagger}_{\mu_P}(k) = (2\pi)^{-1/2} \int \hat{\psi}_{\mu_P}(z)\, e^{-ikz}$$

in which $|\alpha|^2$ defines the number of photons in the input pulse. In order to facilitate the treatment, some approximations need to be used without losing precision, such as an undepleted pump, negligible noise and loss, and using only first order terms in the exponential that involve the biphoton creation operators.

Previous approximations lead us to say that the state of the biphoton generated by the coherent state could by defined by the two mode squeezed state given by

$$|\psi_{\text{gen}}\rangle = \exp\left(\beta \hat{C}_{II}^{\dagger} - \text{h.c.}\right)|\text{vac}\rangle$$

$$\hat{C}_{II}^{\dagger} = \frac{1}{\sqrt{2}} \sum_{\mu_1,\mu_2} \int dk_1\, dk_2\, \phi_{\mu_1\mu_2}(k_1,k_2)\, \hat{a}_{\mu_1}^{\dagger}(k_1)\, \hat{a}_{\mu_2}^{\dagger}(k_2)$$

where $\phi_{\mu_1\mu_2}(k_1,k_2)$ is the biphoton wave function.

Assuming that a TE polarized Gaussian pump is exciting only one cavity resonant mode $N_P$ near to zero dispersion and that the material is amorphous, the subscript $\mu$ can be replaced only by $N$. The photon pair is produced in two resonant cavity modes $N$ and $\bar{N}$ symmetrically separated from the mode $N_P$. Law of conservation of energy implies that $N + \bar{N} = 2N_P$. The pair generation probability for a particular $N\ \bar{N}$ is defined by

$$|\beta_{N\bar{N}}|^2 = |\beta|^2 \int dk_1\, dk_2\, |\phi_{N\bar{N}}(k_1,k_2)|^2$$

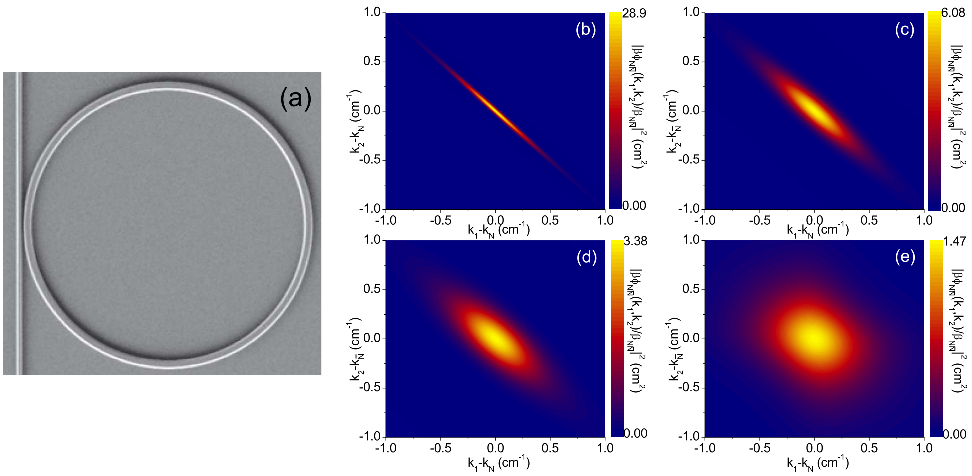


Figure 1. (a) Silicon nitride microring resonator. (b)-(e) Biphoton probability density for (b) T=5 ns, (c) T=1 ns, (d) T=500 ps, (e) T=50 ns [6].

For values of $N$ far from $N_P$, the dispersion produces $N + \bar{N} \neq 2N_P$, implying that this transition is forbidden. In contrast, when $N$ near to $N_P$, all the group velocities can approximately equal the group velocity $v$ of the pump cavity resonant mode. In the c.w. limit the pump can be modeled as a top-hat function of length $\Lambda$, resulting in a pump power average $P_{N_P} = \hbar\omega_0 v|\alpha|^2/\Lambda$. After some algebra with the pair generation probability multiplied by $\hbar\omega_0 v/\Lambda$, we find the expected average power in the cavity resonant mode $\bar{N}$

$$P_{\bar{N}} = \left(\frac{\gamma P_{N_P}}{\pi R}\right)^2 |F_0|^6 \hbar\omega_P v$$

$F_0$ is the on-resonance field enhanced factor which can be approximately $\sqrt{Qv/\omega_P}$ for critical couple microring resonators, giving us an average power proportional to $Q^3$

$$P_{\bar{N}} = \left(\frac{\gamma P_{N_P}}{\pi R}\right)^2 \left(\frac{Qv}{\omega_P}\right)^3 \hbar\omega_P v$$

## 3. Microring resonator as biphoton source

The most common setup used to measure the time-bin entanglement of biphotons is integrated but not restricted by the following components:

- Continuous wave laser source, usually a tunable external cavity diode laser.
- Narrow bandpass filter to remove the fluorescence background generated by the laser.
- The chip with the microring resonator coupled with fiber lenses.
- A frequency splitting device to separate the signal and idler photons.
- Narrow bandpass filters to reject the pump and noise from signal and idler photons.
- Single photon detectors for signal and idler photon.
- Counting electronics.

The main parameters to evaluate the efficiency of biphoton generation are brightness and coincidence accidentals ratio (CAR). The brightness is the number of photons per second in signal and idler beams, which is proportional to their optical intensities. A coincidence occurs when a signal photon is detected in the same time-bin an idler photon is detected, and signal and idler photons have no delay between them. An accidental occurs when a signal photon is detected in the same time-bin an idler photon is detected, but in this case signal and idler photons have a delay between them enough to be far from the peak of coincidences. The coincidence to accidentals ratio is defined by

$$CAR = \frac{R_C + R_A}{R_A}$$

The bigger the CAR and the bigger the brightness, the better is the quality of the biphoton source.

### 3.1. Clemmen S. et al. (2009) [4]

S. Clemmen et al. did the first experiment in which a silicon microring was used to generate photon pairs in 2009. Additionally, this was the first time a continuous wave laser used as input. In this article, the researchers evaluated additionally a silicon waveguide and Sagnac loop interferometer.

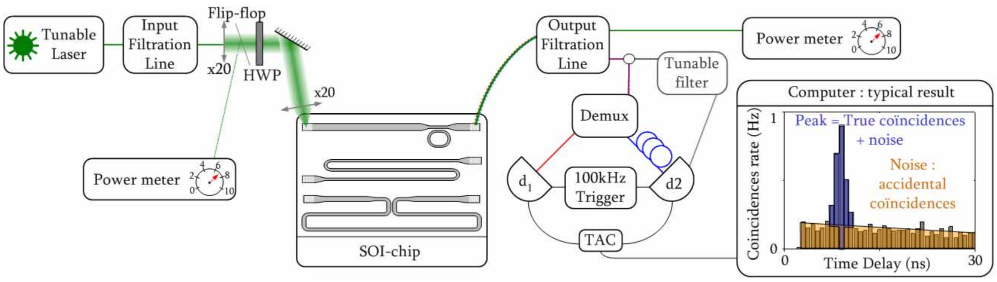


Figure 2. Experimental setup used in [4].

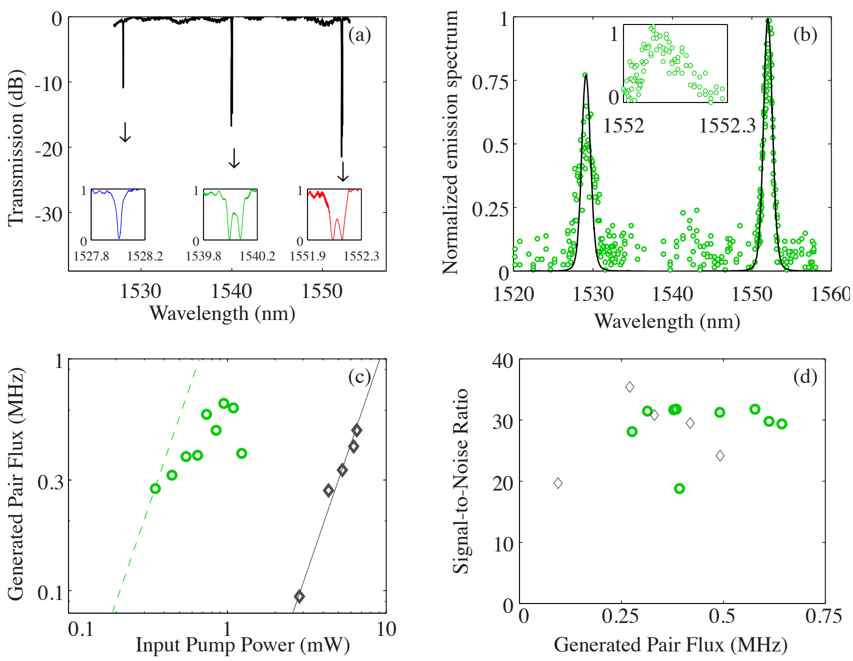


Figure 3. Experimental results show in [4]. (a) Transmission spectrum of the microring resonator. (b) Emission spectrum measured using a band pass filter and single photon detector. (c) Photon pair flux or coincidence rate. (d) Signal-to-Noise Ratio or Coincidence to Accidentals Ratio [4].

An important remark from this experiment is that the coincidence rate of the microring resonator is 2 orders of magnitude bigger than predecessor structures like simple waveguides. From the figure 3 we can observe a photon pair generation rate of 0.3 MHz for a 0.4 mW pump power and coincidence to accidentals ratio of 30.

### 3.2. Azzini S. et al. (2012) [11]

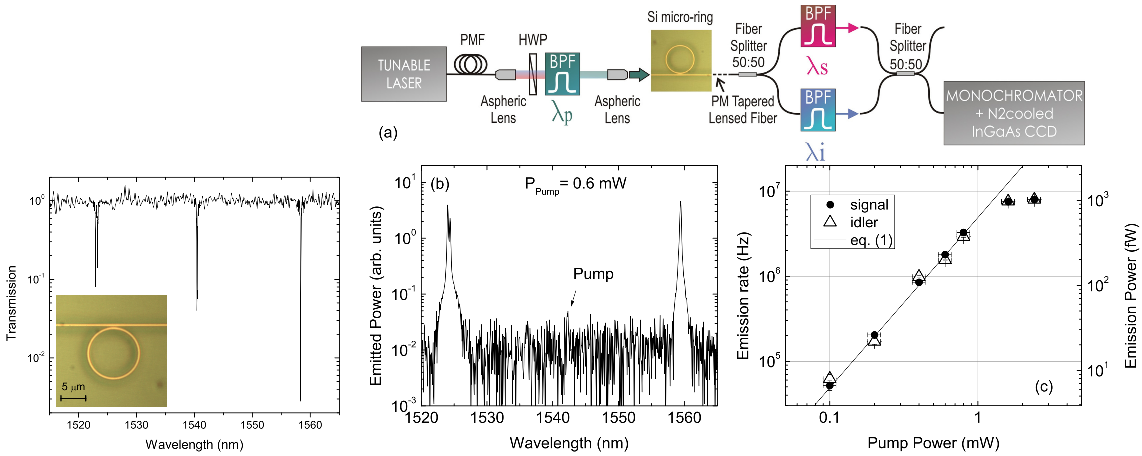


Figure 4. (a) Experimental setup used for spectrum measurements. (b) Transmission spectrum of the ring and emission spectrum. (c) Emission rate vs. pump power [11].

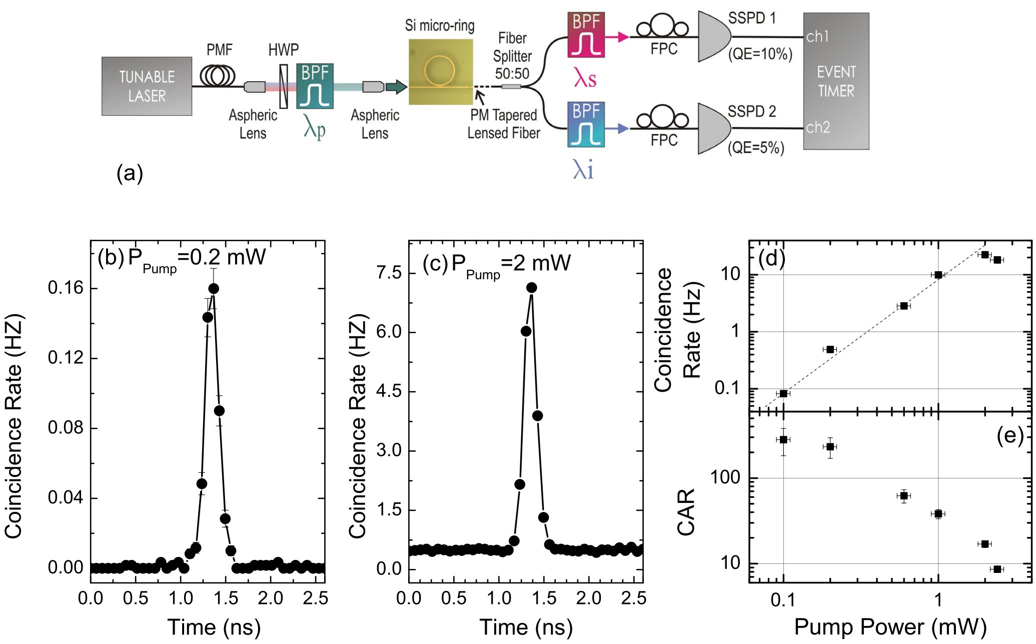


Figure 5. (a) Experimental setup used for coincidence measurements. (b) Coincidence histograms. (c) Coincidence rate and CAR as a function of pump power [11].

The experiment performed by Azzini S. et al. in 2012 showed good improvement over the past experiment in terms of coincidences to accidentals ratio that reached 250. However, the total pair generation rate was 0.2 MHz, below than previously seen. It is noteworthy that the plot coincidence rate versus pump power departs from the quadratic dependence for high values of pump powers due to thermo-optics effect induced by two photon absorption.

### 3.3. Engin E. et al. (2013) [18]

The microring resonator develop by Engin E. et al in 2013 defers from its predecessors in that this has additionally a reverse bias p-i-n structure to overcome free carrier related performance degradations. This fact makes this device to achieve a record of coincidences to accidentals ratio of 602 for a photon pair generation rate of 827 kHz. It is important to note that the filters in this experiment ware implemented using dense wavelength division multiplexer (DWDM).

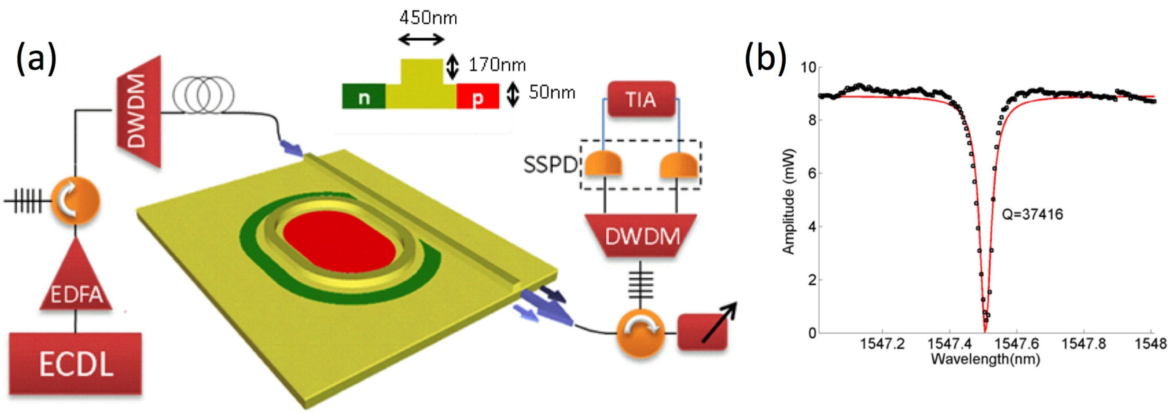


Figure 6. (a) Experimental setup. (b) Transmission spectrum near to pump frequency [18].

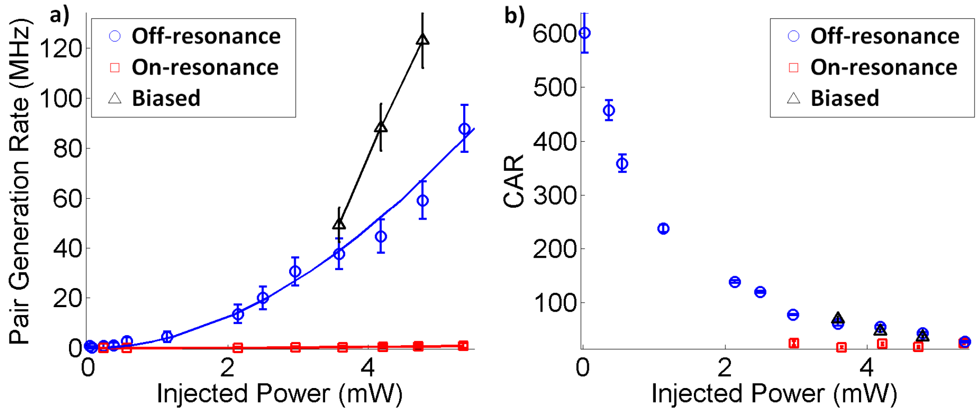


Figure 7. (a) Photon pair generation rate as a function of pump power.
(b) Coincidences to accidentals ratio as a function of pump power [18].

### 3.4. Guo Y. et al. (2014) [20]

The experiments previously showed were based on degenerated four wave mixing process, in which the photon pairs generated are nondegenerate. The experiment performed by Guo Y. et al. in 2014 was focused to produce degenerated-frequency photon pair. This

quantum state of light could have application in the areas of quantum state engineering and quantum metrology in which photon indistinguishability plays an important role. The cavity has the shape of a race track and is accompanied by a heater to accurately tune the resonant frequencies.

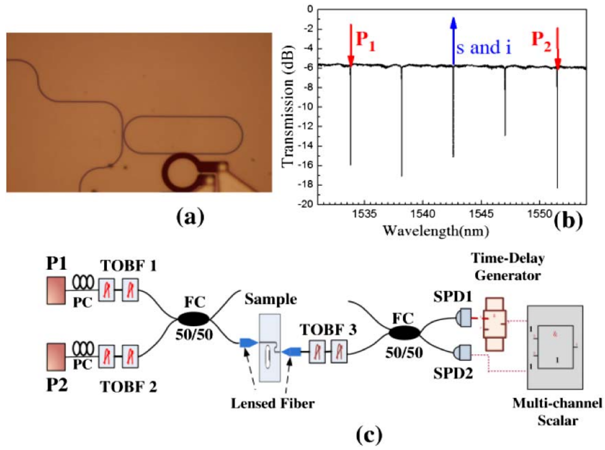


Figure 8. (a) Photo of the silicon microring sample. (b) Transmission spectrum of the microring. (c) Experimental setup [20].

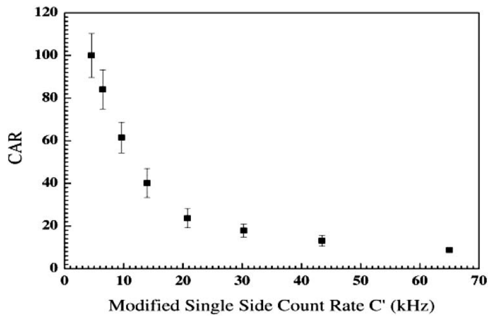


Figure 9. Coincidences to accidentals ratio [20].

## 4. Conclusion

| Reference | Year | Microring Radius | CAR | Photon pair generation rate |
|---|---|---|---|---|
| **[4]** | 2009 | 43 μm | 30 | 0.5 MHz |
| **[11]** | 2012 | 20 μm | 250 | 0.2 MHz |
| **[18]** | 2013 | 73 μm | 600 | 0.8 MHz |
| **[20]** | 2014 | 21 μm | 100 | 4.5 kHz |

Table 1. Comparison between the experiments of biphoton generation using silicon microring on a chip.

This paper shows that biphoton generation devices based on silicon chips is a vibrant research area. Despite the good achievements in recent years, there is still plenty of road ahead in obtaining biphoton sources of better quality. Table 1 shows that the reverse bias approach used in [18] could play an important role in the future of the devices studied. Finally, despite we still need some improvements in the quality of photon pair sources, researchers should start thinking in the integration of these sources with other photonic devices on a chip to solve real quantum information processing tasks [19].

## 5. References


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