EUROPEAN CONFERENCE ON INTEGRATED OPTICS

Fiber-coupled plug-and-play heralded single photon source based on Ti:$LiNbO_3$ and polymer technology

(student paper)

Christian Kießler[1,*], Hauke Conradi[2], Moritz Kleinert[2], Viktor Quiring[1], Harald Herrmann[1], Christine Silberhorn[1]

[1]Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn,

[2]Fraunhofer HHI, Einsteinufer 37, 10587 Berlin

[*]christian.kiessler@uni-paderborn.de

We present the first chip-size fully integrated fiber-coupled Heralded Single Photon Source (HSPS) module based on a hybrid integration of a nonlinear lithium niobate waveguide into a polymer board. Photon pairs are generated via parametric down-conversion and then filtered and routed to two separate outputs. We measure a heralded second-order correlation function of $g_h^{(2)} = 0.05$ with a heralding efficiency of $\eta_h = 4.5\,\%$ at low pump powers.

Keywords: *heralded single photon source, hybrid integration, parametric down-conversion, lithium niobate*

INTRODUCTION

A reliable, but cost-effective generation of single-photon states is key for practical quantum communication systems. Different approaches are studied to build a practicable single photon source, such as quantum dots [1] or nonlinear photon-pair generation with heralding schemes [2]. A major challenge for these sources is an efficient coupling of the generated photons to optical fibers, which is necessary to use these sources practicably. First commercial HSPS are available as bench-top devices [3], but they are still far away from the ultimate goal of realizing a quantum- system-on-chip (QSoC) providing low cost, small size and robustness, which are the essential features for future commercial exploitation. Ultimately, in a fully integrated HSPS all different components for spontaneous parametric down conversion (SPDC), photon separation and pump filtering must be combined on one chip, which has not been demonstrated yet.

Here, we present a fully integrated chip-size, plug-and-play HSPS module based on lithium niobate and polymer technology. A polymer board (PolyBoard) is used as a chip platform, which enables the fabrication of waveguides and etched slots for the integration of different optical components [4]. Filters with various spectral and polarization characteristics can be glued into these etched slots, which open up the possibility for sufficient pump filtering and signal/idler separation. The PolyBoard is therefore a perfect platform for the integration of different optical components on chip. A SPDC process in a titanium-indiffused periodically poled z-cut lithium niobate waveguide (Ti:ppLN) is designed to generate photon pairs at $810\ \mathrm{nm}$ (signal) and $1550\ \mathrm{nm}$ (idler). The high second order nonlinearity of $LiNbO_3$ makes it a favorable choice for an efficient SPDC process [5]. The signal photons are used to herald the telecom photons. The Ti:ppLN waveguide is butt-coupled to the PolyBoard waveguide. The hybrid integration of a Ti:ppLN waveguide into the PolyBoard leads to a fully integrated module, which cannot be realized in one material alone. The signal wavelength of $810\ \mathrm{nm}$ enables the possibility for a future integration of silicon single-photon avalanche diodes (SPADs) to the module and therefore a possible commercially available device with small size, low cost, high robustness and reproducibility.

DESIGN AND COMPONENTS

We fabricated low loss waveguides in z-cut $LiNbO_3$ (typically $< 0.1\ \mathrm{dB/cm}$) by a titanium indiffusion. Periodic poling of the waveguides ensures the quasi-phase-matching condition for the designed type-0 phase-matched SPDC process with a pump wavelength at $532\ \mathrm{nm}$ and signal and idler at $810\ \mathrm{nm}$ and $1550\ \mathrm{nm}$, respectively. The Ti:ppLN crystal has a length of $15\ \mathrm{mm}$ and the endfacets are coated for high transmission efficiency within the module and suppression of pump light. A PM-fiber is glued to the input-facet of the Ti:ppLN waveguide and the output facet is coupled to a PolyBoard with integrated waveguides. A sketch of the module is shown in Figure 1a. An additional filter (LP) and dichroic mirror (DM) are integrated into etched slots in the PolyBoard for pump suppression and photon separation. SM-fibers are glued to the outputs and the whole module is mounted on top of a thermoelectric cooler for temperature control. Figure 1b shows the assembled and packaged HSPS module with PM input-fiber (purple), two SM-output-fibers (yellow) and electrical contacts for temperature control.

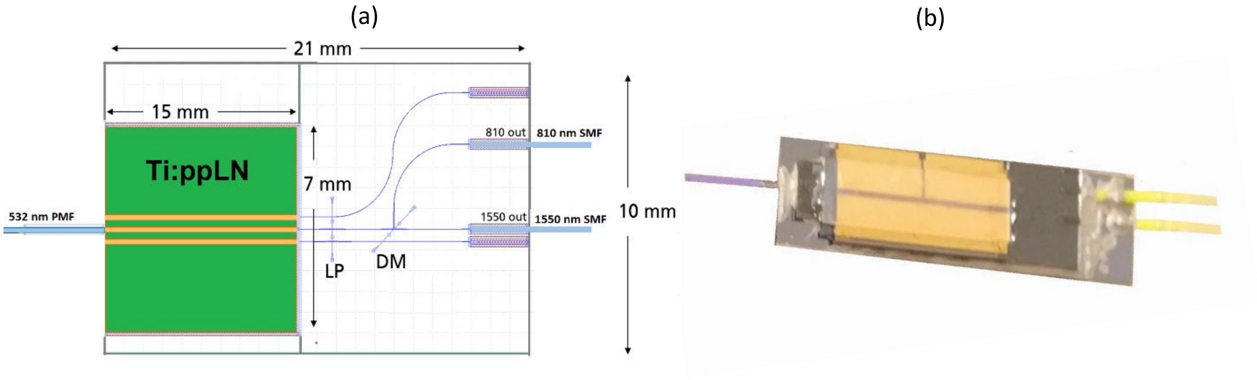

Fig 1. Design sketch of the HSPS module (a) and picture of the assembled module (b).

RESULTS

We performed a first characterization of the assembled module by pumping it with a cw-laser at $532\ \mathrm{nm}$ and analyzing the outputs with a spectrometer at visible wavelengths. Figure 2 shows the measured spectrum of the signal output port at three different temperatures measured with the integrated thermosensor. The intensity drop for high temperatures can be explained by a small misalignment in the module due to different expansions of the components. Peaks from higher-order modes and Cerenkov radiation are visible. We observe a perfect separation of signal and idler, since the spectrum of the idler output port shows no intensity counts at around $810\ \mathrm{nm}$ (see Figure 2, green).

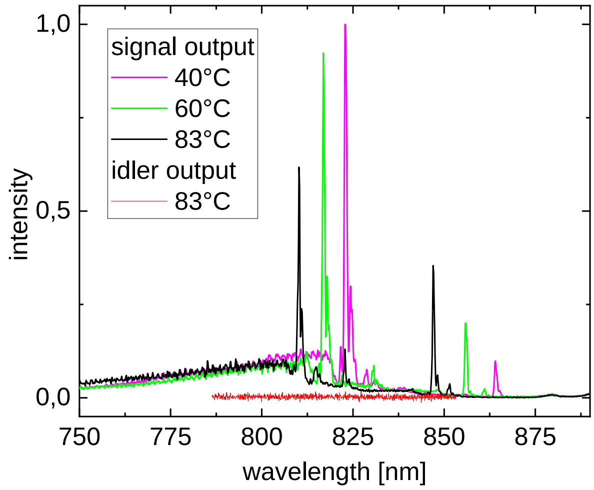

Fig 2. Measured HSPS module output spectra of the signal and idler photons at different temperatures. No counts at around 810 nm in the idler output indicate a perfect separation of signal and idler photons.

We then investigated the single photon characteristics of the module by performing conditioned measurements with superconducting nanowire single-photon detectors. To determine the single photon and heralding performance of the module, we evaluated the heralding-efficiency η_h. The heralding-efficiency η_h describes the probability of a single photon in the idler output upon the detection event in the signal output. The power dependent heralding efficiency of the filtered module is shown in Figure 3a. For low pump powers $< 1\ \mu\mathrm{W}$, we can obtain a constant heralding efficiency of around $\eta_h = 3.5\ \%$. To evaluate the simultaneous generation of multiple photon pairs in the generated SPDC, we make use of the heralded second-order auto-correlation function $g_h^2(0)$. Figure 2b shows the measured $g_h^2(0)$ of the module for different pump powers. For low pump powers $< 1\ \mu\mathrm{W}$ the second-order autocorrelation function reaches values of $g_h^2(0) < 0.005$.

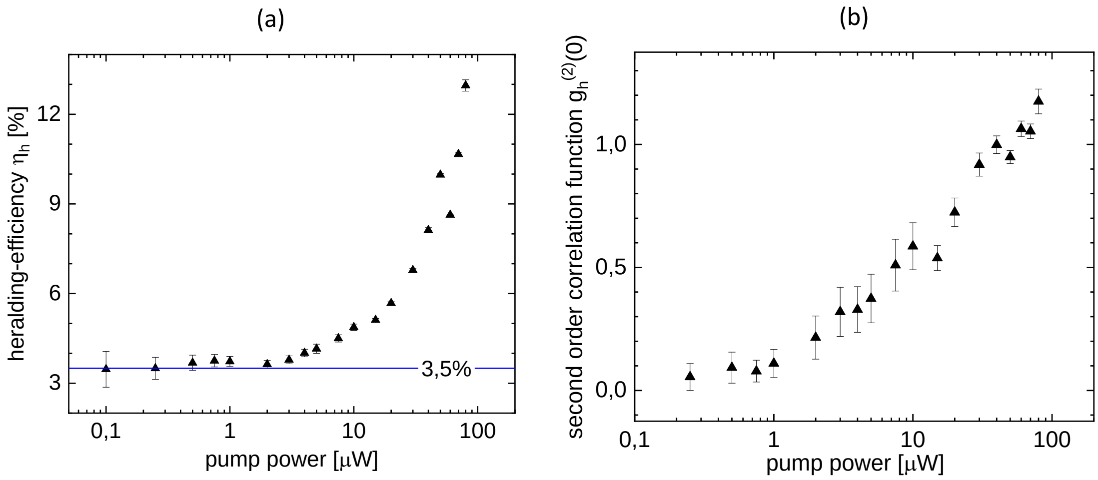

Fig 3. Heralding efficiency η_h vs. pump power of the filtered HSPS module (a). For low pump powers the heralding efficiency approaches a vlaue of $\eta_h = 3.5\%$. Heralded second-order auto-correlation function $g_h^2(0)$ vs. pump power (b). An increase for higher pump powers indicates the generation of higher-order photon components

DISCUSSION

We demonstrated the first chip-size ($(2 \times 1)\mathrm{cm}^2$) fully integrated fiber-coupled Heralded Single Photon Source module based on a hybrid integration of a Ti:ppLN waveguide into a polymer board with integrated optical components. For low pump powers, we can obtain a constant heralding efficiency of around ηh = 3.5%, which is low compared to other works [6]. It is important to mention that our module is a hybrid integration, which is not the case with the comparable sources. Non-optimal coupling between the two material systems leads to additional losses that reduce the heralding efficiency. We estimated the total losses within the assembled module by performing count rate measurements with different additional filter combinations to be $\eta_s = 1.5\ \%\ (18\ \mathrm{dB}$ losses) and $\eta_i = 5\ \%\ (13\ \mathrm{dB}$ losses) in the signal and the idler port, respectively. Significantly improving the coupling in the module could greatly lower losses, which should result in a higher heralding efficiency. For low pump powers the second-order autocorrelation function reaches values of $g_h^2(0) < 0.005$, which indicates an excellent single photon character and is comparable to a previous HSPS based on Ti:ppLN, developed and fabricated in our group [2].

The hybrid integration of Ti:ppLN into a PolyBoard opens up the opportunity for a future multi-channel source and a direct integration of silicon SPAD arrays for the detection of the signal photons on chip. The realization of a quantum system-on-chip (QSoC) providing low cost, small size and robustness is therefore conceivable with a hybrid integration approach.

ACKNOWLEDGEMENTS

This work was funded by the European Union's Horizon 2020 Research and Innovation Programme through Quantum-Flagship Project UNIQORN under Grant 820474.

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