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Towards an Integrated Squeezed Light Source

Tobias Gehring*, Ulrich B. Hoff, Timur Iskhakov, Ulrik L. Andersen

Technical University of Denmark, Department of Physics, Fysikvej 309, 2800 Kongens Lyngby, Denmark

Abstract. Since its first generation more than 30 years ago, squeezed light has developed towards a tool for high precision measurements as well as a tool for quantum information tasks like quantum key distribution. Miniaturization of sensors is an active field of research with the prospect of many applications. The precision of optical sensors based on interferometric measurements is often limited by the fundamental shot noise. While shot noise can be reduced by increasing the employed light power, integrated sensors pose limitations on the maximum possible amount due to damaging effects of high intensity as well as power consumption. Bright quadrature squeezed light produced by the optical Kerr effect in a nonlinear medium offers an opportunity to overcome these limitations. Here, we present first steps towards a bright quadrature squeezed light source produced by the optical Kerr effect in race-track resonators in silicon nitride by presenting characterizations of the chip. Using standard fabrication techniques this source will have the potential of seamless integration into on-chip optical sensors.

Keywords: optics, quantum optics, integrated photonics, squeezed light, silicon-nitride.

* tobias.gehring@fysik.dtu.dk

1 Introduction

The sensitivity of optical sensors and measurement devices is limited by technical noise sources like laser noise or by quantum noise, so-called shot noise. While the former can be eliminated for instance by implementing better – shot noise limited – lasers and by decoupling the measurement from the environment, shot noise is a fundamental property of the employed laser light imposed by quantum mechanics. To achieve better signal-to-noise ratios the power used in the optical sensors and measurement devices can be increased. However, e.g. biological samples, investigated in an optical measurement device, are disturbed and eventually destroyed by laser light, which limits the amount that can be used.¹ In integrated sensors also optical absorption and photo refractive effects limit the amount of laser power.

Quadrature squeezed light is a quantum state of light that exhibits noise properties which show in comparison to shot-noise a reduced amount of noise in one of the quadratures of the light field, and according the Heisenberg's uncertainty relation, an increased amount in the orthogonal quadrature.² This opens the possibility to employ such states in for instance interferometric measurements where the phase of the light is the quantity of interest.³

While squeezed light can improve the signal-to-noise ratio of the measurement without increasing the laser power, state-of-the-art setups to generate the quantum states usually are bulky and, thus, incompatible with state-of-the-art integrated photonics.^{4,5}

Using Silicon photonics photon correlations and intensity correlations, respectively, have been observed.⁶⁻¹² On-chip quadrature squeezed light has so far only been observed in Lithium Niobate waveguides¹³ as well as by utilization of the ponderomotive effect of a cryogenically cooled micro-oscillator in an optical cavity enabled by radiation pressure forces.¹⁴

Here, we present a chip fabricated in Silicon Nitride using standardized lab processes which will enable room-temperature generation of quadrature squeezed light by the nonlinear optical Kerr effect. We describe the design and characterization of the employed race track resonators as well as the

coupling efficiency between a lensed fiber and the waveguides for in-coupling of the pump light as well as out-coupling of the generated squeezed light.

2 Device design and fabrication

Integration of quantum optical processes requires the host material to possess both a strong nonlinearity, essential for implementing high-efficiency parametric interactions, and low material and structural loss in order to preserve the generally fragile quantum states. These requirements are met by LPCVD amorphous stoichiometric silicon nitride (Si_3N_4). With a linear refractive index of $n \approx 2$ and a third order Kerr nonlinearity of $n_2 = 2.5 \times 10^{-15} \text{cm}^2/\text{W}$,¹⁹ it is a suitable core material for high-index contrast waveguides in applications where tight field confinement and small waveguide bending radii are required. For comparison, the nonlinearity of silicon nitride is roughly 10 times the nonlinearity of silica, 2 times that of Hydex, and 0.1 times that of silicon. On the loss side, 200 nm thick channel waveguides with ≤ 0.2 dB/cm propagation loss at 780 nm have been demonstrated,¹⁶ and at 1540 nm propagation losses of 0.12 dB/cm have been measured in channel waveguides of more than 700 nm thickness.¹⁷

The specific device design studied in this work is a buried channel Si_3N_4 waveguide circuit consisting of a racetrack resonator (RTR) with radius of curvature R , laterally coupled to a straight bus waveguide, as illustrated in Fig. 1(a). Coupling to the RTR is achieved by a finite overlap of the evanescent fields of the two waveguide modes in the coupling region, the efficiency γ_c being controlled through the gap size and coupling length parameters g and L_c , respectively. Intra-cavity losses, primarily due to scattering from the waveguide sidewalls, are represented by an intrinsic loss rate γ_0 and the total loss rate is given by $\gamma = \gamma_0 + \gamma_c$ determining the loaded quality factor of the resonator. An important parameter for controlling the squeezed light generation efficiency of the system is the *escape efficiency* $\eta_{esc} = \gamma_c/\gamma$, characterizing the collection efficiency of the intra-cavity field. For the application of squeezed light generation, operation in the over-coupled regime ($\eta_{esc} > 1/2$) is required.

As illustrated in Fig. 1(b), high confinement of the optical resonator mode is provided by a rectangular low-aspect ratio cross sectional geometry of the waveguides. For the sake of minimizing fabrication complexity, we restrict the thickness to a value of 250 nm, yielding the largest possible mode confinement while at the same time eliminating the need for stress-releasing temperature cycling in the deposition process. This in turn puts an upper bound on the width, due to the requirement of single mode operation. To achieve efficient in and out coupling of the optical mode a double layer stack waveguide cross section in conjunction with inverse vertical tapers at the chip facets was adopted. The lower thin-film extends to the chip facet and provides a weak guiding mechanism for the in-coupled light which is subsequently transferred adiabatically to the upper main waveguide by means of an inverse taper (Fig. 2). According to simulations this strategy should enable coupling efficiencies as high as 0.75 dB/facet.¹⁸

3 Device characterization

The integrated devices are associated with two types of loss – coupling loss characterizing the coupling efficiency from free space to the high-confinement waveguide and vice versa and propagation loss in the ring resonator and bus waveguide – which together constitute the total *insertion loss* of the device. For squeezed light generation it is of great importance to know the individual contributions of the two loss sources as they affect different aspects of the device performance. The cut-back method

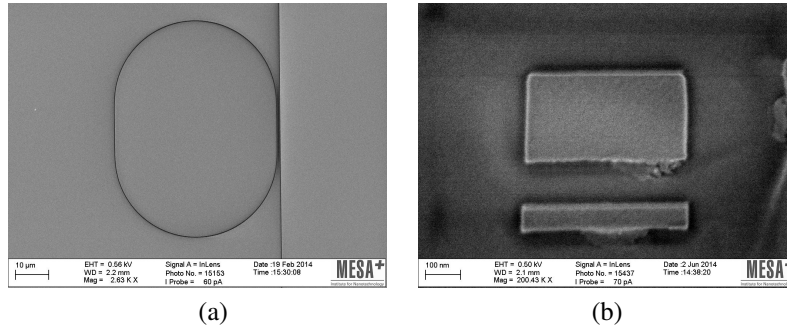


Fig 1: (a) SEM image of an $R = 25 \mu\text{m}$ race track resonator device. (b) SEM image of the waveguide cross section showing the double layer stack with the lower thinfilm coupling waveguide and the upper high confinement waveguide. The devices were fabricated by LioniX, The Netherlands.

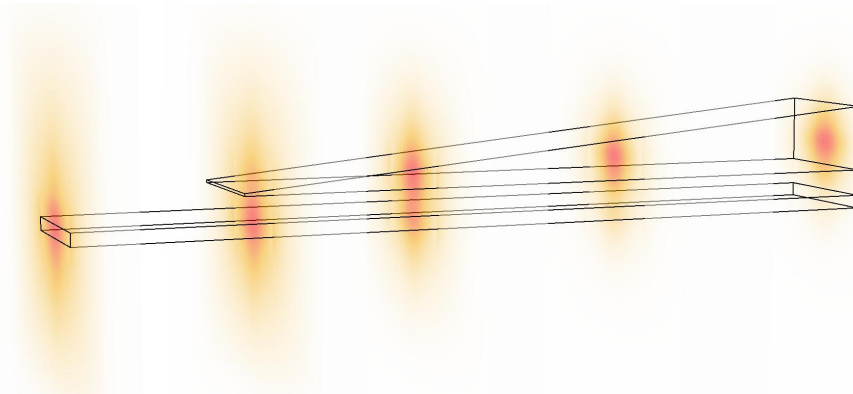


Fig 2: Illustration of the the simulated functionality of the combined double layer stack and inverse vertical waveguide taper for efficient coupling to high-confinement waveguides.

enables an experimental evaluation and separation of these losses. The underlying assumption of the method is that the coupling loss is identical for an ensemble of identically prepared samples, and that propagation losses depend linearly on the waveguide length. In this case a series of measurements of the total insertion loss for step wise reductions (cut backs) of the total propagation length enables an extraction of the loss suffered per unit length through a linear fit to the data. And by extrapolation the total coupling loss can be determined as the inflicted loss at zero length. The method has its origin in the fiber optics community where reduction of the propagation length can easily be done by cleaving the fiber. For integrated waveguides this is generally not possible, particularly not so when inverse waveguide tapers are employed for improved in and out coupling as is the case here. A common implementation of the method is instead to use a series of meander-type delay-line waveguides with different lengths (Fig. 3 (a)).

Figure 3(b) shows exemplary data for cut-back measurements on our devices. These measurements were taken using a lensed fiber for in-coupling and collecting the output with a high-NA objective (Spindler & Hoyer, x63/0.85.). The waveguide insertion loss is calculated relative to the transmission measured with the fiber output coupled directly to the objective. The corresponding fitting results are summarized in Table 1 below. For comparison a second cut-back measurement was performed on W2315-2/0D but using lensed fibers for both in- and out-coupling. The two measurements, plotted

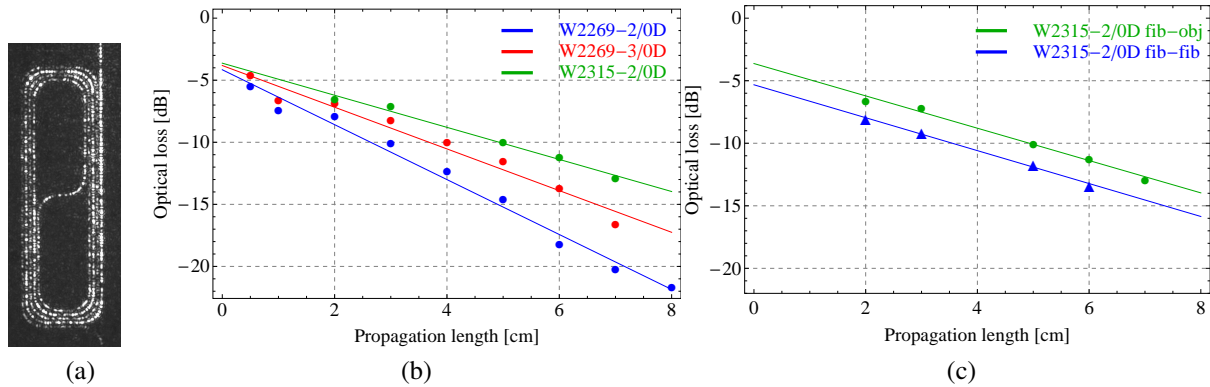


Fig 3: Determination of optical propagation loss using meander-type waveguide delay lines (a) for cut-back measurements. Measurements were performed using different lengths of meanders for (b) different waveguides and (c) for different coupling strategies.

together in Fig. 3(c), yield very similar propagation loss values but the coupling loss is 1.69 dB larger for the dual-fiber configuration. Consequently, we find a coupling loss of 2.66 dB/facet using lensed tapered fibers. Compared to the theoretically anticipated value of 0.75 dB/facet this result is much worse. One possible reason for the observed coupling loss is that the used lensed fibers did not produce Gaussian beam profiles with a mode field diameter of $1 \mu\text{m}$ as assumed for in the design of the inverse waveguide tapers. Whether a higher coupling efficiency can be reached with other tapered fibers coming closer to the design value of the beam diameter will be investigated further in the future. Also relevant would be to extend the above characterization by quantifying the separate contributions to the total measured loss due to scattering and linear absorption. A convenient technique for doing so has been presented by Borselli, et al.¹⁵

Chip ID#	Propagation loss [dB/cm]	Coupling loss [dB]
W2269-2/0D	2.21 ± 0.10	4.15 ± 0.47
W2269-3/0D	1.68 ± 0.13	3.81 ± 0.54
W2315-2/0D	1.29 ± 0.08	3.63 ± 0.40
*W2315-2/0D	1.31 ± 0.06	5.32 ± 0.25

Table 1: Fitted propagation and coupling loss from the cut-back measurements shown in Fig. 3 (b) and (c). Dual-fiber measurement result is marked with *.

For the purpose of squeezed light generation an optimal compromise between resonant enhancement of the intra-cavity field, ultimately limiting the attainable degree of squeezing, and the efficiency with which the generated squeezed field is collected from the resonator has to be identified. To this end we have studied the dependence of the optical quality factor of the race track resonators on the length of the coupling segment L_c . By simply imaging the resulting scattering from resonantly excited resonators for similar optical input powers we clearly see that intra-cavity power strongly depends on L_c , as illustrated in Fig. 4.

To quantify the dependence further, resonator quality factors were deduced from the transmission spectra from devices with varying coupling geometries with L_c values of 2, 5, 8, 9, and $10 \mu\text{m}$. The

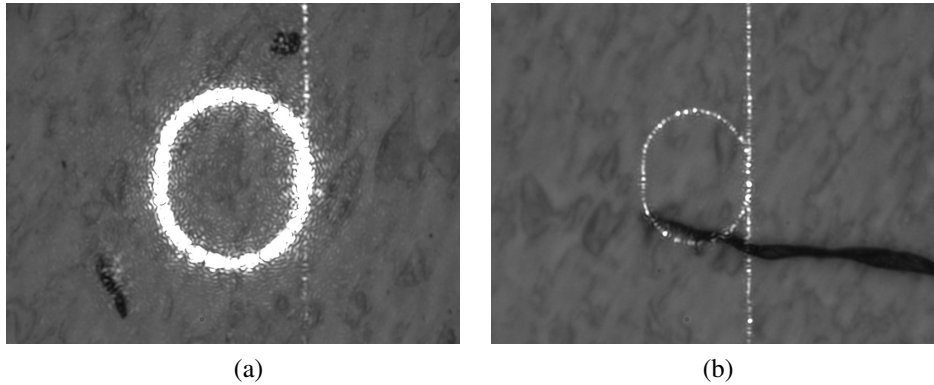


Fig 4: Observed scattering from two resonantly excited race track resonators. (a) High-Q resonator with $L_c = 2 \mu\text{m}$. (b) Low-Q resonator with $L_c = 10 \mu\text{m}$.

corresponding resonance scans and fitted quality factors are presented in Fig. 5, and we see that the devices generally show optical quality factors in the range of $Q = 10^4 - 10^5$.

4 Conclusion and Outlook

Simulations show that for squeezed light generation we will need to pump the resonator with about 200 mW shot-noise limited laser light. We characterized 2 mW of a continuous-wave Msquared SOLsTiS Titan-Sapphire laser and found it to be shot-noise limited in amplitude from about 3 MHz sideband frequency. Extrapolating our measurements to 200 mW we find that the laser should be shot-noise limited above about 7 MHz. The phase noise of the laser will be investigated in the future.

Due to the optical Kerr effect the squeezed light generated at sideband frequencies is co-propagating with a strong carrier laser beam. To be able to measure the squeezed light this strong laser beam has to be attenuated while at the same time the squeezed light has to be preserved. A possibility will be to introduce a filter cavity which transmits the carrier light, while reflecting the squeezed sidebands. We will investigate the inclusion of such an add-drop filter on the chip in the future. At the same time a single-ended cavity could be employed to rotate the squeezed quadrature angle with respect to the carrier to allow for full characterization of the squeezed field using self-homodyne detection.^{20,21}

While detecting the on-chip generated squeezed light will be the next step, we expect the squeezing degree to be mainly limited by optical loss due to inefficient fiber coupling. Achieving better coupling efficiencies, for instance by tuning the Gaussian mode profile given by the lensed fibers, has to be investigated as well as possible reductions of waveguide propagation loss. We note, however, that utilization of the squeezed light in an on-chip interferometer, will not suffer from these interface losses.

We anticipate an on-chip source for quadrature squeezed light to become an indispensable tool in integrated quantum photonics, e.g. for biological measurements, but also for quantum information tasks.²² Due to the standard fabrication process we expect that seamless integration into on-chip sensors and measurement devices will be possible.

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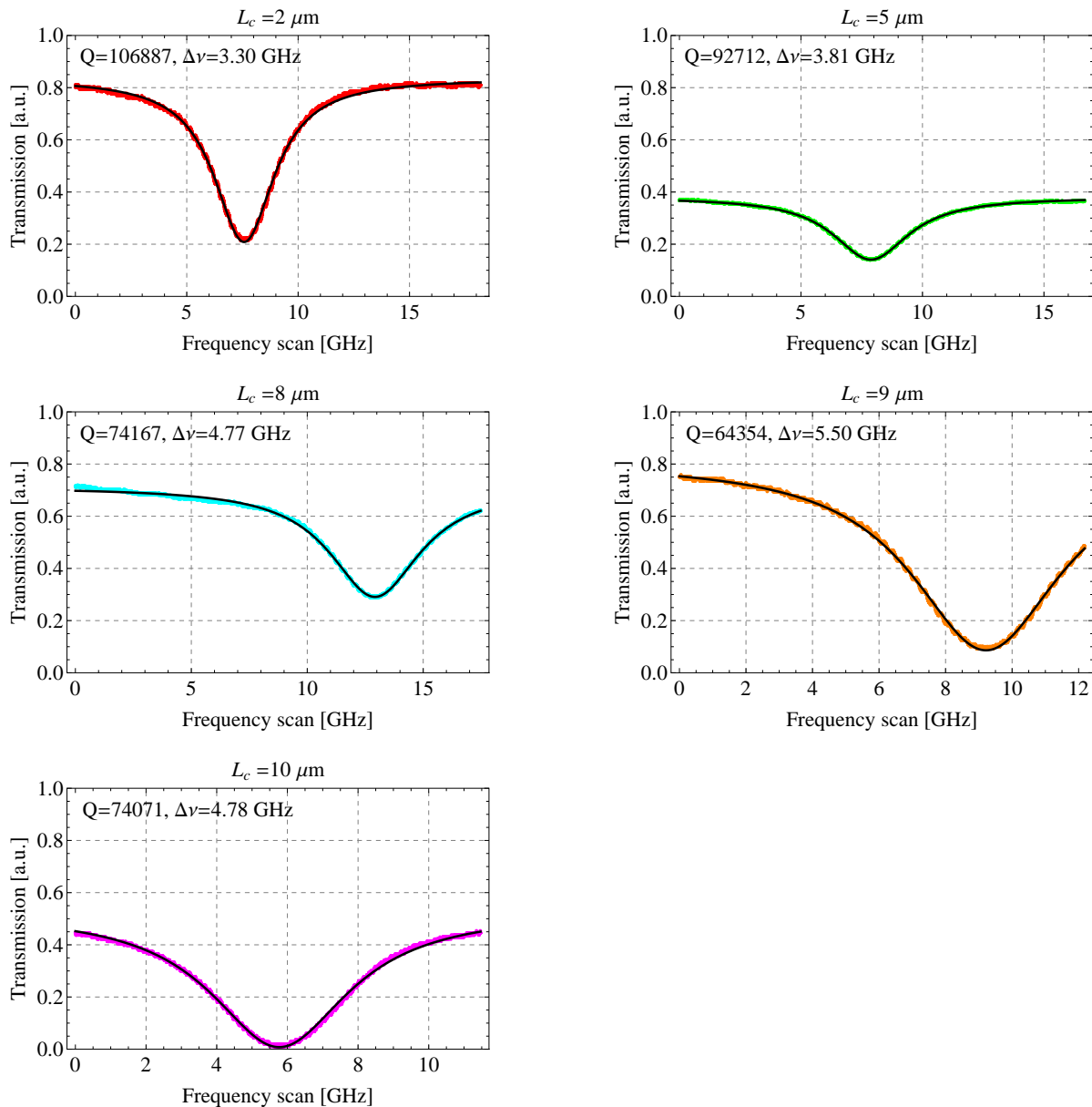


Fig 5: Resonance scans of race track resonators with varying coupling segment lengths, L_c .

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