Single-mode quadrature squeezing using dual-pump four-wave mixing in an integrated nanophotonic device

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Abstract

We report the generation of broadband single-mode (degenerate) quadrature squeezed vacuum from an integrated nanophotonic device based on two coupled silicon nitride microring resonators. Dual-pump spontaneous four-wave mixing in one microring resonator is exploited to generate squeezed light, while unwanted single-pump parametric fluorescence and Bragg-scattering four-wave mixing processes are suppressed by selectively corrupting individual resonances using a second, auxiliary resonator. Balanced homodyne detection is employed for quadrature measurements, with 1.5 dB of quadrature squeezing directly measured. We infer that approximately 6 dB of squeezing is present on-chip, before collection and detection losses.

1 Introduction

Squeezed light sources [1] are a fundamental building block of photonic technologies designed for continuous variable (CV) quantum information processing. Recently, much effort has gone into engineering scalable implementations of such sources using integrated photonics. Here high index-contrast nanophotonic platforms are preferred, as they enable large-scale integration with many hundreds or thousands of components on a single monolithic chip. Within the domain of nanophotonic structures, bright intensity-difference squeezing in a silicon nitride ring resonator driven above the parametric oscillation threshold has been demonstrated [2]. Similar structures driven below threshold have yielded two-mode (nondegenerate) quadrature squeezing and photon number difference squeezing [3]. Some squeezing in a single-mode degenerate configuration has been reported with microrings using a single pump [4], but this suffers from strong excess noise contributions arising from non-parametric effects such as thermorefractive fluctuation [5].

No nanophotonic device has yet been demonstrated which produces quadrature squeezed vacuum in a single, degenerate spectral mode, uncontaminated by excess noise from both non-parametric and unwanted parametric processes. A promising candidate has been proposed based on dual-pump spontaneous four-wave mixing in microring resonators [6, 7]: two classical pumps tuned to independent resonances can produce squeezing in a single, monochromatic, degenerate spectral mode. By using pumps very well separated in frequency from the squeezed mode, noise contributions from non-parametric effects like thermorefractive fluctuations can be avoided. However, in such a system a number of unwanted parametric effects add noise to the squeezing band, irreversibly corrupting the output. The primary culprit for such unwanted noise is single-pump parametric fluorescence [5] driven by the individual pumps; further degradation is caused by Bragg-scattering four-wave mixing [9], which can transfer energy away from the squeezed mode.
Both single-pump parametric fluorescence and Bragg-scattering four-wave mixing effects are strongly enhanced by the presence of resonances that are otherwise unimportant for the desired dual-pump squeezing dynamics. These processes, and the associated resonances involved, are illustrated in Fig. 1(a). To suppress the unwanted processes, it suffices to design a structure for which the two resonances labelled X1 and X2 are removed or suitably corrupted, without significantly degrading the properties of the resonances used for the two pumps and the signal, labelled P1 and P2, and S, respectively. To that end, a multi-resonator structure was designed; as shown in Fig. 1(b), by tuning the auxiliary resonator such that the X1 and X2 resonances of the principal resonator nearly coincide in frequency with resonances of the auxiliary resonator, the resultant hybridized resonances become strongly split and detuned from their original frequencies. The unwanted parametric processes involving the X1 and X2 resonances are thereby highly suppressed. Since this modification to the X1 and X2 resonances occurs without having a significant impact on the P1, P2, and S resonances of the principal resonator, strong enhancement of the desired squeezing process is maintained. This enables degenerate squeezing to be produced without significant degradation from unwanted single-pump parametric fluorescence and Bragg-scattering four-wave mixing. Similar multi-resonator schemes have been used to enable unidirectional frequency conversion [10] and dispersion compensation [11].

In this note we summarize our experimental characterization of this device and the squeezing it generates in the dual-pump configuration, and quantify the degree to which excess noise from unwanted single-pump parametric effects is suppressed by the presence of the auxiliary resonator.

Figure 1: (a) Idealized resonance structure of a single ring resonator, showing the four-wave mixing processes that occur when two resonances P1 and P2 are pumped. (b) Idealized resonance structure of a composite multi-resonator structure, showing the splitting and detuning of the X1 and X2 resonances that arises from the strong linear coupling between the principal and auxiliary resonator. In both cases the desired process, dual-pump spontaneous four-wave mixing (DP-SFWM, shown in green), leads to squeezing of the S mode. The unwanted processes of single-pump spontaneous four-wave mixing (SP-SFWM, red) generate excess noise in the S mode, contaminating the output, while Bragg-scattering four-wave mixing (BS-FWM, orange) transfers photons away from the S mode as photons are exchanged between the two pumps. Both these unwanted processes are suppressed by the presence of the auxiliary resonator, without significantly affecting the desired squeezing process.
Figure 2: (a) Micrograph of the multi-resonator structure. The principal resonator is on the left, coupled at the bottom to a bus waveguide. The smaller ring on the right acts as the auxiliary resonator. (b) Measured TE polarization transmission spectrum (normalized to 0 dB) of the device in the wavelength range of interest. The resonances of the principal resonator are labelled $P_1$, $S$, and $P_2$; the hybridized (split and detuned) resonances of the principal and auxiliary resonators – here labelled $X_1$ and $X_2$ – are evident. Also evident are two resonances of the auxiliary resonator, which are indirectly weakly coupled to the bus waveguide via the principal resonator. The asymmetric extinction of the two split peaks in each of the $X_1$ and $X_2$ resonances is not an important feature; the extinctions can be made equal by slightly further tuning of the auxiliary resonator.

2 Results

The device was fabricated on a commercial stoichiometric silicon nitride strip waveguide platform offered by Ligentec SA. The Si$_3$N$_4$ waveguide cross-section is 1500 nm × 800 nm (width × thickness) and is fully clad in SiO$_2$. This platform and cross-section were selected for low propagation loss, lack of two-photon absorption, and high third-order optical nonlinearity. Independent microheaters were overlaid to provide thermal tuning of the individual resonators. The principal resonator was designed to have radius $R = 114 \mu m$, and the auxiliary resonator to have radius $0.75 \times R$, leading to free spectral ranges of 200 GHz for the principal resonator, and 267 GHz (approximately one third larger) for the auxiliary resonator. A micrograph of the device and the measured transmission spectrum of the fundamental TE resonances in the wavelength range of interest are exhibited in Fig. 2(a) and Fig. 2(b), respectively. The auxiliary resonator microheater was tuned to guarantee spectral alignment of the resonances associated with the auxiliary and principal resonator, leading to the formation of hybrid, split resonances associated with the unwanted single-pump parametric fluorescence and Bragg-scattering four-wave mixing. Three resonances of the principal resonator are preserved, displaying un-split Lorentzian lineshapes with associated quality factors of approximately $3 \times 10^5$. These resonances are strongly over-coupled with escape efficiency approximately 90%.

To generate and measure squeezing, three phase- and frequency-locked beams were generated. Two of these were amplified and filtered to serve as pumps, while the other beam was filtered and reserved for a use as a local oscillator (LO). The process used to generate the three beams ensures that the local oscillator frequency is precisely equal to the average frequency of the pumps. Light was coupled into and out of the chip via edge couplers using ultrahigh numerical aperture (UHNA7) fiber, with index matching gel used to suppress reflections at the facets. One pump was tuned to the resonance near 1560.9 nm (the $P_2$ resonance), and the principal resonator was actively locked to this pump to maximize the circulating pump power in the principal ring. The frequency of the other pump was tuned to a second resonance near 1557.7 nm ($P_1$). The pump powers were set to be equal, corresponding to approximately 50 mW of power in each pump on-chip.

The generated light in the signal resonance was separated from the pumps by wavelength division multiplexing filters, and mixed with the LO on a variable fiber beamsplitter set to 50/50 splitting ratio.
Figure 3: (a) Measured squeezing and anti-squeezing spectrum from 20 MHz to 1 GHz, normalized to shot noise at each sideband frequency. (b) Quadrature variance at 20 MHz sideband frequency (blue trace), plotted as a function of time as the LO phase is ramped. Black trace is the shot noise level.

The outputs of the beamsplitter were directed to a commercial balanced receiver (Wieserlabs), and the resultant difference photocurrent recorded using an electrical spectrum analyzer (Keysight, RBW 1 MHz, VBW 100 Hz). The homodyne detection system had a dark noise clearance of at least 13 dB across the sidebands measured, and was operated in well within the linear response regime. The full collection and detection efficiency was approximately 38% (34% when resonator escape efficiency is included).

The measured squeezing and anti-squeezing spectrum is shown in Fig. 3(a) from 20 MHz to 1 GHz; a representative quadrature variance trace at 20 MHz sideband as the LO phase is ramped is shown in Fig. 3(b). Approximately 1.5 dB of squeezing is directly observable, with about 4.3 dB of anti-squeezing. From this we estimate the on-chip squeezing available before outcoupling to be approximately 6 dB. The degree of antisqueezing and squeezing observed are consistent with the independently estimated 34% total system efficiency.

To assess the importance of the auxiliary resonator in suppressing unwanted processes, the parametric fluorescence noise spectrum generated in the $S$ mode was measured with only the pump at $P1$ turned on. The results are shown in Fig. 4 for a range of voltages applied to the auxiliary resonator. When the auxiliary resonator is tuned such that the $X1$ resonance is no longer affected, a strong noise contribution – more than 1.2 dB above shot noise from each pump – on all quadratures is observed. This excess noise is reduced to less than 0.1 dB above shot noise when the auxiliary resonator is tuned appropriately. In the absence of the auxiliary resonator, several dB of excess noise would therefore be present in $S$ mode, severely degrading the squeezing possible and purity of the generated quantum state.

3 Conclusion

We have demonstrated that suppression of unwanted parametric processes is a crucial consideration in designing integrated single-mode squeezed light sources based on four-wave mixing. A multi-resonator structure was designed to selectively suppress unwanted processes by corrupting resonances associated with their enhancement, without significantly affecting the squeezing process. Degenerate quadrature squeezed vacuum with a noise reduction of 1.5 dB below shot noise was directly observed, corresponding to an inferred 6 dB of squeezing available on-chip before collection and detection losses.
Figure 4: Single-pump parametric fluorescence spectrum (normalized to shot noise) in the $S$ mode, measured using homodyne detection with one pump turned off. The blue trace is taken with the auxiliary resonator tuned such that the $P1$, $S$, and $X1$ resonances are not significantly coupled to the principal resonator, effectively disabling the noise suppression, resulting in the contamination of the signal mode with broadband unwanted noise. The orange trace is taken with the auxiliary resonator tuned to split the $X1$ and $X2$ resonances (Fig. 2(b)), suppressing the noise to less than 0.1 dB above shot noise over the entire measurement band.
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