Low-noise, tunable wavelength-conversion through non-degenerate four-wave mixing Bragg scattering in SiN\textsubscripts{x} waveguides

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Low-noise, tunable wavelength-conversion through non-degenerate four-wave mixing Bragg scattering in SiN\textsubscripts{x} waveguides is experimentally demonstrated. Finite element method simulations of waveguide dispersion are used with the split-step Fourier method to predict device performance. Two 1550 nm wavelength band pulsed pumps are used to achieve tunable conversion of a 980 nm signal over a range of 5 nm with a peak conversion efficiency of \( \approx 5\% \). The demonstrated Bragg scattering process is suitable for frequency conversion of quantum states of light. © 2014 Optical Society of America

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Four-wave mixing in optical fibers has led to parametric amplifiers, oscillators, and wavelength converters [1]. Such behavior has recently been shown in chip-based devices [2], where the strong modal confinement and large \( \chi^{(3)} \) in silicon and silicon nitride (SiN\textsubscripts{x}) waveguides (WGs) enhance the effective nonlinearity compared to fiber, and where group velocity dispersion (GVD) can be tailored to achieve phase matching [3]. Much focus is on the configuration in which a degenerate pump beam is placed near the zero GVD point WG, amplifying a weak input and simultaneously generating a symmetrically-situated idler in frequency space. This has been used to show parametric gain in WGs [4] and frequency comb generation in microresonators [5,6]. However, from the perspective of quantum frequency conversion [7], there is a fundamental problem, as signal amplification comes with amplified vacuum fluctuations, preventing noiseless operation [8]. This process, essential for connecting quantum systems operating at disparate wavelengths, has been applied to single photon states through through sum-frequency-generation in a few cm-long quasi-phase-matched WG [9] and four-wave-mixing Bragg scattering (FWM-BS) in a several meter long photonic crystal fiber [10]. Here, we make progress towards quantum frequency conversion in an integrated platform by demonstrating FWM-BS in SiN\textsubscripts{x} WGs. We show tunable conversion of 980 nm signals via non-degenerate 1550 nm band pumps, with a conversion efficiency reaching 5%.

In FWM-BS, two non-degenerate pumps at frequencies \( \omega_1 \) and \( \omega_2 \) (\( \omega_1 > \omega_2 \)) scatter photons from a signal at \( \omega_s \) to an idler at \( \omega_i \) [11]. From conservation of energy, idlers can be produced at \( \omega_i = \omega_s \pm (\omega_1 - \omega_2) \) (Fig. 1(a)), and phase matching, effective nonlinearity, interaction length, and pump powers determine the conversion efficiency. FWM-BS directly transfers power from signal to idler, rather than from the pumps to the signal and idler. This avoids excess noise associated with parametric gain processes such as modulation interaction, which amplify vacuum fluctuations [8]. Conversion over both small and large wavelength separations is possible if phase-matching can be obtained.

We are interested in quantum frequency conversion of \( \approx 980 \) nm signals, for eventual use with fiber-coupled quantum dot (QD) single photon sources [12]. Conversion is achieved using two 1550 nm band pumps (Fig. 1(a)), where the use of far red-detuned pumps with respect to the signal avoids amplified spontaneous emission from the pumps and potential Raman scattering, an important noise source in fibers [13]. Spontaneous FWM is also avoided, as the process is not phase matched in our waveguides. Together, this ensures that background-free conversion can be achieved. As our pump wavelength separation is limited to 30 nm, the signal will be translated by at most \( \approx 12 \) nm. Such narrowband conversion can restore spectral indistinguishability of independent QD single photon sources. Broader conversion ranges are also of interest [9], and a \( > 100 \) nm conversion range is theoretically possible in the geometries shown here.

We calculate transverse electric polarized modes for a 550 nm tall rectangular SiN\textsubscript{x} WG on a SiO\textsubscript{2} bottom cladding (Fig. 1(b)) over a range of width \( w \) and wavelength, allowing us to estimate dispersion relations and FWM nonlinearity. Figure 1(c) shows a plot of the dispersion parameter \( D = \frac{-2 \pi c d^2}{\lambda^2 \alpha_w^2} \) (\( c \) is the speed of light and \( \beta \) is the WG propagation constant) for \( w=800 \) nm, 1000 nm, and 1200 nm WGs, indicating that as \( w \) increases, the dispersion becomes flatter and its zero point red-shifts. Since we are targeting conversion in the 980 nm band via 1550 nm band pumps, we choose dimensions for which the dispersion zero is close to 1200 nm [11]. Conversion efficiency as a function of pump power (the pumps have equal power) is then calculated via analytical expressions based on coupled mode theory in the non-depleted pump regime [1,11] and a full-field split-step Fourier numerical simulation [1], using a WG loss of 1 dB/cm, ellipsometric measurements of the SiN\textsubscript{x} and SiO\textsubscript{2} linear refractive indices, and a nonlinear refractive index \( n_2 = 2.5 \times 10^{-19} \text{m}^2 \text{W}^{-1} \) [14] that yields an effective nonlinearity parameter \( \gamma \text{eff} \approx 6.3 \text{ W}^{-1} \text{m}^{-1} \) for \( w=1200 \) nm. While the analytical solution is valid at low pump powers, it fails to account for pump depletion and effects such as multi-frequency Bragg scattering (due to secondary generated pumps). The split-step Fourier simulation alleviates this since the single field
launched into the simulation includes all frequencies between the pumps and signal/idlers, with a spectral resolution finer than the pulse bandwidth. Moreover, it takes into account higher-order dispersion (8 orders are included) and pulse-broadening and temporal walk-off effects, which can be important for short pulses and wide frequency separations. Figure 1(d)-(e) shows the results for 12 mm long WGs with w=1200 nm and w=1000 nm, respectively. Both red- and blue-detuned idlers are generated (both are nearly phase-matched) with conversion efficiencies as high as 20 % predicted by the split-step calculation. Pump depletion and mixing lead to the discrepancy between the split-step and analytic results at high powers, as > 40 % of the pump power is consumed by pump mixing for an input power of 10 W.

We fabricate 12 mm long WGs (Fig. 1(b)) through a process similar to that in Ref. [6]. Devices are measured using the setup in Fig. 2(a). To measure conversion bandwidth, two amplified 1550 nm band continuous wave (cw) pumps are combined with a weak signal at 977.4 nm and sent into 1000 nm and 1200 nm wide WGs via a lensed optical fiber. Light is collected at the WG output with a lensed fiber and routed to a wavelength division multiplexer (WDM) that separates the pumps from the signal and idlers. The pumps are monitored on an optical spectrum analyzer (OSA), while a grating spectrometer with a silicon CCD measures the generated idlers and residual signal, which is suppressed by 53 dB using a fiber Bragg grating (FBG) placed before the spectrometer input. Pump 1 is swept between 1535 nm and 1565 nm, while pump 2 is fixed at 1565 nm. Both FWM-BS generated $\omega_i^\pm$ idlers are visible around the signal, and move symmetrically away from it as the separation between the pumps increases (Fig. 2(b)), in agreement with energy conservation. The bandwidth can be deduced from Fig. 2(c), where the internal conversion efficiency $P_i/P_s$ for both idlers is plotted ($P_i$, $P_s$ are the idler and signal powers at the WG output). The 1200 nm WG has a broader conversion bandwidth than the 1000 nm WG.

To reach the high peak powers needed for more efficient conversion, pulses from a 80 MHz repetition-rate mode-locked laser are filtered by 1 nm wide bandpass filters at 1550 nm and 1559 nm. The pulses, with a full-width at half-maximum of 4.2 ps± 1 ps, are each amplified by a 1 W erbium-doped fiber amplifier (EDFA) and temporally overlapped by a tunable optical-delay line before being combined with a weak 979 nm cw signal and sent into the WG. To determine peak power while avoiding spurious effects in the OSA, the average power is first measured at low amplification and scaled by the duty cycle. An auxiliary SiN$_x$ WG showing efficient 3rd harmonic generation is used to calibrate peak powers at higher amplification, due to its cubic scaling with peak power. This allows an estimate of the maximum peak power in the WG of $\approx$ 6.8 W (accounting for $\approx$ 6 dB coupling loss per facet). Keeping the pump and signal wavelengths at 1559 nm, 1550 nm, and 979 nm, the coupled power is varied between 0.5 W and 6.8 W, and the converted idlers are measured at the WG output. The conversion efficiency, which takes into account that the signal is cw while the pumps are pulsed, is determined by integrating over the idler spectrum, scaling by the pulse duty cycle, and dividing by the integrated signal power.

Figure 3(a) shows conversion efficiency for the blue-shifted idler as a function of peak pump power. The data follows the calculated trend and reaches $\approx$ 2.5 %. When the longer wavelength pump is moved to 1557 nm, where the laser power is higher and phase-mismatch is reduced, the conversion efficiency increases to $\approx$ 5 % (inset to Fig. 3(a)). Higher efficiency may be possible with increased pump power (Fig. 1(d)), longer WGs, and more precise dispersion tailoring. In particular, the measured conversion efficiency is consistently lower than predicted.

While imprecise knowledge of the effective nonlinearity and WG input power plays a role in the discrepancy, simulations indicate that non-optimal dispersion can be a dominant factor. An inaccurate estimate of the WG dimensions (by $\approx$ 25 nm) can cause significant changes in the predicted conversion efficiency, with a stretching and shifting of the peaks in Fig. 1(a) to higher powers.

We next studied the 1000 nm width WG using 1 ns long pulses created by electro-optically modulating and amplifying 1559 nm and 1550 nm cw lasers to achieve similar peak powers as the ps pulse experiment. This ns regime is of particular importance for wavelength conversion of single photons from QDs, whose radiative lifetime is $\approx$ 1 ns. Figure 3(b) shows the conversion efficiency as a function of pump power, reaching a maximum of 1.3 %,
The background-free nature of this approach should enable length conversion in a silicon nitride waveguide through the detector dark count level. A 12 dB fiber-to-fiber loss, which is an order of magnitude noise above the detector dark counts, was likely due to damage to the WGs during the course of data accumulation (data was recorded from high to low levels). The two pumps have equal power which is around half the efficiency of the 1200 nm WG at the same peak power. The loss of conversion and deviation from the predicted trend at lower powers is most likely due to damage to the WGs during the course of data accumulation (data was recorded from high to low power), resulting from the high pulse energies.

Despite the high pump energies, no excess noise was seen in the conversion bands (Fig. 2(d)). To confirm this, photon counting measurements were performed. A 0.2 nm bandwidth grating filter was spectrally aligned to the blue-detuned idler, and the output light was detected by a Si single photon counter with the 1550 nm pump fields kept on and the 979 nm signal turned off. No excess noise above the detector dark counts (∼100 s⁻¹) was measured. Thus, an input single photon source producing 10⁶ photons/s [12] should yield a frequency-converted flux > 10³ photons/s (at > 2% conversion efficiency and 12 dB fiber-to-fiber loss), which is an order of magnitude above the detector dark count level.

In conclusion, we have demonstrated chip-scale wavelength conversion in a silicon nitride waveguide through the process of four-wave mixing Bragg scattering. The background-free nature of this approach should enable frequency conversion of quantum states of light.

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