Large Effective $\chi^{(2)}$ Nonlinearity on a Si_3N_4-Chip

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Using coherent photon conversion (CPC) we generate large effective $\chi^{(2)}$ nonlinearities in a $\chi^{(3)}$-nonlinear Si_3N_4 microring-resonator and measure an effective second harmonic generation efficiency of 77%/mW.

It is believed in nonlinear optics that intrinsic material nonlinearities would be far too weak to allow for efficient nonlinear interactions of single photons. This has been challenged by the coherent photon conversion (CPC) scheme [1]: strongly pumping one of the modes in a four-wave mixing (FWM) process one can generate an effective $\chi^{(2)}$ nonlinearity for the remaining three fields (Fig. 1a). In principle, this effective $\chi^{(2)}$ interaction can be made arbitrarily large by increasing the pump power and thus theoretically allowing for efficient single photon level $\chi^{(2)}$ nonlinearities [1]. Experiments implementing CPC at low efficiencies using photonic crystal fibers [1], chalcogenide nanofibers [2] and resonant $\chi^{(3)}$-nonlinearities in warm Rb-vapor [3] have concentrated on effective spontaneous parametric down-conversion. However, CPC can realize any effective 2nd order nonlinear process: when two of the three interacting fields are degenerate the resulting interaction is analogue to second harmonic generation (SHG), albeit with non-harmonic frequencies (Fig 1a). SHG has been a landmark phenomenon of $\chi^{(2)}$ nonlinear optics [4]. Currently, the most widely used $\chi^{(2)}$-material is Lithium Niobate (LN) because of its high intrinsic nonlinearity. Normalized SHG efficiencies in LN waveguides up to 5.4%/mW [5], and 0.1%/mW [6] in integrated and 300%/mW [7] in bulk LN microcavities, have been demonstrated.

Here, utilizing an on-chip high-Q Si_3N_4 microring resonator we generate a strong effective $\chi^{(2)}$ nonlinearity using the CPC scheme and experimentally realize effective SHG with a normalized efficiency of 77%/mW, which is an order of magnitude higher than in LN waveguides and in the range of those observed in LN microcavities.

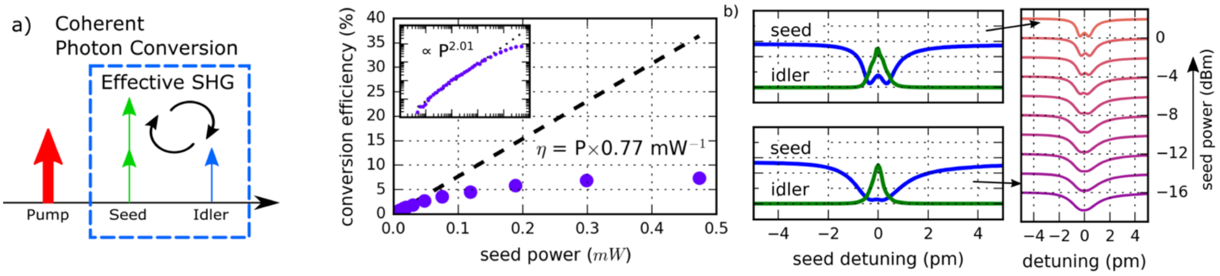

Figure 1. a) CPC energy scheme: a strong pump field in a FWM process drives an effective SHG-interaction between the remaining fields. b) Inferred on-chip SHG efficiency as function of seed power. Fitting the linear, unsaturated part (dashed line) yields a normalized efficiency of 77%/mW. Inset: double-logarithmic plot of the idler power vs. seed power showing the quadratic scaling of effective SHG process. c) 1250 nm power (green) as the 1400 nm seed (blue) is scanned across the resonance for increasing seed power levels. At high, saturated efficiencies the strong induced coupling between 1250 nm and 1400 nm via effective SHG leads to a characteristic splitting of the resonance.

Our on-chip microring resonators were formed by Si_3N_4 waveguides fully clad with SiO^2. Their dimension of 730 nm x 910 nm was designed to yield zero group velocity dispersion (GVD) at 1400 nm. This ensures phase-matching for the pump at 1590 nm and the seed and idler fields (1400 nm and 1250 nm) for which the effective SHG process is induced. With a radius of 45um the microring resonators has a free spectral range of 500 GHz and exhibits loaded Q-factors of 350,000 for the pump (over-coupled), 1.2 million for the seed (close to critical coupling) and 3.5 million for the idler (under-coupled). For our measurements we combine the pump at 1590 nm, which is amplified with an EDFA to 230 mW, with a tunable seed laser at 1400 nm. They are injected into the chip (and collected) via lensed fibers. We then measure 1400 nm seed transmission and generated 1250 nm idler power using filters, InGaAs photodiodes, and for low idler levels a superconducting single-photon detector.

We measure the generated idler power for seed powers ranging over 4 orders of magnitude from 37 nW to 47 μW (Fig 1b). We observe an on-chip, effective SHG efficiency of 77 %/mW, which saturates at 7%. Fitting a power law in the unsaturated region yields an exponent of 2.01 unambiguously verifying the effective SHG quadratic scaling. The saturation starting at ~1% efficiency is a consequence of the modified resonance conditions due to the strong induced coupling of the 1250 nm and 1400 nm resonance. It leads to a characteristic splitting of the resonance, which we indeed observe in the 1400 nm spectra (Fig 1c). A similar phenomenon occurs for SHG in LN microcavities [7], and for Bragg scattering frequency conversion in microrings [8,9].

In conclusion, using the CPC-scheme we realize effective SHG with a normalized efficiency of 77%/mW, an order of magnitude larger than in LN waveguides, with the perspective of reaching efficient single photon nonlinearities by harnessing the rapid advancement of ultra-high-Q microresonator technology.

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978-1-5090-6736-7/17/$31.00 ©2017 IEEE