On-chip optical parametric oscillation into the visible: generating red, orange, yellow, and green from a near-infrared pump: supplement

Xiyuan Lu,1,2,5 Gregory Moille,1,3 Ashutosh Rao,1,4 Daron A. Westly,1 and Kartik Srinivasan1,3,*

1Microsystems and Nanotechnology Division, Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
2Institute for Research in Electronics and Applied Physics and Maryland NanoCenter, University of Maryland, College Park, Maryland 20742, USA
3Joint Quantum Institute, NIST/University of Maryland, College Park, Maryland 20742, USA
4Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA
5e-mail: xiyuan.lu@nist.gov
*Corresponding author: kartik.srinivasan@nist.gov

This supplement published with The Optical Society on 12 October 2020 by The Authors under the terms of the Creative Commons Attribution 4.0 License in the format provided by the authors and unedited. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

Supplement DOI: https://doi.org/10.6084/m9.figshare.12907487
Parent Article DOI: https://doi.org/10.1364/OPTICA.393810
On-chip optical parametric oscillation into the visible: generating red, orange, yellow, and green from a near-infrared pump: Supplementary Material

Xiyuan Lu\textsuperscript{1,2,5}, Gregory Moille\textsuperscript{1,3}, Ashutosh Rao\textsuperscript{1,4}, Daron A. Westly\textsuperscript{1}, and Kartik Srinivasan\textsuperscript{1,3,*}

\textsuperscript{1}Microsystems and Nanotechnology Division, Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA
\textsuperscript{2}Institute for Research in Electronics and Applied Physics and Maryland NanoCenter, University of Maryland, College Park, MD 20742, USA
\textsuperscript{3}Joint Quantum Institute, NIST/University of Maryland, College Park, MD 20742, USA
\textsuperscript{4}Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742, USA
\textsuperscript{5}e-mail: xiyuan.lu@nist.gov
\textsuperscript{*}Corresponding author: kartik.srinivasan@nist.gov

Compiled August 25, 2020

This document presents an estimate of threshold powers and details on fabrication.

I. THRESHOLD ESTIMATION

The threshold of a $\chi^{(3)}$ OPO in microring can be estimated by \cite{1}, assuming perfect frequency and phase matching,

$$P_{th} = \frac{\omega_p Q_{cp}^2}{Q_{tp}^2 V_{tp}^2 Q_{ts} Q_{li}} \frac{e_0 n_{ipsp}^4 V_{ipsp}}{6 n_{ipsp} \chi_{ipsp}^{(3)}}. \quad (S1)$$

where $\omega_p$ is the pump angular frequency, $Q_{cp}$ and $Q_{tp}$ are the coupling and loaded quality factors for the pump mode. $Q_{ts}$ and $Q_{li}$ are the loaded quality factors for signal and idler modes. $e_0$ is the vacuum permittivity constant. $n_{ipsp}$, $V_{ipsp}$, and $\eta_{ipsp}$ are average index, mode volume, and mode overlap for the degenerate four-wave mixing interaction. $\chi_{ipsp}^{(3)}$ is calculated from the $n_2$ value \cite{2} following $\chi^{(3)} = \frac{3}{2} n^2 e_0 c / n_2$, where $n$ is the refractive index and $c$ is the speed of light.

We cannot extract accurate values for the quality factors of the signal and idler modes because of our lack of suitable tunable lasers in those bands, so in the table below, we consider two likely extremes ($Q_{ts}=Q_{li}=1\times10^6$ and $Q_{ts}=Q_{li}=1\times10^5$). The mode volume and mode overlap are extracted from simulations for pump, signal, and idler around 390 THz, 265 THz, and 515 THz. These values depend on wavelengths, but are at similar levels for different OPO signal-idler combinations. With these assumptions in mind, we provide a rough estimate of the expected thresholds using the values in Table S1. This range of estimated thresholds is consistent with those measured in the experiments (Fig. 3(c) and Fig. 4(d)). A better understanding of resonator loss and waveguide-resonator coupling in the visible band is clearly important in future work, to optimize both the threshold as well as the out-coupled power.

Table S1. Parameters in use to estimate the threshold power of the widely-separated OPO. $Q_{cp}$ and $Q_{tp}$ are the estimated values from experiments, where $Q_{tp} \approx 1.5 \times 10^6$ and the cavity mode is undercoupled ($Q_{cp} > Q_{tp}$). Threshold power depends on $Q_{ts}$ and $Q_{li}$ values, and is $\approx 2.8$ mW for signal and idler modes with similar Q ($10^6$) to the pump. Mode volume and mode overlap are from finite-element-method simulation.

| $P_{th}$ | $\omega_p / (2\pi)$ | $Q_{cp}$ | $Q_{tp}$ | $Q_{ts}$ | $Q_{li}$ | $n_{ipsp}$ | $V_{ipsp}$ | $\eta_{ipsp}$ | $\chi_{ipsp}^{(3)}$ |
|----------|----------------------|----------|----------|----------|----------|-----------|-----------|-------------|----------------|
| 28 mW    | 390 THz              | $3.0 \times 10^6$ | $1.0 \times 10^6$ | $0.1 \times 10^6$ | $0.1 \times 10^6$ | 2.0        | 26.6 µm$^3$| 0.94        | $3.39 \times 10^{-21}$ m$^2$/V$^2$ |
| 2.8 mW   | 390 THz              | $3.0 \times 10^6$ | $1.0 \times 10^6$ | $1.0 \times 10^6$ | $1.0 \times 10^6$ | 2.0        | 26.6 µm$^3$| 0.94        | $3.39 \times 10^{-21}$ m$^2$/V$^2$ |
**Supplementary Material 2**

---

**Fig. S1.** $\chi^{(2)}$ versus $\chi^{(3)}$ OPO for visible light generation. (a) The comparison of two schemes of OPO to achieve the result we have shown in this work. Third-order OPO requires an infrared pump at 768 nm, while second-order OPO would require an ultra-violet pump at 384 nm. (b) The material dispersion is much larger at shorter wavelengths. For example, silicon nitride’s dispersion is 11 times larger at 384 nm than at 768 nm, which makes the device design far more challenging.

**II. $\chi^{(2)}$ VERSUS $\chi^{(3)}$ OPO FOR VISIBLE LIGHT GENERATION**

In the main text, we discuss the challenge of achieving such widely-separated OPO via a $\chi^{(2)}$ process, due to the laser requirement and dispersion at shorter wavelengths. In this section, we qualitatively discuss the required laser wavelength and also the corresponding material dispersion, as shown in Fig. S1(a,b). We can clearly see that, in the $\chi^{(2)}$ OPO regime, a UV pump laser is already required to generate the same OPO output frequencies shown in this work, and the dispersion at such a pump frequency is over 11 times that of the dispersion at the pump frequency in our $\chi^{(3)}$ OPO scheme. To generate light even deeper into the visible (e.g., blue, cyan, violet), although both approaches become more challenging, the $\chi^{(3)}$ scheme still allows for visible pump lasers to be used (e.g., 636 nm pump to generate 400 nm signal and 1550 nm idler), while the $\chi^{(2)}$ scheme eventually requires deep-UV pump sources (e.g., 318 nm pump to generate 400 nm signal and 1550 nm idler).

**III. FABRICATION METHODS**

The device layout was done with the Nanolithography Toolbox, a free software package developed by the NIST Center for Nanoscale Science and Technology [3]. The $\text{Si}_3\text{N}_4$ layer is deposited by low-pressure chemical vapor deposition on top of a 3 $\mu$m thick thermal $\text{SiO}_2$ layer on a 100 nm diameter Si wafer. The wavelength-dependent refractive index and the thickness of the layers are measured using a spectroscopic ellipsometer, with the data fit to an extended Sellmeier model. The device pattern is created in positive-tone resist by electron-beam lithography. The pattern is then transferred to $\text{Si}_3\text{N}_4$ by reactive ion etching using a $\text{CF}_4/\text{CHF}_3$ chemistry. The device is chemically cleaned to remove deposited polymer and remnant resist, and then annealed at 1100 °C in an N$_2$ environment for 4 hours. An oxide lift-off process is performed so that the microrings have an air cladding on top, while the input/output edge-coupler waveguides have $\text{SiO}_2$ on top to form more symmetric modes for coupling to optical fibers. The facets of the chip are then polished for lensed-fiber coupling. After polishing, the chip is annealed again at 1100 °C in an N$_2$ environment for 4 hours.

Dilute hydrofluoric acid (DHF) etching is used as a post-processing technique that isotropically removes $\text{Si}_3\text{N}_4$ with sub-nanometer control, providing a level of geometric control beyond what we achieve through electron-beam lithography and dry etching. Using a dilution of 100:1 (H$_2$O:HF), a $\text{Si}_3\text{N}_4$ etch rate of 0.4 nm/min is achieved (the correspond $\text{SiO}_2$ etch rate is 8 nm/min). We also note that DHF etching can also improve resonator quality factor; for example, $>2\times$ improvement in Q values are often observed.

**REFERENCES**

1. X. Lu, G. Moille, A. Singh, Q. Li, D. A. Westly, A. Rao, S.-P. Yu, T. C. Briles, S. B. Papp, and K. Srinivasan, “Milliwatt-threshold visible–telecom optical parametric oscillation using silicon nanophotonics,” Optica 6, 1535–1541 (2019).
2. K. Ikeda, R. E. Saperstein, N. Alic, and Y. Fainman, “Thermal and Kerr nonlinear properties of plasma-deposited silicon nitride/silicon dioxide waveguides,” Opt. Express 16, 12987–12994 (2008).

3. K. C. Balram, D. A. Westly, M. I. Davanco, K. E. Grutter, Q. Li, T. Michels, C. H. Ray, R. J. Kasica, C. B. Wallin, I. J. Gilbert, B. A. Bryce, G. Simelgor, J. Topolancik, N. Lobontiu, Y. Liu, P. Neuzil, V. Svatos, K. A. Dill, N. A. Bertrand, M. Metzler, G. Lopez, D. Czaplewski, L. Ocola, K. A. Srinivasan, S. M. Stavis, V. A. Aksyuk, J. A. Liddle, S. Krylov, and B. R. Ilic, “The nanolithography toolbox,” J. Res. Natl. Inst. Standards Technol. 121, 464–475 (2016).