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Continuous-wave optical parametric oscillation
tunable up to 8 µm wavelength

Ingo Breunig$^{1,2}$, Josef Urban Fürst$^1$, Kevin Hanka$^1$, and Karsten Buse$^{1,2,\ast}$

$^1$ Laboratory for Optical Systems, IMTEK, University of Freiburg, Georges-Köhler-Allee 102, 79110 Freiburg, Germany
$^2$ Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, 79110 Freiburg, Germany

E-mail: \texttt{karsten.buse@ipm.fraunhofer.de}

Abstract. We demonstrate the first cw OPO emitting mid-infrared light at wavelengths up to 8 µm. This device is based on a 3.5-mm-diameter whispering gallery resonator made of silver gallium selenide (AgGaSe$_2$) pumped by a compact distributed feedback laser diode emitting light at 1.57 µm wavelength. Phase-matching is achieved for a c-cut resonator disk pumped with extraordinarily polarized light at this wavelength. The oscillation thresholds are in the mW region, while the output power ranges from 10 to 800 µW. Wavelength tuning is achieved via changing the radial mode number of the pump wave and by changing the resonator temperature. Simulations predict that whispering gallery OPOs based on AgGaSe$_2$ with diameters around 2 mm can generate idler waves exceeding 10 µm wavelength.

1. Introduction
Continuous-wave optical parametric oscillators (cw OPOs) convert cw pump light at the wavelength $\lambda_p$ to signal and idler light at $\lambda_s,i$ in a non-centrosymmetric crystal such that photon-energy conservation is fulfilled, i.e. $1/\lambda_p = 1/\lambda_s + 1/\lambda_i$. Fundamentally, cw OPOs can be tuned to every output wavelength as long as it is larger than the one of the pump wave. This great potential of wavelength tunability is combined with narrow-linewidth emission and even with watt-level output powers employing conventional mirror-based systems. Thus, they are ideally suited for high-resolution laser spectroscopy [1]. A practical limit for the tuning range of cw OPOs is given by the transparency of the nonlinear-optical crystal they are based on. Operating them at wavelengths beyond the transparency range one will face significantly higher oscillation thresholds and lower conversion efficiencies.

The great majority of cw OPOs is based on oxide crystals. In these materials, the upper wavelength limit of the transparency range is given by multi-phonon resonances starting around 4.5 µm. Consequently, the mid-infrared tuning range of cw OPOs has been limited to wavelengths below 5.5 µm for more than half of a century [2].

Here, we present a continuous-wave optical parametric oscillator based on a whispering gallery resonator made of silver gallium selenide (AgGaSe$_2$). This material can be considered as transparent between 0.8 and 17 µm wavelength [3]. Thus, it is suitable for the generation of highly tunable mid-infrared light. For whispering gallery OPOs, the above mentioned photon-energy conservation has to be supplemented by the phase-matching condition $m_p =$
$m_s + m_i + \Delta m$, relating the azimuthal mode numbers $m_{p,s,i}$ (number of field maxima along the propagation distance) of the interacting waves with the phase-matching number $\Delta m$. For $c$-cut AgGaSe$_2$, as in our approach, we find $\Delta m = \pm 2$ [4].

2. Experimental setup and results
The setup sketched in Fig. 1a,b and described in detail in Ref. [5] by Meisenheimer et al. comprises a disk resonator with 3.5 mm diameter and a coupling prism made of silicon. The pump light at 1.57 µm wavelength provided by a compact diode laser is converted in the resonator to signal and idler light. The latter two and the remaining pump light are coupled out via the prism and analyzed with respect to powers and wavelengths.

At pump powers exceeding the oscillation threshold of typically some mW, we observe optical parametric oscillation. By addressing pump resonances belonging to the different mode numbers $q_p$ (number of field maxima along the radial direction), different branches of signal and idler wavelengths between 2 and 8 µm can be selected. Temperature variation enables 100-nm-wide wavelength tuning within one branch of the idler light (see Fig. 1c). The measured tuning branches are in good accordance with theoretical predictions. For a resonator diameter of 2 mm, we expect to extend the tuning range even beyond 10 µm wavelength. At 10 mW pump power, the output power $P_s$ of the signal wave ranges from 100 to 800 µW, depending on the selected branch, i.e. the selected parametric process. For the idler wave, we estimate the output power by using the relation $P_i = (\lambda_s/\lambda_i)P_s$. This is valid if both generated waves are coupled out of the resonator equally. The resulting values are in the range between several 10 and several 100 µW. They can be considered as lower limits for the idler power. Due to the longer wavelength, the coupling efficiency of the idler wave will be stronger than the one of the signal wave.

![Figure 1](image_url)

**Figure 1.** Whispering gallery optical parametric oscillator generating mid-infrared light. a) Sketch of the experimental setup comprising the resonator (WGR) and the coupling prism (P). The arrow indicates the optic axis (o.a.) of the crystal. b) Photograph of the resonator placed close to the coupling prism. c) Wavelength tuning of the idler light. The simulated tuning branches (solid lines) are labeled with the respective radial mode numbers $q_{p,s,i}$ and the phase-matching number $\Delta m$ as $(q_p, q_s, q_i, \Delta m)$.

3. Conclusion
We consider these results to be a first step towards establishing continuous-wave optical parametric oscillators as light sources in the mid-infrared range beyond 5.5 µm wavelength. Further improvements with regard to output power and wavelength tuning are expected to be achieved with recently improved materials, e.g. orientation-patterned gallium arsenide and gallium phosphide.
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