Frequency Stability and Selectivity of a Singly Resonant Continuous-wave Optical Parametric Oscillator

Pro Gradu

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Optical parametric oscillators (OPO) are sources of coherent light, often used to produce laser like light in wavelength regions where ordinary laser operation is challenging. In terms of chemistry, most attractive such a region is in mid-infrared, where strong fundamental vibrational transitions occur. OPOs are based on nonlinear polarization, which some materials exhibit when radiated with strong coherent light and effectively allow transferring optical power from one wavelength region to another. Even a simple OPO setup can offer watt-level of continuous wave power in mid-infrared. There are ongoing challenges with the stability of OPO output frequency and continuous tuning of the wavelength, both of which are important for a light source used in high-resolution molecular spectroscopy.

Theory and literature part of this thesis first covers the fundamentals of the theory behind OPO, centering on a continuous-wave single resonant operation. Afterwards, we look into the more well-known features affecting the stability of the OPO, as well as some common schemes used to combat the instabilities.

In the experimental part, we measure and attempt to characterize some features of instabilities we have previously noticed that are not readily explained by known instability sources. The OPO's output wavelength occasionally changes in discrete jumps known as mode hops. There appear to be some preferences to the magnitude of these jumps that do not seem to fit in the current understanding of OPO operation. We followed the frequency changes of a typical singly resonant continuous-wave OPO for longer time periods and offered some possible explanations for the observations. We utilize a few methods to increase the number of mode hops to produce meaningful statistical data.

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1 Background

The optical parametric oscillator (OPO) offers a versatile coherent light source for applications that require high power and wide wavelength tuning. The OPO is based on nonlinear response of certain materials to the electric field of the incident light. The nonlinearities become significant only when the optical intensity is high enough and so the field of nonlinear optics has its root in the early sixties, when the development of high power coherent light sources allowed for the demonstration of exploitation of the second order nonlinear coefficient.\(^1\) This first demonstration involved second harmonic generation, but was quickly followed by demonstrations of the first pulsed, and later continuously working, OPOs, as the two nonlinear processes are closely related.\(^2,3\) Efficient parametric oscillation requires high optical intensities from the pump laser incident on the nonlinear material, and the early oscillators worked around this requirement by operating in pulsed regime, where instantaneous intensities are high, or by using so-called doubly resonant OPOs (DRO). DRO requires less pumping power, but has problems with stability and tunability. Singly resonant oscillators (SRO) are less problematic, but a continuous wave SRO (CW-SRO) requires more pump power than was practically available at the time. Later developments in both high-power laser sources and nonlinear materials have helped to reach the power requirements of CW-SROs, and allowed for new and rapid development of novel OPO setups. A simple modern CW-SRO still generally requires continuous pumping power of few watts, but this is well within powers available from modern laser sources.

The modern OPOs offer high power coherent light, reaching continuous wave output on the scale of watts, over a wide range of wavelengths. The possible output wavelengths from various OPO setups together range from visible light\(^4\) all the way to mid-infrared (MIR),\(^5,6\) with the tunability of a single system often restricted by the availability of broadband optical components. For comparison, the output wavelength range of a laser system is restricted by the transitions of the lasing material. This makes OPOs especially competitive in applications where high power coherent light is needed along a wavelength range where lasing materials do not exist, or the operation of lasers is otherwise complicated. OPOs are, for example, often used as sources in the near-infrared (NIR) and MIR.
The output power depends on the available power from the pump source and wavelengths of the pump and the output beams. As an example, for MIR output with NIR pump, the output power is usually roughly an order of magnitude lower than the pumping power. That is to say that ten watts of pump power produces output on the scale of watts.

The infrared region is especially interesting for molecular spectroscopy, as the vibrational transitions occur at these wavelengths. The OPO includes many advantageous qualities for spectroscopy: the laser-like coherent and narrow-linewidth output allows for high resolution, the high power output usually means better detection limits, and the robust tunability is often required to measure the shape of spectroscopic bands. The MIR output allows for exciting the fundamental vibrational transition and, for example, has been used as a light source in sensitive cavity ring down measurements.\textsuperscript{7,8,9} The high power output of OPOs is often utilized in photoacoustic spectroscopy, where the pressure variations caused by heating from nonradiative relaxation after absorption of light are observed as sound waves.\textsuperscript{10,11,9,12} In photoacoustic spectroscopy, the power of the light source is directly related to the sensitivity of the measurement. The narrow linewidth of the OPO can also be used in high resolution Dobbler-free spectroscopy.\textsuperscript{13,14} Some challenges still remain with the stability of the output wavelength and particularly with continuous tunability of CW-SROs, both of which are required for high resolution molecular spectroscopy. For example, wavelength tuning often results in discreet steps, called mode hops, rather than smooth shift of the output wavelength.
2 Theory

2.1 Three Wave Mixing

The OPO is based on nonlinear response of a medium’s polarization when it is irradiated with intense light. The electric field of the incident light induces changes in polarization of the propagation medium. In linear case, the induced polarization oscillates with the same frequency as the incoming wave and re-radiates a photon of the same energy. When the light intensity becomes high, the nonlinear contributions to the induced polarization may become significant. The polarization of the nonlinear medium can be expressed as:

\[ \tilde{P} = \epsilon_o (\chi^{(1)} \tilde{E} + \chi^{(2)} \tilde{E}^2 + \ldots) \]  (1)

where \( \chi^{(1)} \) is a coefficient called linear susceptibility and \( \chi^{(2)} \) is the nonlinear susceptibility. The term \( \tilde{E} \) is the electric field of the incident light. The phenomena caused by the second order term in the polarization are called three-wave mixing and there are higher order terms that become significant as the incident power or the nonlinearity of the medium become higher. The coefficient \( \chi^{(2)} \) is a third-rank tensor and expresses how different components of the polarization \( \tilde{P} \) depend on the differently polarised components of the incident light. Here, we are mainly concerned with a case where the incident light is linearly polarized, and the polarization of the medium is along the same direction. Thus we replace \( \chi^{(2)} \) with an effective coefficient \( \chi \), which is the part of \( \chi^{(2)} \) associated with the chosen polarizations, and treat the fields as scalars. Consider the incident electric field to include two sinusoidal waves of different frequencies travelling to the z-direction, both with the same linear polarization in the xy-plane:

\[ E = A_1 \cos(\omega_1 t - k_1 z) + A_2 \cos(\omega_2 t - k_2 z) \]  (2)

Each wave is described by its angular frequency \( \omega \), its amplitude \( A \) and its wave vector \( k \). The wave vector can be defined by the wavelength of the wave \( \lambda \) and the refractive index of the medium \( n \):

\[ k = \frac{2\pi n}{\lambda} \]  (3)
The waves can be expressed in exponential form, and the electric field becomes:

\[ E = E_1^{(0)}(e^{-i(\omega_1 t + k_1 z)} + e^{i(\omega_1 t + k_1 z)}) + E_2^{(0)}(e^{-i(\omega_2 t + k_2 z)} + e^{i(\omega_2 t + k_2 z)}) \]  

(4)

where, for both waves:

\[ E^{(0)} = \frac{A}{2} \]  

(5)

Due to the term involving the square of the electric field in the equation 1, the resulting polarization has terms with the frequency of the sum and difference of the incident light waves’ frequencies, as well as double the frequency of both individual waves:

\[ P^{(2)} = \chi(|E_1^{(0)}|^2 e^{-i(2\omega_1 t)} + |E_2^{(0)}|^2 e^{-i(2\omega_2 t)} + 2E_1^{(0)}E_2^{(0)}(e^{-i((\omega_1 - \omega_2) t)} + e^{-i((\omega_1 + \omega_2) t)})) \]  

(6)

The medium may radiate light with any of the frequencies its polarization is oscillating with and the different terms describe different nonlinear processes: second harmonic generation, sum frequency generation and difference frequency generation. There is also a non-oscillating term, proportional to the amplitudes of the two waves, that is not included above. In equation 6, the phase differences between the waves, described by the wave vector, were ignored. The phase difference is the main factor that determines which of the nonlinear processes is efficient, and is considered in a later paragraph.

The difference frequency generation corresponds to the term in the polarization with the frequency equal to the difference between the frequencies of the two incident waves. This can be used to couple three waves so that their intensities depends on the each others’. When considering OPO:s, the waves are called the pump, the signal and the idler, and are defined by the relations:

\[ \omega_p = \omega_s + \omega_i \]  

\[ \omega_s > \omega_i \]  

(7)  

(8)

The definitions are clarified in figure 1.
Usually only the pump beam is irradiated at the nonlinear medium, which fixes $\omega_p$. The input for the two other beams are provided by quantum noise that can be considered to produce single photon input throughout the whole electromagnetic spectrum.\(^{19}\) When the intensity of the pump beam and the nonlinear coefficient of the medium are large enough, the pump beam and a very weak signal beam provided by the noise can produce an idler beam via difference frequency generation. Similarly, the new idler beam and the pump beam start to amplify the signal beam, as its frequency matches the difference between the frequencies of the pump and the idler. As a result, the energy from pump beam is used to generate beams at two different wavelengths in a process called optical parametric generation (OPG).

![Diagram of three wave mixing](image)

**Figure 1:** The definitions used for the three photons involved in three wave mixing. The highest energy pump photon excites the system to a non-resonant state and is converted into two photons of lower energy. Of the two resulting photons, the higher energy one is labeled the signal, and the other the idler.
2.2 Phase Matching

As described previously, the second order nonlinearities result in a number of different processes and for single one of them to dominate, it must fulfill a condition called phase matching. Similarly, the OPG can technically occur throughout the whole spectrum for any pair of signal and idler frequencies that sum up to the pump frequency, but for the generation to be efficient, the waves must be phase matched.

In OPG, the signal generation is most efficient when signal waves generated throughout the medium are in phase and interfere constructively. The waves are generated from the polarization induced by the pump and the idler:

$$P^{(2)}_{diff} \propto E^{(0)}_p E^{(0)}_i e^{-i((\omega_p - \omega_i)t - (k_p - k_i)z)}$$ (9)

This is the difference frequency part of equation 6, but here we have included the wave vectors of the pump and the idler, which define the spatial phase of the polarization wave. The initial phase of the signal waves generated by this polarization wave depends on its instantaneous phase. When radiated, the free propagating signal wave propagates as:

$$E_s = E^{(0)}_s e^{-i(\omega_s t - k_s z)} = E^{(0)}_s e^{-i((\omega_p - \omega_i)t - k_s z)}$$ (10)

When the polarization and a free wave are propagating in phase, the generated signal waves are also in phase, no matter where and at what time they were radiated. The only term that can vary the phase difference is the wave vector, so the phase matching is fulfilled when the wave vector of the polarization and a free propagating wave are equal: 20,21

$$k_s = k_p - k_i$$ (11)

The equation 11 can also be written as:

$$\omega_s n_s = \omega_p n_p - \omega_i n_i$$ (12)
For any dispersive medium, equations 12 and equation 7 are usually not simultaneously fulfilled. Deviation from phase matching condition is called phase mismatch and is defined as:

\[ \Delta k = k_p - k_s - k_i \]  

(13)

OPG is most efficient when phase mismatch is zero, although it works also with small non-zero mismatches. Efficient OPG requires using some clever phase matching technique to work around the dispersion. Traditionally this can be done by using birefringent crystals as the nonlinear medium. A birefringent crystal has different refractive indexes for waves of different polarization. When the signal and idler waves have different polarization, the angle and temperature of the crystal can be tuned so that the refractive indexes have values that fulfil the equation 12.\(^{22,23}\) This is called birefringent phase matching (BPM).

A more modern method is so-called quasi phase matching (QPM). Even if their phase difference is non-zero, waves have constructive interference as long as their instantaneous phase difference remains less than half an oscillation cycle. With QPM this is ensured by periodically changing the polarity of the crystal. Just as newly generated waves would start to interfere destructively with those generated at some previous point, the polarization of the medium changes sign, effectively changing its phase by half a cycle, and the phase of the newly generated wave is again within half cycle of the previously generated waves. This keeps the interference between waves generated throughout the medium overall constructive, although it is not at maximum. The principle of QPM within the nonlinear medium, and comparison to perfect phase matching is presented in figure 2.

QPM was proposed already at the early years of nonlinear optics,\(^{21}\) but was effectively realised only much later due to manufacturing difficulties.\(^{24}\) QPM can be implemented by altering the construction of the medium, or by changing the properties after construction. In the latter case, the process usually involves dividing a ferroelectric medium, which can retain a permanent polarization after it has been polarized with a sufficiently strong electric field, into equal length domains and applying a high electric voltage over every other domain. The end result is that the permanent polarization periodically alternates in sign
and a change in sign of the permanent polarization corresponds to a change in sign of an induced polarization as well. The periodic structure in the crystal can be considered to provide an additional wave vector to fulfil the phase matching:\footnote{24}
\begin{equation}
  k_p - k_s - k_i - \frac{2\pi}{\Lambda} = 0
\end{equation}

Here $\Lambda$ is called the poling period, and equals to the length from the beginning of a domain with one polarity, to the point where the polarity next time changes to that same polarity, analogous to the wavelength of a periodic structure. The length of one domain is referred to as the coherence length. The control over the physical domain length in the phase matching equation allows practically any pair of signal and idler to be made to fulfil the phase matching. Fine tuning of the phase matching can be achieved by controlling the temperature of the crystal. Temperature alters not only the refractive indexes, but also the domain width by the thermal expansion of the crystal. Although the phase matching is not perfect, which decreases the efficiency in relation to BPM, periodic poling allows coupling of waves with any polarization. The magnitude of effective nonlinear coefficient associated with each polarization combination varies and QPM allows choosing the strongest one, which often makes up for the loss of imperfect phase matching. For example for LiNbO$_3$ the effective nonlinear coefficient related to three waves with extraordinary polarization, which cannot be made use of with BPM, is an order of magnitude higher than the coefficient for other polarization combinations\footnote{24}. 
Figure 2: Gain of the parametric generation as a function of the position within the nonlinear medium. Without phase matching, the gain rises for a coherence length $l_c$, along which the generated waves have a phase difference of less than a half cycle. After the coherence length, the waves start to interfere destructively and the gain drops to zero again. With perfect phase matching allowed by the BPM, the gain rises smoothly. With QPM, waves generated after a coherence length are flipped in phase and the gain varies, but rises constantly. In the figure, QPM and BPM have the same effective nonlinear coefficients, making the BPM the more efficient technique. In practice QPM allows utilizing larger nonlinear coefficients, making it often the best choice.

2.3 Optical Parametric Oscillation

When difference frequency generation is used to transfer power from a pump beam to existing signal or idler wave, the process is called optical parametric amplification (OPA). Assuming the three waves are phase matched and the conversion is weak, so that the pump power remains approximately constant throughout the medium, the amplitudes of the signal and idler are coupled according to\textsuperscript{17,18}:

\[
\frac{\partial A_s(z)}{\partial z} = i\frac{\omega_s}{2cn_s}A_p(o)A_i(z) \quad (15a)
\]

\[
\frac{\partial A_i(z)}{\partial z} = i\frac{\omega_s}{2cn_s}A_p(o)A_s(z) \quad (15b)
\]
The solution for the partial differential equations 15a and 15b is\textsuperscript{17,18}:

\begin{align*}
A_s(z) &= A_s(0) \cosh(gz) + \frac{\kappa_s}{g} A_s^*(0) \sinh(gz) \\
A_i(z) &= A_i(0) \cosh(gz) + \frac{\kappa_i}{g} A_s^*(0) \sinh(gz)
\end{align*}

where

\begin{align*}
g &= (\kappa_s \kappa_i^*)^{\frac{1}{2}} \\
\kappa_j &= \frac{i \omega_j \chi |A_p(0)|}{cn_j}
\end{align*}

When a nonlinear medium inside an optical cavity is irradiated with a pump beam, the signal generated on the first pass through the medium by OPG can act as an input on consecutive passes, if it is coupled into the cavity. The signal builds up within the cavity if its wavelength corresponds to high reflectivity of the cavity mirrors and it fulfills the resonance condition of the cavity:

\[ L_{cav} = m \lambda_s, m \in \mathbb{N} \]  

When the length of the cavity round trip \( L_{cav} \) equals to some integer multiple of the signal wavelength \( \lambda_s \), the signal beam remains in phase after traversing the cavity and can interfere constructively after each round trip. The equation 19, as defined above, applies to all cavities. In literature, however, when considering linear cavities, a factor of two is usually included before cavity length, because the wave traverses the cavity twice for each round trip. In that case, the cavity length refers to the physical length of the cavity instead of the round trip. Resonance condition results in a series of frequencies, called cavity modes, where oscillation is possible. Disregarding effects from dispersive elements within the cavity, the spacing between adjacent cavity modes is constant in frequency units and is called the free spectral range (FSR) of the cavity:

\[ \Delta \nu = \frac{c}{L_{cav}} \]
Figure 3: Principle of a singly resonant optical parametric oscillator. Signal and idler are generated from the pump wave which is coupled into the cavity through one of the mirrors. One of the generated waves, in this case the signal, is reflected by the cavity mirrors and oscillates within the cavity. The idler wave and remainder of the pump wave, which was not depleted in the parametric process, leave the cavity through the second mirror.

If the cavity mirrors transmit one of the generated waves out of the cavity, the system is called a SRO. Here we consider the case, where the idler is a non-resonant wave. A schematic of the SRO is presented in figure 3. For the SRO, $A_i(0)$ in equations 16a and 16b is zero and the equations simplify to:

\begin{align}
A_s(z) &= A_s(0)\cosh(gz) \quad (21a) \\
A_i(z) &= \frac{k_i}{g} A_s^*(0)\sinh(gz) \quad (21b)
\end{align}

We can see from the equation 21a that as the signal gets amplified each pass through the medium, the signal input $A_s(0)$ is larger each time and the process becomes more and more efficient. The signal wave loses power as it propagates through the cavity, mainly due to imperfect mirror reflectivity, but also due to other processes such as scattering and absorption. We define a generic loss parameter as a fractional loss of signal amplitude from unity as the wave propagates through the cavity round trip, when there is no parametric
amplification:

\[ l_s = 1 - \frac{A_s(L_{cav})}{A_s(0)} \quad (22) \]

The signal can only be amplified after the first pass if the gain from the OPA surpasses the cavity losses. Ignoring the cavity losses this time, according to the equation 21a, at the end of a nonlinear medium of length \( L \), the signal amplitude is:

\[ A_s(L) = A_s(0) \cosh(gL) \]

We now define the single pass gain as fractional gain of the signal amplitude over unity, as it propagates through the medium, when the cavity losses are ignored:

\[ G_{sp} = \frac{A_s(L)}{A_s(0)} - 1 = \cosh(gL) - 1 \quad (23) \]

At the oscillation threshold, the single pass gain and cavity losses are equal:

\[ G_{sp} = \cosh(gL) - 1 = l_s \]

For small gain, as is usually the case near the threshold, we can approximate:

\[ \cosh(gL) \approx 1 + \frac{1}{2} g^2 L^2 \]

The threshold condition then becomes:

\[ g^2 L^2 = 2l_s \]

\[ \frac{\omega_s \omega_i \chi^2 |A_p(0)|^2 L^2}{c^2 n_s n_i} = 2l_s \]

\[ |A_p(0)|^2 = \frac{2c^2 n_s n_i l_s}{\omega_s \omega_i \chi^2 L^2} \quad (24) \]

As square of the amplitude is proportional to intensity, equation 24 shows that for certain cavity losses, the incident pump power has to surpass a threshold power so that the signal can begin to oscillate.
3 Frequency Stability

The single pass signal gain, as defined by equation 23, at low gain limit and with small phase mismatch is given by\textsuperscript{17}:

\[ G_{sp}(\Delta k) \approx g^2 L^2 \text{sinc}^2 \left( \frac{\Delta k L}{2} \right) \]  \hspace{1cm} (25)

where

\[ \text{sinc}(x) = \frac{\sin(x)}{x} \]

Plot of the gain as a function of the phase mismatch is presented in figure 4. Signal gain is net positive where equation 25 has values over cavity losses. As such, when pump power is well above the oscillation threshold, there can initially be a non-zero gain for

![Figure 4: Parametric gain as the function of phase mismatch. The correspondence between change in phase mismatch and the signal wavelength or frequency depends on the wavelengths of the three involved waves, but the width of the central peak in the gain curve usually corresponds to a signal frequency change of hundreds of gigahertz, when the medium length \( L \) has a typical value of few centimetres and the pump wavelength is fixed.](image)
a range of signal frequencies around the wavelength corresponding to zero of the phase mismatch. When the OPO starts to oscillate, signal power starts to build up at a cavity mode near the center of the gain curve. Relation of the cavity modes and the gain curve is presented in figure 5. Generally it is assumed that the oscillating mode is the one closest to the peak. As the OPO starts to oscillate, the amplification of the signal and idler deplete power from the pump. Quickly, the pump power drops to a level, where the resonating mode has a gain matching its losses, and the gain of adjacent modes is below the threshold, resulting in a single mode oscillation.\textsuperscript{17}

As the OPO oscillates, the phase matching tends to drift due to effects such as temperature changes in the crystal, which alter the quasi phase matching equation 14, and small physical changes in cavity length or geometry that alter the resonance condition 19. The former causes drifts in the phase matching curve and the latter drifts in cavity modes, relative to the unaltered phase matching curve. Either way, the result could be that a cavity mode other than the oscillating one has the greatest gain. The remainder of the pump power, that has been depleted by the oscillating mode, may then be enough to overcome the threshold at the new mode and, as there is always noise level seeding for all the modes, it may begin to build up in power. The power transferred to the new mode is directly away from the oscillating mode, and depletion due the new mode may deplete the pump power below the threshold of the formerly oscillating mode. As a result, the OPO remains single mode, but the oscillating mode has changed in a process often called a mode hop.

As the effects altering the gain curve should do so continuously, it would seem intuitive that the mode hops would most often be to the neighbouring mode. Observations suggest however that this is not the case and the mode hops are often multiple cavity modes\textsuperscript{25,10,26}. This phenomenon has been ascribed to effects such as ’OPO inertia’\textsuperscript{26} or the fact that the gain curve is usually fairly flat near the maximum in relation to common cavity mode spacings\textsuperscript{27}, so that the phase matching can change more than one cavity mode before change in the gain of the oscillating mode is relevant. The flatness also suggests that fairly minor wavelength dependences in cavity losses could be a major effect on the selection of the resonant wavelength.
The cavity modes, superimposed on the peak of a parametric gain curve of a common OPO design. The horizontal axis is change in signal frequency from the gain maximum. The gain is normalized with maximum value of one to help see the relative changes in parametric gain as the signal frequency changes. The drop in parametric gain when the signal moves single or even a few cavity FSR from the gain peak is small. The cavity FSR is slightly exaggerated for clarity, and in reality it is often in the scale of hundreds of megahertz. Similarly the width of the cavity resonance peaks is drastically larger in the figure compared to a normal high finesse cavity for which the resonance peak width is often in scale of megahertz.

\[ \text{Gain} \]

\[ \text{Cavity modes} \]

\[ -20 \quad 0 \quad 20 \]

\[ \text{Frequency (GHz)} \]

\[ 0.99 \quad 0.995 \quad 1 \]

\[ \text{Gain (A.U.)} \]

3.1 Temperature Effects

The peak of the signal gain curve varies in position with temperature because of the temperature dependence of the refractive indexes in the phase matching equation 12. With QPM, temperature also has a small impact on the domain width in equation 14 due to thermal expansion. An example of the temperature dependence of the phase matched signal wavelength is presented in figure 6, where the medium is LiNbO$_3$, the pump wavelength is 1064 nm and the phase matching is QPM with a poling period of 30.5 µm. Additionally, temperature may also have an effect on the cavity geometry as thermal expansion and changes in refractive indexes throughout the cavity could alter the optical paths of the three beams. Path changes could alter the cavity round trip length in the resonance condition 19 or lead to loss of efficiency if for example the overlap of the beams is degraded.
Figure 6: Temperature dependence of the phase matched signal wavelength using QPM. The nonlinear medium is LiNbO$_3$, the pump wavelength is 1064 nm and the poling period is 30.5 µm.\textsuperscript{28}

Absorption of the three beams can also locally heat the crystal along the beams’ volumes. Temperature gradients and local variations in temperature can result in effects like thermal lensing, where position of the focal points of the beams varies with temperature\textsuperscript{29}. In favourable conditions, thermal lensing can lead to higher intensities along the area where the beams overlap, but detuning of phase matching and distortion of the field profiles caused by non-uniform temperature profile tend to cancel out any increases in efficiency\textsuperscript{30}. However, with high enough pump power, the thermal lensing may form a waveguide within the medium, which increases the overlap of the interacting beams, leading to more effective OPA. At the same time, the appearance of the waveguide can make the OPO insensitive to small changes in the beam paths.\textsuperscript{31}
As an example, a commonly used nonlinear material LiNbO$_3$ has a high transmittance at wavelengths from 0.4 to 5 µm$^{32,33}$. The transmittance is fairly flat along this region, although at MIR, the absorption starts to increase when the wavelength is over 4 µm$^{33,29}$. When all three interacting beams are in the transparent region, the heating of the medium is mostly due to signal absorption, as intracavity power of the resonating beam can rise orders of magnitude higher compared to the other two beams$^{34}$. For example in a setup with pump wavelength of 1064 nm and idler wavelength ranging from about 3 to 4 µm, both were measured to have neglectable effect on temperature of the LiNbO$_3$ crystal that was used as the nonlinear medium$^{29}$. It should be noted that there is a strong absorption peak at around 2.9 µm due to OH-absorption. If idler with a longer wavelength, exceeding 4 µm, is required, idler absorption may become significant as absorptivity of LiNbO$_3$ grows stronger. Even so, efficient continuous wave parametric oscillation is still possible up to idler wavelength of at least 4.7 µm$^{5,6}$.

In addition to the degrading effects, temperature change may in certain cases lead to increase in OPO stability due to thermal locking. Drifting from the center of the gain curve lowers the gain of the oscillating mode, resulting in a decrease of resonating signal power. As previously noted, the signal absorption is often the dominant cause of temperature variation within the beam volume, so a drop in signal power may result in a temperature drop and a change in phase matching. As long as this causes the gain curve to drift in the same direction as the cavity mode originally moved, the oscillating mode may remain closest to the gain maximum, even though it has moved more than half the cavity FSR.$^{29}$
3.2 Modulation Instability

Modulation instability (MI) is a common phenomenon in all nonlinear wave systems, where small perturbations in pure sinusoidal waveform are amplified by nonlinearities\(^{35}\). When the power of the main sinusoidal wave is high enough, MI from second order nonlinearities may break down stable continuous wave behaviour\(^{36,37}\). In frequency space, MI manifests as generation and amplification of side modes nearby the frequency of the original sinusoidal wave. In an OPO, the side modes of one beam may couple to the other beams and lead to appearance of side modes at all three. If the nonlinear gain of signal side modes is higher than cavity losses they suffer, oscillation may become unstable\(^{38}\). Calculations performed by Kreuzer predicted that the instabilities become an issue when the pump power is high enough, namely 4.6 times the oscillation threshold power\(^{39}\).

Calculations by Philips and Fejer studied the process in more detail, removing some of the assumptions made by Kreuzer and describing the effects that the OPO setup has on the instability threshold due to such effects as group velocity mismatch and group velocity dispersion\(^{38}\). They concluded that the instability threshold, that the pump power has to surpass, can be as low as 2.5 times the oscillation threshold, or alternatively much higher than the previous prediction 4.6 times the oscillation threshold, depending on the exact setup.

The calculations mentioned above also predicted that when working below the instability threshold, the OPO remains modulationally stable as long as the phase mismatch of the oscillating mode fulfils \(|\Delta k L| < \phi_{th}\).\(^{38}\) In other words, the signal mode could remain the oscillating mode as long as the phase mismatch, multiplied by the length of the medium \(L\), remains under a threshold value \(\phi_{th}\). The threshold depends on many variables, such as pump power and group velocity dispersion, but the calculations suggested that it is generally over \(0.2\pi\).\(^{38}\) As this is often larger than the difference in phase mismatch between two adjacent cavity modes for a common cavity and moreover independent of the cavity FSR, this suggest that a mode may remain oscillating even if it is not the mode with the lowest phase mismatch. The phase matching could then drift more than one cavity mode before a mode hop occurs and the mode hop can be a multitude of cavity modes.
3.3 Idler feedback

When the OPO cavity is able to resonate both of the generated waves, the system is known as a DRO. Compared to SRO, the DRO has a considerably lower pump threshold requirement, as both the signal and the idler build up within the cavity and act as input for the OPA. Due to dispersion, the two waves with different wavelengths have different resonance conditions for the same cavity. Figure 7 shows the principle of a DRO. This generally makes DRO an unstable system, at least in the CW setups, as the two resonance conditions have to be fulfilled simultaneously and oscillation can occur only where the resonant modes of both waves coincide at a frequency where the gain is over the threshold. Changes in cavity geometry vary the modes of different waves a different length and whereas a mechanical change in SRO may result in only the resonant mode moving in frequency, in DRO the result usually is that the overlap of signal and idler cavity modes near the gain maximum deteriorates and the oscillation ceases.

If the residual idler power, that is reflected by the mirrors which transmit most of it, is high enough so that a small amount of idler wave reaches the nonlinear medium after the cavity round trip, instabilities similar to DRO may be observed in SRO. Even a small idler feedback may lead to the system preferring the modes where the idler and signal cavity modes meet, and appearance of power drops and frequency instabilities when the cavity geometry is perturbed. The effect is generally important only near the oscillation threshold of the system, as the idler feedback lowers it to the point where the power at the threshold is not enough to initiate oscillation if the DRO condition is not met, and at higher powers, even with small idler feedback, the system starts to practically behave like a SRO.
4 Stabilization Techniques

4.1 Intracavity Etalon

One of the most common intracavity elements used to suppress changes in OPO oscillation frequency is a Fabry-Perot-etalon, usually simply referred to as an etalon. This is a simple interferometer design, where two parallel partially reflective surfaces form a low finesse cavity. The principle of etalon transmission is presented in figure 8. The light with wavelength that matches the resonance condition of the etalon, analogous to equation 19, interferes constructively. The constructive interference raises the transmittance at the resonant wavelength and it experiences relatively small reflection losses. Resonance wavelengths are called etalon modes, and light at other wavelengths are more strongly reflected from the etalon surfaces, which raises the cavity losses. Reaching OPO’s oscil-

![Figure 7: Principle of DRO operation. The figure shows cavity modes of the two waves generated in OPG. The waves generally have different wavelengths, so their resonance conditions and FSR are different as well. The DRO can oscillate only with wavelengths where the cavity modes of the two waves meet.](image)
Figure 8: Principle of an etalon. The transmittance is highest when the transmitted waves (T0, T1 and so on) are in phase and interfere constructively. The waves are in phase, when the path difference between T0 and T1 equals to the wavelength of the wave. Maximum transmittance is associated with minimum reflectance, as the path difference between R0 and R1 also equals to the wavelength of the wave, but R0 reflects from air-etalon interface and undergoes a phase shift.

Oscillation threshold requires the signal gain to overcome cavity losses according to equation 24, so oscillation is practically possible only at the etalon modes. Figure 9 shows an example of etalon modes in relation to the parametric gain curve. When the etalon thickness is chosen so that only one etalon mode overlaps with the gain curve, the OPO is forced to oscillate at a wavelength near the peak of the etalon mode, which can be used to stabilize the OPO signal into a single mode\textsuperscript{25,10}.

Changing the angle of incidence changes the length a beam has to travel through the etalon. This alters the resonance condition and the etalon angle can be used to fine tune the OPO signal wavelength. An etalon works best in an normal incident, where the beams reflected within the cavity overlap completely. When the angle of incident is not perpendicular to the etalon surface, the consequently reflected beams within the cavity experience sideways displacement. This so called etalon walk-off results in lower transmittance and finesse that depend on the incident angle and the etalon width\textsuperscript{43}. Tuning of the signal by tilting a simple solid etalon, where beam is resonating within a thin sheet of transparent material, is complicated by the walk-off losses, because they result in substantial power
fluctuations\textsuperscript{25}. An air spaced etalon, where the reflecting beams propagate between an airspace confined within two mirrors, allows for etalon tuning by changing the distance between the mirrors. This should result in smaller power fluctuations, if the angle of incidence is small so that the change in etalon width does not alter the sideways displacement of the reflected beams. Air spaced etalon does however often come with higher cavity losses, compared to a solid etalon, and the tuning may still involve power fluctuations, if for example tuning of the displacement is not completely uniform and causes misalignment of the parallel plates\textsuperscript{10}.

Figure 9: Etalon transmission overlaid on a gain curve. Lower transmission means higher cavity losses so the OPO can oscillate only at a cavity mode with the frequency where the peaks of both an etalon transmission and the parametric gain coincide.
4.2 Diffraction Grating

A grating diffracts incident light outwards in a pattern with a series of intensity maxima, called diffraction orders, each with different discrete angles. The diffraction angles depend on the wavelength of the incident light, and the dependence between the incident angle $\theta_i$ and the diffraction angle $\theta_d$ for order $m$ diffraction is given by equation:

$$\sin \theta_d = \sin \theta_i + \frac{m\lambda}{d}$$ (26)

The parameter $d$ is the groove spacing of the grating. When the angle of incidence is fixed as:

$$\sin \theta_i = \frac{\lambda}{2d}$$ (27)

it can be seen that the diffraction angle of order $m = -1$ equals to the incident angle and the grating is said to be in Littrow-configuration.

The grating can be transmitting, where the light is diffracted, but travels through the grating, or reflective, so that the beams are diffracted to the side of the grating plane where the incident beam was travelling from. The principle of a reflective grating in both normal and Littrow-configuration are presented in figure 10. A reflective grating in Littrow-configuration can be used to replace a plane mirror in a linear OPO cavity. As the Littrow-configuration is different for different wavelengths, only certain wavelengths can be coupled to the OPO cavity. The distribution of optical power of the incident light into the diffracted beams of different orders is determined by the nature of the incident light and the structure of the grating. With a right grating design, the retroreflected $m=-1$ beam can have the majority of the diffracted power so that enough of the incident light is coupled back to the OPO cavity and the parametric oscillation threshold does not become unreachable, although it is generally higher compared to using a common cavity mirror.

The equation 27 shows that the Littrow-configuration links certain angle of incidence and wavelength of the incident light. Changing angle of incidence changes the wavelength that is retroreflected in the Littrow-configuration. This way the setup also allows controlling the resonant wavelength by rotating the grating.
Figure 10: Principle of a reflective grating in normal incident and Littrow angle. A reflection of a monochromatic beam is diffracted into discrete beams with different angles of diffraction. The beam diffracted to zero order maximum (m=0) follows the law of reflection where the angle of reflection equals to the angle of incidence. As the absolute diffraction order of a diffracted beam increases, the angle difference from the zero order angle increases. In Littrow-configuration, the incident beam overlaps with the diffracted beam with order m=-1.

4.3 Locking to a Reference

Instead of using passive elements, such as etalons and gratings, the OPO can be stabilized by actively controlling the output frequency. The signal frequency can be stabilized by measuring changes in the frequency and varying the cavity length to minimize such changes. The cavity length can be tuned by moving one of the mirrors using a piezoelement. The changes in signal frequency can be measured against an arbitrary setpoint by simple interferometric technique\(^4\) or for example to an absorption peak of an reference chemical substance, which will simultaneously lock the frequency to a well known absolute value\(^13\).

Although an atomic or molecular resonance can be used as an absolute reference, direct locking would require the locked beam to have a wavelength near the resonance. A wider range of wavelengths can be used, when a frequency comb is used as a reference source. A frequency comb refers to a coherent light source with a special characteristic that its spectrum has a series of discrete peaks with well known frequency separation, over a wide range of frequencies\(^13\). The difference between the frequencies of the beam to be locked and the nearest comb peak can be measured, and the difference can be used as the locking signal. The frequencies of the comb peaks can be locked using, for example, an atomic clock, which means that the absolute frequencies of the comb peaks are known ac-
curately\textsuperscript{47}. Knowing the difference between the locked beam and the nearest comb peak, and the absolute frequency of this comb peak, means that the beam is locked to a known absolute frequency. Figure 11 demonstrates the frequency comb locking scheme.

A problem arises when the idler with its wavelength in MIR is used as the output and needs to be locked, as MIR frequency combs are not yet readily available. Locking of the idler can still be achieved by stabilizing both the pump and the signal, as the energy conservation ensures that the idler always corresponds to their difference in frequency. The signal frequency can be controlled by tuning the cavity length, if the cavity is unstable, and the pump source often allows tuning of its frequency. A NIR frequency comb can be used as a reference to directly lock the pump and the signal as they are often within the frequency span of such a frequency comb\textsuperscript{48} or, for example, a frequency comb near visible wavelengths can be used, if the pump and the signal are frequency doubled before the reference measurements\textsuperscript{49}. Alternatively the idler itself can be frequency doubled and referenced to an optical frequency comb\textsuperscript{50}.

4.4 Injection Locking

Injection locking is a mechanism, where laser light with stable wavelength is irradiated to a cavity of another optical oscillator working near the same wavelength. The second, or slave oscillator generally has better output power, but worse spectral characteristics. Process is in practice similar to driving an oscillator: The weaker, but more stable oscillator is coupled to another oscillator with nearly the same frequency, to drive the latter one to oscillate at the exact frequency of the former oscillator. Injection locking is widely used to stabilize lasers.\textsuperscript{51,52,53} Coupling external laser light into the optical cavity has been used to improve the spectral properties of pulsed OPOs, but the process is slightly different and is more precisely described as injection seeding. The injected light helps the build up process to create a pulse with narrower linewidth.\textsuperscript{54,55,56} With CW-OPOs there are some difficulties in realizing the injection locking scheme. For example, the spatial injected frequency has to be within a narrow frequency window around the oscillating signal to drive the oscillator and the spatial mode of the oscillating signal has to be of high-quality, but at least one successful injection locking setup has been reported.\textsuperscript{57}
Figure 11: Frequency comb locking. The figure shows an rough spectrum of an frequency comb (red) and the frequency of the OPO output beam (green). When the frequency difference between the locked beam and the nearest comb peak is measured, as long as the comb is locked to an absolute reference, the absolute frequency of the locked beam is known. Any variations in the frequency can then be compensated by for example tuning the pump frequency, so that the frequency difference to the comb peak remains constant.
5 Experimental

The purpose of the experimental part was to observe instabilities and mode hopping behaviour of a typical singly resonant CW-OPO, designed for ordinary laboratory use, over long time periods, and attempt to characterize them. It had been noticed in the past with various OPO setups in our laboratory that when mode hops occurred, their magnitudes were usually many cavity modes, often 6 GHz or multiples of this. The idea was to look into this phenomenon more analytically. As mentioned in the theory part, other groups have reported similar occurrences as well.

Although the frequency instability and mode hopping are an issue with classic SR-OPO designs and although there is a constant effort to find ways to minimize these problems, there is little analysis of the mode hopping behaviour in the literature. There exist many constantly developing methods to increase the stability as described previously in the literature part, but these methods often introduce challenges of their own to the system, for example as addition of intracavity elements that increase the cavity losses or as locking schemes that often complicate the overall measurement setup. The current stabilization schemes do not usually completely stop the mode hopping and a better understanding of the origin and characteristics of the instabilities could assist in choosing the best stabilization scheme with the minimum amount of sacrifices to the simplicity of the system. Additionally, for example, shrinking an OPO into a monolith system, where the nonlinear medium itself forms the whole cavity, would require stable operation without the use of intracavity elements.

Even when the OPO is running without much attempts to counter instabilities, other than air currents by enclosing it in a box and vibrations by mounting it on a floating optical table, mode hops occur relatively rarely, on the time scale of minutes. To induce more mode hops, several methods were used to destabilize the oscillation as described later on. To gather meaningful statistical data and to observe if any long term effects took place, the measurements were run over multiple hours, often overnight.
5.1 OPO Design

The OPO consisted of a bow-tie cavity formed of two concave and two planar mirrors (Quality Thin Films) and periodically poled LiNbO$_3$ (PPLN) crystal (HC Photonics) between the concave mirrors. Both concave mirrors had a radius of curvature of 75 mm. A schematic of the OPO is presented in figure 12. The pump was radiated into the cavity through one of the concave mirrors. The mirror coatings were reported, by the manufacturer, to have reflectance of over 99.5% at wavelengths 1400-1600 nm and less than 3% at wavelengths 1063-1065 nm and 3200-4400 nm. Thus, the signal wavelength could resonate within the cavity, whereas the pump and the idler left the cavity immediately after exiting the crystal, through the other concave mirror. The cavity was enclosed in a protective box with holes for in- and out-coupled light and a removable cover. The walls of the box were metal plates covered with foam sheets to reduce thermal and mechanical disturbances. The whole system lies on an optical table which is floating on air cushions to reduce coupling of vibration from the surrounding to the system through the table supports. The enclosure and optical table floating are the two common ways to reduce instability that are used in most of the practical OPO designs, and they were used in some of the measurements in this experiment as well in an attempt to have a better control over the origin of the instabilities.

The PPLN crystal was 5 cm in length and had a series of separate poling periods ranging from 29.5 to 31.5 µm. The crystal was doped with magnesium oxide to decrease photorefractive damage which could occur when an undoped LiNbO$_3$ crystal is irradiated with high power coherent light in lower temperatures. Photorefraction is a phenomenon where high power coherent light causes a net flux of electrons away from the area with high optical power as they are excited to the conducting band. Redistribution of charge can cause localized changes in refractive index and result in refraction and distortion of the transmitted beam profiles. MgO decreases the effects that the charge distribution has on the refractive index and additionally increases the mobility of charge carriers, both of which act to minimize the effects of the photorefraction$^{58}$. Periodic poling also makes LiNbO$_3$ less susceptible to photorefractive damage$^{59}$. 


The PPLN crystal was surrounded by an aluminium heat sink which was kept in constant temperature with Peltier elements underneath it. The Peltier elements were driven with temperature controllers (PTC5000, Wavelength Electronics) that followed the heat sink temperature using an NTC thermistor. The front and back surfaces of the crystal were cut in angles of $1^\circ$ in opposite directions to suppress residual etalon effects. Both crystal surfaces had an antireflection coating that was optimized for wavelength ranges 1063-1085, 1450-1700 and 2960-4005 nm.

The two concave mirrors were roughly 12 cm apart and the optical path the signal travels from one concave mirror to the other via the two planar mirrors was about 36 cm, making the total physical cavity length 48 cm. The refractive index of PPLN around the used signal wavelengths is 2.2160, which makes the optical path of the cavity round trip for the signal beam 54 cm. The cavity FSR is then 555 MHz.

Figure 12: The SRO cavity design used in the experiments. The PPLN used as the nonlinear medium lies between two concave mirrors. Pump enters the cavity trough one of them and exits the cavity, together with the generated idler, trough the other concave mirror. The mirror reflects the generated signal beam to the two planar mirrors, which direct it back to the first mirror, and the signal is left to oscillate within the cavity in a bow-tie pattern. Also presented in the figure near the secondary focus between the planar mirrors, is the solenoid controlled chopper which can be used to block the path of the signal beam to stop the oscillation.
5.2 Measurement Setup

The measurement setup is presented in figure 13. The pump source was a fiber amplifier (YAR-20K, IPG photonics) working at wavelength 1064 nm, seeded with a single-mode diode laser. The maximum power output from the amplifier was 20 W. The polarization of the pump wave was matched to the extraordinary axis of the crystal using a half-wave plate and a beam splitting polariser. The pump beam was irradiated into the OPO cavity through mode matching optics, so that its focus was in the middle of the crystal with a beam waist of 50 µm, to achieve maximum overlap with the TEM$_{00}$-mode of the cavity. There is a secondary focus in the cavity, midway between the two planar mirrors.

After the OPO, the idler and the residual signal beams were filtered off using dichroic mirrors and the remaining power of the pump beam was measured with a power meter (1918-C, Newport). The residual signal leaking out from one of the plane mirrors was led to an optical spectrum analyser (AQ-6315E, ANDO) with an optical fibre to measure the signal wavelength and the spectrum near the oscillating mode. The measurement data recording was controlled by a computer running LabView (National Instruments).

5.3 Disrupting the OPO

The OPO was disturbed by periodically blocking the resonating signal beam at the secondary focus within the cavity, using a cardboard sheet controlled by a rotary solenoid. The idea was to see if the OPO starts to oscillate in the same mode every time and to induce more mode hops, as the OPO seems more unstable right after it has started to oscillate. The progression of the chopping measurement is outlined in figure 14. Every two minutes the solenoid was connected to a voltage, causing it to rotate and turn the sheet to block the resonating beam, shutting down the OPO. After ten seconds the voltage was cut off, the sheet would rotate away from the beam path, and the OPO started to oscillate again.
Figure 13: The measurement setup. Before the OPO, the polarization of the pump is controlled using a half-wave plate (HWP) and a polarization beam splitter (PBS). The residual pump beam exiting the OPO cavity is filtered from the idler using a dichroic mirror. The power at the pump wavelength is then measured with a power meter. The signal beam leaking through one of the planar OPO mirrors is lead to an optical spectrum analyser with a single mode optical fibre. Before the fibre, wavelengths under 1500 nm are cut off using a longpass filter. The measurements from the power meter and the spectrum analyser are recorded using a LabView program, which also controls chopping of the oscillating signal when needed. L: Lense, M: Mirror

The performance of the solenoid was measured using a HeNe-laser. The laser beam had a diameter of 0.9 mm and, after connecting the solenoid to a voltage, the beam was unblocked in time scale of 200 µs. The beam waist of the OPO signal in the secondary focus is in the scale of 100 µm, meaning that the solenoid unblocks the whole beam in approximately 20 µs. It is uncertain if this relatively slow time scale in relation to the OPO build up time makes the unblocking effectively gradual and what effects this may have on the build up process. The periodic blocking was also controlled by the LabView program.

In some measurements the OPO was kept resonating constantly and it was disturbed by removing the cover from the enclosing box and running a fan nearby. The air currents were directed over the OPO, causing pressure and temperature alterations within the cavity and around the crystal. For a single run, no additional disruption mechanisms were used, but the floating of the optical table was disabled allowing any vibrations from the surroundings to mechanically shake the cavity.
Figure 14: The progress of the chopping measurement. The OPO is let to oscillate for two minutes, after which the path of the resonating signal is blocked and the OPO ceases oscillating. After ten seconds, the signal path is unblocked again and the oscillation resumes. The signal path is blocked again after another two minutes and the same process continues throughout the experiment run. While the OPO is not oscillating, the pump power is unaffected by the OPO, apart from losses due to the optical components, and the pump residual power is high. When the OPO starts to oscillate, the pump is depleted in the parametric amplification and the residual pump power drops to a lower level. The signal spectrum was measured with an optical spectrum analyzer.

5.4 Results and Discussion

5.4.1 OPO Operating Conditions

The periods 30.5 and 31 µm were used, in cooperation with the temperature control of the crystal, to produce signals with wavelengths at 1556, 1578 or 1615 nm (table 1). The pump power at the crystal was estimated as an average of the pump power measured before and after the OPO cavity. The oscillation threshold pumping powers were 2.9 W with the signal wavelengths 1556 and 1578 nm, and 3.3 W at the signal wavelength 1615 nm. The threshold is higher at 1615 nm as the cavity mirror reflectance starts to decrease already at 1600 nm.

Table 1: The PPLN crystal conditions used to produce the different signal wavelengths used in the measurements.

<table>
<thead>
<tr>
<th>Poling period (µm)</th>
<th>Crystal temperature (°C)</th>
<th>Resulting wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5</td>
<td>60</td>
<td>1556</td>
</tr>
<tr>
<td>30.5</td>
<td>100</td>
<td>1578</td>
</tr>
<tr>
<td>31</td>
<td>60</td>
<td>1615</td>
</tr>
</tbody>
</table>
With the signal wavelength of 1556 nm, maximum pump depletion of 61% was achieved with pump power of 8.5 W, corresponding to 2.9 times the threshold. That is to say that 61% of the pump power was converted to signal and idler power in the parametric processes when the OPO was oscillating. At pump power 6.0 W, the depletion was 55% and with higher pump power of 9.5 W, the depletion remained around 60%. Theoretical maximum conversion efficiency is reached with pump power that is $(\pi/2)^2 \approx 2.4$ times the oscillation threshold, which in our setup at this wavelength corresponds to pump power of 7.0 W and so falls between the used pump powers 6.0 and 8.5 W\textsuperscript{39}. When the pumping power is higher than what is needed for the maximum conversion, the signal and idler start to produce more pump power via sum frequency generation and the pump depletion does not rise any more. With the signal wavelength 1578 nm, the maximum depletion was 69% at pump power 8.6 W and with 1615 nm the maximum was only 29% at pump power 8.3 W.

5.4.2 Long Term Trends

The freely oscillating OPO, between chops when chopping was used, would rarely stay in a single mode for a long time. Even just disabling the optical table floating was enough to cause constant mode hopping. The OPO did, however, generally prefer one mode over the others and when it hopped to a another mode, it would quickly return back to this dominant mode. On a long term, the dominant mode would sometimes change. This could be due to small changes in the temperature of the surroundings over longer time periods. An example of this behaviour can be seen in figure 15.

When the OPO had been running for a long time, the mode hops sometimes slowly became smaller and more infrequent (figure 16). This improvement in stability, as the OPO oscillates for a long time, has been noticed in our laboratory in the past as well. The long time scale suggests something like photorefractive effect, although MgO-doping and the periodic poling of the crystal should counteract photorefraction. No obvious changes in the beam profiles, or other clear signs of photorefractive damage, were observed. At the beginning, there is often a period of high instability, especially with higher pump powers, while the pump laser stabilizes.
5.4.3 Effects of Chopping

After chopping, when the OPO started to oscillate again, there was usually a clear step like change in the oscillation frequency. Presumably this is due to temperature changes within the beam volume as the signal starts to oscillate. When the signal builds up in the cold cavity, the oscillation starts in one mode, but due to the competition of the absorption of the rising signal or idler power and the temperature control of the heat sink, the beam volume reaches a new steady state temperature. This alters the phase matching and the OPO jumps to a mode near the maximum of the new phase matching.

At the signal wavelength 1578 nm, it can be seen that with higher pump power, the steady state mode lies at a slightly lower frequency (figure 17). This is expected if the higher pump power leads to higher steady state temperature along the beam volume. The difference is only a few cavity modes though and at some of the used wavelengths the effect was less apparent. Within the relatively small range of pump powers, ranging from about 1.5 to 4.3 times the oscillation threshold, the different intracavity signal power levels, together with the heat sink temperature control, seem to result in only small changes in
Figure 16: Signal frequency of the OPO when the pump power was 12.6 W and the signal wavelength was around 1578 nm. Even disregarding the drastically unstable period in the very beginning, that is likely caused by stabilization of the pump laser, it can be seen that as the OPO oscillates for a long time, it appears to become more stable and the larger mode hops seem to become less frequent.

The beam volume temperature, clear in relation to the cold cavity temperature without any absorption, but almost indistinguishable from each other.

The time the OPO spends in the mode corresponding to the phase mismatch zero of the cold cavity varies a lot, but the jump to the mode corresponding to the steady state temperature is rarely completely gradual, even though it lies multiple FSR from the cold cavity mode. Figure 18 shows the effect of chopping on the signal frequency. Sometimes there is only a single large jump, but often the system reaches the steady state mode in a few steps. Even in those cases, most steps, especially the first few, were many cavity modes, and the time spent in the transient modes can be long as well, which shows that the case was not simply such that the gradual change happened below the time scale of the measurement sampling. Once the OPO jumps near the steady state mode, the system usually stabilizes to it with a few single FSR steps. Sometimes, the oscillation stays in the cold cavity or a transient mode for the whole two minutes before a new chop. The jump to the steady state mode can be a single quick jump so that our measurement setup does not always pick up the cold cavity mode, as the reaction time scale of our instruments was on the scale of seconds.
Figure 17: Histogram of measured signal frequencies over the measurement periods with three different pump powers around the signal wavelength 1578 nm. The signal frequency was measured about every second over multiple hours. The vertical axis is scaled differently for the different measurement runs to help fit them in one figure, but it is logarithmic in all cases. The figure only shows the frequencies immediately around the dominant frequencies, while there are numerous bins further away. The width of each bin is 0.1 GHz. It can be seen that the cavity mode that the OPO preferred to oscillate with was different at different measurement runs and drifted to lower frequencies with higher pump powers.

The pump depletion can be seen to drop when the OPO remains in the cold cavity mode, or a transient mode for a longer time. The clear discrete jumps could mean that an unintended etalon or some other wavelength dependent losses are involved. The OPO could then jump to the transient mode corresponding to low losses as the phase matching is passing by it when the temperature is reaching the steady state. The losses at the transient mode may be higher, or the gain maximum might not be exactly at the transient mode, lowering the oscillating signal power. This would slow down the speed with which the phase matching is reaching the steady state value or it could completely change the steady state, although in most cases the oscillation at some point reaches almost the same steady state frequency before the next chop. This could explain why the OPO could remain on a transient mode for a longer time. On the other hand the fast jumps suggest that very little
time of oscillation in the cold cavity mode is enough to bring the temperature profile near the steady state, which would suggest that even if the oscillation is happening at a transient mode, the peak of the gain curve quickly reaches the steady state mode and would be quite far from the oscillating mode. Moreover the steady state mode would, of course, also correspond to low losses, if wavelength dependent losses are involved, suggesting that the OPO might be oscillating with a mode far from the highest gain, even when the highest gain mode has comparable losses.

Figure 18: The signal wavelength behaviour when the OPO turns on when it is chopped. The figure shows both the signal frequency and the residual pump. When the OPO is not oscillating, the pump power is not spent in the parametric conversion, so the chops can be seen as the peaks of the residual pump. The pump power was 4.2 W and the signal wavelength was around 1578 nm. After a chop, the signal frequency often starts oscillating in a mode with higher frequency. The signal frequency then jumps to the main oscillation mode in discrete steps of multiple FSR, often spending a moderate amount of time in the transient modes. When the oscillating in a transient mode, the undepleted pump power can be seen to raise slightly, showing that oscillation in the transient modes is less efficient.
5.4.4 Mode Hopping

Due to many long term effects that the OPO poses, we were mainly concerned with the magnitude of the mode hops, as measured by subtracting the signal frequency measured in consecutive time steps. The magnitudes of the mode hops were plotted in histograms (see for example figure 19). The mode hop histograms as plotted like this show some exaggerated symmetry due to the OPO’s tendency to jump right back to the dominant mode after a mode hop away from it. Additionally, the measurement system does not differentiate between the cases where there was no mode hop between the two measurement points and where the OPO might have briefly stopped oscillating and hopped back to the same mode, so the zero of the mode hop histograms is practically a measure of how often the OPO simply remained at the same mode without a mode hop, as this is the more likely case. This does allow for an estimation of the OPO’s stability from the relative height of the bin at the zero in the mode hop histograms.

The mode hop histograms usually showed clear peaks at certain differences, the lowest of which was often either around 6 or 10 GHz. The gaps between these peaks still had some number of hops, but in some cases there were practically none. In general, the large hops were a result of the OPO turning on again, after being blocked, and finding the mode corresponding to the steady state temperature, which was often many cavity modes from the cold cavity mode. The large hops did however also appear during normal operation between chops and in cases where chopping was not used at all. For example, when the OPO was let oscillate freely without chopping, but the optical table floating was disabled, the mode hop histograms showed peaks with two maxima at $\pm 8.7$ GHz and $\pm 12.6$ GHz (figure 19). A histogram of the actual measured signal frequencies for the same measurement run is presented in figure 20. The latter figure shows that the OPO oscillated mainly at three adjacent modes and the two maxima in the mode hop histograms corresponded to jumps to and from two clusters of modes at different sides of the three dominant modes, and with different separations from them.
Figure 19: Histogram of mode hops when the optical table floating was disabled. The mode hops were recorded as the difference in signal frequency of two consecutive measurement points. The pump power was 4.2 W and the signal wavelength was around 1578 nm. The size of each bin in the histogram is 0.5 GHz.

When the signal wavelength was 1556 nm, the largest peak in the mode hop histograms was, in all but one measurement run, at about ±6 GHz. Figure 21 shows an example of a mode hop histogram at this wavelength. Higher pumping power seemed to slightly push the peak to larger differences, being at ±5.6 GHz at pump power 4.3 W and ±6.1 GHz at pump power 12.8 W. While the peaks at the mode hop histograms seemed to coincide well between the different measurement conditions, looking at the actual frequencies, the peak structures of the different measurements were not at the same frequencies. Often the peaks of one measurement run were at frequencies were the signal had spent near zero amount of time in other measurement runs. The cavity modes spacing was apparent in all the measurement runs, and the modes coincide between them, suggesting that this was not simply due to inaccuracy of the OSA. The same feature was apparent in the measurements with other signal wavelengths as well and an example of this can be seen in figure 22, where signal wavelength was 1615 nm.
Figure 20: Histogram of the measured frequency of signal, when the optical table floating was disabled. The pump power was 4.2 W and the signal wavelength was around 1578 nm. The size of each bin in the histogram is 0.1 GHz.

With the signal wavelength of 1578 nm, the peak structure in the mode hop histograms was the most apparent. Figure 23 shows an example of this. At higher pumping powers, especially with pump power of 8.6 W, the large mode hops mostly occurred at the beginning of the measurement run, when the pump laser was probably still stabilizing. Later on, there were still some larger hops, but even the jumps due to chopping rarely appeared. On the other hand, with lower pump power, the hops due to chopping were numerous. The difference could be simply that with higher pump power, the temperature takes a shorter time to reach the steady state and the system fails to register the cold cavity mode. This does not explain though why the transient modes do not appear as clearly as in other measurements. The highest peak in the mode hop histograms was usually at around 10 GHz. In these cases, the higher pump powers seemed to decrease the hop magnitude, as opposed to what was observed at 1556 nm. The peaks were also usually either wide and flat, or had multiple maxima. Like before, this was usually due to the peaks to lower and higher frequencies in actual frequency histograms having slightly different separations from the dominant frequency. At pump power 4.2 W, the peak had two maxima at ±10.8 GHz and ±12.4 GHz. At pump power 12.6 W, the peak was flat and covered a
Figure 21: A mode hop histogram with the signal wavelength around 1556 nm and with pump power of 4.3 W. Each hop is recorded as the signal frequency difference between two consecutive measurement points. The bin width is 0.5 GHz.

Wide range from ±6.0 GHz to ±9.6 GHz. On one measurement run with pump power of 8.6 W, practically all hops where within 3 GHz from the zero, with only tens of jumps of higher frequency difference over the measurement period of 24 h.

Around signal wavelength of 1615 nm, the OPO seemed more unstable than in the shorter wavelengths. There was not as clearly a mode that the OPO preferred over the others, but in a few dominant modes the OPO spent a similar amount of time over the measurement period. The OPO had sometimes multiple oscillating modes, starting at pump power of 8.3 W. Although the peak structure was still somewhat apparent when looking at the actual frequencies, it did not seem to appear in the mode hop histograms as strongly. Figure 24 shows an example of a mode hop histograms at this wavelength, with pump power of 4.5 W. Usually the mode hop histograms at this wavelength had the large peak at zero with wide shoulders reaching to around ±20 or ±30 GHz where they somewhat suddenly dropped near zero.
Figure 22: Histograms of measured signal frequencies with signal wavelength around 1615 nm and with various pump power. The OPO preferred oscillating at distinctive signal frequencies and while there is some correspondence of the peak structure between the different measurement runs, there is also clear distinctions. For example near 185 667 GHz the measurement run with 12.6 W of pump power shows a peak in the histogram, while the other runs do not. Similarly, with pump power 8.3 W, the OPO seemed to prefer oscillating near 185 690 GHz, whereas with other pump powers, the OPO spent little time oscillating with that signal frequency.

Such clear peaks in the mode hop histograms could suggest involvement of an unintended etalon. The only clear contender for the unintended etalon would be the nonlinear crystal, but the angle-cut surfaces and antireflection coatings should minimize such effects. Furthermore, the FSR of the crystal would be about 1.5 GHz, which is smaller than the lowest peak in the histograms, although most of the peaks were approximately multiples of this. Thus, even if the crystal posed an etalon effect, some other factors are needed to explain why only higher multiples of its etalon modes were significant. The ring cavity design should eliminate most other parasitic etalons as it reduces the number of surfaces perpendicular to each other.61.
Figure 23: A mode hop histogram with signal wavelength around 1578 nm and with pump power of 4.2 W. Each hop is recorded as the signal frequency difference between two consecutive measurement points. The bin width is 0.5 GHz. Most of the mode hops are either in a peak near the zero, or at well defined peaks about 12 GHz away from the zero.

Another possibility is wavelength dependent losses, for example, from the crystal or the mirror coating. However, the fact that looking at the actual frequency histograms, the peaks did not always coincide, argues against losses involving material properties, where the wavelength dependences should remain the same. Additionally the transmittances of the PPLN crystal and a mirror similar to the once used in the cavity, as measured with a Fourier transform infrared spectrometer (FTIR), showed no clear variance near the used signal wavelengths that would match with the observed structure in the mode hops (figures 25 and 26).

The weakening of the peak structure in the mode hop histograms with the signal wavelength 1615 nm could suggest that the peak structure has its origin, or at least is affected by the high signal power, as both the oscillation threshold and pump depletion were substantially worse at this signal wavelength compared to the others. The cause could be related
Figure 24: A mode hop histogram with signal wavelength around 1615 nm and with pump power of 4.5 W. Each hop is recorded as the signal frequency difference between two consecutive measurement points. The bin width is 0.5 GHz. There are still some magnitude ranges that the mode hops seem to prefer, but much less so than with the other wavelengths.

to, for example, nonlinear effects or photorefractive effect. One possible explanation is that the separation corresponds to a change in phase matching equal to the threshold $\varphi_{th}$, where the oscillation becomes modulationally unstable. Surpassing the threshold would lead to unstable oscillation and force a mode hop, increasing the number of hops to frequencies just above the threshold. The hops corresponding to multiples of the smallest separation could then simply be multiple hops in rapid succession that our system failed to register as such. However already the minimum value of $0.2\pi$, that computations have suggested for the threshold\textsuperscript{38}, would in our system correspond to a frequency change of about 20 GHz.
5.4.5 Disruption by Fan

The disrupting the oscillator by an ordinary table fan running nearby, with the air currents flowing over the cavity, resulted in substantially more instabilities than in the case where chopping was used. In addition to increased number of mode hops, the jumps also covered a large frequency range. The random air currents can affect at least the heat sink temperature, the cavity length by shaking the mirrors and even the optical paths, if the currents cause gradients in the refractive indexes the beams experience in the air. The combined effects lead to chaotic changes in the oscillation frequency. Increasing the pumping power resulted in jumps with even larger frequency difference. The jumps covered the whole range with no gaps as sometimes was the case with chopping, but there was a clear peak structure. In the mode hop histograms, the peaks appeared at frequency differences that were multitudes of about 10 GHz. Higher pump power seemed to lead to the peaks with a shoulder towards lower frequency differences, corresponding to what
Figure 26: Transmittance spectrum of a mirror with high reflectance at the signal, around the wavelength 1578 nm (189.987 GHz). The spectrum was measured with an FTIR. There is practically no variance in the transmittance over the whole highly reflective range, although the very low transmittance could be interfering with the accuracy of the measurement.

was seen at this wavelength with chopping as well. Looking at the actual frequencies, the peaks did not appear at the same frequencies at different runs. Interestingly, at pump power of 8.6 W, most of the jumps were to frequencies that were lower than the frequency of the steady state mode and with pump power of 4.2 W, the distribution was much more symmetric, with little more jumps to higher frequencies.
Figure 27: Histograms of the OPO’s mode hops when it was disturbed with a table fan. The signal wavelength was around 1578 nm in both cases and the pump powers were 4.2 W (a) and 8.6 W (b). The bin size in both histograms was 0.5 GHz.
6 Conclusions

The theory and literacy part describes known effects that cause instabilities in traditional SRO designs, as well as common schemes that are utilized in attempts to achieve stable single frequency output. In the experimental part, we study and attempt to characterize instabilities and mode hopping behaviour of a typical ring cavity SRO, which has been before utilized in normal laboratory use. The mode hopping behaviour, which resembles what other research groups have also observed, is not readily explained by the better understood instability sources. There appeared to be some periodic like modulation in the parametric gain of the OPO system, which made the OPO to prefer oscillation at certain frequencies over others. Such behaviour resembles that which is seen when an intracavity etalon is used to control the signal oscillation frequency, but no clear source of a parasitic etalon could be identified within our OPO cavity. Other explanation could lie in variations in transmission of the crystal, or the surface coatings of the crystal and the cavity mirrors. In addition to no such effect being apparent in FTIR measurements, the fact that the periodic structure seemed to change depending on the exact measurement conditions argues against losses connected to the transmission spectra. The periodic nature is then possibly connected to the high optical power within the cavity. Possible causes could be related to MI, nonlinearities or generation of grating like structure from interference or photorefraction.

The origin of the periodic like structure affecting the mode hops may be better understood if the loss profile of the OPO cavity, while it was oscillating, was known better. Observing if the gain profile has any modulation, which does not correspond to losses observed while the system is not oscillating, could help to identify if nonlinear effects or phenomenon like photorefraction form some periodic structures that could lead to wavelength dependent losses and explain the apparent periodic nature of the peaks in the mode hop histograms. One way to measure the loss profile is using an OPO system with a narrow mode selection that ignores selectivity from the cavity losses. If the narrow mode selection was tunable and the tuning itself did not affect the cavity losses, as it often does, changes in signal output power would correspond to changes in cavity losses. A grating would allow for quite a narrow mode selection, but the bandwidth of a common grating
might still be too wide to completely suppress mode hopping to nearby modes.

Suppressing the temperature changes along the beam profile when the OPO is turned off and on could lead to better understanding of the selection of oscillating mode during signal build up, as the rising power would have less of an effect on the mode matching. The changes in temperature resulting from the signal absorption could be minimized by lowering the intracavity signal power, for example by introducing an output coupler, and changing the chopping behaviour so that the OPO was off only for a minimal amount of time, so that a temperature differences would not have time to develop. This could also help to identify if the high signal power indeed affects the observed discrete nature of the mode hopping, although it would not differentiate whether the cause is related to thermal effects or the existence of the strong electric field of the signal.

References


