Practical Continuous-Wave Intracavity Optical Parametric Oscillators

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1. Introduction

The mid-infrared spectroscopic region (~1.5-5µm) is one of ever increasing importance. Many hazardous, contraband or otherwise important molecules and compounds exhibit their peak rotational and vibrational absorption features over this wavelength range and so can be readily detected and identified through the use of spectroscopic techniques. There is an urgent requirement, therefore, for high spectral purity, compact and wavelength-flexible optical sources operating over this range. Laser based spectrometers operating at visible or near-infrared wavelengths offer a combination of unprecedented resolution and ease of use due to their extremely high spectral brightness and tunability. Mid-infrared laser-based spectroscopy is, however, far less developed (even though this spectral range is arguably of more scientific importance) due to a severe lack of suitable continuous-wave (cw), broadly tunable laser sources. Whilst this area has attracted intense research interest over the past decade, current state-of-the-art mid-infrared laser systems are still not poised to address this shortfall. Quantum-cascade, difference-frequency mixing techniques and lead-salt diodes produce very low output power, limited tunability, poor spatial mode quality, require liquid cryogens, or a combination of these.

Fig. 1. The generation of long wavelength light through parametric frequency down-conversion. Here, $\nu_p=\nu_s+\nu_i$.

The use of nonlinear optical techniques to convert the output of laser systems operating at too short a wavelength, but otherwise exhibiting meritorious characteristics (e.g. high efficiency, robust design, etc) to the low frequency, mid-IR band of interest has received considerable interest since the invention of the laser in the early 1960s. Such nonlinear devices are called *optical parametric oscillators* (OPOs) and they operate by dividing the energy of an incoming, high energy pump photon into two lower energy photons (denoted the signal and idler); the energy (and hence, frequency) of which add up to that of the pump

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(see Fig. 1). One of the simplest incarnations of this device is the externally-pumped, or *extra-cavity, singly-resonant OPO* (ECOPO) - (see Fig. 2(a)). Here, a nonlinear optical crystal is placed within an optical cavity exhibiting high finesse at one of the down-converted waves (most usually, the signal wave). Once pumped hard enough, the parametric gain overcomes the round-trip loss experienced by the resonant wave and the OPO reaches threshold: down-conversion from the incident pumping wave to signal and idler begins. Crucially, as the parametric process is not limited to a particular electronic or vibrational transition (as in the case of a laser), the tuning range of the down converted signal and idler waves are limited only by the transparency of the nonlinear dielectric material in which they are generated. Hence it is possible to realise devices which exhibit very broad tunability in the down-converted signal and idler waves even if the pumping laser is not itself tunable (although pump-laser tunability does enable an additional tuning mechanism).

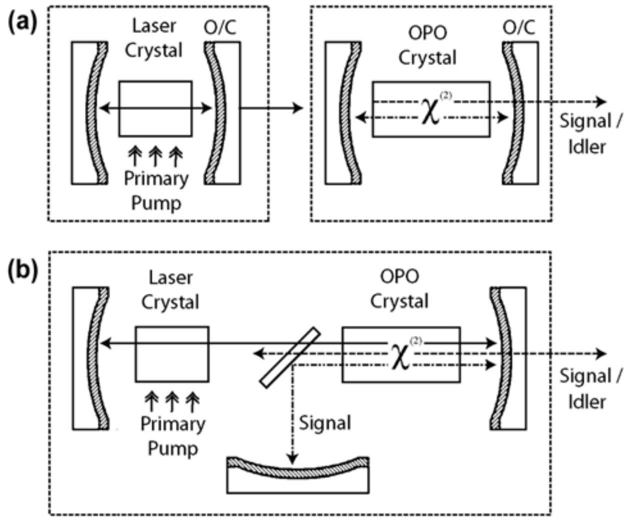

Fig. 2. Externally-pumped (a), and intracavity (b) optical parametric oscillators (ECOPO and ICOPO). Note that in both of these geometries, the optical cavity in which the nonlinear crystal resides is resonant at only one of the down-conveted waves (i.e. either signal *or* idler).

It is the large offset pumping power needed before downconversion begins (the *threshold* pumping power) which is the main objection to the widespread implementation of the ECOPO. Before the advent of long interaction length periodically-polled nonlinear crystals exhibiting comparatively large nonlinearity-interaction length products, threshold pumping powers were on the order of many tens of watts – therefore precluding their use with all but the most powerful cw pump lasers. When one takes into account the primary pumping power required to excite the pumping laser gain medium then the overall efficiency picture of these devices looks even bleaker. This has changed with the introduction of the aforementioned periodically-poled nonlinear materials, most notably the now-ubiquitous periodically-polled $LiNbO_3$ (PPLN) crystal. This brought threshold pumping powers down to the 3-5W level, i.e. within the reach of moderately powered cw laser systems. Overall "wall-plug" efficiency is however still very poor, though, unless ECOPOs are operated well above (~2-3x) threshold (more of this on section 2.1). The highly efficient production of multiple-watt output in the down-converted signal and idler fields is therefore perfectly possible (and indeed has been amply demonstrated (Bosenberg, Drobshoff et al. 1996)) in the ECOPO geometry *but* very poor efficiency results when the output is in the 10s-100s mW region (i.e. the device is operated closer to threshold). This is problematic as many (if not most) of the potential applications of a broadly tunable mid-IR source only require moderate power levels. In addition to this, for many industrial, medical, forensic and field uses, high efficiency, highly compact devices (i.e. battery powered, air-cooled) are a must.

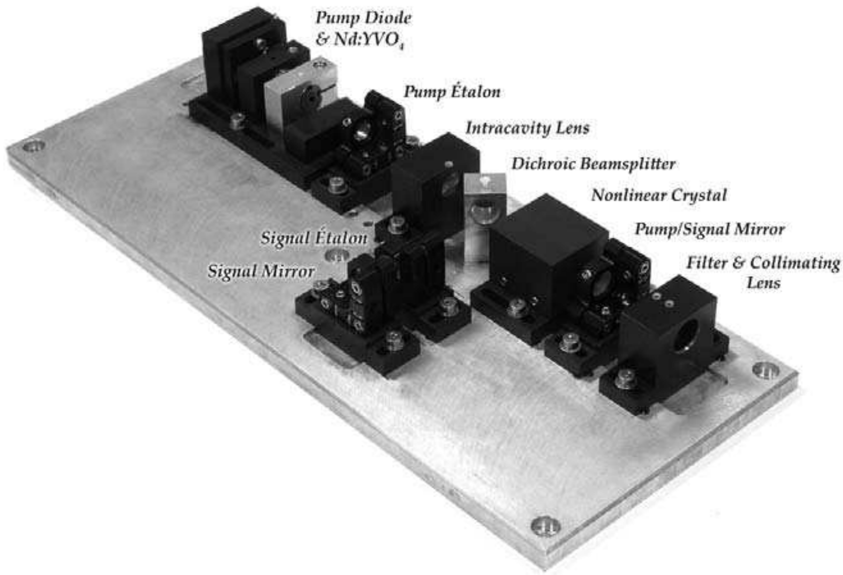

Fig. 3. A well-engineered, all solid-state miniaturised cw-ICOPO. This device consumes just ~10W electrical power, can deliver >500mW in the down-converted optical fields and requires no forced cooling. The function of the various components is discussed later in the text.

An elegant solution to this problem comes through taking advantage of the very high circulating field found within the (high-finesse) cavity of a laser. If one replaces the lasers' output coupling mirror with a high reflector, very high (10's W) circulating fields can result even when pumped at low (100's mW) levels. Placing the OPO *inside* the laser cavity (see Fig. 2(b)) then gives the parametric process access to this high field and the OPO comes to threshold at very much lower primary pumping powers than is the case with the ECOPO, thus obviating the high primary pumping power threshold requirements associated with that geometry. This, the *intracavity optical parametric oscillator* (ICOPO) enables the realisation of extremely compact, highly efficient devices which can exhibit high output powers in the down converted waves (100's mW) when pumped with only very modest (1's W) primary (i.e. diode-laser) pumping sources. An important consequence of the unprecedented down-conversion efficiency afforded by the intracavity approach, coupled with the robust operating nature of the singly-resonant design, is the possibility of realising battery / field operable systems as the need for large frame pumping lasers, forced water cooling and high cost is eliminated. A photograph of such a system is shown in Fig. 3. Here, for just 3W of primary pump power from the integrated diode laser pump module, 300mW and 150mW of broadly tunable signal and idler power are delivered. Because of the very high efficiency exhibited by the ICOPO, no forced air or water cooling is required. The device consumed <10W electrical power, making it ideal for battery power, portable or remote operation.

From a power and efficiency point of view, then, the cw-ICOPO represents an excellent solution to the problem of inadequate spectroscopic laser-source coverage over the mid-IR range. Unfortunately, there is a particular problem associated with the intracavity approach which has to date severely hampered its widespread implementation. The practical application of very narrow linewidth (sub MHz), diode pumped ICOPOs requires continuous wave output and therein lies a serious limitation inherent in the underpinning physics of the ICOPO. This is due to the impact of the OPO upon the transient dynamics of the Neodymium-based pump lasers in which to date they have been operated. Clearly, maintaining a diode pumped, all solid-state parent laser is highly desirable and hence the majority of ICOPO research has been predicated upon the use of Neodymium (Nd) based laser gain media. Whilst exhibiting many excellent characteristics ideally suited to this technology, their long upper state lifetime (compared to the decay time of the laser and signal waves in their respective cavities) leads to unpredictable and prolonged bursts of relaxation oscillations when used in consort with the intracavity technique. Such behaviour has an unacceptable impact on the frequency and amplitude stability of the down-converted waves and has to date precluded the Nd-based CW ICOPO from having lived up to its considerable potential.

In this chapter we will explore the design criteria for the realisation of practical intracavity cw-OPO systems, with a particular emphasis on overcoming their susceptibility to the spontaneous onset of relaxation oscillations. We shall begin with a comparison between the operating characteristics of cw intracavity OPOs and their externally-pumped counterparts (without becoming bogged down in a turgid foray into nonlinear optical theory (Oshman & Harris 1968)), and the design rules which must be fulfilled in order to realise optimal operation in the intracavity regime. These rules will be applied and tested by then considering the design and realisation of a real-life system previously reported in the literature; the steps taken in order to maximise the chances of successful operation of the device will be reviewed. The discussion will then move on to the vexing problem of relaxation oscillations which occur in the intracavity context; this will be investigated with the aid of a simple numerical model showing how and why they occur. The remainder of the chapter will then describe two examples of state-of-the-art diode laser pumped, cw-ICOPOs which are designed to obviate the problem of relaxation oscillations without losing any of the significant advantages which the intracavity technique confers.

2. The power characteristics of optical parametric oscillators

Much has been written on the principles underpinning the operation of OPOs and we shall avoid repetition here. For a theoretical and analytical thorough discussion of the physical processes underpinning these devices the reader should refer to (Ebrahimzadeh & Dunn 1998). In this section we shall describe the different operating regimes of both intra- and extra- cavity OPOs and examine those best suited to each geometry. Finally, we shall briefly discuss a strategy for operating the ICOPO under optimal efficiency conditions.

2.1 Power characteristics and the advantage of the intracavity technique

It is a common misconception that the ICOPO is somehow fundamentally superior to the ECOPO in terms of conversion efficiency, due to its much lower external threshold pump power requirements. Whilst this is certainly true at lower powers, where the ICOPO is capable of efficient output when the ECOPO would not even be able to achieve threshold, at higher pump powers we shall see that the ECOPO is also capable of exhibiting excellent conversion efficiency. The crucial disadvantage of the ECOPO is its large offset threshold pumping power requirement.

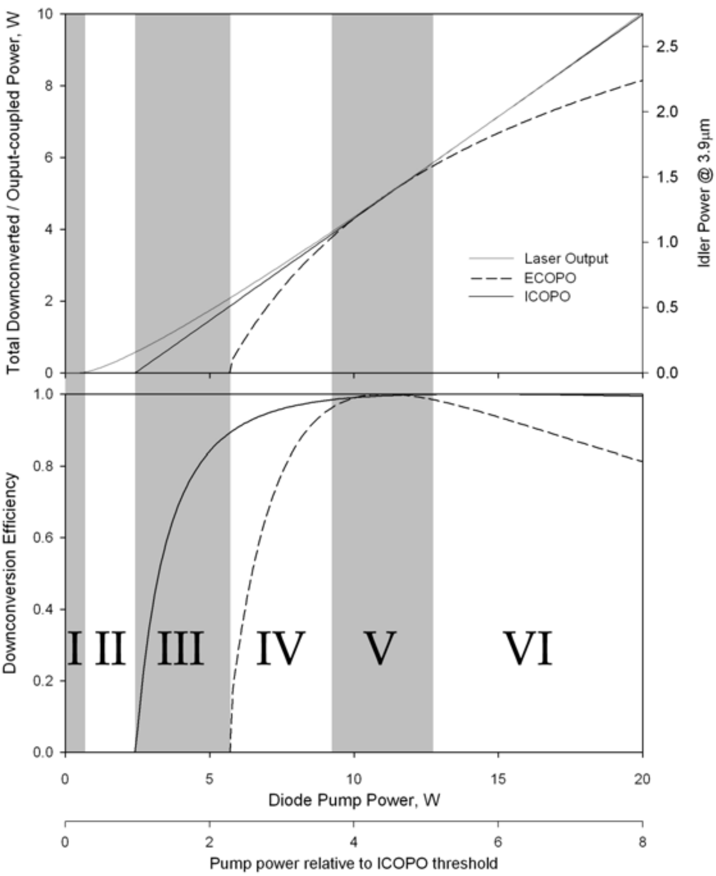

Fig. 4. Down-conversion characteristics of IC- and EC-OPOs

Even with high quality, modern nonlinear crystals exhibiting a high nonlinearity and interaction length, the finite cavity round trip loss for the down converted wave sets the minimum attainable ECOPO threshold in the region of ~2-5W, which would require at least 5-10W of primary optical diode pump power *simply to reach threshold*. However, once above threshold the down conversion efficiency (that is, the fraction of incident pump power down converted to longer wavelengths) rapidly increases to the point at which 100% down conversion efficiency is achieved once the ECOPO is pumped ~2.5 times above its threshold level (Ebrahimzadeh & Dunn 1998). A good example of this is (Bosenberg, Drobshoff et al. 1996) where ~93% of the incident 1μm pumping power was down converted into signal and idler power. ECOPOs have enjoyed something of a revival in recent years due to the availability of high power, high spatial and longitudinal mode quality fibre lasers and the drop in cost of their associated diode laser pumping modules. The requirement to operate these devices 2-3 times threshold, and the limitations in nonlinear crystal interaction length / nonlinearity and finite signal round-trip loss, still results in the requirement for many 10's W electrical power required in order to operate these devices efficiently. Such a requirement precludes the realisation of the ECOPO in compact, low power designs.

The various operating regimes in which the devices can be operated are shown graphically in Fig. 4, where the output power characteristics of the parent pump laser, an ECOPO and an ICOPO are contrasted. In this model, a typical parent laser is assumed (i.e. Nd:YVO_4, pumped by an 808nm laser, ~2% round trip parasitic loss) and the linear loss effects of the intracavity OPO components is ignored. A note on nomenclature: "down-conversion efficiency" and "down-converted power" refer to the total power converted through the parametric process, i.e. both idler *and* signal. In general, only the longer wave idler is of interest and none of the signal is usefully extracted (although this need not be so – output coupling of the signal field is perfectly possible if this wavelength is also required). Therefore, a second axis has been added in the figure to indicate the total idler power obtained from the device, taking into account the quantum defect between the diode pump and generated idler field wavelengths.

So that the performance of each pumping geometry can be better compared, the threshold condition of the ICOPO and ECOPO in the model have been tailored such that maximum efficiency in either case occurs at the same pumping power (in this example, at about 11.5W). In reality this means artificially increasing the threshold of the ICOPO (by modelling the pump and signal field with only a very weak focus in the nonlinear material); real-world ICOPOs exhibit OPO threshold at far lower pumping powers than shown here – as little as a few hundred mW (Stothard, Ebrahimzadeh et al. 1998). We can see that Fig. 4 has been separated into 6 'zones' of operation. The first and second are merely below and above laser threshold, respectively. The ICOPO comes to threshold at the beginning of zone III, still well before threshold occurs in the ECOPO. In zone IV, ECOPO operation is achieved but the down converted power is still significantly less than in the case of the ICOPO. Clearly, if the available pump power were limited to the range ~2.5-8W then the ICOPO is obviously the superior choice in terms of the amount of mid-infrared light generated. As the down-conversion efficiencies in either case become optimised (i.e. near unity), the total down- converted power is comparable in each case (zone V) and there is little to differentiate between the two devices in terms of performance. In order to optimise for maximum overall efficiency, both devices would be operated in this zone. As the pump power is increased beyond the optimum operating condition (zone VI), the efficiency in each case drops (markedly so in the case of the ECOPO). Here, back conversion of the signal and idler takes place. In practice, one would not operate either device in this zone; in order to obtain very high output powers and maintain optimal efficiency the threshold of each OPO would be *increased* such that optimal down conversion (zone IV) occurs at the required operating point. The crucial advantage of the ICOPO over the ECOPO is that in a practical device, zone V can be achieved at very much lower primary pumping levels, whereby a combination of very high efficiency and moderate down-converted output power is possible. In the ECOPO, high efficiency is only achievable at ~2.5x threshold. As this threshold is locked at relatively high powers by the finite parametric gain / signal wave loss product (~2-5W of incident pumping power), high efficiency only occurs when very high powers are being obtained. For clarity, we summarise these operating regimes in tabular form.

Zone	Operating Regime	Notes
I	Laser below threshold	
II	Laser above threshold	
III	ICOPO above threshold	If diode pump power is limited then ICOPO performance clearly superior over these zones
IV	ECOPO above threshold	
V	Down conversion approaches 100%	Little to differentiate between devices in terms of down-conversion performance
VI	Over pumping	Would never operate either device here in practice

Table 1. Summary of the operating 'zones' depicted in Fig. 4

In the above treatment, the linear loss of the intracavity OPO components placed within the parent pump laser is ignored. In the case of the ECOPO, the pump is only used on a single pass and so linear loss effects, to a first approximation, have little impact upon performance. However, placing lossy components within a laser cavity has obvious consequences in terms of laser performance. With reference to Fig. 2(b) we see that the two additional components which the laser cavity must tolerate are the dichroic beamsplitter and nonlinear optical crystal. Clearly, these components must be antireflection coated in order to minimise loss at the pump wavelength. It is particularly important to secure the finest coatings available upon the nonlinear crystal and inner surface of the beamsplitter as these need to be specified at three separate wavelengths. However, coating techniques have now matured to the point at which such advanced coatings are generally obtainable, particularly in devices which do not require broad tuning of the OPO (and, hence, broad-band AR/HR coatings). For a well established nonlinear crystal such as PPKTP or PPLN, absorption at the pump wavelength is negligible and so the additional round trip loss of the ICOPO components can be as low as ~3-5% at the pumping wavelength. Significant crystal-induced loss is only encountered, and is therefore problematic, when the intracavity technique is used in conjunction with lossy nonlinear materials, such as ZGP pumped at ~2μm. In this case, care has to be taken that the round trip loss of the laser cavity accommodating such lossy components does not impact too heavily on the attainable circulating field and, hence, obviate the advantage that the intracavity technique confers. The use of such crystals is beyond the scope of this chapter.

2.2 ICOPO efficiency optimisation

Unlike the case of a laser, minimizing the point at which the ICOPO comes to threshold (in terms of the primary pump power from the laser-diode) does not necessarily bring about the highest output (or efficiency) at the maximum available pump power. This is because the nonlinear parametric process acts as the output coupler for the laser, and so for a given pumping power one requires that the OPO operates in such a way that it behaves as an optimal output coupler for the pump cavity (i.e. is operating in zone V (Fig. 4) for a given primary pumping power). Therefore, the threshold level of the OPO, in terms of external pumping power, is a function of both laser threshold and the external pumping power at which the device is to be optimised. If the OPO comes to threshold too quickly, then at the maximum available primary pumping power the laser will be over coupled, hence reducing the down-converted power obtained. For a particular value of laser threshold and maximum available primary pumping power, optimum down-conversion efficiency occurs when the condition

$$P_{th}^{OPO} = \sqrt{P_{th}^{L} \cdot P_{in}} \qquad (1)$$

is met (Colville, Dunn et al. 1997), where P_{th}^{L} and P_{th}^{OPO} are the primary pump powers at which the laser and OPO, respectively, reach threshold, and P_{in} is the primary pumping power at which the device is to be optimised. When operated in this regime, the ICOPO acts as an optimum output coupler to the parent pump laser and maximum conversion of primary pump to down-converted power is achieved (this power being equal to that extractable from the pump laser under optimal output-coupling conditions with the OPO components accommodated within the pump cavity but with down-conversion suppressed).

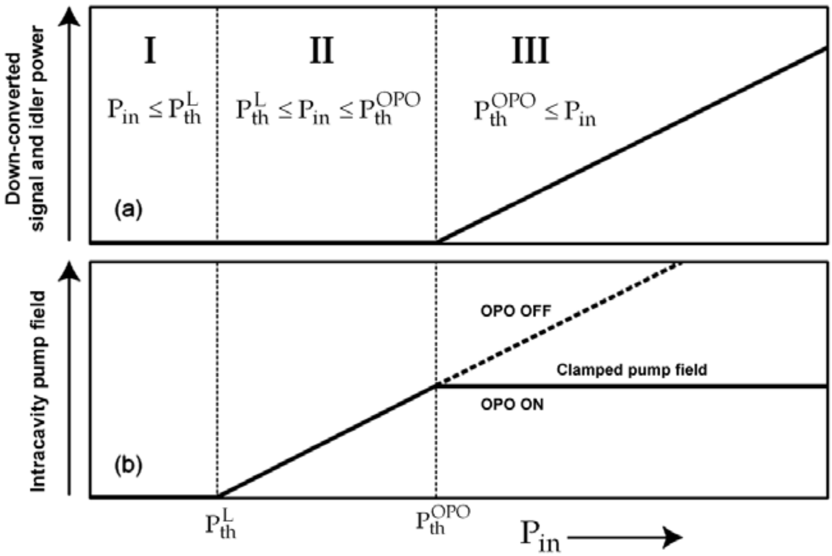

Fig. 5. (a) Linear output power of OPO once above threshold and (b) clamping effect of the ICOPO upon the circulating field (Turnbull, Dunn et al. 1998)

Whilst a very low value of P_{th}^{OPO} is highly desirable when the available primary pumping power is limited, reduced down-conversion powers are experienced when higher power pump sources are used as the system is operated too many times above threshold (because of the aforementioned over coupling of the pump field). Due to the high pumping fields available when using the intracavity technique, coupled with the low parametric thresholds enabled by long interaction-length, high-nonlinearity periodically-poled crystals, a choice can therefore be made when optimising the performance of the device either for maximum down-converted power or minimising parametric threshold in terms of primary pump power. Both of these cases are considered in a practical system later on in section 5.2.

Once above threshold, the parametric oscillator acts like an optical zener diode and 'clamps' the circulating field at the OPO threshold value, as shown in Fig. 5(b). Increased pumping power is then transferred from the laser gain medium population inversion, through the circulating field into increased power in the signal and idler waves, which grow linearly. When characterising the performance of an ICOPO, it is often well worth measuring the

quality of the pump-field clamping above OPO threshold as the primary diode pump power is increased. Good clamping is indicative of a well designed pump and signal cavity which is either free of (or robust in the presence of) any dynamic thermal effects which may be present within the laser gain medium and nonlinear optical crystals. Significant thermal lens effects manifest themselves in poor clamping of the pump field and a non-linear relationship between primary pumping and down-converted power. We shall see examples in the following section of how to calculate the circulating field required to bring the OPO to threshold, and experimental observations of the pump-field clamping effect.
Let us now take these simple design rules and see how they are applied when planning, constructing and characterising a system on the optical bench.

3. Designing a cw-ICOPO

In this section we shall take a specific example of a previously demonstrated ICOPO system reported in the literature (Stothard, Ebrahimzadeh et al. 1998) and walk through the process of realising such a device, ensuring that the first-time experimentalist will maximise his or her chances of success – by which we primarily mean at least getting the OPO above threshold. Here we will assume the experimenter has access to readily available pumping sources, Nd laser gain media and nonlinear crystals.

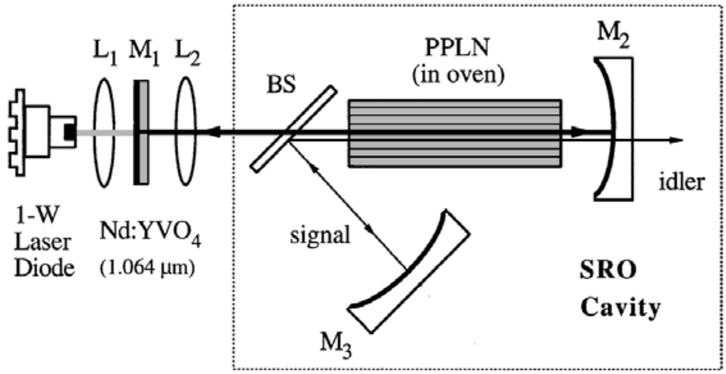

Fig. 6. A simple cw PPLN- Nd:YVO_4 ICOPO (Stothard, Ebrahimzadeh et al. 1998)

Our requirement is that the device, once constructed, will operate comfortably above threshold, delivering 10's mW of tunable power in the down-converted waves. Steps to circumvent the onset of relaxation oscillations will not be addressed in this discussion; here we will restrict ourselves to simply realising a low threshold, high efficiency device. In particular, we will consider the practical design choices which were taken in order to realise the first ICOPO based upon Nd as reported in (Stothard, Ebrahimzadeh et al. 1998), and use the physical parameters as used in that case. A schematic of that device is shown in Fig. 6.
The system was pumped by a c-packaged, temperature stabilised diode laser capable of delivering just 1W of optical power into the rear face of a 1% doped Nd:YVO_4 laser crystal. The laser cavity was defined by a highly reflective (at 1.064μm) coatings applied directly to the outer-most facet of the laser gain crystal and mirror M2. All of the components within the cavity were anti-reflection coated, such that the round trip loss experienced by the pump field was ~3%. Mirror M2 was also coated to be highly reflecting at the signal wavelength,

as was M3 and the dichroic beamsplitter BS, thus defining the signal cavity. Due to the limited diode pump power available (only 1W), a crystal exhibiting a high nonlinearity / length product (more on this in the following section) was required in order to minimise parametric threshold, and so a 50mm long PPLN crystal was procured. This was placed within an oven to avoid the effects of photorefractive damage.

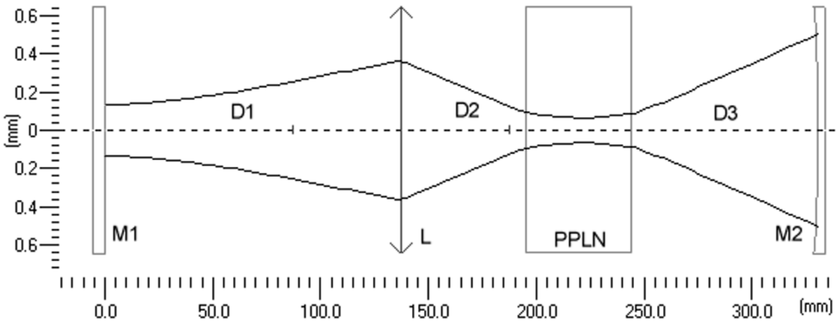

Fig. 7. Stability simulation of the pump cavity. Note that the beamsplitter has no focal power and is therefore omitted. Its optical length is encorporated into distance D2.

The cavity was modelled and its pump mode diameter, as a function of cavity position, is shown in Fig. 7. It is important that the cavity remain stable over a wide range (~50mm → ∞) of thermally-induced (by the diode pump) radius of curvatures modelled in mirror M1. Note the somewhat large distance D3 between the PPLN crystal and M2; this was set by the mirror substrate radius of curvature available at the time of the experiment (200mm). Such a long distance and the use of a relatively weak focal-length mirror results in a somewhat "loose" cavity, more susceptable to the effects of thermally-induced lensing prevalent in the PPLN crystal. A better solution is to use a substantially shorter curvature mirror, perhaps 25mm, placed close in to the PPLN crystal. This has the added advantage of increasing the free-spectral range of the pump cavity: helpful when trying to line-narrow the pump field.

3.1 Parametric gain and threshold

Clearly, it is of crucial importance that the OPO exhibits a threshold pumping requirement that is significantly less than the circulating pumping field available within the cavity of the pump laser, so ensuring that the threshold pumping level can comfortably be reached and exceeded. Let us examine the physical parameters which effect this level, and the steps which can be taken in order to minimise it.

When pumped by a polarized laser beam exhibiting sufficient spectral and spatial coherence, a nonlinear optical crystal designed for use in an OPO will exhibit fluorescence (i.e. gain) over its phase-matched bandwidth in much the same way that a laser crystal will exhibit gain over its gain-bandwith (albeit by a different physical process). This gain is given by (Vodopyanov, 2003)

$$G = \frac{P_{out}}{P_{in}} - 1 = \sinh^2(\Gamma \ell) \qquad (2)$$

where ℓ is the length of the nonlinear crystal and Γ is the gain increment given by

$$\Gamma^2 = \left(\frac{d_{eff}^2}{n^3}\right)\frac{2\omega_s\omega_i I_{pump}}{\varepsilon_0 c^3} = \left(\frac{d_{eff}^2}{n^3}\right)\frac{8\pi^2 I_{pump}}{\lambda_s\lambda_i\varepsilon_0 c} \tag{3}$$

Here, I_{pump} is the power density of the laser mode within the crystal, ω_s, ω_i, λ_s & λ_i represent the signal and idler angular frequency and wavelength, d_{eff} is the effective nonlinearity of the nonlinear crystal and n^3 is the product of the nonlinear material refractive index at the three transmitted wavelengths. Note that the factor d_{eff}^2/n^3 is referred to as the *figure of merit* (FOM) and indicates that a high nonlinearity alone does not necessarily yield high gain: it is moderated by ever-increasing refractive index. This is particularly important at longer signal and idler wavelengths where transparency issues mandate the use of semiconductor-based nonlinear crystals whose refractive indices are significantly larger than their phosphide- or arsenide-based counterparts. At low gains ($\Gamma\ell \leq 1$, as is experienced in the cw-regime), equation (2) approximates to

$$G_{cw} \approx \Gamma^2\ell^2 \tag{4}$$

And therefore, when properly phase-matched, the single pass gain has a quadratic dependence upon $\Gamma\ell$. The full expression describing the parametric gain experienced as a function of circulating pump power P_{circ}, when the OPO is placed within the cavity of the pump laser, is then

$$G_{cw} = \left(\frac{d_{eff}^2}{n_p n_s n_i}\right)\frac{4\omega_s\omega_i\ell^2 P_{circ}}{\varepsilon_0 c^3\pi(\varphi_p^2+\varphi_s^2)} \tag{5}$$

Where the refractive index at each of the propagating waves is now explicitly stated, as is the radii of the confocally-focussed pump and signal beams, φ_p and φ_s. This waist radius is given by

$$\varphi_\lambda = \sqrt{\frac{\lambda\cdot\ell}{2\pi}} \tag{6}$$

Note the factor of 2 increase in (5) over (2); this is a consequence of the signal field experiencing gain on each pass of the pumping field, which is of course travelling in both directions through the nonlinear crystal on each round-trip of the pump cavity. Threshold occurs when the circulating pumping field is sufficiently powerful that the parametric gain exceeds the round-trip loss experienced by the resonated down-converted (in this case, the signal) wave:

$$G_{cw} \geq \alpha_{cav} \tag{7}$$

Where α_{cav} is the round-trip loss of the signal cavity. Finally, therefore, we define P_{th} as circulating pumping field (*not* the threshold diode pump power) at which the OPO comes to threshold and re-arrange (5) to give

$$P_{th} = \frac{n_p n_s n_i\varepsilon_0 c^3\pi(\varphi_p^2+\varphi_s^2)}{4\omega_s\omega_i\ell^2 d_{eff}^2}\cdot\alpha_{cav} \tag{8}$$

This relation, then, lets us examine the various parameters we can influence in order to attain parametric threshold for the minimum of circulating pump field and, hence, primary pump power. It also reminds us that we are always limited by the material properties of the crystals available to us and the wavelengths over which we wish the device to operate, and illustrates why advances in this field often go hand-in-hand with the development and improvement of new nonlinear materials.

Clearly, in order to obtain the lowest possible threshold we need to maximise the denominator of (8) which means utilising a nonlinear material which offers the largest d_{eff} - ℓ product. This is why, given the very modest primary pump power used in this experiment, the nonlinear material PPLN was selected: this crystal exhibiting a then unprecedented 17pm/V nonlinearity and available in lengths as long as 50mm. It is also clearly crucial to minimise the signal cavity round trip loss α_{cav}. When procuring the optical coatings applied to the beamsplitter and signal cavity mirrors it is wise to place most emphasis on the best specification at the signal wavelength. The coating applied to the inner face of the beamsplitter, which must be anti-reflecting at the pump wavelength and broad-band highly reflecting at the signal, is particularly challenging for coating manufacturers. When specifying this coating, it is often helpful to encourage the coating engineer to let the incidence angle and polarisation of the pump and signal waves 'float' in his or her modelling calculations (if these parameters are not fixed by other demands placed on the system design), thereby giving him or her the freedom to maximise the performance of this challenging coating. Typically, one can conservatively expect the round-trip loss of the signal cavity to be ~2-5% (i.e. $\alpha_{cav} \approx 0.02 - 0.05$).

The chosen length of the crystal, along with the desired signal and idler wavelengths, fixes the confocal beam waist radius of the two resonant beams, as given by (6). The refractive index of PPLN at the three different wavelengths is calculated using Sellmeier equations (which shall be addressed in the following section). For the particular case under discussion, where the pump, signal and idler wavelengths were ~1.0, 1.5 and 3.6μm respectively, and a signal cavity round trip loss estimated to be 4%, we find upon solving (8) that parametric threshold occurs when ~3.5W is circulating within the pump cavity.

We now need to assess whether this intracavity field can be comfortably reached and exceeded with the available pumping power. With knowledge of the gain parameters of the laser gain medium and cavity (upper-state life time, stimulated cross-section, pump mode intensity, parasitic loss, etc.) the relation between the primary diode pumping power and the circulating pump field can be accurately modelled. However, it is often more straight forward to simply measure the output power of the laser through a well-chosen output coupler and then infer the intracavity field. For instance, with mirror M2 in Fig. 6 removed and replaced with an (optimal) 5% transmissive output coupler, 510mW of power at the pump wavelength was extracted. This indicates that 10W of field was circulating within the cavity, easily enough to bring the OPO to threshold when the laser is tolerating the additional loss of the output coupler. When highly reflecting mirror M2 was replaced, we estimated that the circulating field increased above 20W – enough to place the OPO well above threshold.

In marginal threshold cases it is possible to lower the threshold requirements of the OPO by increasing the intensity of the resonant fields within the nonlinear crystal. This is achieved by reducing the spot sizes of the pump and signal waists φ_p and φ_s. This however results in less optimised operation at higher pumping powers and can have practical consequences such as mode aperturing at the facets of the crystal, increased susceptibility to the effects of thermal lensing (and, in extreme cases, optical damage) but is a useful trick to try when out of other options.

3.2 Phase-matching and tuning

Much has been written about phase matching in nonlinear optical processes and for the sake of space it will not be repeated here save for a brief overview. Most applications to which the ICOPO will be turned will require the production of a specific idler and, hence, signal wavelength pair. Many applications (e.g. spectroscopy) also place both a coarse and fine tunability requirement on the device. For energy conservation, the signal and idler wavelengths are related to that of the pump by the relation

$$\nu_p = \nu_s + \nu_i \tag{9}$$

or, more usefully,

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \tag{10}$$

This, however, implies an infinite combination of signal and idler wavelengths for a given pumping wavelength. How does one successfully achieve device operation at the required signal and idler wavelengths?

The particular signal and idler frequency pair that is generated is governed by the *phase-matching* criterion of the nonlinear optical crystal employed. The efficient flow of power from the pumping wave into signal and idler waves only occurs when the three waves (pump, signal and idler) are travelling at the same speed (i.e. are in phase) within the nonlinear medium. When this condition is satisfied then the process is said to be phase-matched. Clearly, this criterion cannot be met in isotropic media due to linear refractive dispersion and so more subtle phase-matching schemes are called for. Phase-matching has traditionally been achieved by using bi-refringent crystals through which the waves were propagated at an appropriate angle and polarisation with respect to the crystallographic axis such that the respective refractive indeces experienced by the different wavelengths were equal, satisfying the condition

$$\frac{n}{\lambda_p} - \frac{n}{\lambda_s} - \frac{n}{\lambda_i} = 0 \tag{11}$$

Unfortunately these angles of propagation rarely coincided with that which the optimal nonlinearity of the material was encountered, leading to low overall nonlinear coefficients. In addition, tuning of the signal and idler waves was often achieved through rotation of the crystal angle, thus leading to complicated mechanical designs required to keep the optical cavity stable whilst crystal rotation took place. This changed with the advent of periodically poled nonlinear media where the phase-matching criteria could be “engineered” into the material by periodic inversion of the crystallographic domains (as shown in Fig. 8(a)), thereby making the generated signal and idler wavelengths simply a function of polling period (and crystal temperature). This enabled the somewhat cumbersome tuning mechanisms associated with conventional bi-refringently phase-matched devices to be dispensed with. The axis of propagation could also now be chosen in order to access the highest material nonlinearity. We shall only concern ourselves with these *quasi-phase-matching* (QPM) schemes in this discussion as all of the devices described in this chapter utilised this method of phase matching

The period Λ of the domains (often called the *grating period*, but not to be confused with diffraction gratings) written within the nonlinear crystal is chosen such that it takes up the 'slack' in the phase-mismatch so that phase-matching is achieved:

$$\frac{n_p(\lambda_p,t)}{\lambda_p}-\frac{n_s(\lambda_s,t)}{\lambda_s}-\frac{n_i(\lambda_i,t)}{\lambda_i}-\frac{1}{\Lambda(t)}=0 \tag{12}$$

Note that the refractive index of the material is a function of both wavelength and temperature. Due to thermal expansion of the nonlinear crystal as its temperature is varied, the grating period is also somewhat dependent upon temperature. It is the dependence of these parameters on wavelength and temperature, along with the need for the conservation of energy, which enables the OPO to be tuned by crystal temperature as well as and pump wavelength. Recently more advanced grating patterns have been demonstrated where the grating period varies linearly across the lateral axis of the crystal. In this, the so-called fanned grating design (Fig. 8(b)), the phase-matching condition is therefore a function of crystal position and very rapid tuning of the signal and idler can be achieved by translating the crystal through the circulating pumping field.

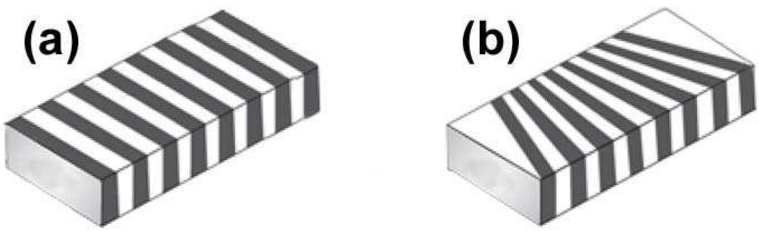

Fig. 8. Periodically-poled nonlinear crystals with (a) single and (b) fanned grating designs.

Relation (12) is solved by using empirically-derived Sellmeier equations which relate the refractive index of a particular material to the wavelength of light propagating within it. Modified Sellmeier equations also include temperature-dependence terms in order to enable the modelling of temperature tuning of the phase-matched condition. Not only is the format of each Sellmeier equation (and the constants used) specific to a particular nonlinear material, it is also often specific to the method of crystal growth used during manufacture. Whilst most commonly used nonlinear materials are very well characterised and their Sellmeier equations are available in the literature, it is often prudent to contact the crystal manufacturer and either ask which Sellmeier equations best describes their material, or better still let them calculate the required grating period in order to phase-match for the desired signal and idler wavelength pair at the required temperature.

The Sellemeier equation and its coefficients describing the PPLN nonlinear crystal used in this particular experiment is described in (Jundt 1997) and the accuracy with which it was able to predict the refractive index of the PPLN crystal and, hence, the phase-matched signal and idler wavelength pair for a given material temperature and grating period is shown in Fig. 9. The PPLN crystal used in the experiment had eight discrete grating zones of different polling periods written within it and so Fig. 9 comprises eight pairs of signal and idler curves, each particular pair corresponding to a different grating zone.

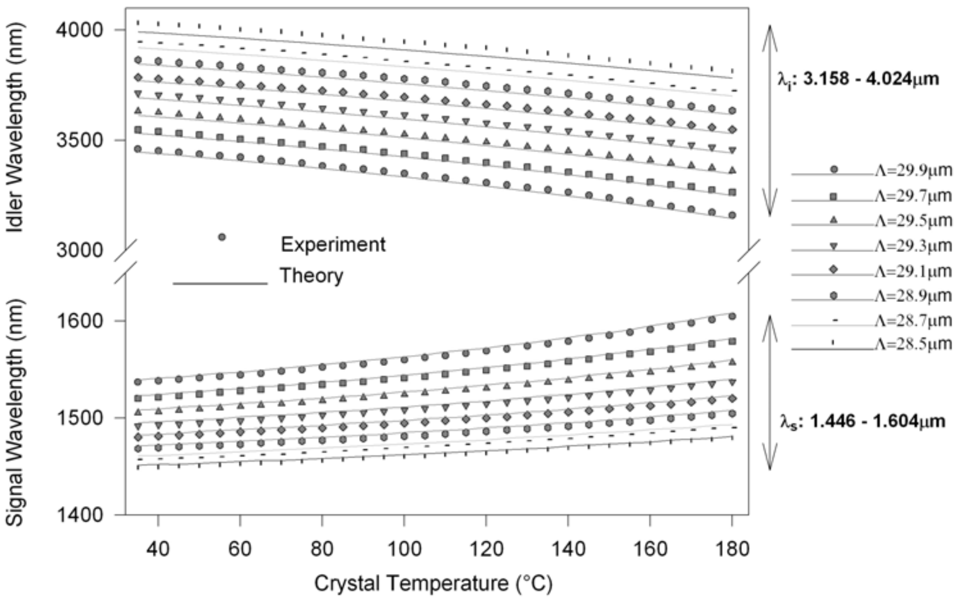

Fig. 9. Predicted and measured tuning of the signal and idler wavelengths

An accurate determination of the anticipated signal and idler wavelengths and tuning ranges is important, not only from the point of view of the end application of the device, as this information must be first determined before specifying the centre-point and bandwidth of the coating pertaining to the idler and, of particular importance for the reasons outlined above, the signal wavelength. The threshold pumping power requirement often rises substantially at the extremes of the tuning range as signal cavity round trip loss creeps in at the edge of the coating bandwidth. On condition that it does not compromise overall performance, it is often prudent to specify a coating bandwidth exceeding the tuning range over which the parametric process is expected to phase-match in order to obviate this effect.

3.3 Performance evaluation and optimisation

The down-conversion performance of the device is indicated in figure Fig. 10, where the extracted idler is shown as a function of increased primary diode pump power as is the circulating pump field both in the presence and absence of down-conversion. The laser and OPO threshold occurred at a diode pump power of 69 and 310mW respectively. In this latter case, 5.2W of circulating pump power was present, a figure somewhat larger than the anticipated threshold field of 3.5W. This is accounted for by sub-confocal focussing of the pump and signal fields resulting in reduced field intensity. Whilst this leads to the increase in threshold pump power, the cavity resistance to thermal lensing effects within the PPLN crystal was significantly reduced leading to more robust performance of the device. Despite this increase, the primary advantage of the ICOPO approach is still clear. In order to bring the OPO to threshold in an extra-cavity system, 5.2W of power from the pumping laser would be required, which itself would therefore require ~10W of primary optical pumping power. We achieve the same here for just 310mW of primary pump power – a significant drop indeed. The robust nature of the system is evident from the both linear relationship between the circulating field and pump power in the absence of parametric down conversion and the excellent clamping of the pump field once the OPO is above threshold. It is worth comparing the measured performance of the device as indicated in Fig. 10 with the theoretical behaviour shown in Fig. 5.

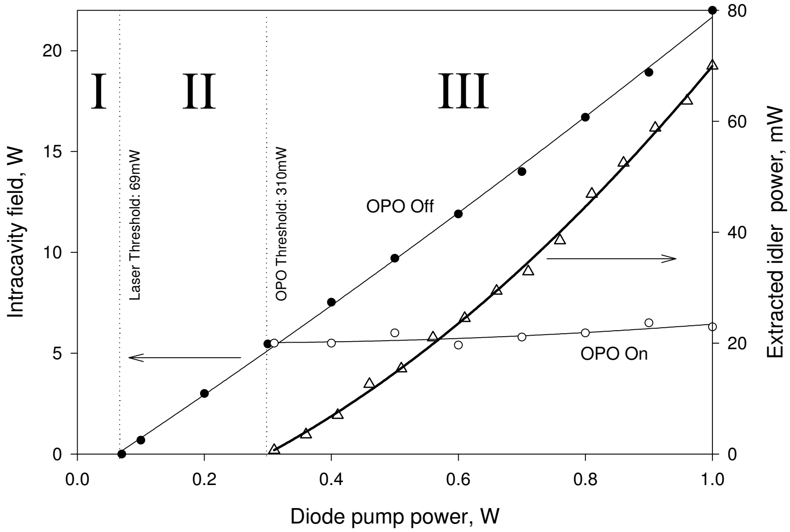

Fig. 10. Extracted idler (triangles) and pump-field with (open circles) and without (closed circles) operation of the OPO as primary diode pump power is varied. The idler wavelength was 3.66μm.

The slightly super-linear nature of the extracted power is a consequence of a thermally-induced increase in the focal power induced in the Nd crystal reducing the mode size (and hence, increasing intensity) of the pump field within the PPLN crystal at higher primary pump powers

At the maximum pump power of 1W the device delivered 70mW of tunable idler through M2. In order to calculate the total down-converted power (that is, the total signal and idler power generated) we need to take into account the quantum defect between the signal and idler waves and for the fact that the idler is generated in both directions within the PPLN crystal (the 'other' direction being lost within the system). The total down-converted power is therefore

$$P_{DC} = 2 \cdot P_i \cdot \left(1 + \frac{\lambda_i}{\lambda_s}\right) \tag{13}$$

This, for an idler power of 70mW and an idler wavelength of 3.6μm, corresponds to a total down-converted power of 476mW from the pump wave into the signal and idler. Recall that when mirror M2 was replaced with an optimal output coupler for the pump cavity, 510mW of power at the pump was obtained. We can therefore take the *down-conversion efficiency* of the device (that is, the fraction of the total obtainable power which is down-converted) to be 476/510 = 93%. A down-conversion efficiency of unity can only be achieved when the OPO is optimally output coupling the pump field through the parametric effect, which is achieved when relation (1) is satisfied. For a laser threshold and operating pump power of 69 and 1000mW respectively, the optimal OPO threshold is then 250mW – slightly less than is the case in this system. As we have said, the stability of the cavity has been improved by slightly defocusing the pump (and signal) waists within the PPLN crystal which has raised the OPO threshold to this non-optimal level. The resulting improvement in performance, however, makes this slight drop in overall efficiency a price worth paying.

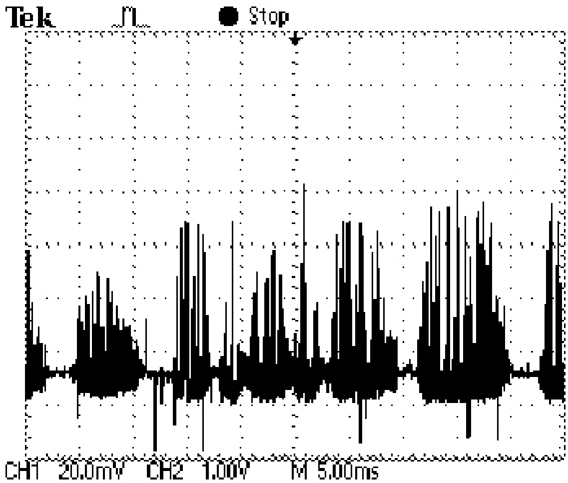

Fig. 11. Spontaneous and long-lived bursts of relaxation-oscillations manifesting themselves on the circulating pump field.

Finally, we turn our attention to the transient stability of the device which was measured by directing the small amount of pumping field reflected off of the rear face of the beamsplitter onto a fast photodetector. An example of the resulting trace is shown in Fig. 11. In the absence of any external perturbation mechanism the pump (and hence signal and idler) fields exhibited spontaneous and very long-lived bursts of high frequency relaxation oscillations. This resulted in ~100% modulation of the extracted idler field and erratic longitudinal mode hopping of the pump field, both of which are most undesirable in the context of high resolution spectroscopy and renders the device unsuitable for all but mean power, “crude” mid-IR applications. This is regrettable as in all other respects this system displays the very many highly desirable characteristics as discussed in sections 1 & 2,, such as very high efficiency, broad tunability, compact geometry, etc. In order to release the potential of this technology, a solution to the problem of relaxation oscillations is crucial. Let us now focus on the nature of these oscillations, the physical processes underpinning their behaviour and some real-life strategies for their elimination.