Advances in Intra-Cavity OPO's

Ben Pulford, Andreas Schmitt-Sody

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In the following paper we will review the characteristics of an intra-cavity optically pumped parametric oscillator. By utilization of intra-cavity pump power, automatic mode-matching and the stability introduced by negative feedback we will briefly present a possible application of use as an intra-cavity pulsed laser gyroscope.

1 Introduction

Ultrafast optically pumped parametric oscillators (OPO), with their broad range of wavelength tunability (UV-IR), have an untold number of applications in many fields in optics. Such applications include ultrafast spectroscopy, quantum optics, high resolution sensors and the study of other nonlinear optical phenomena. In the following sections ultrafast synchronously pumped OPO's and their applications in sensitive gyroscopes will be discussed. We will begin with an understanding of the basic physics of OPO's, followed by a comparison of intra-cavity OPO's with externally pumped OPO's, and conclude with a brief discussion of intra-cavity OPO's as highly sensitive sensors in gyroscopes.

2 OPO Basics

2.1 Externally Pumped OPO

Optical parametric oscillation is a second order nonlinear process based on difference frequency generation, see figure 1. A nonlinear crystal (for example LiNbO3) is placed inside of a resonant cavity and pumped by an external laser source, ω_p. Due to the phase matching conditions of the crystal, as met by temperature tuning and period polling (or angle tuning depending on the crystal geometry), two output frequencies will be observed, both signal and idler (ω_s and ω_i respectively). For a singly resonant OPO only ω_s oscillates inside the OPO cavity, see figure 3. By tuning the temperature of the crystal it is possible to tune the output wavelength of both ω_s and ω_i due to the changing of the crystal's physical properties and thereby altering the phase matching condition.

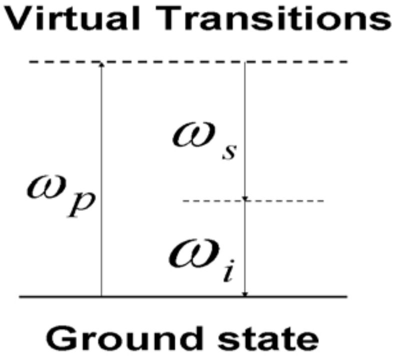

Figure 1: Feynman diagram of $\chi^{(2)}$ process, difference frequency generation.

2.2 Threshold Condition of OPO

An OPO is similar to a laser in that threshold conditions must be met in conjuction with phase matching conditions (OPO only). Just like a laser there are cavity losses, γ_s, that must be overcome as well as length (gain) considerations

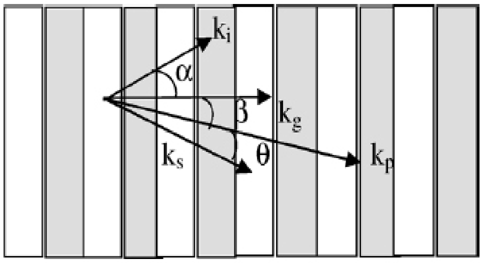

Figure 2: Periodically polled nonlinear crystal geometry for noncollinear propagation of pump and signal pulses.

due to the length, L, and nonlinear susceptibility, d_{eff}, of the crystal, as seen in equation1[3].

$$P_{th} = \frac{\epsilon_o\ n_s\ n_i\ n_p\ c\ \pi\ (\omega_p^2 + \omega_s^2)\ \lambda_s\ \lambda_i\ \gamma_s}{16\ \pi^2\ d_{eff}^2\ L^2} \quad (1)$$

For a femtosecond OPO P_{th} represents the peak power of the pump pulse.

3 Intra-Cavity vs. External Synchronously Pumped OPO's

3.1 More Pump Power

For multipass, synchronously pumped OPO's there are two key advantages in utilizing intracavity pumping verse pumping with an external laser source. The main advantage is in the achievement of high pump powers. The basic physics behind CW and modelocked lasers show that the intensity of a wave or pulse inside of the resonant cavity is roughly 10 to 100 times higher (as controlled by outcoupler transmission, 10% to .01%) than the intensity outside of the outcoupler. Therefore inserting the OPO crystal inside the laser cavity allows access to more pump power and therefore more pump to signal conversion. This is important from a cost of experiment perspective. Lasers with high intensity outputs tend to be very expensive and cumbersome whereas it is possible to purchase simple low output power semiconductor lasers at lower cost and still utilize high intra-cavity intensity.

3.2 Mode Matching

Another important advantage of intra-cavity pumping is that the external pump cavity, relative to OPO, automatically mode matches all counter propagating pulses in a multipass geometry. This ultimately improves the stability of the OPO in comparison to that of an externally pumped geometry by eliminating any mode volume mismatch between counter propagating pulses [5].

3.3 Stability through Negative Feedback

Another means of improving OPO stability is by the introduction of 'passive negative feedback' from the pumped nonlinear crystal back into the pumping laser cavity[6, 4]. This is accomplished by a 'negative' response from the OPO crystal to a variation in the power from the pumping cavity (i.e. from mechanical noise). As can be seen from equation 2 [1] the conversion efficency increases essentially exponentially ($cosh(\ )$) as the pump power is also increased; and decreases as the pump power is decreased. This means that as the pump power fluctuates the output of the OPO will also fluctuate accordingly (i.e. reverse the change induced by the pump fluctuation) so as to stabilize the pump power in both cavities.

$$\eta = \frac{I_{so}(z)}{I_{si}(z)} = cosh^2(\kappa z) \quad (2)$$

$$\kappa \propto \sqrt{I_p(z)} \quad (3)$$

There is one issue that needs to be addressed when introducing negative feedback to the pump laser cavity from an OPO. If the OPO depletes the pump power from one round trip more than can be compensated for by the pump cavity gain medium the pump pulse intensity will eventually decrease to zero before building back up. This effectively q-switches the pump cavity, making steady state operation impossible to accomplish [6,4]. By choosing a high gain medium for the pump cavity (i.e. semiconductors) this effect can be avoided.

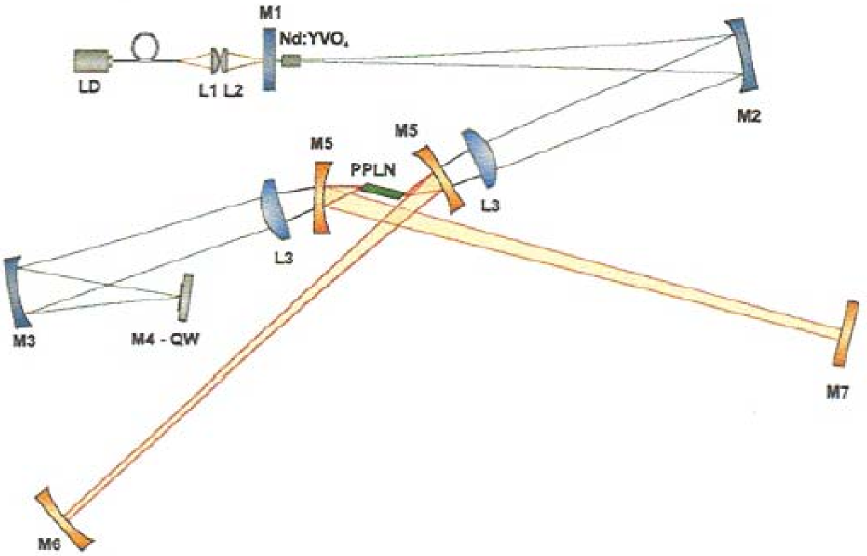

Figure 3: Experimental setup for synchronously pumped OPO by picosecond optically pumped $Nd : YVO_4$ [5]

3.4 Group Velocity Mismatch Optimization

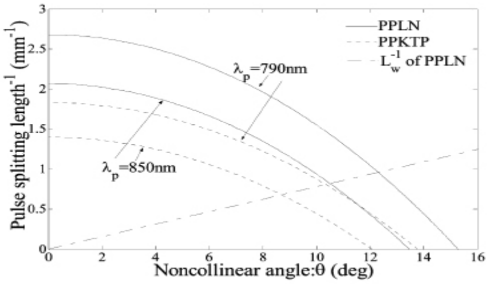

Figure 4: Reciprocal pulse splitting length L_{ps}^{-1} and reciprocal spatial walk-off splitting length L_w^{-1} versus noncollinear angle for $\lambda_p = 790$ nm, 850 nm and $\lambda_s = 1350$ nm.

Because the application section of this paper will focus entirely on ultrafast pulsed OPO's, it is important to introduce the concept of group velocity mismatch optimization. Due to the large difference in signal and pump wavelength each pulse will experience a different group index of refraction. Because of the different group indices each pulse will traverse the crystal at a different velocity. If the crystal is too long the pulses will separate in space, along the direction of propagation, and no longer interact with each other, as seen in equation 4.

$$L_{ps} = \tau_p\left(\frac{1}{v_{gp}} - \frac{1}{v_{gs}}\right)^{-1} \tag{4}$$

To compensate for the difference in group index, noncollinear propagation of the signal and pump pulses is applied, as seen in figure 2. Unfortunately noncollinear propagation will introduce a spatial separation, perpendicular to direction of propagation, between the two pulses that will continue to increase the further the pulses propagate in the crystal. The threshold power and small signal gain of the OPO can be optimized, as done in [3] by determining the optimal combination of spatial walk-off and temporal walk-off, as can be seen in figure 4.

4 Application - Gyroscope

Because of excellent stability and robustness, a potential application for an intra-cavity pumped

OPO is as a reliable and cost effective gyroscope. Because of the nature of a ring cavity OPO there are at least two pulses propagating in opposite directions inside the OPO cavity. If the OPO cavity were to rotate on its axis, perpendicular to the plane defined by the path of pulse propagation inside of the OPO, each pulse will experience a Doppler shift in wavelength proportional to the velocity of rotation. If both pulses are extracted from the cavity (i.e. at outcoupler) and made to overlap and interfere at a detector, a beat note will be measured. The measured beatnote can then be directly related to the rotational velocity of the gyroscope through Doppler formulae.

There are three key advantages to this type of gyroscope versus the more established HeNe gyroscope in use today. The first advantage is the elimination of the 'lock in' effect commonly seen in HeNe gyroscopes. 'Lock in' is an effect caused by the "scattering from one sense of circulation in the cavity into the counter-circulating mode resulting in an injection locking of the two frequencies that would otherwise constitute a beat note" [5]. This effect is eliminated by designing the cavity in such a way that the counter propagating pulses cross only in vacuum as apposed to inside or at the surface of a scattering medium.

A second advantage of an intra-cavity OPO gyro over the HeNe gyro is the elimination of gain competition. By its very nature there is no energy stored in the nonlinear crystal when there is no pump pulse present. This limits or eliminates noise and other unwanted nonlinear effects such as intensity dependant phase shifts (i.e. optical Kerr effect) inside the OPO.

A third, more practical advantage, is the relative compactness of an intra-cavity OPO gyroscope. This allows for more suitable use in things like planes and orbiting satellites.

5 Conclusion

By utilizing the properties mentioned above: more available (cost effective) pump intensity, automatic mode matching, and increased pump and OPO stability from negative feedback, it is possible to produce a laser gyro not susceptible to the problems current HeNe laser gyros experience ('lock in' and other nonlinear effects). Combining these properties with its relative compactness provides a potential replacement for the current, more problem prone, HeNe laser gyro.

References

1. Robert W. Boyd, *Nonlinear Optics 2nd Ed.* (Academic Press, San Diego, CA, 2003).

2. Jean-Claude Diels et al, "Bidirectional, Synchronously Pumped, Ring Optical Parametric Oscillator," *Optics Letters*, Vol. **26**, No. **5** 2001, pp. 265–267.

3. Ye Liu, Jean-Claude Diels, Senior Member, IEEE, "Group-Velocity Matched Femtosecond Parametric Oscillation by Noncollinear Quasi-Phase Matching," *IEEE Journal of Quantum Optics*, Vol. **42**, No. **8** 2006, pp. 760–764.

4. Andreas Velten, "Enhancement of Q-Switching by an intra-cavity Pumped OPO," *CLEO 2007*, 2007.

5. A. Zavadolova, V. Kubecek, J-C Diels, "Picosecond Optical Parametric Oscillator Synchronously intra-cavity Pumped by Mode-Locked $Nd : YVO_4$ Laser," *Laser Physics Letters*, Vol. **1**, No. **1** 2005, pp. 1–5.

6. Alena Zavadilova, Vaclav Kubecek, Jean-Claude Diels, Andreas Velten, "intra-cavity Pumped Picosecond Optical Parametric Oscillator for intra-cavity Interferometry," *CLEO 2006*, 2006.