A simple technique to achieve active cavity-length stabilisation in a synchronously pumped optical parametric oscillator.

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Abstract

The dependence of oscillation wavelength on cavity length in a synchronously pumped optical parametric oscillator provides the basis of a scheme for stabilisation of the cavity length and wavelength. The design and performance of a simple implementation of this scheme via the use of a position-sensitive detector is reported for a lithium triborate optical parametric oscillator. The stabilisation scheme has proved effective over the entire tuning range of the oscillator (0.65-2.65μm), giving stability against fluctuations up to 200Hz, with greatly improved amplitude stability, and allowing smooth wavelength tuning over a signal range of ~5nm.

1. Introduction:

The first reported cw synchronously pumped optical parametric oscillator (SPOPO) was demonstrated by Piskarskas *et al.*[1] in 1988.This was a doubly resonant device with the crystal Barium-sodium niobate being pumped by a frequency doubled actively mode-locked Nd:YAG laser. The rapid recent growth of interest in these devices dates from around 1989, when Edelstein *et al.*[2] demonstrated a singly resonant KTP optical parametric oscillator pumped intra-cavity by a mode-locked dye laser. This rapid growth of interest has been in part due to the availability of new high quality nonlinear materials, such as KTP, LBO and BBO, and in part due to the availability of reliable sources of mode-locked pulses in the picosecond and femtosecond regime. SPOPO's pumped by femtosecond mode-locked Ti:sapphire[3],[4] (see eg. Reference 3 and associated papers in the same special issue) and self-mode-locked diode-pumped Neodymium lasers ooperating in the picosecond regime[5],[6],[7], now promise practical and reliable sources, attractive for the many applications requiring widely tunable ultrashort pulses.

Important attributes required for most applications are amplitude stability and wavelength stability. These requirements predicate the use of a singly resonant oscillator, in which the idler wave is then free to adjust its frequency and phase to those dictated by the pump and resonated signal wave. This relaxes the tolerance on control of the OPO resonator length, and for picosecond pump pulses oscillation can typically be achieved over a range of a few tens of microns of resonator length change (correspondingly reduced for femtosecond pulses). However, although oscillation can occur over these considerable length changes, the signal/idler wavelengths vary significantly with cavity length, so resonator length control is needed in practice. In this paper we describe a simple technique which has proved very effective for a LBO, SPOPO operating with pump pulses in the picosecond regime. The same technique should also be widely applicable to femtosecond OPO's.

First we discuss the origin of the dependence of wavelength on cavity length and then consider some possible schemes for stabilising the cavity length. Then we describe the technique used, with results that demonstrate the very significant improvement in stability and reliability of performance in a LBO, SPOPO.

2. Background.

The change of signal/idler wavelengths with resonator length has its origin in the group velocity dispersion (GVD) characteristics of the OPO resonator. In practice this is usually dominated by the GVD of the nonlinear crystal since this is often the only optical component in the resonator. A change of resonator length requires a change in the group delay of the resonated (signal) wave in order to maintain synchronism with the next pump pulse after one round trip. This required change of group delay is obtained, via the GVD of the nonlinear crystal, by a change of signal (and hence also idler) wavelength. In practice, for a 15mm LBO crystal, pumped by ~2psec pulses at 523.5nm, signal wavelength tuning with cavity length has been ~1nm/μm for a signal wavelength in the region of ~800nm as shown in figure (2). For femtosecond pulses, a correspondingly shorter crystal would be used, and a correspondingly smaller group delay would be tolerated. Hence essentially the same overall wavelength detuning would occur, although produced by a correspondingly smaller change of cavity length.

Not only is the oscillation wavelength dependent on cavity length detuning but so also are the average output power and the pulse duration. So, one has the choice of three stabilisation schemes based on a) maintaining maximum power, b) maintaining a minimum pulse duration or c) maintaining a fixed oscillation wavelength. In assessing these three possibilities, it should be noted that the average output power of the SPOPO was found to have a cavity-length dependence as depicted in figure (1). The form of this curve is asymmetric around the zero detuning point with the output power dropping quickly for longer cavity lengths and more slowly for negative cavity length detuning. The output power is almost constant over a range of $\pm 4\mu$m either side of the zero point. Possible stabilisation points that could be used to provide an error signal suitable for feedback control are on the slope of the curve either side of zero detuning. The disadvantages of this scheme are the need to dither the cavity length in order to provide the necessary discriminant error signal and the requirement that the OPO be operated away from maximum output power. Cavity length dither would also entail a dither in the oscillation wavelength.

A second method which has been used to stabilise a synchronously pumped mode-locked dye laser involves monitoring the average second harmonic power (inversely proportional to the pulse width for a constant output power) generated by the output pulse train as a function of cavity length detuning[8]. For the dye laser, the pulse duration (and hence the second harmonic signal) is a sensitive function of cavity length detuning. In the case of the lithium triborate SPOPO, the output pulse width variation with cavity length detuning is only small,changing from 1.5psec to 1.35psec as the cavity length goes from negative to positive detuning and therfore only provides a rather small error signal discrimination.

Figure (2) shows the monotonic shift in central wavelength of the OPO as the cavity length is varied, indicating a linear variation of 0.88nm/μm. This linear and easily monitored wavelength variation provides the basis of a very convenient scheme for cavity length stabilisation in which the signal spectrum is dispersed by a grating onto a position sensitive detector (PSD). This then provides a wavelength-dependent output voltage which can be used for feedback control of the cavity length. The use of a PSD proves to be much more convenient to implement than the technique first reported for a SPOPO by Wachman[9] and in more detail later by Edelstein[10], in which stabilisation was achieved by using two separate matched photodiodes in the dispersed spectrum. The PSD package contains all the required electronic processing, and furthermore provides a very convenient means for tuning of the OPO over limited spectral ranges.

3. Experimental details.

The basic experimental arrangement is shown schematically in figure (3). The synchronously pumped lithium triborate optical parametric oscillator and pump source used in these experiments have been described in detail elsewhere and will not be reported here [7,11]. A small fraction (~1%) of the signal wave output from the OPO is extracted by a glass plate beam splitter (near Brewster's angle) and impinges on the grating near grazing incidence. The diffracted beam is then brought to a line focus, using a cylindrical lens, on the surface of the position sensitive detector (PSD). The device used here is a one-dimensional PSD with a photoconductive active area of 1 x 12 mm^2. The PSD works in such a way that it can be considered as an optically triggered equivalent of a resistance divider. The PSD has typically

50kΩ surface resistance. When a light spot is incident on the p-layer (see figure 4), and a reverse bias applied (V_R) , the region where the light spot is incident becomes photoconductive and current flows to the two end electrodes producing currents I_1 and I_2 . When the electrical centre of the PSD is assumed to be the position of incident light where detected current I_1 = I_2 , position detection in any incident position can be defined according to the following formula.

$$Relative\ position = \frac{I_1 - I_2}{I_1 + I_2} \tag{1}$$

By suitable signal processing of I_1 and I_2 , this analog divider output provides a voltage output which varies linearly with position of the light spot. This voltage is used, after amplification to provide the drive for a PZT on which one of the OPO mirrors is mounted, thus stabilising the resonator length.

The choice of grating and focal length of the cylindrical lens were made from what was readily available to us rather than on the basis of a detailed optimisation. For convenience, the requirements were that the grating should be able to direct a first order diffracted beam onto the PSD, covering the range of signal wavelengths from 650nm to ~1000nm simply by tilting the grating appropriately. A 1200 lines/mm grating was used (Edmund Scientific, Part No. P43,209). The grating was set for grazing incidence at the longest signal wavelength. The diffracted light is collected and focused down onto the PSD (Hamamatsu, PSD S3932) by a cylindrical lens of focal length *f*=300mm to provide a line focus. The focal length (and hence the distance to the PSD) was chosen to ensure that the calculated spectral range (33nm) that could be intercepted by the PSD was somewhat greater than the full range (~22nm) over which the OPO would tune via cavity length change. The PSD was biassed with a reverse voltage (V_R) of 10Volts, allowing an incident power of up to 400μW to be used without saturation. In fact saturation is not a serious problem, its main effect being to effectively broaden the width of the region in which photoconduction is induced, thus reducing the potential resolution. A change of wavelength produces a shift in position of the beam on the PSD and the two currents I_1 and I_2 from the PSD are amplified and processed by an analog divider circuit. This is self-contained in the signal processing unit (Hamamatsu, C3683-01) and provides a linear output of -10V to +10V as the light spot is scanned across the surface along its full extent of the PSD[12]. According to the manufacturer's data[12] the positional resolution of the device is 1μm even when a 200μm light spot is used to illuminate (below saturation) the detector. The spot size in our arrangement was of this order, thus even if the resolution was considerably reduced by saturation this could still result in a resolution much better than the OPO spectral width.

The signal from the processing circuit is then sent to an offset amplifier where a zero voltage reference level can be set. Deviations from this reference level are monitored and used to provide feedback control. This is via a high voltage amplifier which drives the piezo-electric transducer (PZT) on which the rear high reflector of the OPO is mounted. Active cavity length control is ensured when the sign of the error signal has the correct polarity ie. as the OPO goes to shorter wavelengths and negative cavity length detuning (figure 2), then the PZT provides compensation by lengthening the cavity and returning the wavelength to its set point.

Should the OPO operation become interrupted and the circuit lose the locking point (eg.

pump laser perturbation), a simple recovery circuit is enabled which scans the PZT over its full extension range until the locking point is re-established.

4. Results and Discussion:

Without the stabilisation circuit engaged the central wavelength of the OPO was observed to fluctuate randomly over a range of ~3nm as shown in figure 5(a). This depicts the random variation of the wavelength over a period of ~20 seconds. The wavelength spectra were recorded on an Ando optical spectrum analyzer with the resolution set to 0.1nm. The cavity length perturbations are to due to mechanical vibrations or environmental disturbances along the optical path (thermal expansion of the optical bench and optical components, air-index variations...). With the feedback circuit engaged, the central wavelength showed no noticeable deviation with time (ie. <0.1nm), as shown in figure 5(b), again for a period of ~20 seconds.

An interesting feature of this stabilisation scheme was the ability to continuously tune the central wavelength of the OPO over a range of ~15nm simply by adjusting one variable resistor which controls the offset reference voltage for locking. However, this range of tuning caused a significant drop in output power due to its dependence on cavity length as shown in figure 1. It was however possible to tune by ~5nm without a significant fall in output power as a consequence of the constant output power behaviour around zero cavity length detuning. The output power fluctuations were measured to be $\pm 3\%$ rms. (DC to 5kHz), essentially the same as the fluctuations in the mode-locked frequency-doubled pump laser.

As a check on the capability of this new stabilisation circuit we deliberately introduced a sinusoidal variation at 40Hz to the cavity length by using a second PZT on the translation stage of the OPO output coupler. The amplitude of this variation was $\pm 5\mu$m corresponding to a round trip cavity length detuning of $\pm 10\mu$m, which allows the OPO to remain oscillating over this range. The output power variation with and without active stabilisation is shown in figure 6. The total width of the horizontal scale is 5 seconds. The OPO was set to stabilise at the wavelength that provided maximum output, in this case 140mW at 800nm.

The response time of the PSD and signal processing is 300μsec, so a much faster response is possible than that of the above test. In fact, observation of the error signal into the high voltage amplifier used to drive the PZT indicated that corrections at up to 200Hz were occurring in response to vibrations of the optical table.

5. Conclusions:

We have demonstrated a simple technique for cavity length/wavelength stabilisation for a singly resonant OPO based on LBO, operating in the picosecond regime. The availability of position sensitive detectors, with detector response spanning the full signal wavelength range, makes the system very easy to implement. Cavity length fluctuations up to 200Hz have been corrected for. The use of a PSD also allows for very straightforward wavelength tuning over ~5nm of signal wavelength range.

Applicability is not limited to the wavelength range we have used (ie. 650nm to 1000nm) but is equally suited for a wide-range of broadly-tunable visible and near infrared OPO's based on BBO, LBO, KTP, KTA etc. as the spectral response of this silicon PSD covers the range 320nm to ~1100nm. Also, the PSD is not limited to the wavelength response of silicon but could be extended to cover the 0.8-1.8μm region by substitution with a Germanium position sensitive device[13] .

While we have demonstrated this technique for use with an OPO in the picosecond regime it can be readily applied to femtosecond sources, for which a similar range of wavelength tuning is anticipated (~20nm) but with correspondingly smaller changes in cavity length required to cause the tuning. Again, the same method as applied to the picosecond regime should provide wavelength stabilisation to much less than the signal bandwidth.

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Figure captions:

Figure 1. Output power variation with cavity length detuning.

Figure 2. Variation of central wavelength with cavity length detuning. Linear regression of 0.88nm/μm.

Figure 3. Schematic diagram of the experimental arrangement and active stabilisation circuit.

Figure 4. Principle of operation of the PSD.

Figure 5(a). Central wavelength fluctuation with no active stabilisation.

Figure 5(b). Central wavelength fluctuation with active stabilisation circuit engaged.

Figure 6. Output power variation without and with active stabilisation under 40Hz external driving signal to the output coupler.

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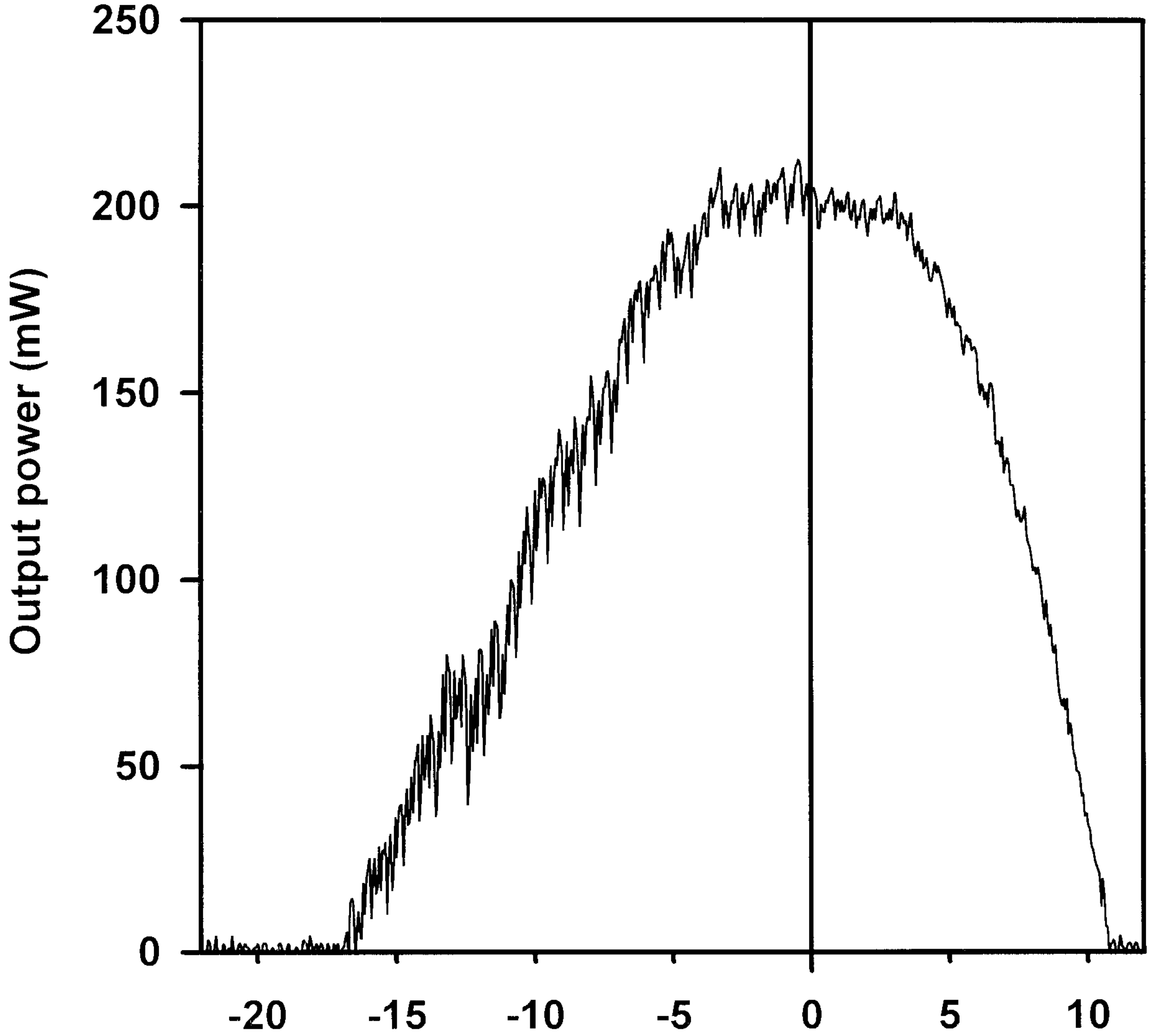
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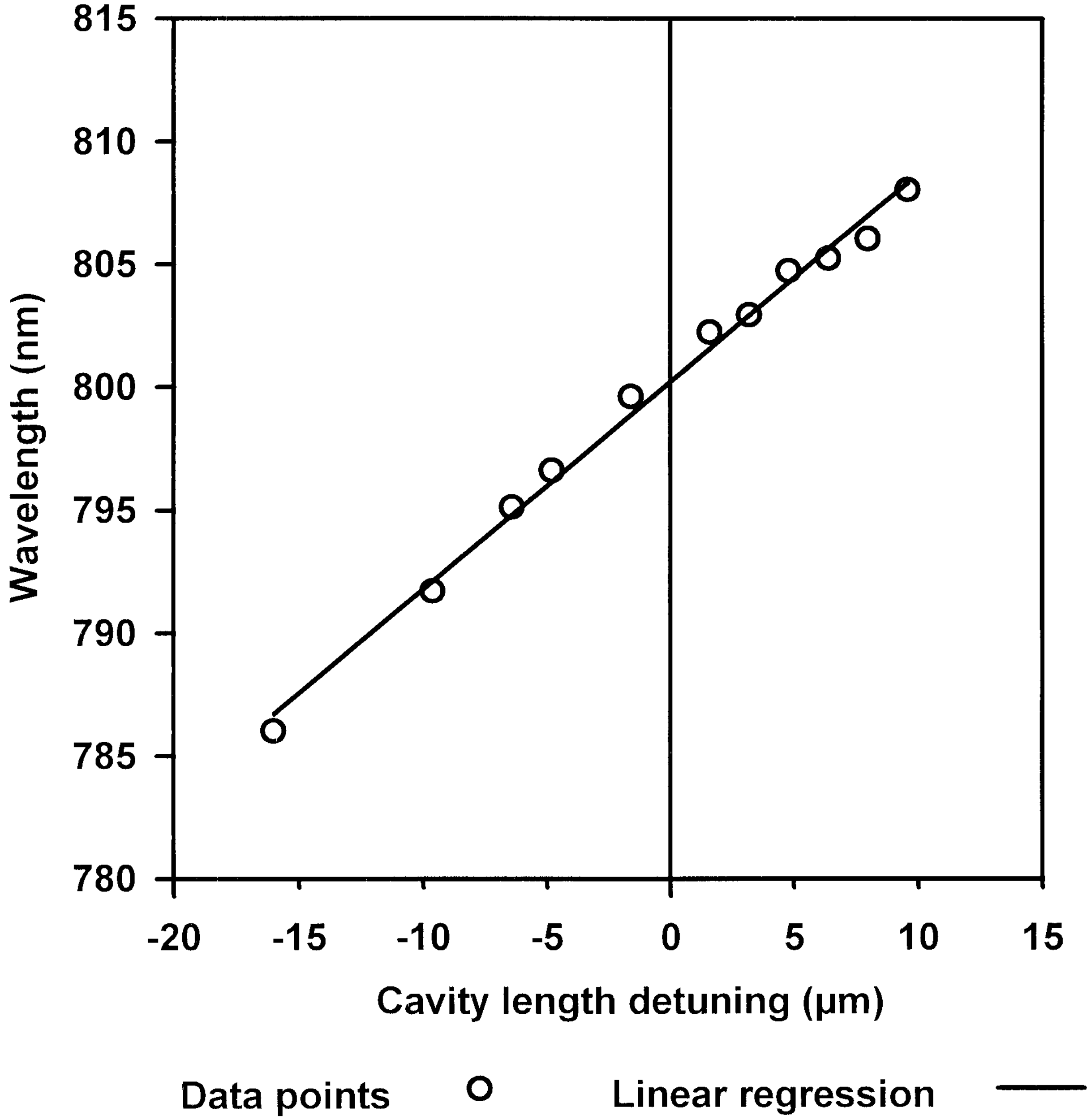
Cavity length detuning (µm)



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800
795
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-15
-10
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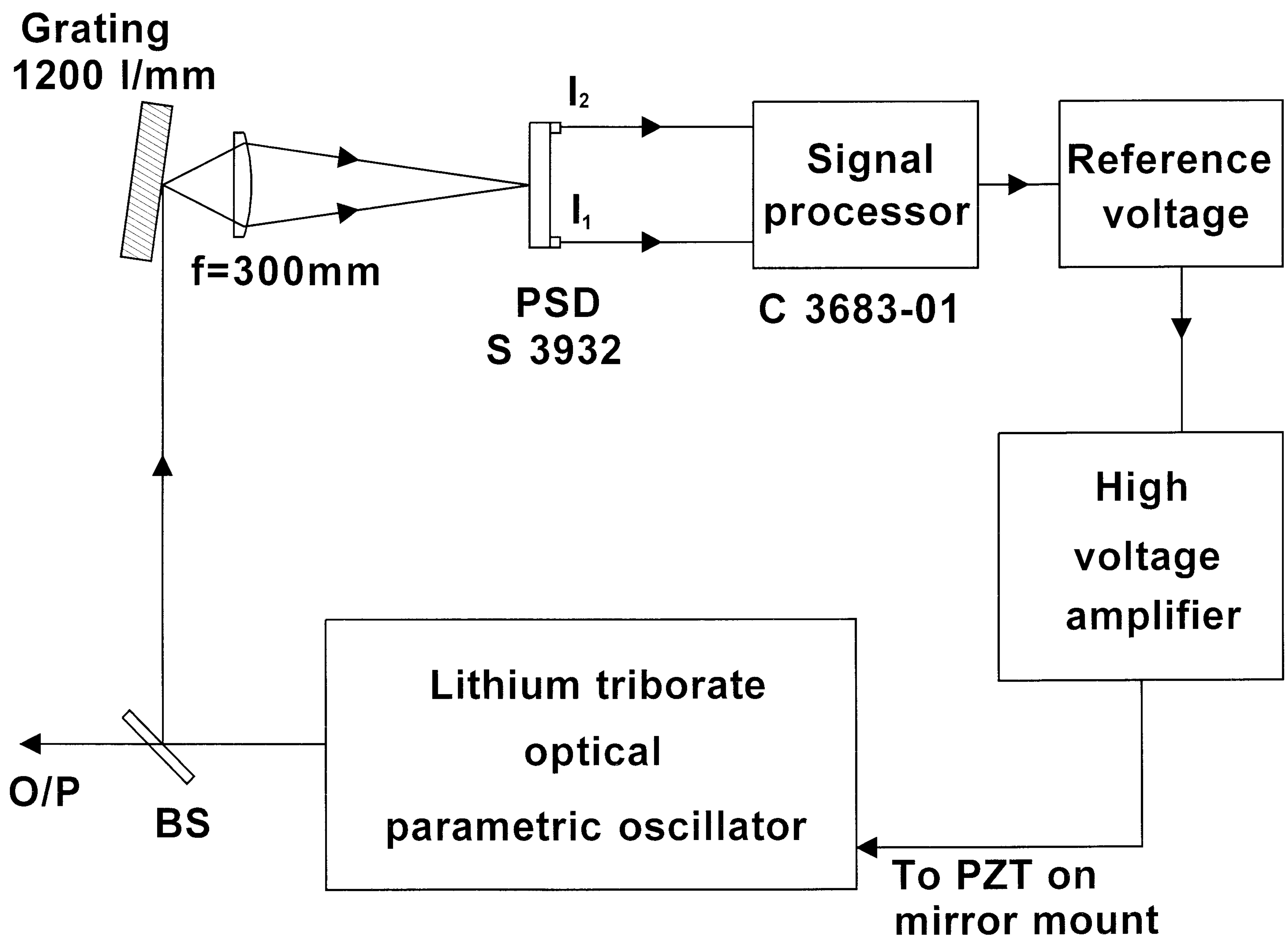
5
10
15
Cavity length detuning (µm)
Data points
Linear regression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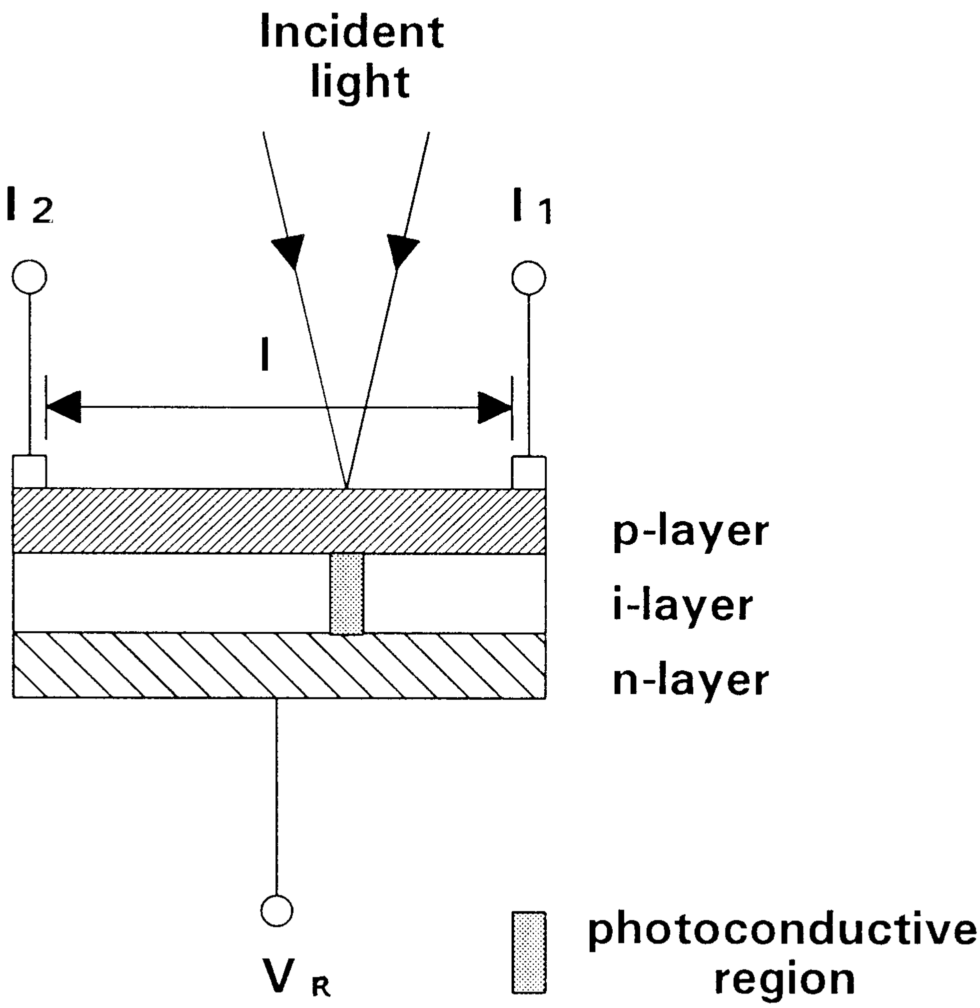

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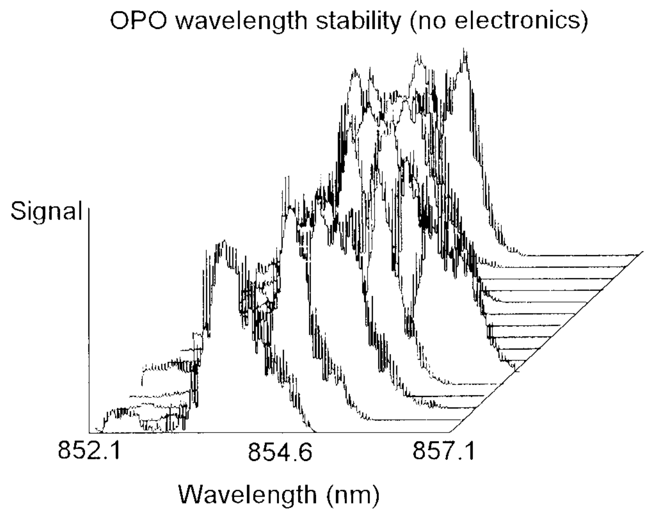
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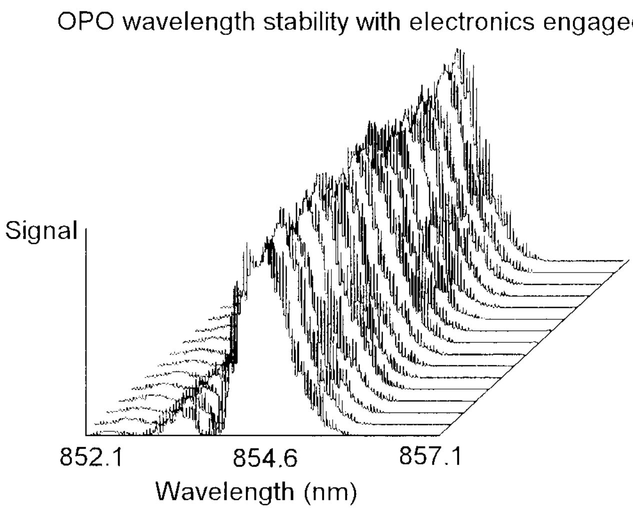
854.6
857.1
Wavelength (nm)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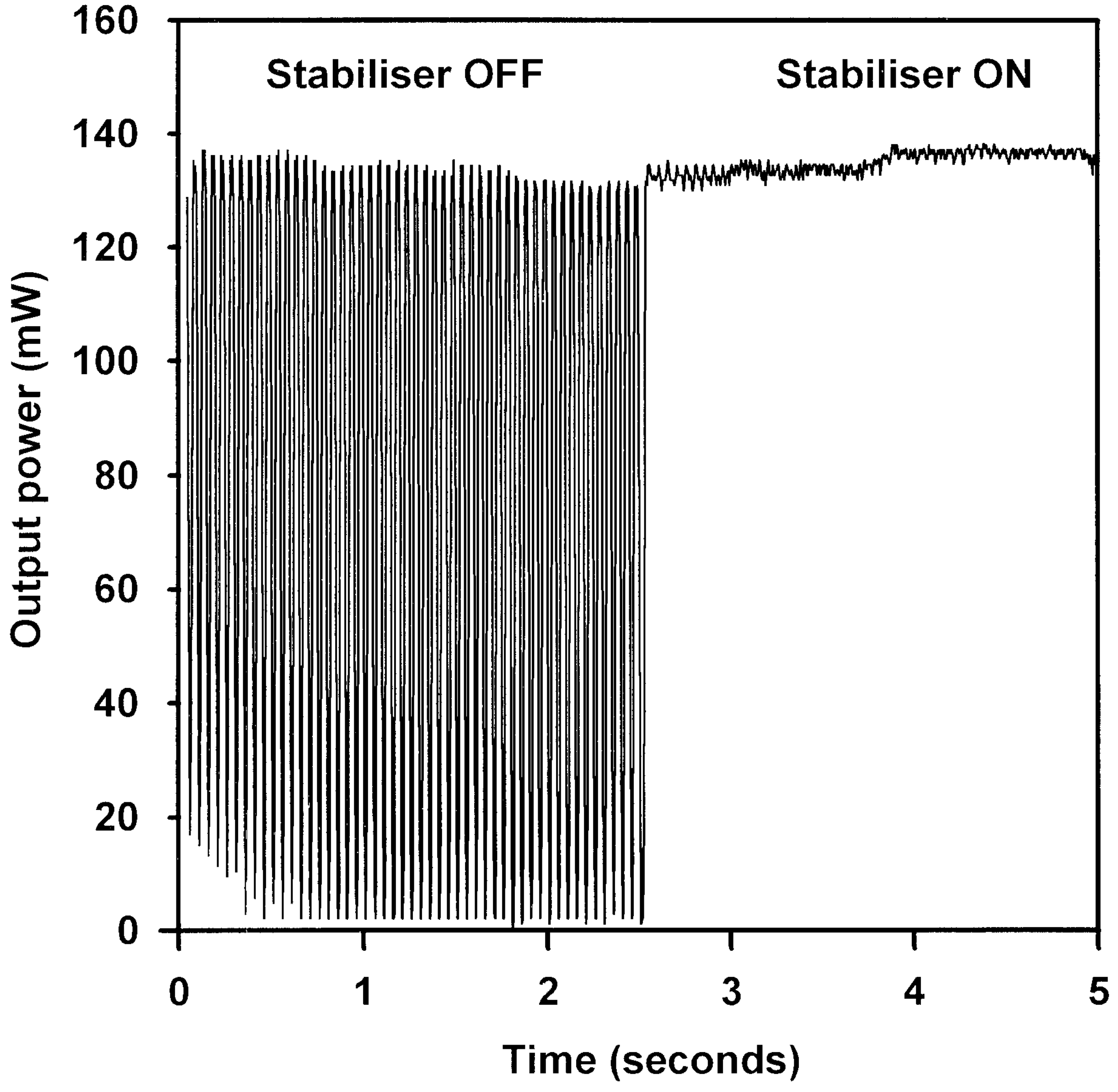
857.1
Wavelength (nm)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2
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Time (seconds)