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Master in Photonics

MASTER THESIS WORK

SATURATED ABSORPTION FREQUENCY LOCKING AND SECOND HARMONIC GENERATION FOR NARROWBAND ENTANGLED PHOTON PAIR GENERATION

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Saturated absorption frequency locking and second harmonic generation for narrowband entangled photon pair generation

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Abstract. The design of two locking systems for light sources desired to generate narrowband photon pairs is under study. First a DBR laser will be locked to the D1 transition frequency of ^{87}Rb using a Doppler-free Saturated Absorption Spectroscopy. Afterwards the frequency-locked light will be doubled in a nonlinear PPKTP crystal resulting in a frequency stabilized source at 397.5 nm.

Keywords : Saturated Spectroscopy, Second Harmonic, Frequency Locking

1. Introduction.

In Quantum Optics the stability in frequency of the light sources is crucial to conduct successfully most of the experiments. For instance the generation of quantum entanglement and the areas that make use of it like Quantum Information or Quantum Metrology, often requires a perfect stabilization of the frequency, specially if they involve light matter interaction, since the atoms have well determined transitions and a narrow linewidth so to improve this interaction the frequency of the photons must be precisely stabilized.

Our group is currently developing a single atom trap experiment which once it is finished we expect to be able of trapping a single Rubidium atom within a 3D Magneto Optical Trap (MOT). The objective is to study the interaction between this atom and indistinguishable photon pairs where we expect to observe interferometric effects such as single atom Hong-Ou-Mandel, where the two photons will be scattered both in one direction.

The indistinguishable photon pairs will be generated by a Cavity-Enhanced Spontaneous Parametric Down Conversion (CESPDC) configuration which is explained in detail in [1]. This configuration takes advantage of SPDC which is a nonlinear process by means of which a photon at 2ω will down convert to two photons at ω. As the name says, the process is spontaneous and it also has a wide bandwidth of generation. To solve this broadening the CESPDC configuration places two nonlinear crystals (PPKTP and a KTP) with a ring cavity which will resonate only the modes that are allowed by this cavity and both the cavity and the pump system for SPDC need of stabilized frequency sources in order to avoid as much as possible the fluctuations.

The aim of this thesis is to build the necessary systems to lock in frequency the pump laser for the cavity and the cavity itself so that once this project is finished, we will be able to generate single photon pairs and send them to the trapped atom. The cavity was built to generate photons at the ^{87}Rb D1 transition frequency so to lock the laser source (a DBR laser) to this frequency, a saturated absorption spectroscopy technique will be used. The stability of this first laser source will be doubled in a nonlinear PPKTP crystal and sent to a the cavity for generating the photon pairs. This generated will be of the order of μW so to overcome this problem and obtain a higer power, we propose to use it to lock an ECDL laser at 397.5 nm with a maximum output of 80 mW.

2. Light sources and experimental description

2.1. Distributed Bragg Reflector laser and External Cavity Diode Laser

Due to the importance of the light sources in this project, it is relevant to talk about how the light is produced and which factors might affect the "purity" of this light.

In the cavity locking case, the laser is a Distributed Bragg Reflector (DBR) diode laser with a center wavelength at 795 nm, the transition wavelength of the D1 line in Rubidium. This laser is formed by a wavelength-selective reflective diffraction grating on one end of the laser and the gain medium on the other end, separate from the reflection zone. This will select for feedback and oscillation those wavelengths that are in resonance with the grating parameter, which ensures not only a single-spatial mode but also a single longitudinal one. The DBR lasers are usually diode lasers so one can tune them by adjusting the current and temperature parameters, but since the grating will then resonate a new wavelength, it will remain single mode. This characteristics ensure a good stability due to its insensitivity to mechanical vibrations which despite its larger linewidth makes them more desirable for locking purposes in quantum optics experiments that the ECDL.

On the other hand, the laser that will act as a source for the CESPDC is an external cavity diode tunable laser emitting at 397.5 nm, which is the second harmonic of the 795 nm. The laser has a tunability thanks to an external grating which can be rotated to select the wavelength that will be powered. The first diffraction order, also provides a feedback that will lock the emission mode of the laser. This is translated to a laser source capable of high output powers (up to 80 mW) at a single frequency with a narrow linewidth ($\sim$ 2 MHz) and a mode-hop-free scanning range of approximately 50 GHz.

2.2. Experimental setups

The DBR 795nm laser has two functions, one is to lock the cavity in charge of the generation of the photon pairs that will interact with the trapped atom and the other is to produce SHG in the PPKTP crystal (see Figure 2).

Figure 1 is a scheme of the optical setup for the saturated absorption spectroscopy and the laser locking to the D1 transition. First of all the laser source formed by a DBR diode laser in a handmade cage and an optical isolator to prevent the back-reflection of light, which the diode is sensitive to. Since the light emitted by the diode has an elliptical shape, two cylindrical lenses of L_1 and L_2 of 60 and 22.5 mm focal length respectively, are placed in order correct this ellipticity. Afterwards the light is separated with a half wave plate (HWP) and a polarizing beam splitter (PBS1) in order to send most of the light to the fiber coupling and use it in the SHG setup and part of the light will go to the spectroscopy branch.

In this second part of the setup, the laser beam passes through a double pass with an acousto optic modulator (AOM) centered at 80 MHz, fed with an amplified VCO signal and experiencing a total shift of 160 MHz, where the +1 mode of the modulation was selected thanks to two iris. Since the beam coming out from the AOM is divergent, a lens was placed at its focal distance to ensure that the different orders will go and back through the same path. Notice that if in first place the beam turned at PBS2, in the way back it will continue straight since in the double pass it passed twice through a quarter wave plate (QWP) experiencing a total variation of $\lambda/2$.

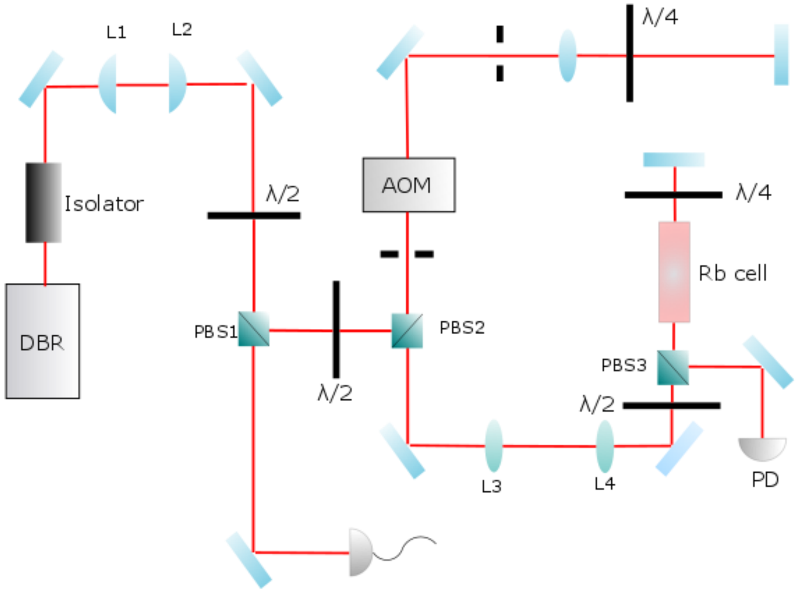

Figure 1. Scheme of the setup for the saturated spectroscopy

Finally when the beam is already shifted it goes to the spectroscopy part. As the signal will depend on the number of atoms excited, enlarging the spot size is a good option to improve the signal obtained so the beam passes a telescope composed by L_3 (f = 15 mm) and L_4 (f = 100 mm) before the rubidium cell obtaining the expected result of a better signal to noise ratio (SNR). The configuration for the spectroscopy is the following : The polarization of the incident beam (that will act as the pump) is changed with a HWP, then passes straight in PBS3 and is absorbed by the rubidium atoms in the cell, saturating the transitions. The beam that comes out of the cell passes through a QWP, is reflected in a mirror and passes again for the QWP experiencing a total retardation of $\lambda/2$ and acts as the probe beam in its way back along the cell and at the PBS where due to the QWP double pass. The signal obtained is finally recorded by a photodetector (PD) which output is presented in Figure 3

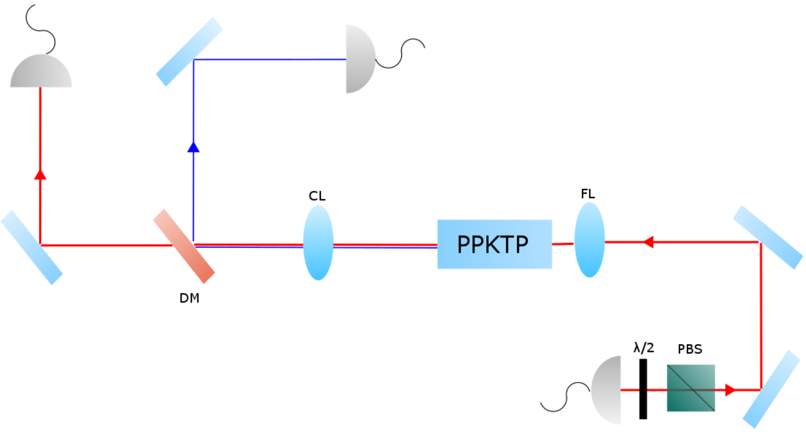

Figure 2. Scheme of the setup for the second harmonic generation

Figure 2 shows the second setup involved in this experiment, which will generate light at SH of the DBR laser and interfering it with the ECDL from Toptica at 397.5 nm will provide a reliable narrow-linewidth light source.

The light will come out the fiber from the Figure 1 setup and passing by a HWP will be focused in the nonlinear PPKTP crystal by FL to a waist $\omega_0 = 22.4\ \mu m$ which value has been extracted from Equation 4 . The reason to add the waveplate is due to the fact that the PPKTP presents a birefringence so it proceeds to play with the polarization of the light in order to enhance the phase matching condition.

Another important factor to improve the efficiency of the SHG is the temperature of the crystal. To have a control of that I used a handmade circuit connected to an HTC1500 temperature controller from Wavelength Electronics, a NTC Peltier and a PTC sensor to provide a feedback of temperature variations.

If the first lens focus the beam into the crystal, the second lens collimates the divergent beam coming out of it. The selected lens has an AR coating for the blue, since the lenses with AR coating for the red are poorly transparent to the blue wavelengths. A dichroic mirror placed after the lens has the function to split both wavelengths, reflecting the 397.5 and transmitting the 795 nm laser.

SHG is a process with a poor efficiency so most of the light coming from the DBR will pass through the crystal without being converted. To not throw away this light a good option is to couple in fiber this excess of light and use it to lock the cavity. If the couplings has a relatively-good efficiency ($\sim 76\%$) and the loses in the path are minimized the light reaching the cavity will be largely enough for locking.

With the same low efficiency, the blue path is also affected. The expected output was calculated with computer simulations and it is of the order of tens of μW in the best cases. The output power, however, will be enough since the main purpose of it, is to do the beat note in a fiber-beamsplitter and this method does not require large field amplitudes. The resulting signal is the SHG, the beat note between this and the ECDL is need to lock the ECDL to the SHG such that the down-converted photons are in resonance with the D1 transition of ^{87}Rb

3. Saturated absorption spectroscopy and frequency locking

3.1. Saturated absorption spectroscopy

The Absorption spectroscopy technique, has a common resolution limit in the Doppler broadening of the absorption spectrum. This is because of the mobility of the atoms in the sample and according to the Doppler effect, the atoms moving in the direction of the beam will experience the photons at a frequency $\nu = (1 + \frac{v}{c})\nu_0$ called blue detuned (at a higher frequency) meanwhile the atoms moving towards the beam if they are moving towards the beam the frequency will be $\nu = (1 - \frac{v}{c})\nu_0$ or red detuned (lower frequency). This is called the Doppler-broadening and will cause that instead of having narrow peaks at the transition frequencies, what will be recorded is an spectrum with broad dips with a gaussian profiles, since the velocities distribution of the atoms at a room temperature follows a Maxwell distribution.

One possible way to solve that is the Saturated Absorption Spectroscopy. The scheme this technique proposes is to have two counter-propagating beams called pump and probe. The pump beam is selected to bleach the atomic gas i.e saturates the transition between a ground state $|g\rangle$ and an excited state $|e\rangle$, then the signal of the probe beam passing through this saturated sample will experience a weak absorption because of the depopulation of the $|g\rangle$ level.

With this basis, the only atoms that will be able to interact with the photons of both counter-propagating beams are those that sees the beams at the same frequency or in other words, the atoms that stay at rest or are not propagating in a parallel direction with respect one of the beams. This causes the appearance of narrow peaks in the bottom of the absorption dips giving resolution over the hyperfine structure.

Figure 3 shows the commented peaks of the transmission spectrum in the bottom of the doppler-broadened deeps. Since the Rb cell contains the two most common isotopes some of this transitions correspond to the ^{85}Rb and some to ^{87}Rb, and the peaks show the hyperfine transitions between the different energy levels of this atoms and also crossover transitions. The relevant peak for this work corresponds corresponding to the D1 transition of the ^{87}Rb ($F = 2 \rightarrow F = 1$). The reason to use this transition is to be able to lock the SPDC cavity, which was designed to generate photons at this wavelength.

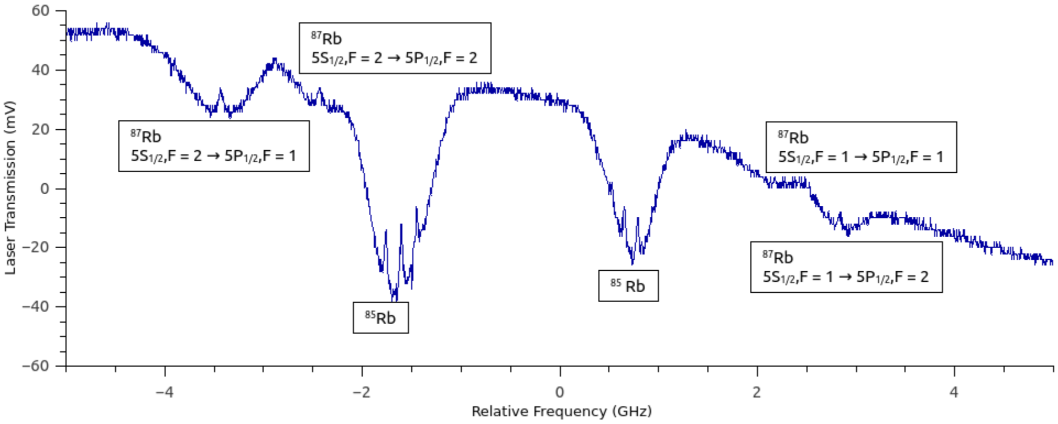

Figure 3. Saturated absorption spectroscopy signal obtained for the Rb cell

3.2. Error signal and frequency locking

The output of the DBR laser will be stabilized by means of a controlled loop-feedback where a Proportional-Integral-Derivative (PID) controller is used. The PID will take an error signal $e(t)$ calculated as the difference between a given set point and the actual input to the system. With this, it will generate a response $u(t)$ that will feedback the laser source to correct the possible deviations from the set values.

In general the output of a PID takes the form :

$$u(t) = k_P e(t) + k_I \int_0^t e(t)dt + k_D \frac{de(t)}{dt} \tag{1}$$

where k_P, k_I and K_D are the Proportional, Integral and Derivative gains that we need to find in order to achieve a good and stable locking for our purposes. In order to understand the role of each of those constants let's see the role that they play in the control of the system.

The Proportional will produce term an output proportional to $e(t)$, adjustable by means of its k_P gain. For lower values of k_P the system will be practically insensitive to the changes at input and for large values it will overreact to this changes and then the system will be unstable.

The Integral term will be affected by the amplitude and duration of the error input. This term gives an amount of the offset accumulated that should be corrected and also controls the velocity of response to drive the system at the set values.

Finally the derivative term will be determined by the slope of the error and multiplied by its k_D gain. This term gives a prediction of the system behavior which will help to improve the stability of the system.

In this work, the PID parameters will be software-tuned in a Labview custom program and connected to a Field Programmable Gate Array (FPGA). This method will provide an improved stability with respect to traditional systems since it will be insensitive to vibrations and environmental changes in the laboratory.

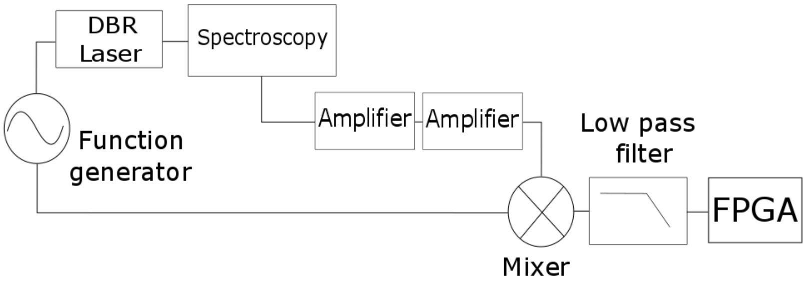

Figure 4. Demodulation Circuit for obtaining the error function

To obtain the error signal that will be send to the PID controller it is necessary to have a modulation applied to the laser source (Figure 4). This modulation is splited in two parts, one to the laser and the other one directly to a demodulation circuit. The modulated laser light is recorded by the photodiode after passing the spectroscopy setup and then is amplified and mixed with the second part of the modulation signal. Finally the resulting output passes by a low-pass filter to avoid the higher orders and results in the blue signal observed in Figure 5. The shape of this signal can be adjusted by tuning the relative phase between the modulation signals, the amplitude, etc in order to obtain the proper characteristics, in this case are the slope, amplitude and symmetry of the error signal, since this will determine the values for the gain coefficients in the PID and then the quality of the coupling.

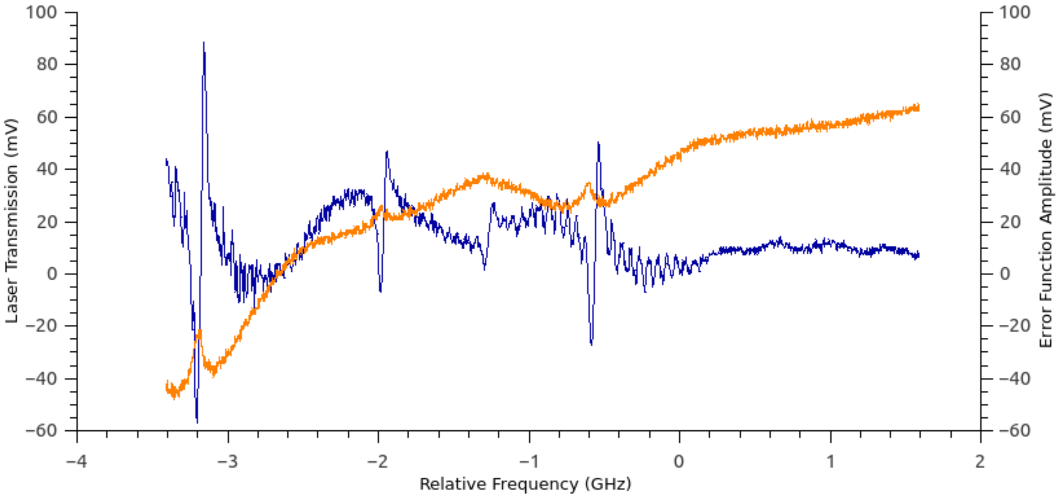

Figure 5. Error function (blue) obtained from the spectroscopy (orange)

In this case the selected coefficients are $k_P = 1.61 \cdot 10^{-3}$ and $k_I = 2.87 \cdot 10^{-4}$ which give a linewidth of $\Delta\nu = 1.9MHz$, below the natural linewidth of the rubidium transitions and then suitable for the main objective of the experiment.

4. Second Harmonic Generation

In order to lock the 397.5 nm laser, a well-determined frequency source at that wavelength is necessary. Since 397.5 nm is the double of what will be used to lock the cavity, the light coming from the DBR will be doubled in a nonlinear crystal, and the outcoming light will be beatnoted against the ECDL and will lock it.

The SHG consists in the absorption of two photons at frequency ω_1 by a nonlinear crystal and the remission of a photon at $\omega_2 = 2\omega_1$. This is a second order nonlinear process and thus is proportional to the squared amplitude of the electric field and to the nonlinear coefficient $\chi^{(2)}$.

For the case of two planar waves the equations describing the evolution of the coupled amplitudes of both fields (the fundamental and the second harmonic) with respect to z are :

$$\frac{dA_1}{dz} = \frac{2i\omega_1^2 d_{eff}}{k_1 c^2} A_2 A_1^* e^{-i\Delta k z} \tag{2}$$

$$\frac{dA_2}{dz} = \frac{i\omega_2^2 d_{eff}}{k_2 c^2} A_1^2 e^{i\Delta k z} \tag{3}$$

where $d_{eff} = 1/2\ \chi^{(2)}$ and $\Delta k = 2k_1 - k_2$ is the mismatch factor between the two waves. The last factor will be relevant when dealing with the efficiency of the non linear process since it limitates the fraction of light that will be up-converted by the phase matching condition. A more detailed developement of Equations (2),(3) can be found in [3] and [4]

The phase matching condition is in general difficult to achieve since it directly depends on the refractive index which is wavelength-dependent but there are some techniques to overcome this problem, such as heating of the nonlinear crystal to tune the thermal walkoff, adjusting the inclination angle or adjusting the polarization of the incident beam with a waveplate. Sometimes these methods are not enough cause of the properties of the crystal that one is using and a common approach is the use of a periodically poled material, which consists in the periodic inversion of the crystalline axis and as a result induces a sign change in the d_{eff} coefficient which can compensate a non-zero phase mismatch by providing the crystalline moment k_q, and changing the matching condition to $\Delta k = 2k_1 - k_2 + k_q$.

In the case of this experiment, a periodically poled potassium titanyl phosphate (PPKTP) which d_{eff} coefficient has an approximate value of $3.56pm/V$ according to [7]. Despite the fact that focusing the beam into the crystal would improve the efficiency, there is an optimal value of the beam waist for which the SHG reaches its maximum efficiency value. In [3], [5] and [6] we can find that in a crystal with a length L, the

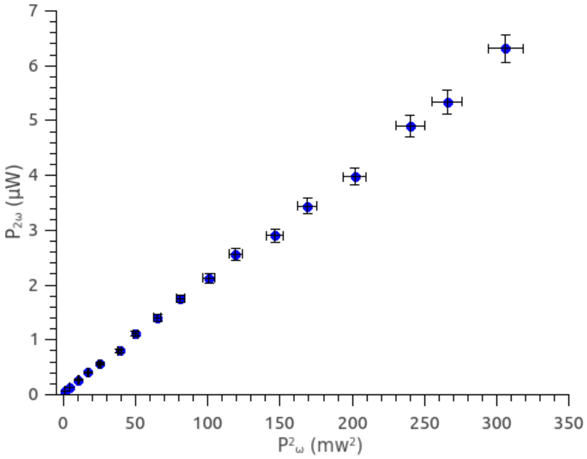

Figure 6. Second Harmonic Generated as a function of the pump squared

optimal ratio for improving the SHG is $L/b = 2.84$. With this value and replacing it in Equation 4, the optimal value for the beam waist is $\omega_0 = 29.858\ \mu m$.

$$\omega_0 = \left(\frac{\lambda}{2\pi b}\right)^{\frac{1}{2}} \tag{4}$$

In Figure 6 we can observe the expected quadratic dependence of the second harmonic generated power in the pump power whose resolution is limited by a 3% accuracy at 795 nm and by a 5% at 397.5 nm that the Thorlabs S120C Si detector has. The efficiency is typically calculated as $\eta = \frac{P_{2\omega}}{P^2_\omega} \sim 0.0197\ W^{-1}$

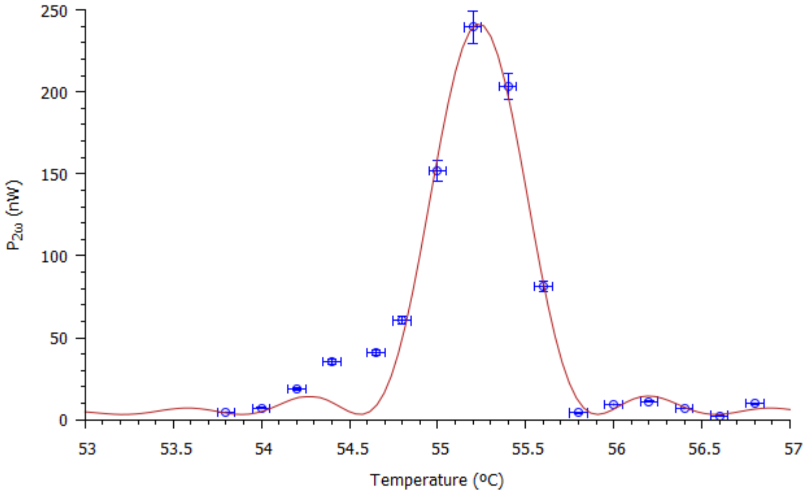

Figure 7. Second harmonic generated power as a function of temperature

As previously discussed, changes in temperature affect the phase-matching condition and consequently will affect the power that can be converted in the crystal.

Figure 7 shows clearly that the SHG is only remarkable when the temperature matches a certain value (in this case 55.2 °C) with a FWHM of 0.7 °C being sensitive to a small change of temperature and then being necessary to implement an accurate temperature control system if we want this light to be used as a reference source for the ECDL laser.

5. Final Remarks

The frequency stabilization of a DBR diode laser emitting at 795 nm was developed. For this purpose, an error signal obtained from the modulated saturated spectroscopy of the D1 line of ^{87}Rb was used.

This stabilized light source was also doubled in a PPKTP crystal, and when the necessary electronics is ready we will proceed to the stabilization of the ECDL at 397.5 nm by means of a phase-locked loop (PLL).

Finally with the cavity locked at the D1 transition and the ECDL stabilized, the generated light will be sent to the cavity and will generate the entangled photon pairs to interact with the single trapped atom.

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References

[1] F. Wolfgram, *Atomic Quantum Metrology with Narrowband Entangled and Squeezed States of Light*, Ph.D Thesis. *ICFO - The institute of Photonic Sciences*, 12 2011

[2] P. L. Stubs, *Laser Locking with Doppler-free Saturated Absorption Spectroscopy*, MSc Thesis., *College of William and Mary*, 5 2010

[3] R. W. Boyd, *Nonlinear Optics*, 3rd edition, Academic Press (2008)

[4] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*, 2nd edition, J. Wiley (2007)

[5] D. A. Kleinman, A. Ashkin and G. D. Boyd, *Second Harmonic Generation of Light by Focused Laser Beams*, Phys. Rev. V 145 (1966)

[6] G. D. Boyd and D. A. Kleinman, *Parametric Interaction of Focused Gaussian Light Beams*, J. Appl. Phys. 39-8 (1968)

[7] R. C. Eckardt and R. L. Byer *Measurement of nonlinear optical coefficients by phase-matched harmonic generation*, SPIE V 1561 119-127 (1991)