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Megahertz Measurement Rate Wavemeter with Sub-Picometer Resolution using Second Harmonic Generation

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ABSTRACT

Information on the wavelength is essential for most laser applications and a wide range of devices are available for measuring it. Commercially available wavemeters can provide femtometer resolution in a wide wavelength range but their refresh rate rarely goes into the kHz range. Streak cameras, on the other hand, provide extremely fast measurements with a wide spectrum. However, the spectral resolution is severely limited due to the use of a grating as the wavelength separating element. Here we present a wavemeter that combines a megahertz measurement rate and sub-picometer wavelength resolution. The technique uses the steep wavelength acceptance curve of a thick non-linear crystal to calculate the wavelength from just two power measurements. The bandwidth is limited only by the speed of a photodiode while the resolution and wavelength range can be engineered by choosing a suitable crystal type and geometry. We use the wavemeter to examine how the longitudinal mode evolves during a single pulse from a tapered diode laser. High resolution, high speed measurements of the wavelength can give new information about laser diodes, which is valuable for applications requiring short but wavelength stable pulses, such as pulsing of the second harmonic light.

Keywords: Laser beam characterization, diode lasers, harmonic generation and mixing.

1. INTRODUCTION

There is a wide array of techniques and devices available for measuring the wavelength of light. One of the most widely used when it comes to lasers are scanning Michelson interferometry-based optical spectrum analyzers (OSAs)[1], characterized by resolutions of roughly 10 pm. The main drawback is the slow speed of the scanning process which typically limits these to an update rate of at most a few Hz, while either spectral or power changes during the measurement can lead to artifacts. Measurement rates in the kHz range can be reached with grating based spectrometers and by using a double echelle monochromator the spectral resolution can even be pushed to 1 pm in the range available to Si detectors[2]. Streak cameras can reach GHz measurement rates of full spectra but they are limited to nm resolutions due to the use of a single grating. If a higher wavelength resolution is needed one typically has a wavemeter instead which only gives a single value for the wavelength. This can also be done with interferometry but recently it has also been shown that analyzing the speckle pattern produced when a coherent beam hits a rough surface can yield sub femtometer resolution[3]. However, these methods are again limited in their measurement rate by either scanning or array detectors.

Non-linear optics are often used when there is a need to resolve ultrafast optical phenomena. Techniques such as autocorrelation and frequency resolved optical gating (FROG)[4] use a thin non-linear crystal to ensure phase matching over the whole wavelength range at the same time and a delay line is then scanned to probe the ultrashort pulse at different times. A special variation of FROG replaces the very thin crystal with a thicker birefringent crystal and exploit the wavelength dependence of the phase matching angle to map wavelength onto a camera instead of using a grating based spectrometer[5]. All of these methods rely on a wide wavelength acceptance of the non-linear crystals, which means that they typically employ birefringent crystals with a low non-linear efficiency and are, therefore, only appropriate for short pulses with high peak powers.

Here we present a highly customizable technique to measure the wavelength of a single frequency laser using second harmonic generation (SHG). The technique relies on the steep wavelength dependence of the non-linear efficiency for thick non-linear crystals, and the high efficiencies achievable through quasi phase matching (QPM) means the technique can be used for CW and quasi-CW lasers.

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Periodically poled non-linear crystals are crystals where the crystallographic axes are inverted, typically by using a high electrical field. This way the phase relation between the fundamental and the generated second harmonic light can be inverted and if this is done with a period that matches the dispersion of the material, phase matching can be achieved for polarizations along a crystallographic axis which would otherwise not allow phase matching. Probably the most common crystal used with QPM is lithium niobate since this crystal has a very high non-linearity and can be poled with strong electrical fields. For efficient SHG the poling period needs to match the wavelength-dependent dispersion. This means that, for a crystal with a given poling period and temperature, the conversion efficiency is strongly dependent on the wavelength of the incoming light. This is typically called the wavelength acceptance curve and the width of this curve can be selected by choosing a crystal of the appropriate length[6]. The shape of the curve also depends slightly on the focusing of the beam but unless the beam is very tightly focused, the acceptance curve can be well approximated by that of an infinite plane wave[7]. We use QPM crystals in this work because of their high non-linearity and high design freedom, but other types of phase matching could be used if needed.

The wavelength of the fundamental light can be deduced by measuring the power of the fundamental light simultaneously with the power of the second harmonic and then mapping this onto a known wavelength acceptance curve of a non-linear crystal, in our case a periodically poled lithium niobate (PPLN) crystal. Since the measurement mainly relies on two power values it can be performed with very fast photodiodes. This way we achieve sub-picometer resolution and a measurement rate above 1 MHz.

2. SETUP AND RESULTS

We have used the technique to examine the longitudinal mode structure of a tapered laser diode during a single square pulse of injection current. A sketch of the setup is shown in Figure 1.

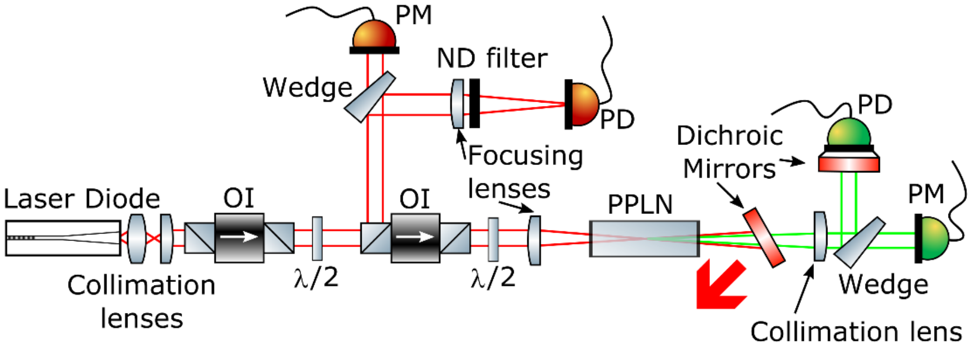

Figure 1. Sketch of the wavemeter setup. OI = optical isolator, λ/2 = half-wave plate, PM = thermal power meter, PD = fast photodetector, ND = neutral density.

The laser diode is a wavelength stabilized tapered laser diode at 1062 nm. These laser diodes are divided into three sections: a distributed Bragg reflector (DBR) to select a single longitudinal mode, a ridge waveguide section to define a high beam quality and a tapered amplifier[8]. The laser diode is collimated and a 30 dB isolator is used to protect it from optical feedback. After this a combination of the first PBS of a second 30 dB isolator and a half-wave plate is used to pick out a portion of the fundamental beam to measure the power input to the PPLN crystal. The transmitted beam from the second isolator is focused into the PPLN crystal after which the remaining fundamental light is dumped and the second harmonic power is measured. Both in the case of the fundamental and second harmonic a thermal power meter is used to calibrate the photodiodes which are connected to an oscilloscope (Lecroy WaveSurfer 104MXs-A 1 GHz). A Thorlabs DET210 photodiode is used for the fundamental light and a Thorlabs PDA100A-EC is used for the second harmonic light. An optical spectrum analyzer (OSA) from Advantest (Q8347) is used for measuring the wavelength acceptance curves and to check the measurements of our SHG technique.

The relation between the second harmonic power, the fundamental power and the non-linear efficiency is given as[9]:

$$P_{2\omega} = \eta P_{\omega}^{2}, \tag{1}$$

where $P_{2\omega}$ is the second harmonic power, P_{ω} is the fundamental power and η is the non-linear conversion efficiency, often given in units of %/W. This relation is only strictly true in the approximation of no depletion of the fundamental power, however, it shows very good agreement with experiments up to approximately 5% depletion. To stay in this low depletion regime and to avoid thermal effects in the PPLN crystal the fundamental power is kept below 2W for these measurements.

To get a good mapping of measured powers to the wavelength acceptance curves the following fit is used:

$$\eta = a\mathrm{sinc}^2\left({}^{\Delta\lambda}/_{b}\right), \tag{2}$$

where a and b are fitting parameters and $\Delta\lambda$ is the change in wavelength from the wavelength at which the maximal non-linear efficiency is attained. Measurements of the wavelength acceptance curve is shown in Figure 2 along with fits to sinc^2 curves. The fitting is limited to the low wavelength flank of the acceptance curves and only to the region where there is a one to one correspondence between the efficiency and the wavelength (see the black curves in Fig. 2). The parameters of the best fits are: a = 0.805 %/W and b = 307 pm for the 8 mm crystal, and a = 2.09 %/W and b = 137 pm for the 20 mm crystal.

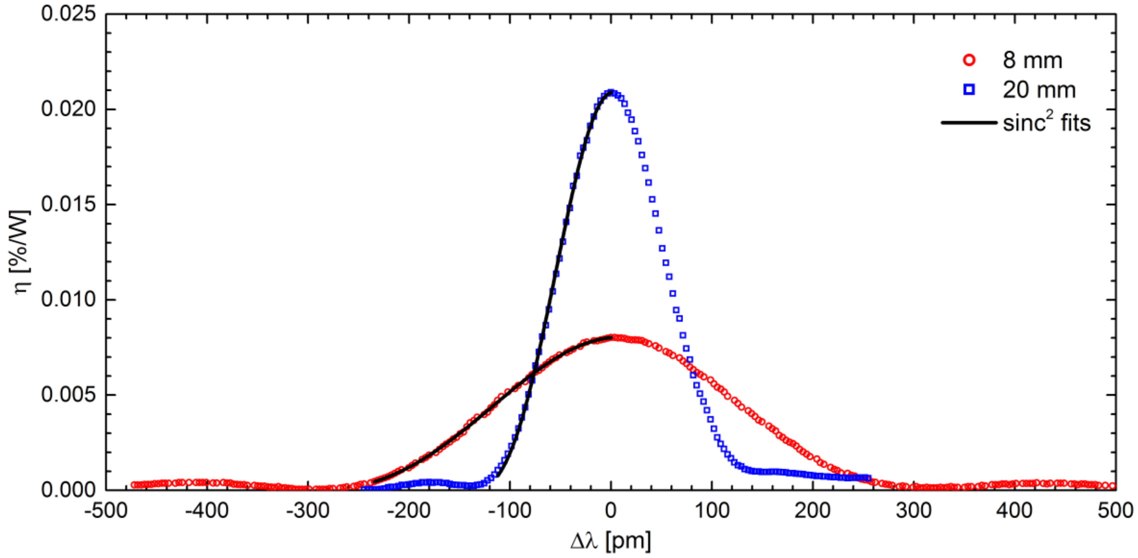

Figure 2. Wavelength acceptance curve for the 8 mm and 20 mm crystals together with their respective sinc^2 fits used for the measurements. The wavelength of the laser is only calculated for η values inside of the range of the fit.

To avoid ambiguous measurements η is only measured for power values significantly above the background level. It is also important to ensure that measurements are performed on the correct flank of the acceptance curve. In our measurements this was done by operating the laser in CW (or quasi CW for pulsed measurements) and tuning the crystal temperature first to the maximum point and then increase the crystal temperature until the measured power was at half the maximum obtainable value. To find an absolute value for the wavelength the wavelength of the maximum point of the acceptance curve is needed. This maximum wavelength changes linearly with the temperature at a rate of 82.1 pm/K for the 8 mm crystal and 80.3 pm/K for the 20 mm crystal. This linear dependence is a very good approximation for the combination of crystal type and wavelength range examined in this work. The acceptance curve is completely defined by material parameters, the temperature and the beam path through the crystal, so the calibration of the system is very robust. Since this demonstration was performed using a free space setup, we recalibrated the system when exchanging the laser or crystal to maintain high absolute wavelength accuracy despite small changes in the beam path. However, this can in general be mitigated by using a fiber to define the beam path through the crystal. In the model it is assumed that the laser is instantaneously single frequency. In some cases measurements can be performed with lasers with multiple coexisting longitudinal modes, however, the interpretation of the data can become more complex[10,11].

A comparative test between our technique with the 8 mm crystal and the spectrum analyzer is shown in Figure 3. A slow change is induced in the wavelength by applying a sinusoidal change in the laser heat sink temperature. This leads to a large perturbation of the second harmonic power (68%) despite only a small perturbation of the fundamental power (1.5%). From these two values the non-linear efficiency η can be calculated, which in this case is almost proportional to the second harmonic power due to the small change of the fundamental power. The measured η values are then converted to absolute wavelengths and shown together with the measurements from the OSA. The two measurements show good agreement over the 3 hour measurement shown here. The resolution of the SHG technique with an 8 mm crystal is 0.7 pm.

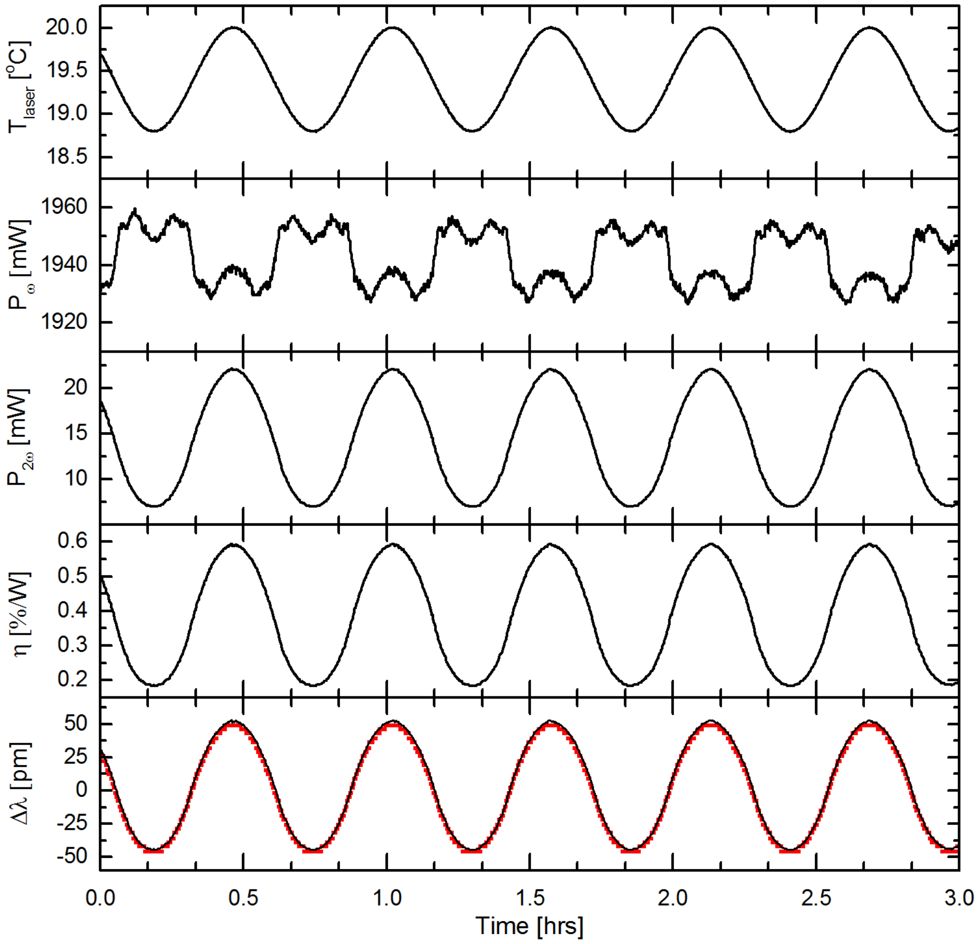

Figure 3. Example of the data used to calculate the wavelength and a comparison between the SHG technique and the OSA. T_{Laser}: laser heatsink temperature, P_{ω}: fundamental power into the 8 mm crystal, $P_{2\omega}$: generated second harmonic power, η: non-linear efficiency, Δλ: change in wavelength from the mean (1061.7 nm). The SHG technique (black line) and the OSA (red squares) show very good agreement over the 3 hour measurement.

To demonstrate even higher resolution, a similar measurement was performed with the 20 mm crystal. The results are shown in Figure 4. In this case the wavelength was varied by applying a sinusoidal current from 270 to 300 mA to the ridge waveguide of the laser diode. In this figure it is shown that the wavelength shift of the laser diode is not exactly proportional to the shift in current, which is probably due to thermal effects in the laser. In this case a resolution of 0.4 pm was achieved and this value could be further increased by using a longer crystal or low-noise power meters.

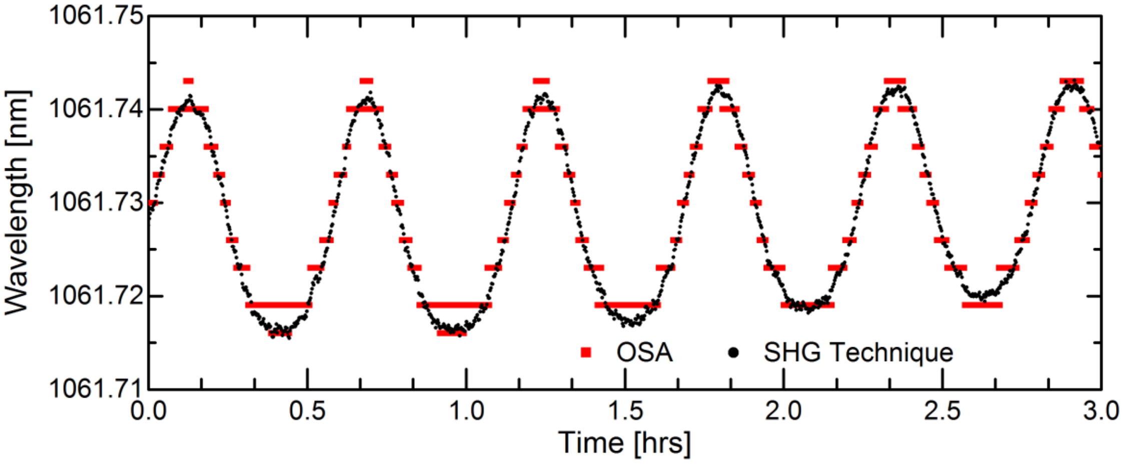

Figure 4. Comparison between the SHG technique with a 20 mm crystal and the OSA. Here the wavelength was varied by applying a very slow sine modulation to the injection current for the ridge waveguide. The resolution of the SHG technique is about 10 times better than that of the OSA.

Figure 5 shows wavelength measurements in which the ridge waveguide current is modulated from 235 mA to 300 mA at 200 kHz, which was the limit of the driver electronics. Here, the power was measured using the calibrated fast photodiodes rather than the power meters. In this case the wavelength follows more closely the sinusoidal pattern of the current, presumably because the modulation is significantly faster than any thermal timescale of the laser diode. The technique can easily resolve the 200 kHz pattern, however, the resolution is slightly lower in this case because of the sampling noise of the oscilloscope.

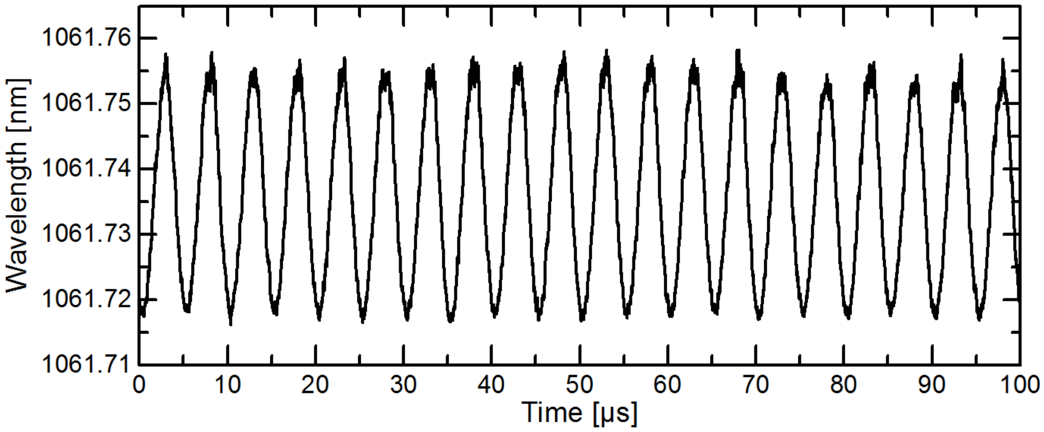

Figure 5. Measurement of wavelength using the SHG technique with the 20 mm crystal during a 200 kHz sine modulation of the ridge waveguide injection current . The technique can easily resolve this modulation which was the fastest possible with the available driver electronics.

To measure the bandwidth of the system a step-change in the wavelength was induced by provoking a longitudinal laser mode-hop. This was done by increasing the current through the tapered amplifier sufficiently slowly that the current could be considered constant for the duration of the measurement. The result is shown in Figure 6. The difference between the two “steady-state” wavelengths is 55 pm which is consistent with a longitudinal mode-hop of the laser diode. The fall time of the signal is 0.2 µs (90% to 10%) which is consistent with the specified bandwidth of the photodiode used to measure the second harmonic power.

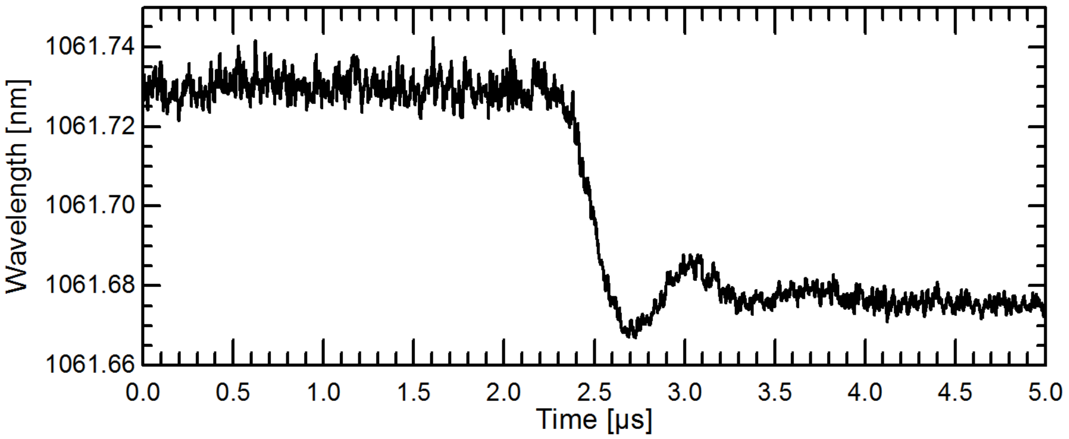

Figure 6. Measurement of the response of the system to a step change in the wavelength. Measured using the 20 mm crystal. The step change was produced by provoking a longitudinal mode-hop of the laser diode with a very slow increase of the tapered amplifier current. The fall time was measured to be 0.2 µs (from 90% to 10%), which is consistent with the bandwidth of the photodiode.

The SHG technique was also used to measure the wavelength of the laser diode during a single pulse. This was done operating the laser diode with a fixed current through the ridge waveguide and then applying a square pulse signal to the tapered amplifier with a duty cycle of 10%. In Figure 7 it is shown that while the fundamental power stabilizes after roughly 500 µs, the laser diodes goes through 6 mode-hops during the first 13 ms after the tapered amplifier is turned on and the total drift in the wavelength is roughly 200 pm.

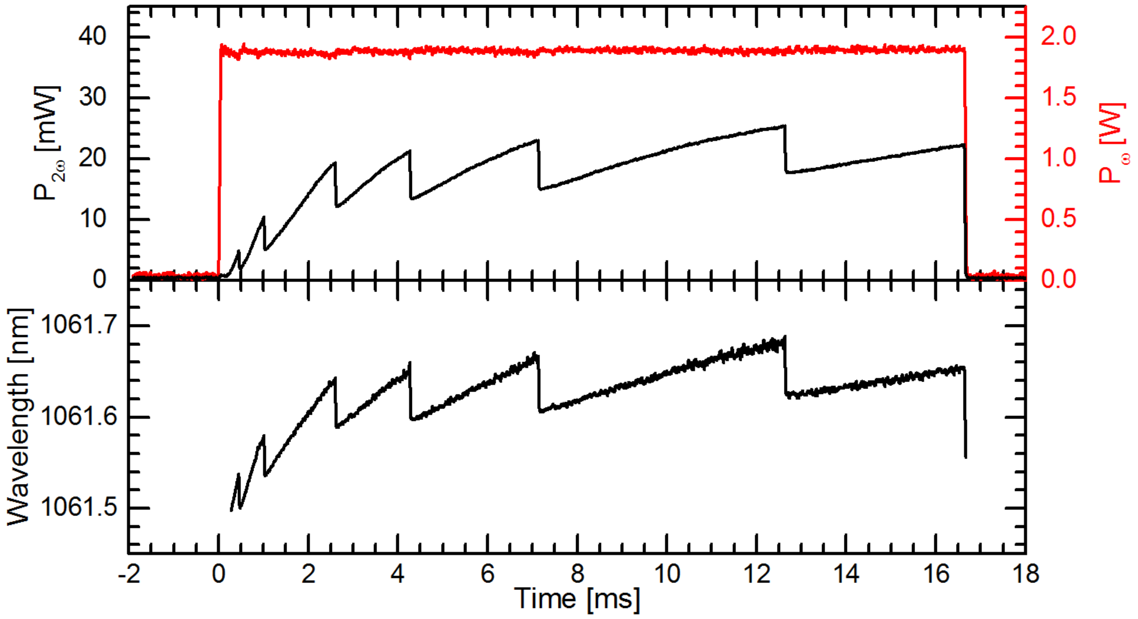

Figure 7. Measured wavelength during a single pulse from the laser diode using the 8 mm crystal. The pulses were produced by applying a square pulse modulation to the injection current for the tapered amplifier with a duty cycle of 10%. The SHG technique clearly resolves both the timing of the mode hops and the changing slope of the wavelength in between.

3. CONCLUSION

We have demonstrated that the second harmonic from a long periodically poled non-linear crystal can be used as a wavemeter for single frequency lasers. We have shown resolutions of 0.7 and 0.4 pm depending on the crystal length used and a measurement rate of several MHz. The system was used to measure wavelength shifts and longitudinal mode hops of a tapered laser diode during a single pulse of injection current. The bandwidth of the system is limited only by the bandwidth of the photodetectors and can, therefore, be extended to GHz if necessary. The system is highly customizable due to the high design freedom of periodically poled crystals, however, since each crystal has only a limited measurement range, a suitable crystal must be chosen before the system can be used. The system can be used to gain more insight into, e.g., the wavelength behavior of low- and high power laser diodes where there is often a complex coupling between thermal, electronic and optical effects. This could be useful for achieving arbitrary on/off modulation of the second harmonic light which is needed for, e.g., medical treatments[12].

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