A245
Optical Frequency doubling

Revision: August 2015

Note: Double credit experiment

1 Aim of the Experiment

The area of non-linear optics is of great importance for basic research as well as for industrial applications. In this experiment optical frequency doubling is performed in a non-linear crystal. Specifically, the beam of a high-power diode laser at 987 nm (infrared, fundamental wave) is frequency doubled in a potassium niobate crystal to visible light at 493.5 nm (second harmonic). The crystal is adjusted to optimize the second harmonic generation, and the power of the second harmonic is measured as a fuction of the power and the polarization of the fundamental wave and the crystal temperature. The wavelengths of fundamental and harmonic waves are compared with a diffraction grating. A Michelson interferometer is used to compare the wavelengths with interferometric precision. The experiment is buildt up from individual components (mirrors, lenses, filters, beam splitters, gratings, photodiodes, etc.), which can be placed freely on an optical table ("breadboard").

2 Required knowledge

- Generation of harmonics by nonlinearities
- Birefringence, retardation plates
- Phase matching
- Gaussian Beams
- Determination of wavelengths with gratings
- Michelson interferometer
- Coherence and coherence length
- Working principle of diode lasers

3 Literature

The following can be obtained from the tutor (partly in German), together with detailed experiment instructions:

- D. Meschede: *Optics, Light and Lasers*, selected chapters, Wiley VCH, Weinheim, 2007
- D. Meschede: *Optik, Licht und Laser*, ausgewählte Kapitel, Vieweg+Teubner, Wiesbaden 2008
- R. W. Boyd: *Nonlinear Optics* 2nd ed., chapter 2, Academic Press, San Diego, 2003,
- A. Yariv: *Quantum Electronics* 3rd. ed., selected chapters, John Wiley & Sons, New York, 1989
- A. Yariv: *Optical Electronics* fourth ed., selected chapters, Saunders College Publishing, Philadelphia, 1991
- *Technical Properties of* $KNbO_3$ compiled from (former) vendors of nonlinear crystals (Casix Inc., Spectragen Inc.).

Further reading: Any textbooks in optics.

4 Assignments

1. Getting familiar with the diode laser: output power versus injection current, threshold current and quantum efficiency.
2. Calibration of the variable attenuator.
3. Focusing the laser beam into the crystal and optimizing the second harmonic power.
4. Measurement of the harmonic power versus the crystal temperature.
5. Measurement of the harmonic power versus the input fundamental power.
6. Measurement of the harmonic power versus the polarization of the fundamental wave.
7. Comparison of fundamental and harmonic wavelengths using a diffraction grating.
8. Setting-up and adjusting a Michelson interferometer; interferometric comparison of the wavelengths of fundamental and harmonic waves.

5 Procedure and analysis

5.1 Laser safety instructions

Since frequency doubling is a nonlinear process requiring high laser intensities, the laser employed in the current experiment has an output power of up to 180 mW at 987 nm (infrared, i.e. invisible radiation). This laser belongs to the laser class 3B: “The available laser radiation is dangerous for the eyes and in special cases also for the skin”. Therefore, **it is obligatory to wear laser protection goggles when the laser is switched on**. The laser protective goggles filter the infrared light with dye-filled polycarbonate windows (attenuation better than 10^{-5} at $980 - 1070$ nm) and, thus, less than 1 μW (harmless) of laser light can reach the eye. The protective goggles should cover the side of the face so that the cance of a laser beam can passing them and hitting the eye is minimized.

As an additional measure of protection, all laser beams have to stay horizontal at the height of the optical table; powerful individual beams have to be blocked by beam dumps. **Never** look towards the optical setup with your head on the height of the optical table!

If an infrared laser beam hits the eye, it is most important to immediately visit an eye specialist (ophthalmologist), since subsequent damage may appear at a later time.

To indicate that the laser is switched on, a laser warning light outside the experiment room is turned on when the experiment is running. When entering the room, an interlock circuit closes the laser shutter as soon as the door is opened. Put on the protective goggles before closing the door or opening the shutter. Put the goggles off only after closing the shutter or switching the laser off.

The second harmonic light at 494 nm has only a power of $< 60\,\mu$W and hence belongs to laser class 2: “The available laser radiation is in the visible spectral region (400 nm to 700 nm). For short irradiation durations (up to 0.25 s) it is not dangerous for eyes ($<$ 1 mW CW)”. Laser radiation of the class 2 is harmless only if the automatic eyelid closure reflex protects the eye after the perception of a laser beam (light flash). Intentional prolonged or direct staring into the laser beam has to be avoided. The second harmonic light is **not** filtered by the protective goggles.

5.2 Handling optics

Some things to know about working with optics on a table:

1. Do not touch optical surfaces, neither with your fingers nor with paper or infrared cards. Finger prints should be removed by the tutor using a proper cleaning provedure.

2. Always fix all optics with clamps - tipping over an optic can cause hundreds of euro damage and send laser beams in your face!

3. Always tighten the fork screw and adjustable posts. If they are loose, your careful alignment will be ruined soon.

4. Do not use force.

5.3 Diode laser and power measurements

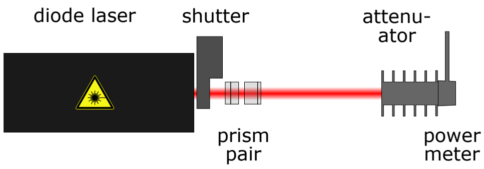

Figure 1: Setup for characterizing the diode laser.

The diode laser is a commercial, grating-stabilized (Littrow) external cavity diode laser system. After the laser, a shutter connected to the safety interlock controls the beam, and an anamorphotic prism pair converts the very elliptic beam into a more round shape. Laser, shutter and prism pair should not be touched.

Laser output power vs. injection current

To become familiar with the diode laser, first measure the laser output power (fundamental wave) versus the injection current. The injection current of the laser diode is increased from 0 mA to 280 mA in steps of 5-10 mA (and read out by the indicator "Iact"). The laser power is measured using the Coherent power meter (center beam on detector sarea, verify wavelength setting!). For powers above about 20 mW the sensor becomes non-linear and thus the scew-on attenuator should be used (check alignment of the beam on the attenuator). Re-check the the background light reading (offset) after a change of the measurement range or after adding/removing the attenuator. The attenuator should be calibrated at several laser powers (above the laser threshold, but below 20 mW).

Analysis and interpretation: Show the data graphically, determine the threshold current and calculate the differential slope efficiency (in W/A) and the differential quantum efficiency. Assume reasonable measurement uncertainties and perform all calculations with a well-documented error analysis. Note: The error of the attenuator is a global scale error, which affects all data points (measured with the attenuator) likewise. It should therefore not be included into the statistical error of the individual data points on the graph (error bars), but it should be taken into account for results that depend on absolute values of laser powers.

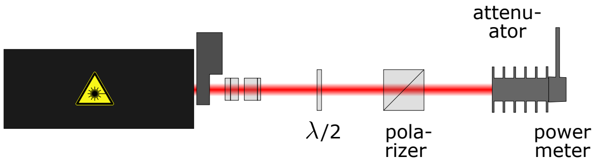

Figure 2: Setup for calibration of the variable attenuator.

Calibration of the variable attenuator

When the laser power is changed by changing the diode current, small jumps in laser frequency and power (mode hops) can occur. To vary the laser power without changing the diode current, a $\lambda/2$-plate mounted in a rotatable holder together with a polarizer is used: the $\lambda/2$-plate rotates the linear polarization of the laser beam, while the polarizer transmits only one polarization component. Position the $\lambda/2$-plate perpendicular to the laser beam in front of the polarizing beam splitter cube. Make shure that the polarizer is rotated such that it maximally transmits the laser beam without the $\lambda/2$-plate present. Note: The polarizer can slightly tilt the laser beam, check the position of the power meter head.

For a direct measurement of the frequency doubling efficiency, the powers of both the fundamental and harmonic wave would have to be measured simultaneously while the fundamental power is changed. Since there is only one power meter available, the power of the fundamental wave as a function of the $\lambda/2$-plate rotation angle is measured first (see fig. 2), and later the same is done for the second harmonic power under otherwise identical conditions (laser current etc.) to obtain the desired relation.

The rotation angle should be changed in steps of $2.5°$ (note scale, rotation direction and orientation of the $\lambda/2$-plate). The rotation range should contain two power maxima.

Analysis and interpretation: What dependence of the transmitted power on the rotation angle do you expect? Fit the obtained data and interpret the parameters of the fitting function. Determine the achieved extinction ratio (defined as maximum to minimum transmitted power).

5.4 Focusing the laser beam into the crystal and optimizing the harmonic power

Practical guidance: focusing and collimation

To focus a laser beam consider the following:

1. In order to minimize aberrations (in particular, spherical), the collimated/parallel beam has to meet first the curved surface of a plano-convex lens or the stronger curved surface of an achromatic lens.
2. To avoid astigmatism and coma aberrations, the beam should propagate parallel to the optical axis of the lens, i. e. the lens has to be oriented perpendicular to the beam. To achieve this condition, keep the beams always parallel to the rows of holes on the table and parallel to the surface of the table (i. e. at constant height). Then visually align the lens holders perpendicular to the laser beam, using the rows of holes as alignment marks.
3. The beam has to go through the center of the lens. Since this is not easy to see directly, use the following method: on a screen placed at a convenient location behind the planned lens position, mark the laser beam spot. Then, insert the lens and position it such that the center of the new beam spot coincides with the marked point.

To collimate a divergent beam coming from a focus, the collimation lens has to be carefully placed along the optical axis such that the diameter of the collimated beam does not change over a long distance such as 1-2 m (but less than the Rayleigh length) behind the lens. For checking the beam size along the beam you may use a ruler or a mark on a paper. Also check the beam in between the end points that there is no intermediate focus.

Reminder: Optical surfaces of lenses, mirrors, windows etc. should not be touched, neither with your fingers, nor with infrared detection cards or pieces of paper.

Nonlinear crystal

The nonlinear material used here for the frequency doubling is a potassium niobate crystal ($KNbO_3$). The crystal (cross-section $2 \times 1.8\,\mathrm{mm}^2$, length 5 mm, b-cut, end faces with antireflection coating at 987 nm and 494 nm) is mounted in a temperature-stabilized holder under a dust cover. **The crystal is sensitive to pressure, shaking, mechanical shocks and fast temperature changes.**

Optimization of second harmonic power

The collimated laser beam is focused a $f = 60\,\mathrm{mm}$ plano-convex lens into the crystal, see fig. 4. To obtain good focusing, and thus a high efficiency of the frequency doubling, the lens has to be centered and set perpendicular to the beam in correct orientation (see sec. 5.4).

The temperature of the crystal is increased **slowly** ($0.5°$ at once) up to $36°$ C. When the crystal is moved into the focus, the frequency-doubled light can be observed on a screen (white paper) placed after the crystal.

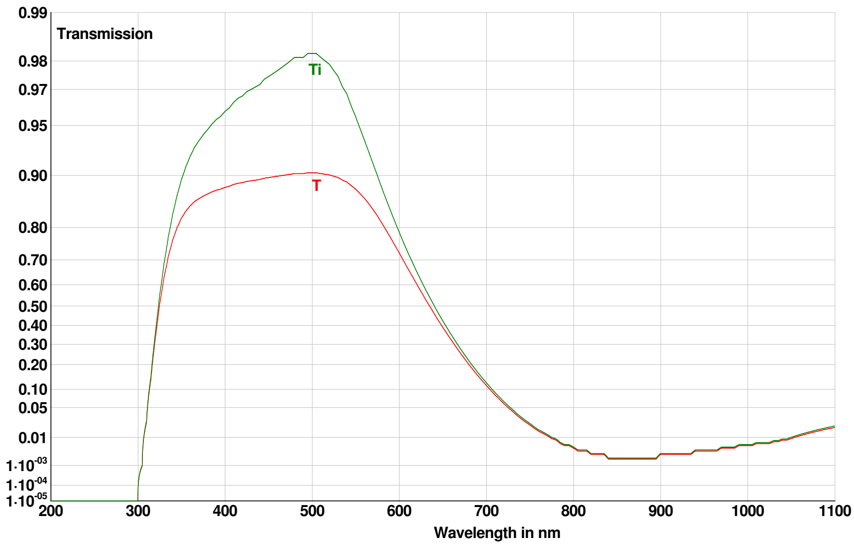

Figure 3: Transmission of a 1 mm BG40 color filter glass. Ti: internal transmission (without losses due to reflections on filter surfaces), T: total transmission (including losses of about 4 % on each surface.)

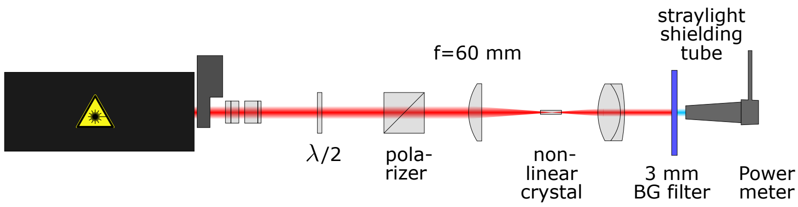

Figure 4: Setup for measuring harmonic power.

The second harmonic power should be optimized by slightly moving and rotating the crystal. For the fine optimization, the power of the blue light is measured by the Coherent power meter (verify wavelength setting!!). For this purpose, the frequency-doubled light is collimated by an achromatic lens, and the infrared light is filtered out by a 3 mm BG40 glass filter, see figs. 4 and 3. To minimize the amount of infrared stray light that could still reach the detector, mount the straylight shielding tube to the power meter's measuring head and place it directly (few mm) behind the filter (without touching it). After the optimization, the harmonic power should be at least 40 μW.

Analysis and interpretation: How large are beam waist and Rayleigh length z_0 (resp. confocal parameter $b = 2z_0$) of the laser beam in the crystal? How well do they fulfil the Boyd-Kleinman condition for the optimal efficiency of second-harmonic generation ($L/b = 2.84$)? Which focal length would be optimal? Parameters: the diameter of the collimated beam before the lens is about 3.5±0.5 mm, the approximate value of the crystal's refractive index is $n = 2.2$. Remark: the radius of the beam waist w_0 inside the crystal is the same as if the beam would propagate in air. Give errors for all values!

5.5 Properties of second-harmonic generation

Harmonic power vs. crystal temperature

The temperature of the crystal is **slowly** (about 0.5° at once) reduced to about 27° C. Then the crystal temperature is increased up to about 40° in steps of 0.2°C while the power of the second harmonic light is measured. Observe the monitor-output of the temperature sensor (1 Volt/degree C) on the oscilloscope and wait each time until the temperature has settled. Especially when the harmonic power is low, pay attention to the background (block stray light with black paper, subtract background power).

Analysis and interpretation: Present the data such that the minima and secondary maxima can be clearly seen. Can it be fitted with a sinc-function? Why could the curve be asymmetric?

Harmonic power vs. fundamental wave power

The temperature of the crystal is **slowly** set to the optimum value. After the temperature is settled, the power of the second harmonic is measured while rotating the $\lambda/2$-plate.

Analysis and interpretation: Plot the second harmonic power vs. fundamental power. What dependence do you expect? Are there significant deviations? Interpretation? Give the frequency doubling efficiency $\eta = P_{\mathrm{SHG}}/P_{\mathrm{FUN}}^2$.

Harmonic power vs. polarization of fundamental wave

After removal of the polarizing beam splitter cube, the linear polarization of the fundamental wave can be rotated using the $\lambda/2$-plate. Depending on whether type I or type II phase matching has been achieved, different results are expected.

Analysis and interpretation: What dependencies of the second harmonic power on the polarization angle are expected for crystals of type I and type II phase matching? Explain your results and present your data with an appropriate fit. Are the fitting parameters consistent with your expectations?

5.6 Comparison of the wavelengths of fundamental and harmonic waves

Diffraction grating

At first a rough comparison of the two wavelengths should be done by means of a diffraction grating (600 lines/mm, blazed). When the grating is placed into the optical beam, diffracted beams of the fundamental and second harmonic waves of different diffraction orders appear. By comparison of the diffraction angles of n-th order of the fundamental wave and the $2n$-th order of the harmonic wave, the ratio between the wavelengths of the two beams can be obtained. The diffraction angles should be compared carefully by observing the spots on the wall after a long beam propagation distance. In order to illuminate more lines of the grating (and thereby increasing the theoretical resolution), the beam emanating from the crystal should be collimated with the achromatic lens having the largest focal length ($f = 125\,\mathrm{mm}$). For best resolution, you can adjust the lens slightly to get a smaller beam diameter at the screen, but keep the beams centered on the lens in order not to induce chromatic dispersion.

Analysis and interpretation: Show all used lengths, distances and angles in a drawing. Given your experimental measurement uncertainties, how accurately can the relationship of 1:2 between two wavelengths be confirmed (or disproved) using this method, i. e. what is the experimental resolution? Compare that to the theoretical resolution $A = \lambda/\Delta\lambda$ of your grating setup. For your calculations, the wavelengths and the grating constant given in this document can be used.

Interferometrical comparison using Michelson interferometer

To perform more precise interferometrical comparison of the wavelengths, a Michelson interferometer is built up and aligned, see fig. 5. The interferometer consists of a partially transmitting beam splitter plate and two silver end mirrors. One of the end mirrors is mounted on a precision ball bearing slide, on which it can be moved to change the optical path length of one arm of the interferometer. To avoid the reflection of the fundamental beam back into the laser, its intensity is reduced by the thin blue filter (1 mm thickness) placed after the collimating lens.

The interferometer works best (and is easiest to align) with a rather narrow, well collimated laser beam. To obtain a small beam diameter, the beam emanating from the crystal has to be *carefully collimated* by the short focal length (f = 30 mm) achromatic lens, see section 5.4. Align the blue beam through the beam splitter onto the end mirror on the slide. Make sure that the beam is parallel to the axis of the slide, use the corresponding row of holes as alignment mark. The beam splitter should be rotated such that it reflects part of the beam at an angle of 90° onto the other end mirror. The

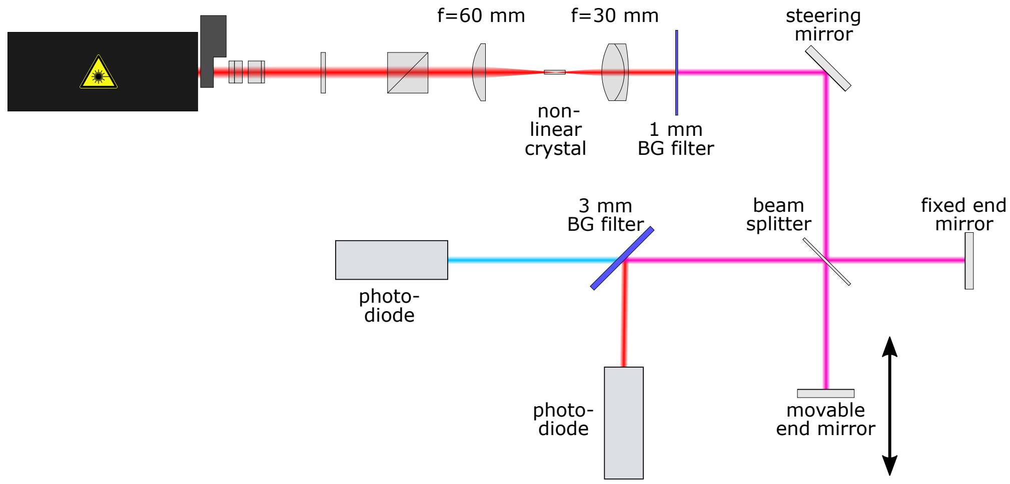

Figure 5: Setup for two-color Michelson interferometer. Note that the reflected IR beam in front of the photodiode may be too weak to see on the IR card; adjust to the overlapped residual blue beam instead.

beams back-reflected from both end mirrors have to be overlapped perfectly at the output of the interferometer. Watch out for multiple reflections from the beam splitter glass plate, they easily confused.

In order to obtain good interference contrast over the entire travel range of the slide, the output beam coming from the movable end mirror must not move (or change size) when the slide is shifted. To optimize this, block the stationary end mirror, place a white screen at the interferometer output with a cross marking the beam position, and adjust the steering mirror and the movable end mirror such that the beam spot remains completely staionary when the slide is moved end to end (if the spot changes its size than your collimation is not good).

Now optimize the overlap of the beam coming from the fixed arm of the interferometer using the stationary end mirror. You may see, on very close inspection, very fine interference stripes on the overlapped spot (you can use a lens to enlarge the beam diameter in front of the screen). If so, try to enlarge the period of the stripes using the stationary end mirror until the stripes become “larger” than the beam size. The goal is to have the entire output beam become brighter and darker when you change the path length difference of the interferometer by a few hundred nanometers(!), e. g. by pressing somewhere on the optical table.

The screen at the output of the interferometer is now replaced by a thick blue filter (3 mm) at 45° to the beam, in order to separate the fundamental and second harmonic waves. The two fast photodiodes are installed in the reflected (fundamental) and in the transmitted (second harmonic) beam. By slightly moving back and forth the end mirror on the optical rail, the sinusoidal interference signals should be observed clearly on the oscilloscope. Their amplitudes are maximized by adjusting the positions of the photodiodes and finally by tiny adjustments of the fixed end mirror. The amplitudes of both interference signals should be well above the electronic noise, but must be below the saturation voltage of the photodiodes of about 3 V. Sometimes it is necessary to change the diode laser current by 10-15 mA to achieve a reasonably constant amplitude of the interference signals over the travel range of the slide (single-mode operation of the laser).

The best way of displaying the photodiode signals is in x-y mode with roughly equal amplitudes. Slightly moving the slide (or just knocking on the table) will show you patterns that you may recognize as Lissajous figures. Move the mirror on the slide and observe the three characteristic shapes. Precisely measure the distance between the corresponding mirror positions; find as many positions as possible without otherwise readjusting the interferometer.

Analysis and interpretation: Explain the meaning of the observed interference pictures seen on the oscilloscope. Determine the deviation from the exact 1:2 ratio of the two wavelengths (with error estimate). What is the cause? Compare with the literature value, and give the spectroscopical resolution A of the interferometer. Motivate your formulas.

5.7 General remarks

Please follow the "Guidelines For The Advanced Lab Course Report".

Tell how you calculate the errors, since already for determining the error of a weighted mean there are two different possibilities. Estimate reasonable errors for all measured values.

6 Appendix

Approximate formulae for calculation of the refractive index of air (15°, atmospheric pressure) by B. Edlen: *The Refractive Index of Air*, Metrologica **2**, 71-80 (1966):

$$10^8\big(n(\lambda_{\mathrm{Vac}}) - 1\big) = 8342.13 + \frac{2406030}{130 - s^2} + \frac{15997}{38.9 - s^2}, \tag{1}$$

with

$$s = \frac{1}{\lambda_{\mathrm{Vac}}[\mu\mathrm{m}]}. \tag{2}$$