Research-Group Internship

Understanding the emitted green light of the Thomson Nd:YAG lasers

Philip Geißler

Physics Institute,

University of Greifswald

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Internship Reasons and Goals

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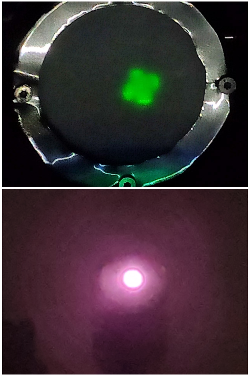
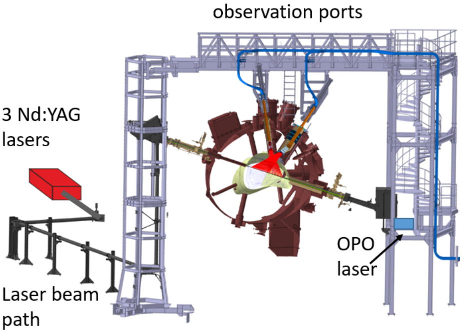
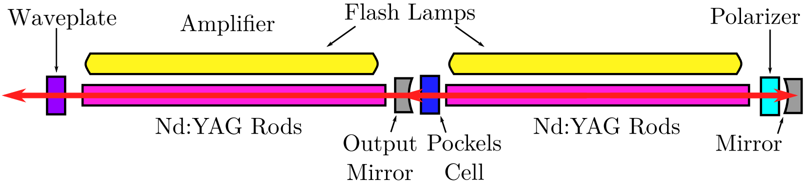


Images of diffusor under $1064\,\mathrm{nm}$ laser light, with (b) and without (t) $1064\,\mathrm{nm}$ filter.



Thomson Scattering beampath

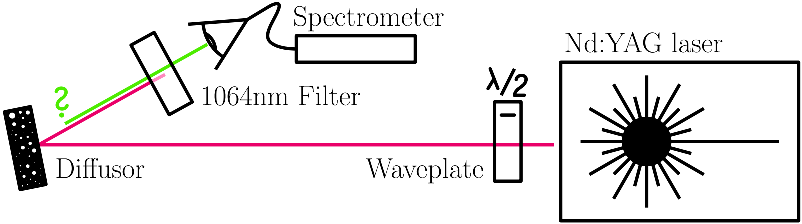
The Nd:YAG laser



Nd:YAG schematic

- four level laser, $1064\,\mathrm{nm}$
- polarized output light
- experiment lasers rotate polarization via waveplate
- pulsed with $10\,\mathrm{ns}$ and $1.8\,\mathrm{J}$

Spectrum Measurements



Experimental setup for the frequency distribution measurement

- goal: measure spectrum of the emitted green light to gather information about its cause
- spectrum measurement of scattered light

Spectrum Measurements

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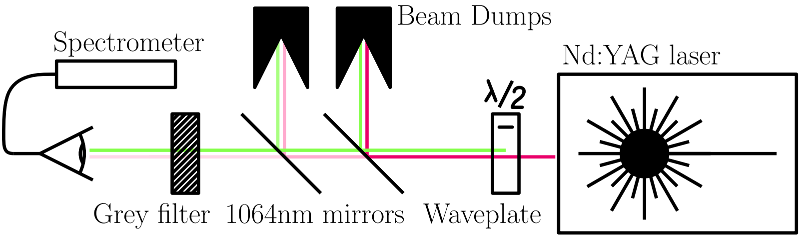
- tested $1064\,\mathrm{nm}$ experiment lasers, varying power of green light
- switch to laboratory $1064\,\mathrm{nm}$ laser during the experiment campaign no green light
- sanity check of visible light generation from original lasers after campaign easily visible green light

results not reproducible
only viable difference: quartz $\lambda/2$-waveplate

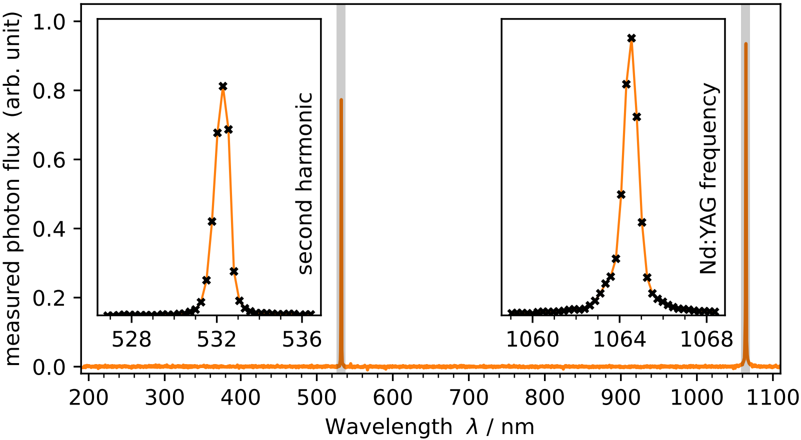
Spectrum Measurements



New experimental setup for the frequency distribution measurement

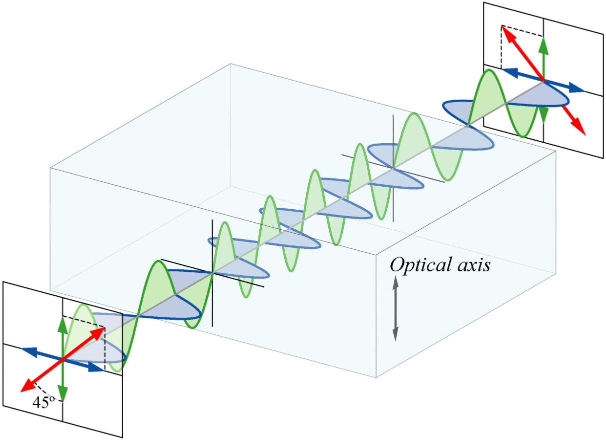
- new hypothesis: generation of green light in waveplate
- spectrum measurement of unscattered light possible
- $1064\,\mathrm{nm}$ light filtered after waveplate to reduce energy influx

Spectrum Measurements



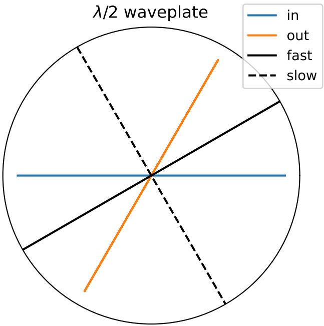
Frequency distribution measurement of the visible green light

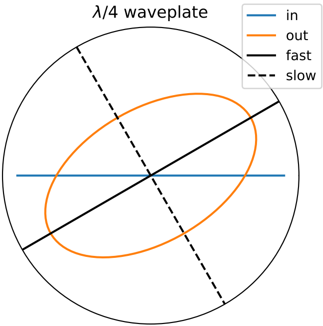
Intro to Waveplates



$\lambda/2$ – waveplate (positive uniaxial medium)

Intro to Waveplates

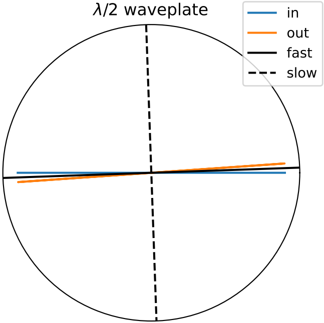


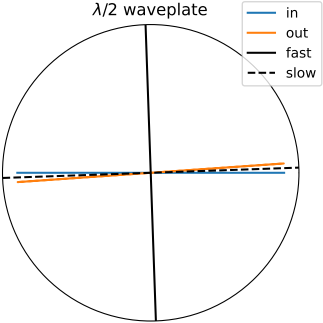


phase changes due to $30°$ rotated waveplates ($\Delta\varphi_{\text{left}} = \pi$, $\Delta\varphi_{\text{right}} = \pi/2$)

Given $\Delta\varphi(L) = \frac{2\pi}{2} = \pi$, and a angle α between the input polarization and the fast axis, the polarization is rotated by 2α.

Intro to Waveplates





phase changes due to $\approx 0°$ and $\approx 90°$ rotated waveplates ($\Delta\varphi = \pi$)

Given $\Delta\varphi(L) = \frac{2\pi}{2} = \pi$, and a angle α between the input polarization and the fast axis, the polarization is rotated by 2α.

Intro to SHG

History

VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

FIG. 1. A direct reproduction of the first plate in which there was an indication of second harmonic. The wavelength scale is in units of 100 A. The arrow at 3472 A indicates the small but dense image produced by the second harmonic. The image of the primary beam at 6943 A is very large due to halation.

First published SHG spectrum

Intro to SHG

History

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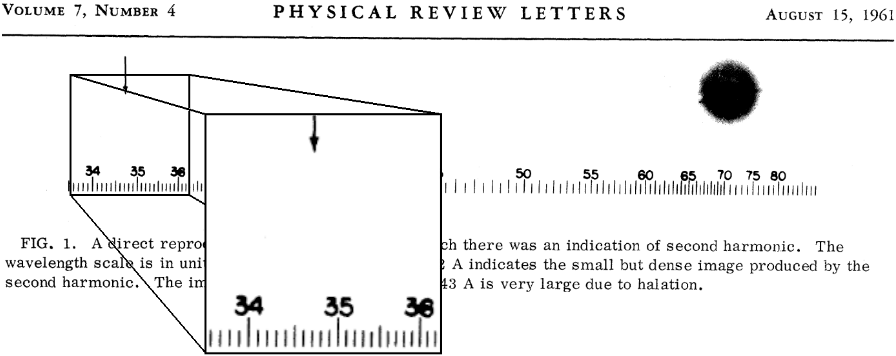
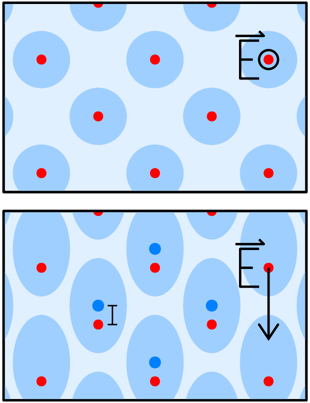


First published SHG spectrum

Intro to SHG

Microscopic Scale



Polarization in crystals

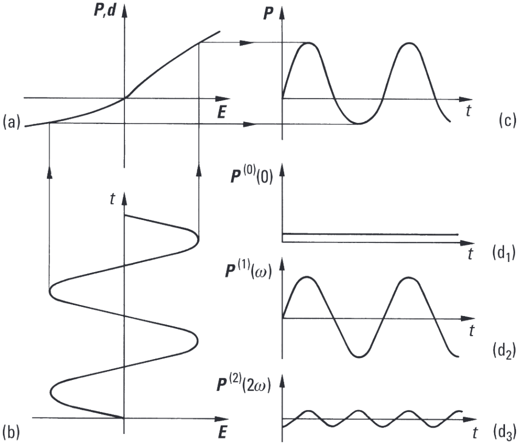
- $\vec{E}$ field polarizes crystal
- $\vec{P} = P_0 + \varepsilon_0 \chi^{(1)} \vec{E} + \mathcal{O}(\vec{E}^2)$

However

- $\vec{P}$ dependent on unit cell choice
  $\rightarrow \Delta\vec{P}$ independent
- χ frequency dependent
- $\vec{P} \propto \vec{E}$ only holds for small $\vec{E}$ in isotropic materials

Intro to SHG

Microscopic Scale



Effect of 1D $\vec{P}(\vec{E})$ nonlinearities

Intro to SHG

Microscopic Scale

$E(t) = E_0 \sin(\omega t)$

$\frac{P(E)}{\varepsilon_0} = \frac{P_0}{\varepsilon_0} + \chi^{(1)} E + \chi^{(2)} E^2 + \mathcal{O}(E^3)$

non-pyroelectric (Quartz):

$P(0) = 0 \implies P_0 = 0$

$$\implies \frac{P(t)}{\varepsilon_0} = \frac{P_0}{\varepsilon_0} + \chi^{(1)} E_0 \sin(\omega t) + \chi^{(2)} E_0^2 \sin^2(\omega t)$$

$$= \left(\frac{P_0}{\varepsilon_0} + \frac{\chi^{(2)} E_0^2}{2} \right) + \chi^{(1)} E_0 \sin(\omega t) - \frac{\chi^{(2)} E_0^2}{2} \cos(2\omega t)$$

$\implies$ SHG for 2nd order terms in $P(E)$

Microscopic Scale

$$E(t) = E_0 \sin(\omega t)$$

$$\frac{P(E)}{\varepsilon_0} = \frac{P_0}{\varepsilon_0} + \chi^{(1)} E + \chi^{(2)} E^2 + \mathcal{O}(E^3)$$

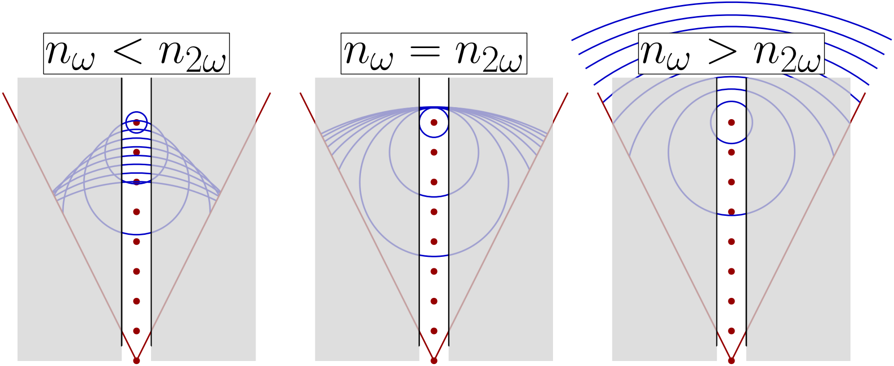
non-pyroelectric (Quartz):

$$P(0) = 0 \implies P_0 = 0$$

$$\sin^n(\omega t) = 2^{1-n} \begin{cases} \frac{1}{2}\binom{n}{\frac{n}{2}} + \sum_{k=1}^{\frac{n}{2}} \binom{n}{\frac{n}{2} - k} (-1)^k \cos(\underline{2k}\omega t) & n \text{ even} \\ \sum_{k=0}^{\frac{n-1}{2}} \binom{n}{\frac{n-1}{2} - k} (-1)^k \sin((\underline{2k+1})\omega t) & n \text{ odd} \end{cases}$$

Intro to SHG

Macroscopic Scale



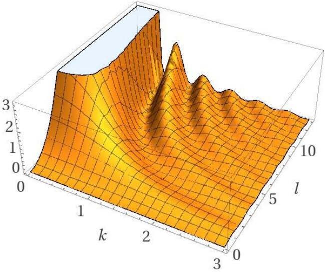
SHG interference at and near phase-matched conditions

$$\Delta k = k_{2\omega} - 2k_\omega = \frac{2\omega}{c}\left(n_{2\omega} - n_\omega\right) = \frac{2\omega}{c}\Delta n$$

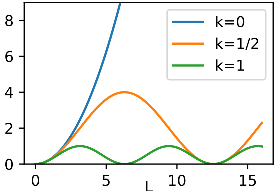
Intro to SHG

Macroscopic Scale

$$I_{2\omega}(l) \propto \left[\frac{\sin(\Delta k\, l/2)}{\Delta k}\right]^2 d_{\text{eff}} w^2 I_\omega^2$$
$$\propto \left[\frac{\sin(\Delta n\, l\omega/c)}{\Delta n}\right]^2$$



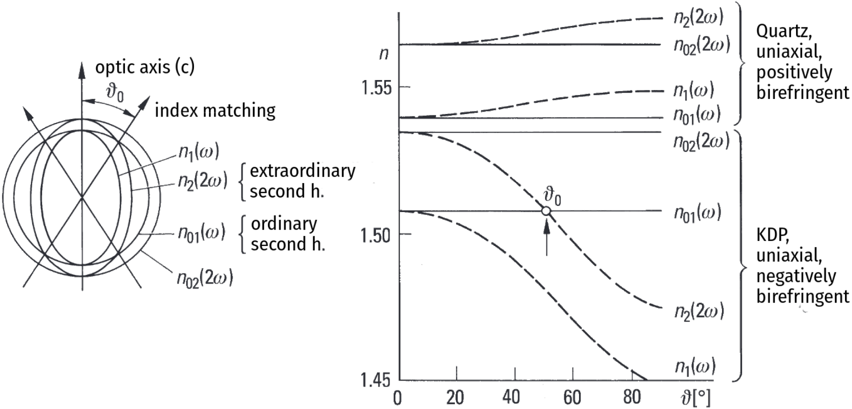
- minimize Δn
- for $\Delta n > 0$:
  - $\hat{I} \propto \Delta n^{-2}$
  - $\lambda_I = \dfrac{\pi c}{\Delta n\, \omega}$



$[\sin(kl/2)/k]^2$

Intro to SHG

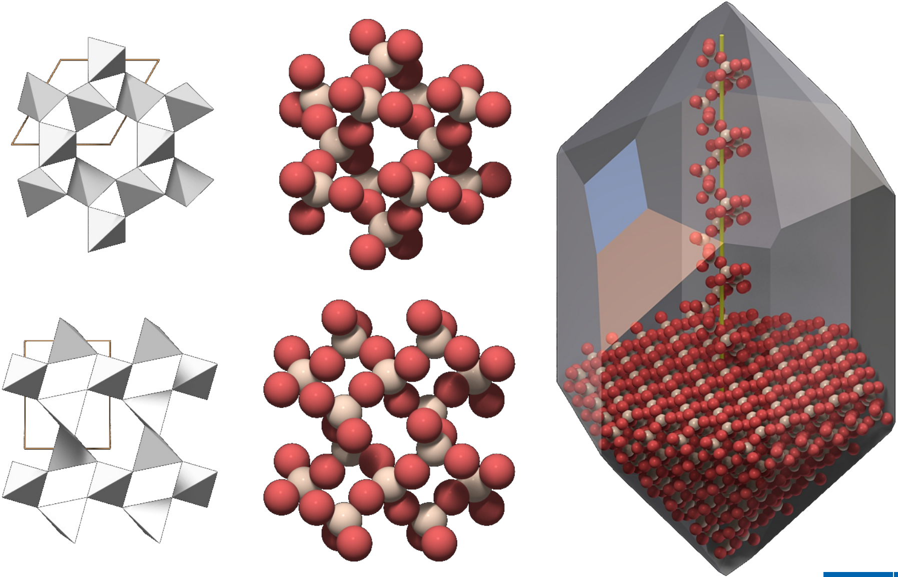
Macroscopic Scale



Index matching concept for KDP and quartz. Quartz not possible:

$$[n_{\text{o}}(\omega), n_{\text{eo}}(\omega)] = [1.534, 1.543] < [1.547, 1.556] = [n_{\text{o}}(2\omega), n_{\text{eo}}(2\omega)]$$

Quartz and its Properties



Quartz and its Properties

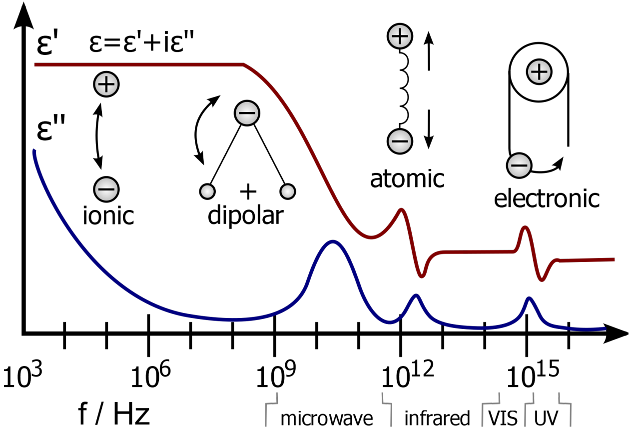
Electric Susceptibility Tensors

$P_0 = 0$ as quartz is non-pyroelectric

Quartz and its Properties

Electric Susceptibility Tensors

$P_0 = 0$



Quartz Structure

Quartz and its Properties

Electric Susceptibility Tensors

$P_0 = 0, \quad \chi^{(1)} \approx 1.5$

$$\varepsilon_r^0 \approx \begin{pmatrix} 4.64 & & \\ & 4.64 & \\ & & 4.85 \end{pmatrix} \qquad \varepsilon_r^\infty \approx \begin{pmatrix} 2.51 & & \\ & 2.51 & \\ & & 2.55 \end{pmatrix}$$

$\implies \chi^{(1)} = \varepsilon_1 - 1 \approx 3.7$ in the DC region

≈ 1.5 in the NIR and VIS region

Quartz and its Properties

Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5$$

$$\vec{P}^{(2)}_{\mu}(t) = \varepsilon_0 \iint_{-\infty}^{\infty} \chi^{(2)\,\text{sum}}_{\mu\alpha\beta}(\omega_1, \omega_2) \vec{E}_{\alpha}(\omega_1) \vec{E}_{\beta}(\omega_2) e^{-i(\omega_1+\omega_2)t} \, \mathrm{d}\omega_1 \, \mathrm{d}\omega_2$$

assuming frequency independence of χ for SHG, and monofrequent input EM-waves $(\omega_1 = \omega_2 = \omega)$

$$\vec{P}^{(2)}_{\mu}(2\omega) = \varepsilon_0 d_{\mu\alpha\beta} \vec{E}_{\alpha}(\omega) \vec{E}_{\beta}(\omega)$$

$$d, \chi^{(2)} \in \mathbb{C}^{3\times3\times3} \qquad d_{\mu\alpha\beta} \coloneqq \tfrac{1}{2}\chi^{(2)}_{\mu\alpha\beta}$$

Quartz and its Properties

Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5, \quad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}_\mu^{(2)}$$

$d \in \mathbb{C}^{27}$ in general

Quartz and its Properties

Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5, \quad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}_\mu^{(2)}$$

$d \in \mathbb{C}^{27}$ in general

$\mathbb{C}^{18}$ including symmetry in α and β $(d_{\mu\alpha\beta} = d_{\mu\beta\alpha})$

$$\begin{array}{rc} \alpha\beta = & xx \quad yy \quad zz \quad yz \quad zx \quad xy \\ \mu = \begin{matrix} x \\ y \\ z \end{matrix} & \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} = d_{\mu[\alpha\beta]} \end{array}$$

Quartz and its Properties

Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5, \quad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}^{(2)}_\mu$$

- $d \in \mathbb{C}^{27}$ in general
  - $\mathbb{C}^{18}$ including symmetry in α and β $(d_{\mu\alpha\beta} = d_{\mu\beta\alpha})$
  - $\mathbb{R}^{10}$ Kleinmann's rule for lossless media $(d_{\mu\alpha\beta} = d_{\alpha\mu\beta})$

$$\begin{array}{c} \alpha\beta = \\ \mu = x \\ y \\ z \end{array} \begin{array}{cccccc} xx & yy & zz & yz & zx & xy \end{array}$$

$$\mu = \begin{matrix} x \\ y \\ z \end{matrix} \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{31} & d_{21} \\ d_{21} & d_{22} & d_{23} & d_{32} & d_{14} & d_{12} \\ d_{31} & d_{32} & d_{33} & d_{23} & d_{13} & d_{14} \end{pmatrix} = d_{\mu[\alpha\beta]}$$

Quartz and its Properties

Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5, \quad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}_\mu^{(2)}$$

$d \in \mathbb{C}^{27}$ in general

$\mathbb{C}^{18}$ including symmetry in α and β $(d_{\mu\alpha\beta} = d_{\mu\beta\alpha})$

$\mathbb{R}^{10}$ Kleinmann's rule for lossless media $(d_{\mu\alpha\beta} = d_{\alpha\mu\beta})$

$\mathbb{R}^{2}$ Neumann's point group principle $(d_{\mu\alpha\beta} = (Td)_{\mu\alpha\beta})$

$$\begin{array}{r} \alpha\beta = \\ \mu = x \\ y \\ z \end{array} \begin{array}{c} \begin{array}{cccccc} xx & yy & zz & yz & zx & xy \end{array} \\ \begin{pmatrix} d_{11} & \overline{d_{11}} & & d_{14} & & \\ & & & & \overline{d_{14}} & \overline{d_{11}} \\ & & & & & \end{pmatrix} \end{array} = d^{(32)\text{ sym.}}_{\mu[\alpha\beta]}$$

Quartz and its Properties

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Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5, \quad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}^{(2)}_\mu$$

- $d \in \mathbb{C}^{27}$ in general
  - $\mathbb{C}^{18}$ including symmetry in α and β $\quad (d_{\mu\alpha\beta} = d_{\mu\beta\alpha})$
  - $\mathbb{R}^{10}$ Kleinmann's rule for lossless media $\quad (d_{\mu\alpha\beta} = d_{\alpha\mu\beta})$
  - $\mathbb{R}^{2}$ Neumann's point group principle $\quad (d_{\mu\alpha\beta} = (Td)_{\mu\alpha\beta})$
  - $\mathbb{R}^{1}$ Neumann's principle & Kleinmann's rule

$$\begin{array}{c} \alpha\beta = xx \quad yy \quad zz \quad yz \quad zx \quad xy \\ \mu = \begin{matrix} x \\ y \\ z \end{matrix} \begin{pmatrix} d_{11} & \overline{d_{11}} & & & & \\ & & & & & \overline{d_{11}} \\ & & & & & \end{pmatrix} = d^{(32),\text{ no loss}}_{\mu[\alpha\beta]} \end{array}$$

Quartz and its Properties

Electric Susceptibility Tensors

$$P_0 = 0, \quad \chi^{(1)} \approx 1.5, \quad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}^{(2)}_\mu, \quad d_{11} \approx 0.3\,\mathrm{pm/V}$$

- $d \in \mathbb{C}^{27}$ in general
  - $\mathbb{C}^{18}$ including symmetry in α and β $\quad (d_{\mu\alpha\beta} = d_{\mu\beta\alpha})$
  - $\mathbb{R}^{10}$ Kleinmann's rule for lossless media $\quad (d_{\mu\alpha\beta} = d_{\alpha\mu\beta})$
  - $\mathbb{R}^{2}$ Neumann's point group principle $\quad (d_{\mu\alpha\beta} = (Td)_{\mu\alpha\beta})$
  - $\mathbb{R}^{1}$ Neumann's principle & Kleinmann's rule

$$\begin{matrix} \alpha\beta = & xx & yy & zz & yz & zx & xy \\ \mu = x & \multicolumn{6}{l}{\left(\begin{matrix} d_{11} & \overline{d_{11}} & & & & \\ & & & & & \overline{d_{11}} \\ & & & & & \end{matrix}\right)} \\ y & \\ z & \end{matrix} = d^{(32),\ \text{no loss}}_{\mu[\alpha\beta]}$$

Quartz and its Properties

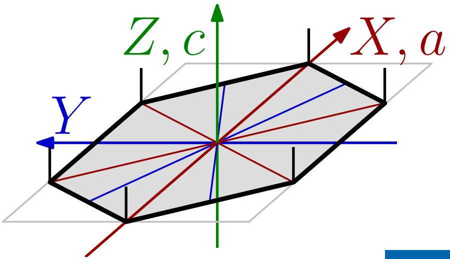
SHG Direction Dependence

$$d_{11} = -d_{12} = -d_{26} \approx 0.3\,\mathrm{pm/V} \qquad \varepsilon_0 \vec{E}_\alpha \vec{E}_\beta d_{\mu\alpha\beta} = \vec{P}^{(2)}_\mu$$

$$\Rightarrow \frac{\vec{P}(2\omega)}{d_{11}\varepsilon_0} = \frac{1}{d_{11}\varepsilon_0}\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} E_x^2 - E_y^2 \\ -2E_xE_y \\ 0 \end{pmatrix} = \begin{pmatrix} \cos 2\theta \\ -\sin 2\theta \\ 0 \end{pmatrix} E^2 = E^2 R_{2\theta} \hat{e}_x$$

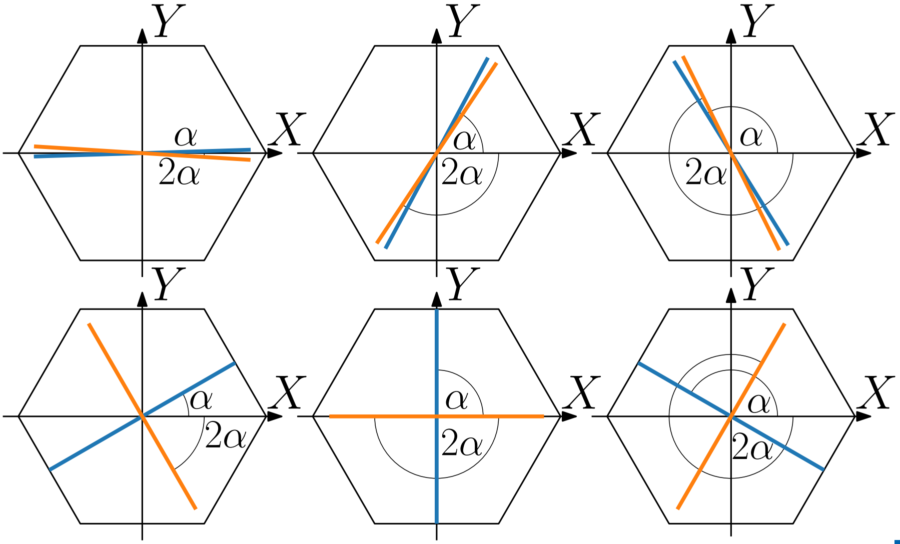
with $\vec{E}$ rotating in the XY-plane with magnitude E and angle θ to $\hat{e}_x$
Thus, for $E_z = 0$:

$$\vec{E}^2 \propto \|\vec{P}\| \not\propto f(\theta)$$

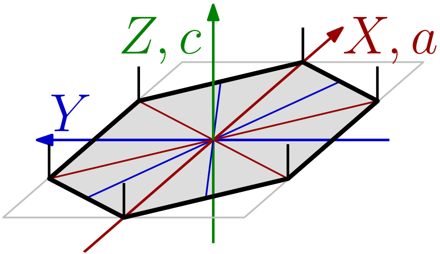


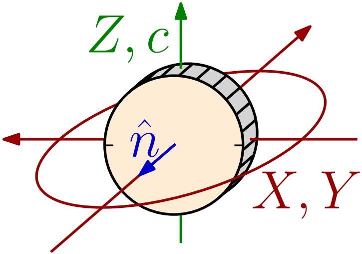
Quartz and its Properties

SHG Direction Dependence



Effects in our Waveplate



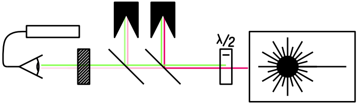


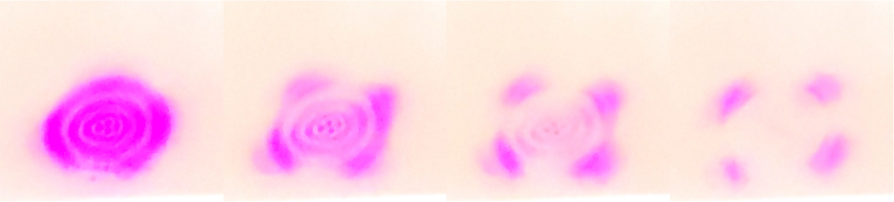
- laser light along $\hat{n}$ polarized in XY-plane and angle $\theta = \angle \hat{e}_x \vec{E}$

$$\Longrightarrow P_{\perp \hat{n}} = \|\vec{P} \times \hat{n}\| \propto \|\cos 2\theta \cos \theta - \sin 2\theta \sin \theta\| = \|\cos 3\theta\|$$

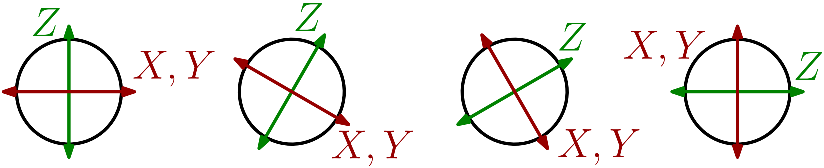
  - for $\vec{E} \parallel \hat{e}_x$, SHG along $\hat{n}$ is maximized
  - for $\vec{E} \parallel \hat{e}_y$, SHG along $\hat{n}$ is minimized
- no phase matching possible, but for our laser, $I(2\omega)/I(\omega) \sim 10^{-7}$ non phase-matched intensity is enough

Effects in our Waveplate

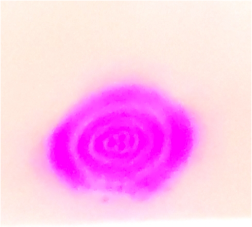




visible SHG at rotation angles $\Delta\alpha \approx 0°$, $30°$, $60°$ and $90°$. (inverted)

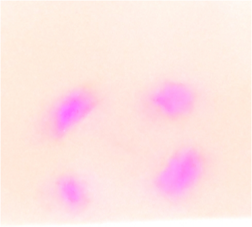


Effects in our Waveplate



- $\vec{E}_{\text{out}}(\omega) \parallel \vec{E}_{\text{in}}$, unchanged, horizontally pol.
- $\vec{E}_{\text{out}}(2\omega) \parallel \vec{E}_{\text{in}}$, mostly horizontally pol.

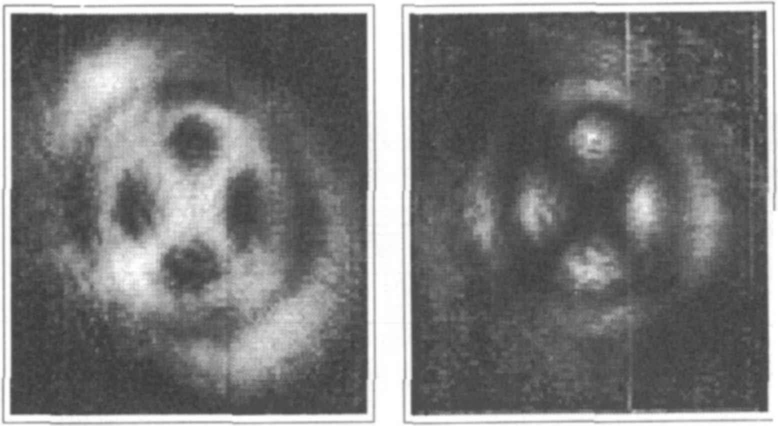
$\rightarrow$ Nd:YAG light frequency doubled



- $\vec{E}_{\text{out}}(\omega) \parallel \vec{E}_{\text{in}}$, unchanged, horizontally pol.
- $\vec{E}_{\text{out}}(2\omega) \perp \vec{E}_{\text{in}}$, mostly vertically pol.

$\rightarrow$ depolarized Nd:YAG light frequency doubled

Nd:YAG Depolarization



Captured Nd:YAG light passing through a polarization filter polarized parallel (left) and perpendicular (right) to the intended laser polarization

Conclusion & Outlook

The goal of the internship was achieved:

- quartz waveplate is responsible for green light instead of diffusor
- green light is second harmonic ($532\,\mathrm{nm}$) of Nd:YAG wavelength
- the theory on SHG and waveplates can explain the observed light and its intensity distribution can be explained by

$\Longrightarrow$ Possible combined SHG+waveplates for use in laser adjustment

- improvement in adjustment visibility, with only diffusive elements needed as detector cards
- non-hazardous adjustment together with filter for fundamental wavelength

References I

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UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Research-Group Internship

Understanding the emitted green light of the Thomson Nd:YAG lasers

Philip Geißler

Physics Institute,

University of Greifswald

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