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The influence of attenuation on a self-organized second harmonic generation in a germanium doped microstructured silica fiber

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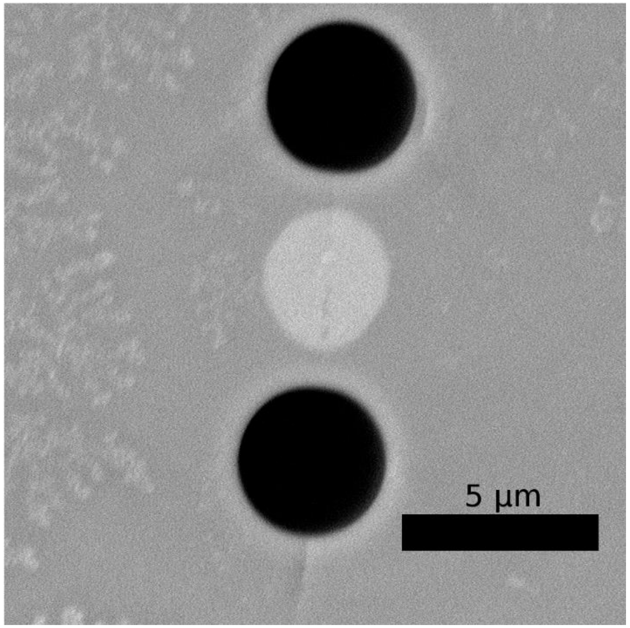
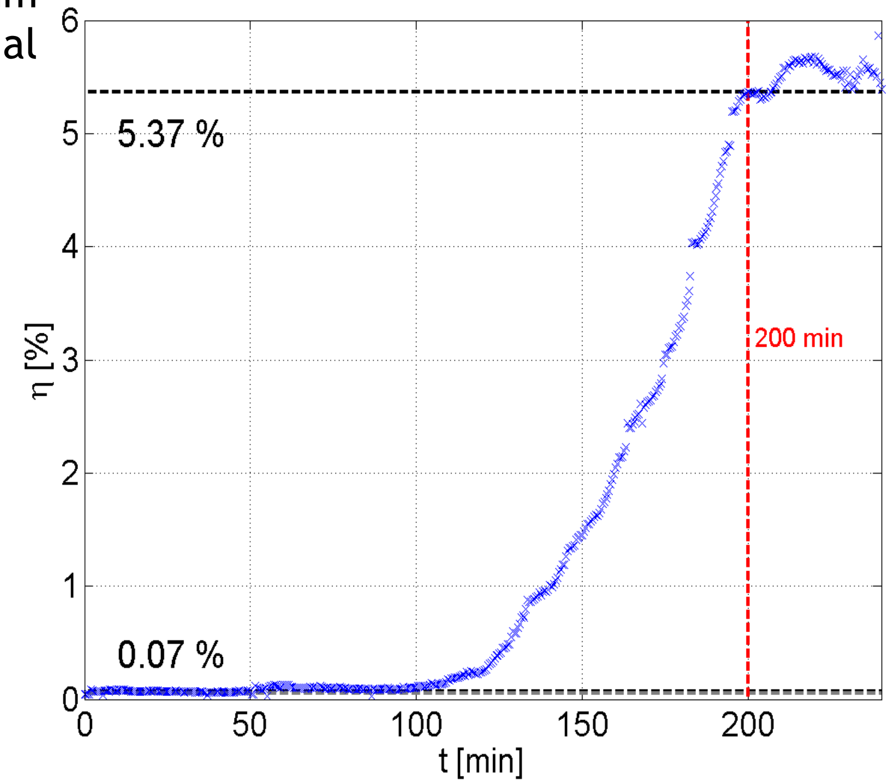
Outline

1. Experimental results - what did we observe?
2. SHG in silica fibers - why should not it occure?
3. $\chi^{(2)}$ in centrosymmetric media - so how is it possible?
4. Numerical model - how can we describe it?
5. Influence of attenuation - what did we do?
6. Data Fitting - how does it look in comparison to experiment?

Results of experiment
conducted in side-hole optical fiber

Measurements of the efficiency of SHG (λ_{SHG} = 532 nm) over time in a 1m long microstructured side-hole germanium doped silica fiber piece. The SH signal grows up to ~5,4% after 200 minutes.





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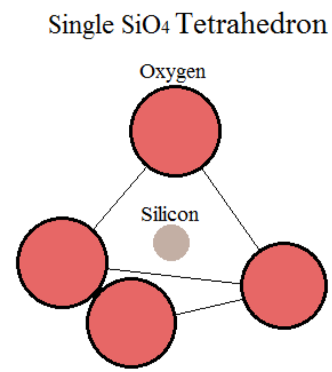
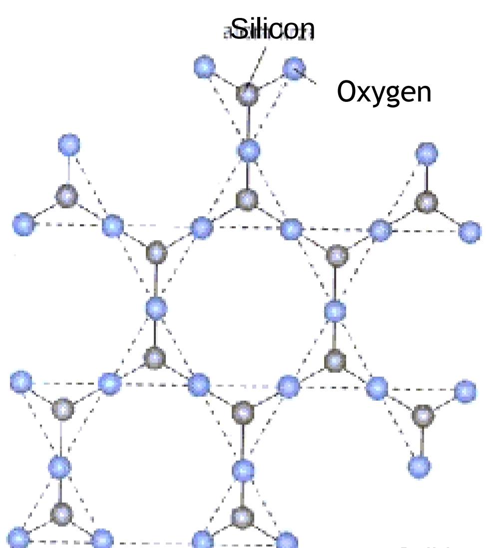
Second harmonic generation

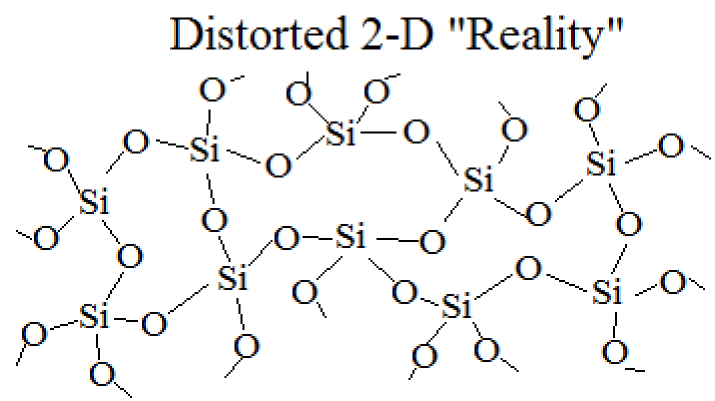
in silica optical fibers

The limitation of silica fibers, in the context of investigating nonlinear optical phenomena, is the centrosymmetricity of this material. It leads directly to the zero value of the nonlinear second-order susceptibility. As a result, the second harmonic generation (SHG) should not be efficient.





[wikipedia.org]

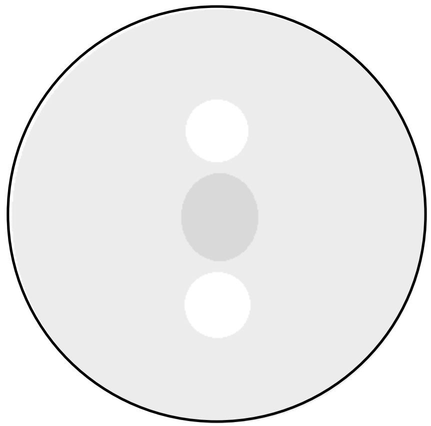


Charge transfer states in GeO_2-doped silica fibers

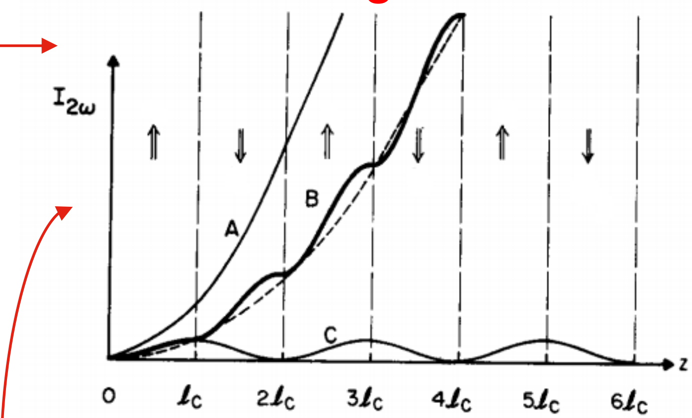
Antoniuk's Model

Seed

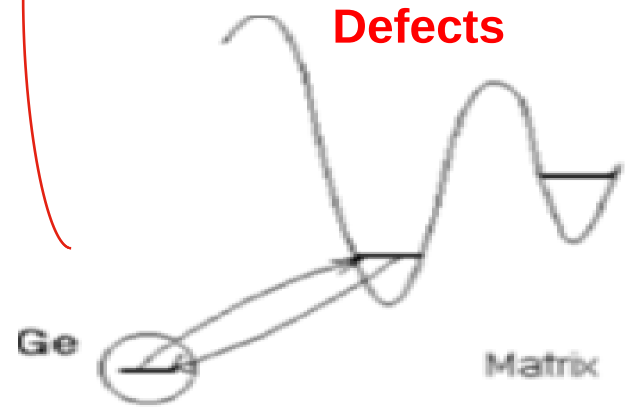
The cross-section of the optical fiber, which core is doped with germaniu.



Selforganization



Defects



Simulations of second harmonic generation

- Attenuated Highly Efficient SHG (AESHG)

$$\begin{cases} \dfrac{\mathrm{d}A_0\exp\{i\Psi_0\}}{\mathrm{d}t} = \alpha_2 A_2^2\left(u\exp\{i\left(\Psi_2-2\Psi_1\right)\}-A_0\exp\{i\Psi_0\}\right) \\ \dfrac{\mathrm{d}A_1\exp\{i\Psi_1\}}{\mathrm{d}z} = -\,i\dfrac{4\pi\omega\chi^{(3)}}{cn_\omega}A_0A_1A_2\exp\{-i\Psi_0-i\Psi_1+i\Psi_2\} - \dfrac{\alpha_\omega}{2}A_1\exp\{i\Psi_1\} \\ \dfrac{\mathrm{d}A_2\exp\{i\Psi_2\}}{\mathrm{d}z} = -\,i\dfrac{4\pi\omega\chi^{(3)}}{cn_{2\omega}}A_0A_1^2\exp\{i\Psi_0+2i\Psi_1\} - \dfrac{\alpha_{2\omega}}{2}A_2\exp\{i\Psi_2\} \end{cases}$$

Fiber's parameters

$$\begin{aligned} n_\omega &= 1{,}456 \\ n_{2\omega} &= 1{,}469 \\ \alpha_\omega &= 0{,}0176\ \mathrm{dB/m} \\ \alpha_{2\omega} &= 0{,}0002\ \mathrm{dB/m} \end{aligned}$$

Introducing the dimensionless variables

$$E_0 = \frac{A_0}{u}$$

$$E_1 = \frac{A_1}{u}$$

$$E_2 = \frac{A_2}{u}$$

$$S = \kappa_0 z,$$

$$\tau = \alpha_2 u^2 t$$

$$\tilde{\alpha}_i = \frac{\alpha_i}{\kappa_0} \quad \text{dla} \quad i = \omega, 2\omega$$

$$\kappa_0 = \frac{4\pi\omega\chi^{(3)}u^2}{\mathrm{c}}$$

$$\begin{cases} \dfrac{\mathrm{d}E_0}{\mathrm{d}\tau} = -\,E_2^2\left(E_0-\cos(\Psi_0+2\Psi_1-\Psi_2)\right) \\ E_0\dfrac{\mathrm{d}\Psi_0}{\mathrm{d}\tau} = -\,E_2^2\sin(\Psi_0+2\Psi_1-\Psi_2) \\ \dfrac{\mathrm{d}E_1}{\mathrm{d}S} = -\,\dfrac{1}{n_\omega}E_0E_1E_2\sin(\Psi_0+2\Psi_1-\Psi_2) - \dfrac{\tilde{\alpha}_\omega}{2}E_1 \\ E_1\dfrac{\mathrm{d}\Psi_1}{\mathrm{d}S} = -\,\dfrac{1}{n_\omega}E_0E_1E_2\cos(\Psi_0+2\Psi_1-\Psi_2) \\ \dfrac{\mathrm{d}E_2}{\mathrm{d}S} = \dfrac{1}{n_{2\omega}}E_0E_1^2\sin(\Psi_0+2\Psi_1-\Psi_2) - \dfrac{\tilde{\alpha}_{2\omega}}{2}E_2 \\ E_2\dfrac{\mathrm{d}\Psi_2}{\mathrm{d}S} = -\,\dfrac{1}{n_{2\omega}}E_0E_1^2\sin(\Psi_0+2\Psi_1-\Psi_2) \end{cases}$$

Scaling

$$\kappa_0^{-1} \approx 100\,\mathrm{cm}$$

$$u \approx 10^5\ \mathrm{V/cm}$$

$$(\alpha_2 u^2)^{-1} \approx 5\,\mathrm{min}$$

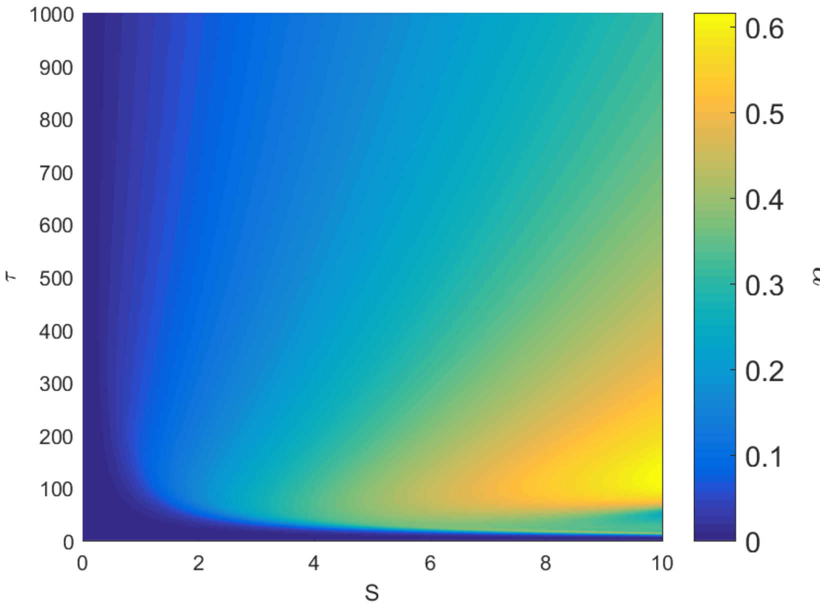
Attenuated Highly Efficient SHG
- comparison between low and high material loss

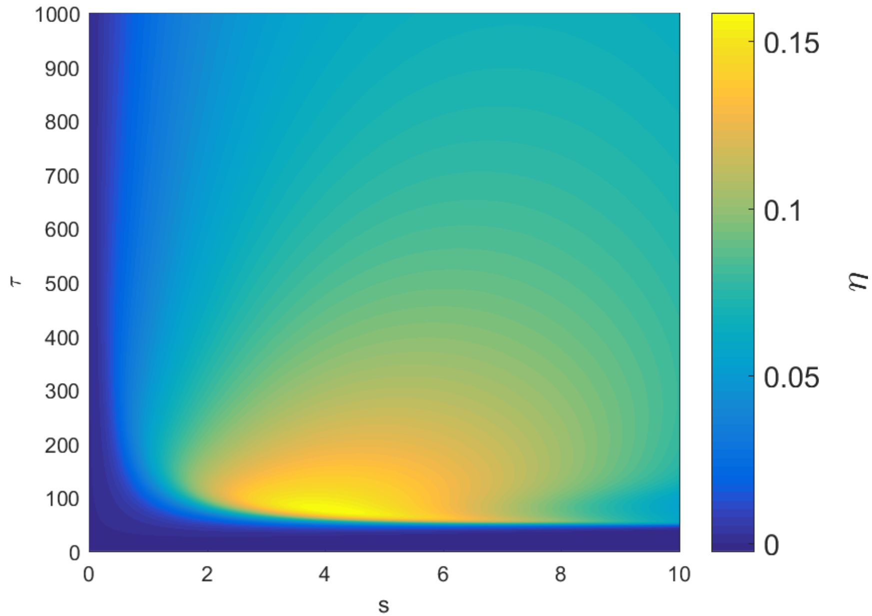
$$\eta = \frac{E_2^2(S,\tau) - E_2^2(0,\tau)}{E_1^2(0,\tau)}$$

$$E_1(0) = 1$$
$$E_2(0) = 0{,}05$$

$$\alpha_\omega = 0 \text{ dB/m}$$
$$\alpha_{2\omega} = 0 \text{ dB/m}$$

$$\alpha_\omega = 0{,}159 \text{ dB/m}$$
$$\alpha_{2\omega} = 2{,}551 \text{ dB/m}$$





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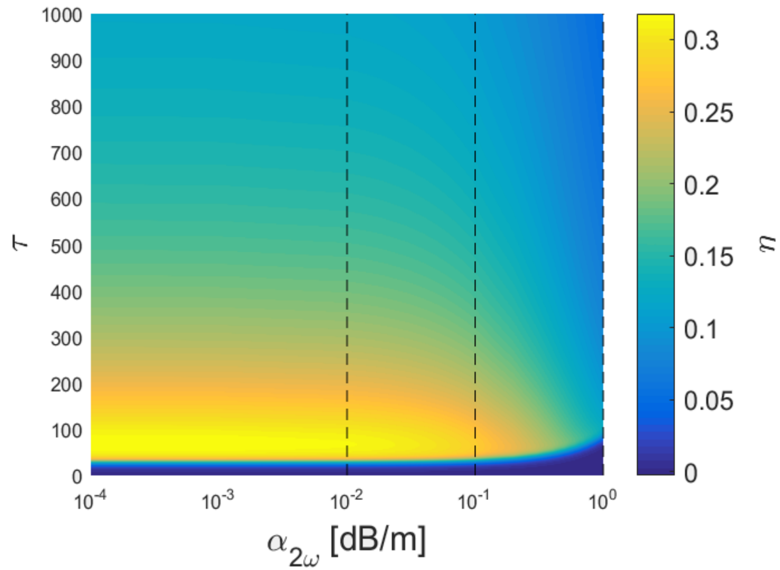
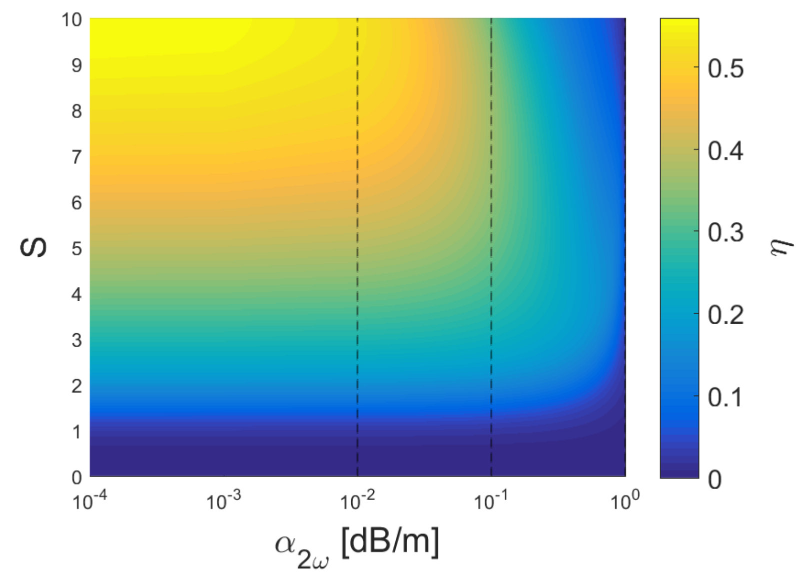
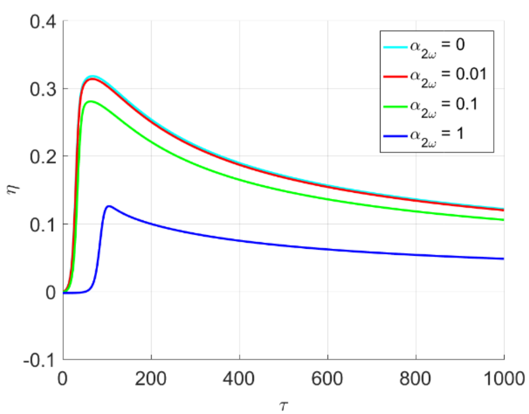
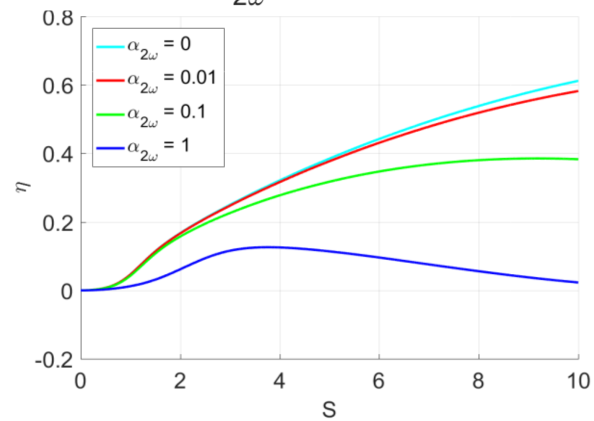
Attenuated Highly Efficient SHG

- influence of attenuation on SHG in Ge-doped silica fiber



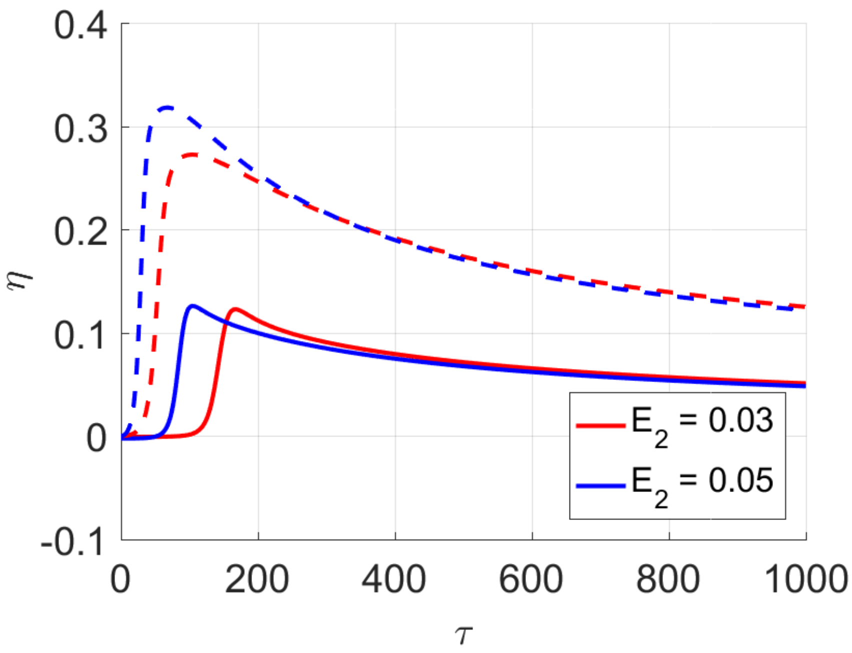


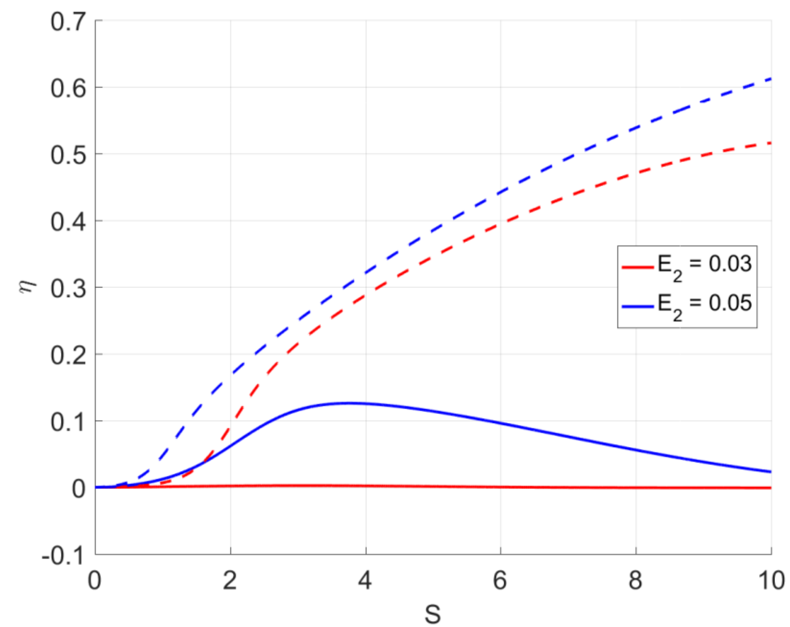




Attenuated Highly Efficient SHG
- influence of primary value of E_2

$\alpha_{2\omega} = 0$ dB/m (dashed), $\alpha_{2\omega} = 1$ dB/m (solid)





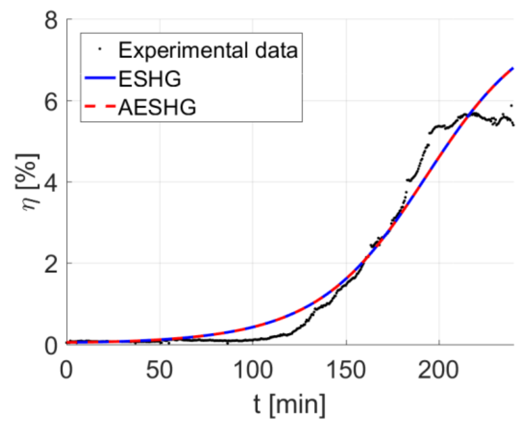
Adjustment of the theoretical curve
to the measurement data

Initial conditions:

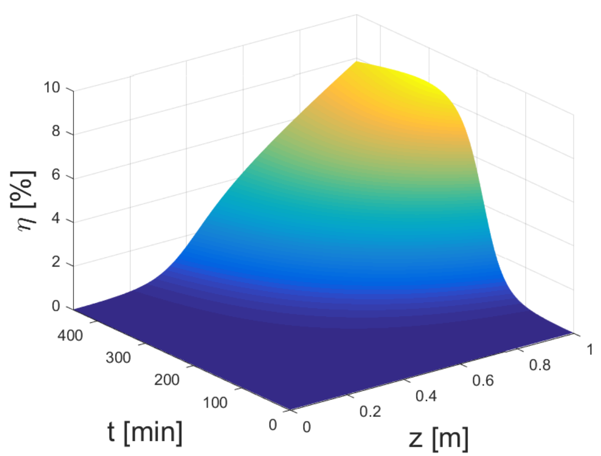
$$E_0(S,0) = 0$$
$$\Psi_0(S,0) = 0$$
$$E_1(0,\tau) = 2{,}2$$
$$\Psi_1(0,\tau) = 0$$
$$E_2(0,\tau) = 0{,}057$$
$$\Psi_2(0,\tau) = 0$$

P_{av} = 200mW,
f = 20 kH , t = 0,7 ns

0,07% initial value



$$\alpha_{\omega} = 0{,}0176 \text{ dB/m}$$
$$\alpha_{2\omega} = 0{,}0002 \text{ dB/m}$$



$$\alpha_{\omega} = 0{,}159 \text{ dB/m}$$
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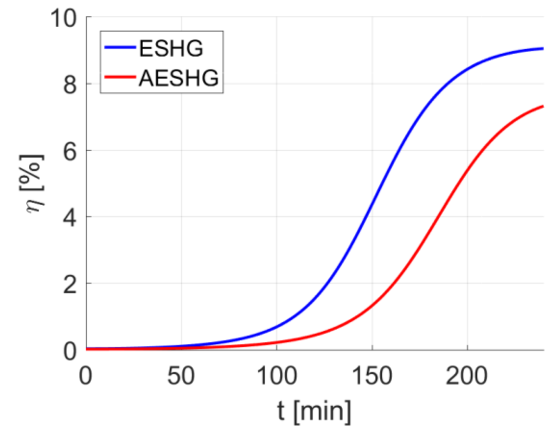
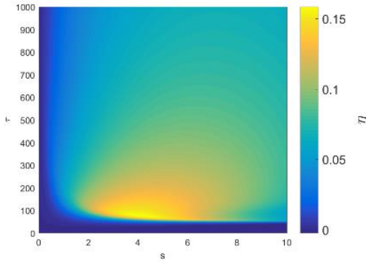
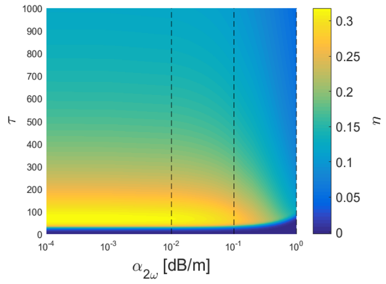
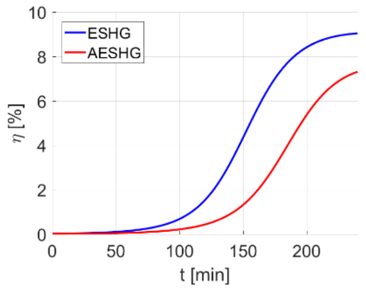


The main results

- we extended a theoretical model of the self-organized second harmonic generation to include an attenuation and investigated the influence of fiber loss on the self-organized SHG process
- we performed calculations of energy conversion efficiency for the second harmonic generation in microstructured optical fibers
- we referred the simulation results to the measured SHG efficiency in a microstructured side-hole germanium doped silica fiber







The extended model should be applied for the fibers with loss beyond 0.01 dB/m. Even in such fibers the efficient second harmonic generation without an external second harmonic beam is possible.

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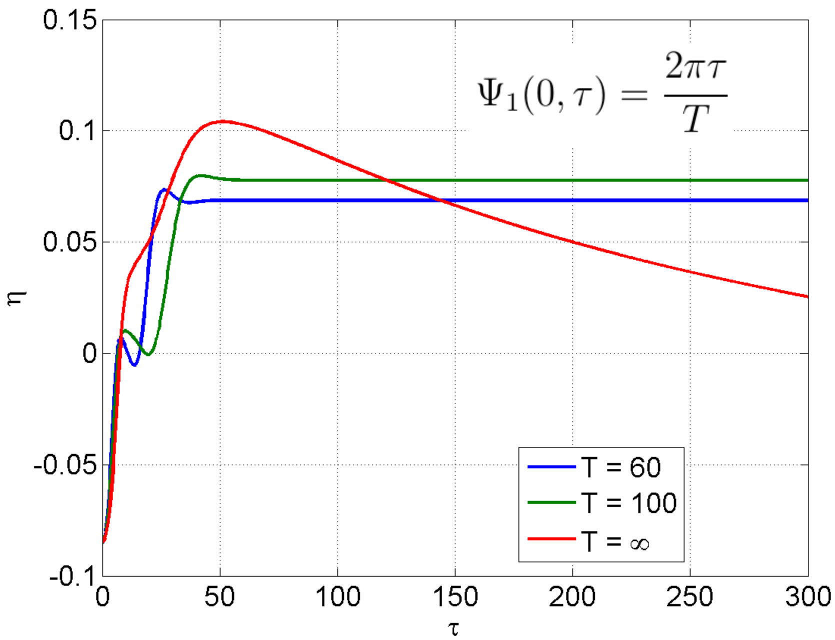
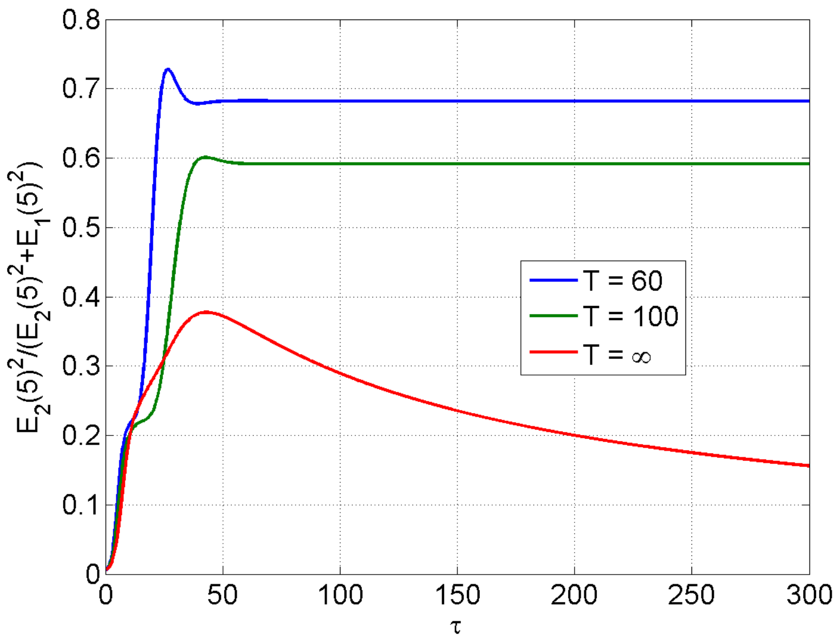
Effective frequency doubler (?)

The conversion efficiency changes in time - after the initial growth the subsequent decay takes place. Complete decay can be avoided by variation of input beams parameters - for example, one can vary the phase of the fundamental beam





Phase change after some time

Complete decay can be avoided by variation of input beams parameters.

$\Delta\Psi_2 = \pi$ for $\tau = 25$

$E_2(0) = 0{,}8$

In the case $E_\omega^2 >> E_{2\omega}^2$:

$$\frac{\mathrm{d}A_0 \exp\{i\Psi_0\}}{\mathrm{d}t} = \alpha_2 A_2^2 (u \exp\{i\Psi_2\} - A_0 \exp\{i\Psi_0\})$$
$$\frac{\mathrm{d}A_2 \exp\{i\Psi_2\}}{\mathrm{d}z} = i\frac{4\pi\omega}{cn_{2\omega}} \left(-\chi^{(3)}\right) A_0 A_1^2 \exp\{i\Psi_0\}$$