Thermal tuning of phase-matching in a multimodal SOI waveguide with $\chi^{(3)}$ non linearity

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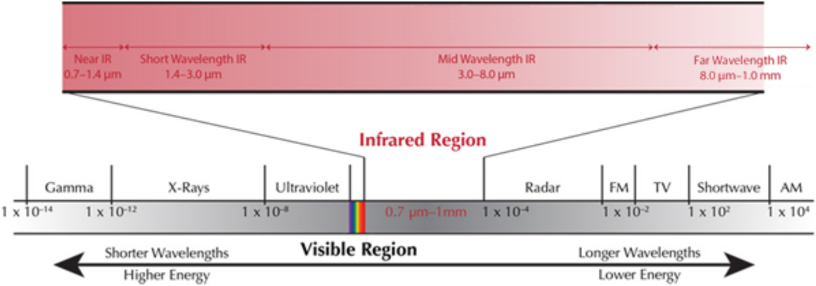
Outline

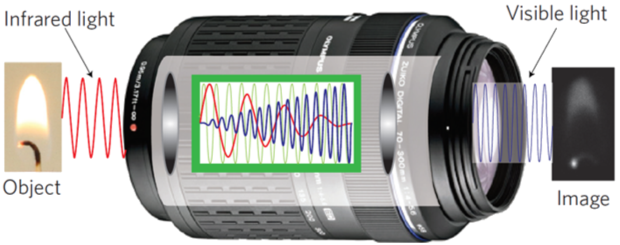
Introduction

Research field:
bio-sensors, gas sensors and bio-medical instrumentation

Problem:
lack of sources/sensors in the MIR (3-10μm)



Solution:
frequency down convertion from NIR/VIS sources to MIR
frequency up convertion from MIR signals to NIR/VIS sensor



Aim:
Develop integrated frequency converter tunable with temperature

Nonlinear Optics

Frequency convertion employs nonlinear properties of materials

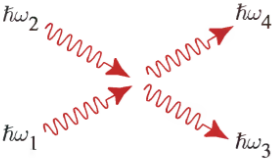
$$(1) \quad \mathbf{P} = \varepsilon_0 \left(\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{E}^2 + \chi^{(3)} \vdots \mathbf{E}^3 + \cdots \right) = \mathbf{P}_{\mathrm{L}} + \mathbf{P}_{\mathrm{NL}}$$

- $\chi^{(1)}$: linear part
- $\chi^{(2)}$: 2^{nd} order nonlinearity (SHG, TWM)
- $\chi^{(3)}$: 3^{rd} order nonlinearity (THG, FWM)

Four-Wave Mixing

FWM uses 3^{rd} order nonlinearity $\chi^{(3)}$.

It consists of the interaction between four EM waves of different frequencies.

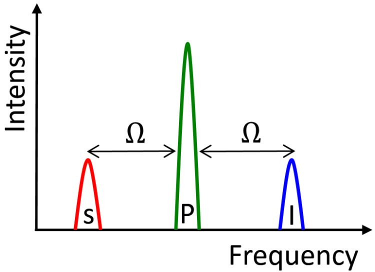


(2) $$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

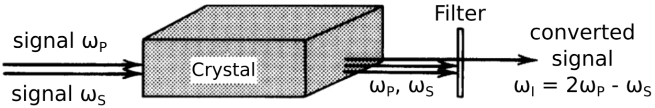
(3) $$k_1 + k_2 = k_3 + k_4$$

Special case:

$\omega_1 = \omega_2 = \omega_P$, with stimulation.



Conservation of energy and momentum



Conservation of energy is naturally verified

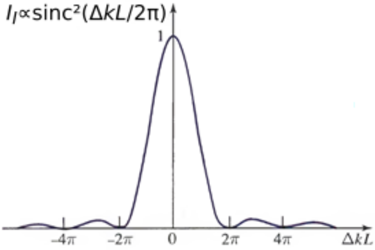
$$\omega_I = 2\omega_P - \omega_S = \omega_P \pm \Omega \tag{4}$$

Conservation of momentum is imposed in the phase-mismatch

$$\Delta k = 2\, k_P(\omega_P) - k_S(\omega_S) - k_I(\omega_I) = 0 \tag{5}$$

Generation happens also for $\Delta k \approx 0$, but at lower efficiency.

$$(6) \quad I_I \propto \left| \int_0^L exp(\mathrm{i}\Delta kz)dz \right| \propto L^2 sinc^2(\Delta kL/2\pi)$$

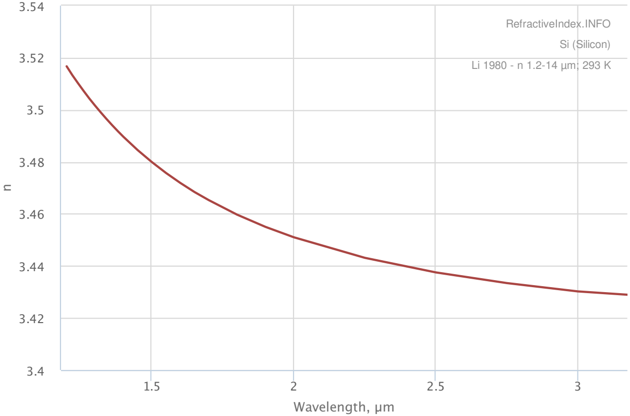


We define the coherence length

$$(7) \quad L_{coh} = \frac{2\pi}{|\Delta k|}$$

Bulk silicon does not permit to verify both equations.

$$k(\omega) = k_0 n(\omega) \tag{8}$$



Multimodal Waveguides

In silicon waveguides both equations can be verified.
Therefore Eq. (5) becomes:

$$\Delta k = 2\,\beta_P(\omega_P) - \beta_S(\omega_S) - \beta_I(\omega_I) \tag{9}$$

$$\text{where} \qquad \beta(\omega) = k_0 n_{eff}(\omega)$$

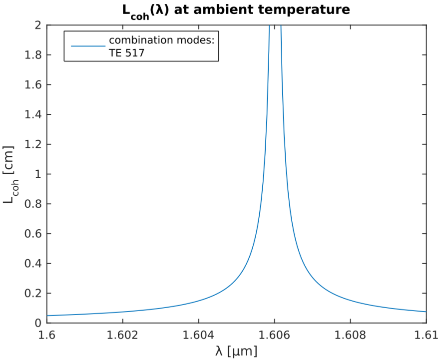
- If the waveguide supports only one mode, phase-matching is only near the frequency of the pump and $\Omega \ll \omega_P$
- If the waveguide is multimodal, there are more matching conditions and also $\Omega \lesssim \omega_P$.

Phase-matching tuning

Phase-matching conditions have narrow bandwidth.

It is difficult
to obtain phase-matching
at the required wavelength.

We aim
to tune with temperature
the range where
phase-matching is verified.



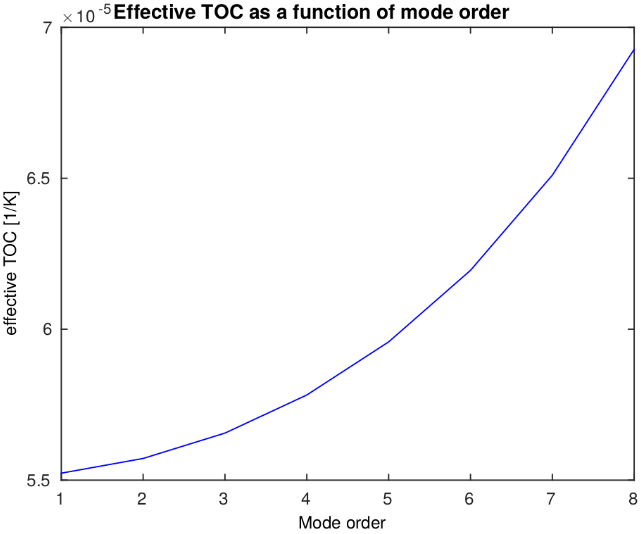
Thermo-Optic Coefficient

Refractive index of silicon is influenced from the temperature.

$$
\begin{aligned}
n &= n(\omega, T(x,y)) \\
&= n(\omega, T_{amb}) + \mathrm{TOC} \cdot (T(x,y) - T_{amb})
\end{aligned}
\tag{10}
$$

Different modes react differently at the change of temperature.

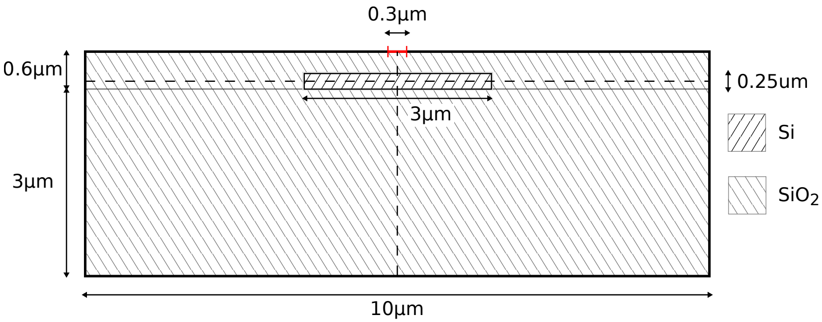
$$
n_{eff} = n_{eff}(\omega, T_{amb}) + \mathrm{TOC}_{eff} \cdot (T_H - T_{amb}) \tag{11}
$$



It should be possible to control phase-matching with temperature.

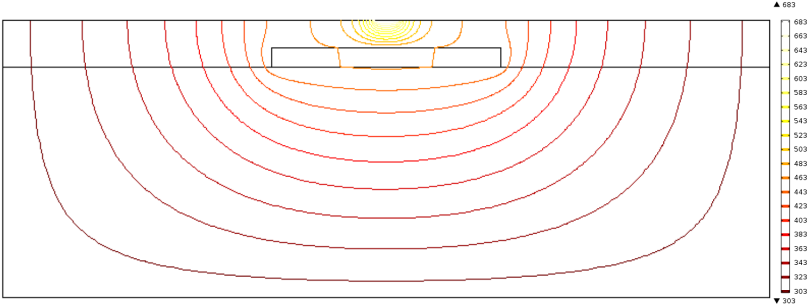
Computational model

Definition of the problem: geometry, materials.
Simulation with FEM in Comsol.



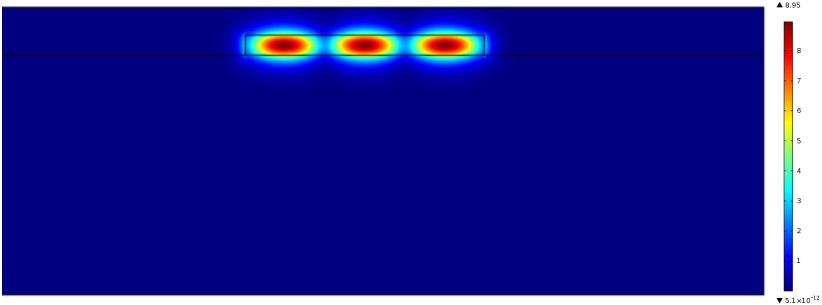
Temperature simulation

Stationary solution of heat transfer equation: parameter T_H and boundary conditions.



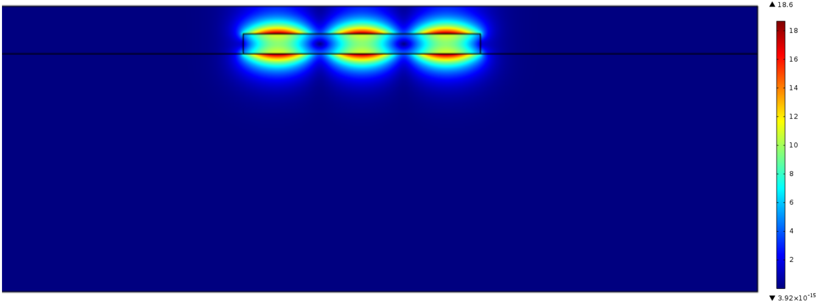
Mode simulation

Modes as solutions of the Helmholtz equation:
frequency as parameter and boundary conditions.



Mode simulation

Both TE, TM, and *leaky* modes were obtained.



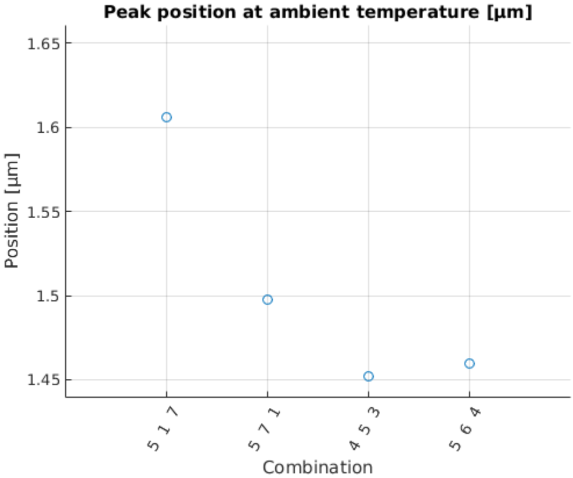
Data analysis

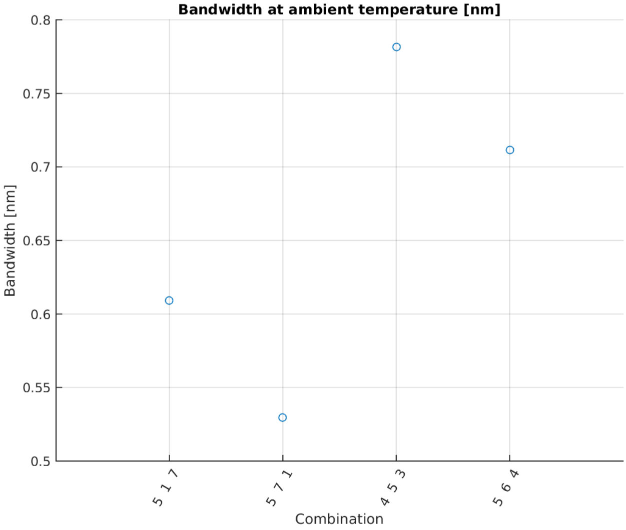
- Data extraction from comsol to matlab.
- Data classification (TE/TM, order).
- Data processing:
  - polynomial fit of λ and T_H.
  - evaluation of phase-mismatch (5) with (9) and (11) (12)

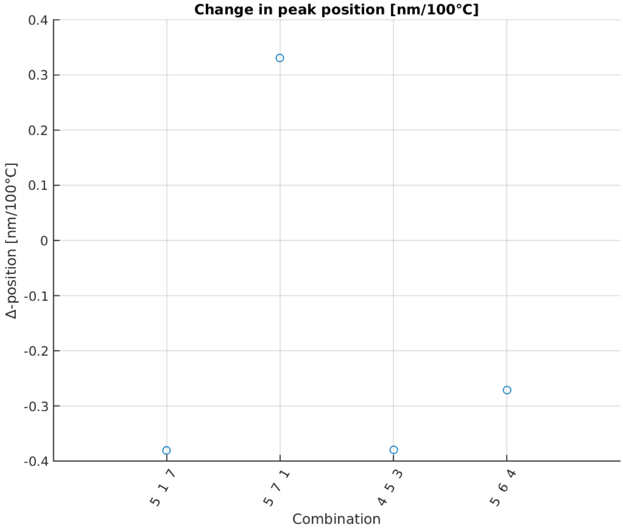
    $$\Delta k = 2\frac{2\pi}{\lambda_P} n_{eff}(\lambda_P, T_H) - \frac{2\pi}{\lambda_S} n_{eff}(\lambda_S, T_H) - \frac{2\pi}{\lambda_I} n_{eff}(\lambda_I, T_H)$$

    and coherence length $L_{coh} = \frac{2\pi}{|\Delta k|}$.
- Data selection: verify condition $L_{coh}/L_{sam} \geq 1$.
- Data aggregation.

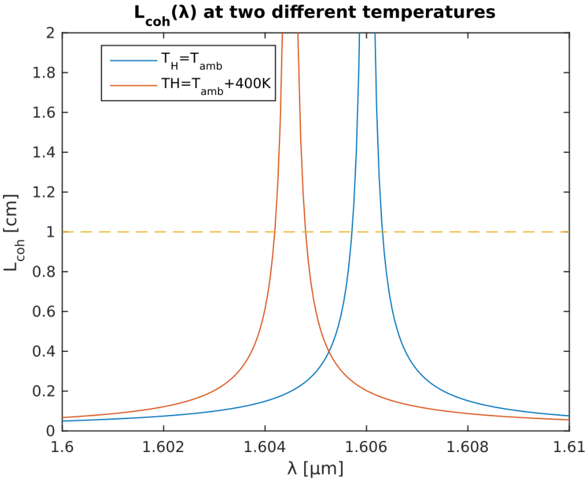
Results: symmetric configuration




Bandwidth at ambient temperature [nm]
Bandwidth [nm]
0.8
0.75
0.7
0.65
0.6
0.55
0.5
5 1 7
5 7 1
4 5 3
5 6 4
Combination

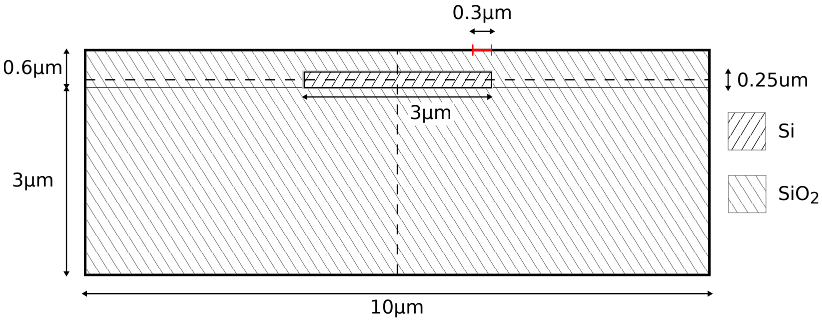

Change in peak position [nm/100°C]
Δ-position [nm/100°C]
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
5 1 7
5 7 1
4 5 3
5 6 4
Combination

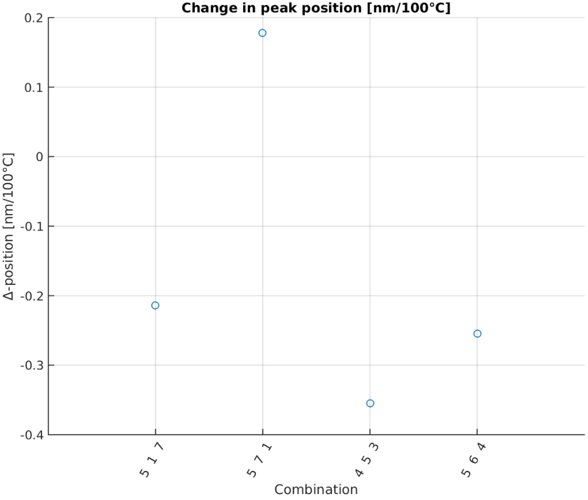
Combination TE 517, symmetric configuration.



Asymmetric configuration

We aimed to increase the difference of behaviour between low and high orders.




Change in peak position [nm/100°C]
Δ-position [nm/100°C]
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
5 1 7
5 7 1
4 5 3
5 6 4
Combination

Improvements

- The heater should be simulated as a metal conductor media, instead of a simple boundary condition (TM modes).
- Thermo-Optic Coefficient also depends on the wavelength of the signal. It is important for high Ω conversions.
- Different core geometries should be studied.
- Develop the correlation also between temperature and efficiency of energy conversion.

Summary

- Configurations with a high difference in TOC between their orders are to be preferred.
- Optimization of the overlap between the thermal and optical spatial profiles in order to maximize the difference of effective TOC in the selected modes.
- Thermal tuning of the FWM phase-match is, in fact, possible.