

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

Davide Bazzanella

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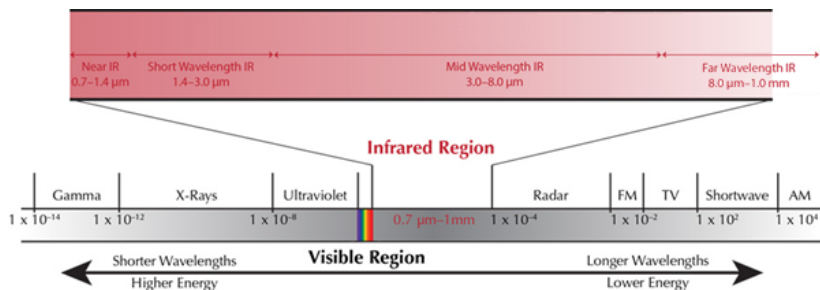
Introduction

Research field:

bio-sensors, gas sensors and bio-medical instrumentation

Problem:

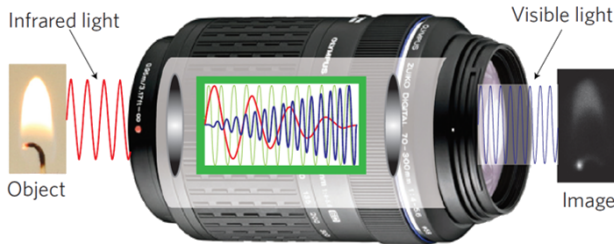
lack of sources/sensors in the MIR (3-10 μ m)



Solution:

frequency down conversion from NIR/VIS sources to MIR

frequency up conversion from MIR signals to NIR/VIS sensor

**Aim:**

Develop integrated frequency converter tunable with temperature

Nonlinear Optics

Frequency conversion employs nonlinear properties of materials

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

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



Four-Wave Mixing

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

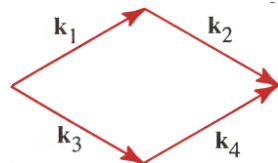
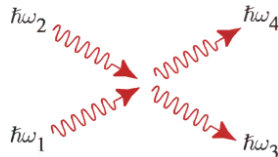
It consists of the interaction between four EM waves of different frequencies.

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

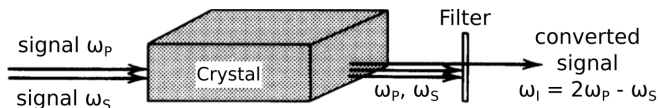
$$(3) \quad k_1 + k_2 = k_3 + k_4$$

Special case:

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



Conservation of energy and momentum



Conservation of energy is naturally verified

$$(4) \quad \omega_I = 2\omega_P - \omega_S = \omega_P \pm \Omega$$

Conservation of momentum is imposed on the phase-mismatch

$$(5) \quad \Delta k = 2k_P(\omega_P) - k_S(\omega_S) - k_I(\omega_I) = 0$$

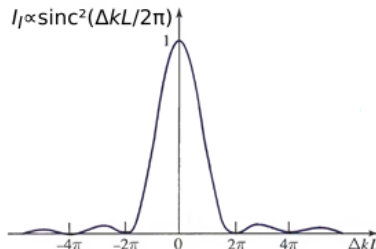
Generation happens also for $\Delta k \approx 0$, but at lower efficiency.

$$(6) \quad I_I \propto \left| \int_0^L \exp(i\Delta k z) dz \right|$$

$$\propto L^2 \text{sinc}(\Delta k/2\pi)$$

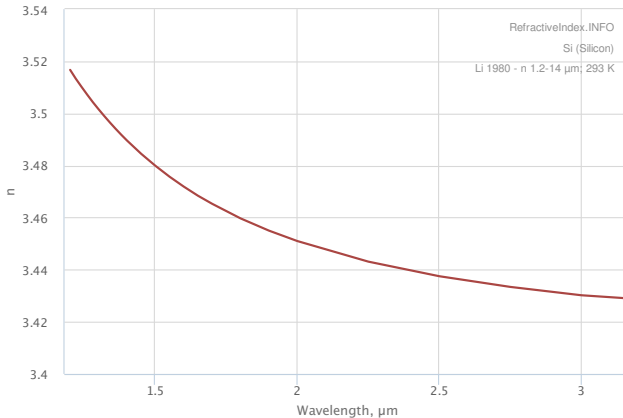
We define the coherence length

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



Bulk silicon does not permit to verify both equations.

$$(8) \quad k(\omega) = k_0 n(\omega)$$



Multimodal Waveguides

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

$$(9) \quad \Delta k = 2\beta_P(\omega_P) - \beta_S(\omega_S) - \beta_I(\omega_I)$$

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

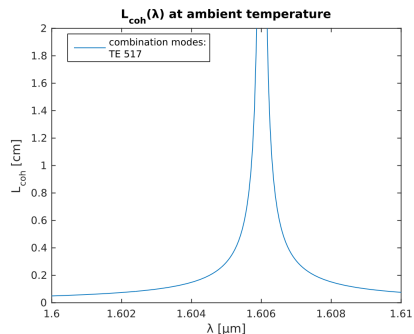
- ▶ If the waveguide supports only one mode, phase-matching is only near the frequency of the pump and $\Omega \ll \omega_P$
- ▶ If the waveguide is multimodal, there are more matching conditions and also $\Omega \lesssim \omega_P$.

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.



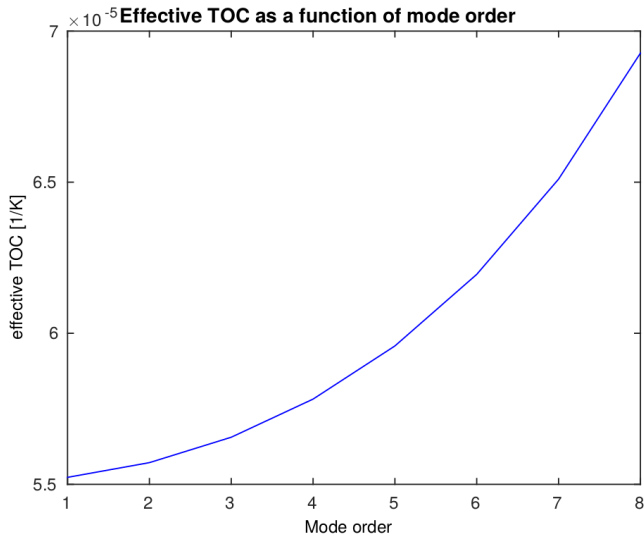
Thermo-Optic Coefficient

Refractive index of silicon is influenced from the temperature.

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

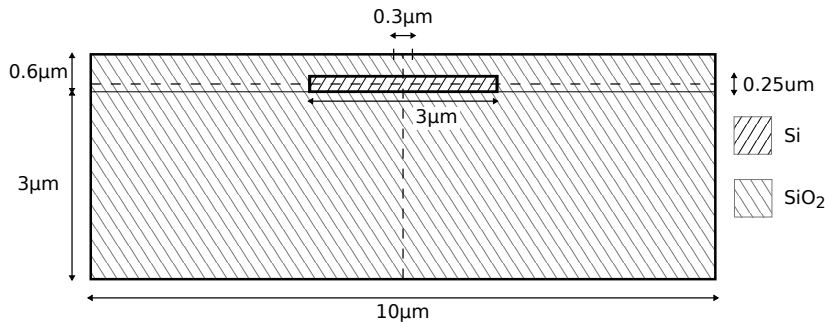
Different modes react differently at the change of temperature.

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

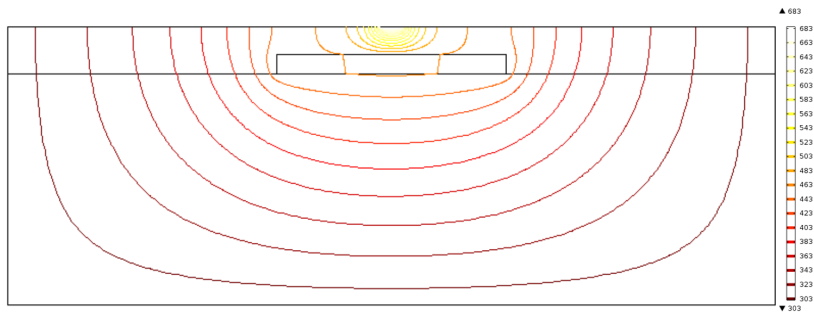


It should be possible to control phase-matching with temperature.

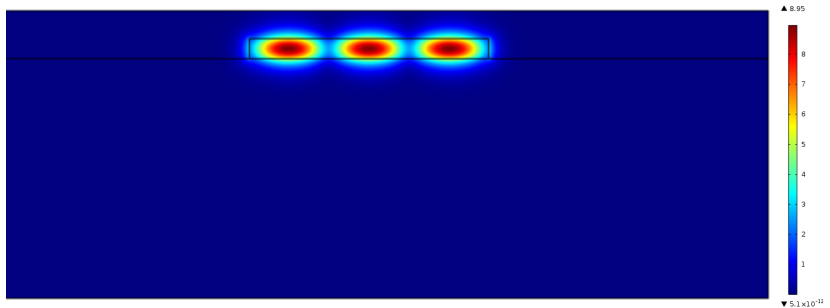
Computational model



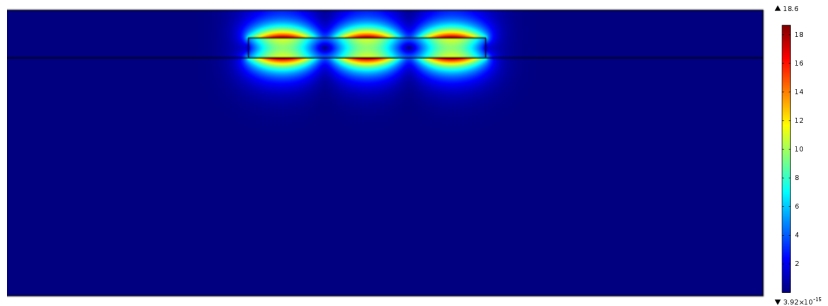
Temperature simulation



Mode simulation



Mode simulation



Data analysis

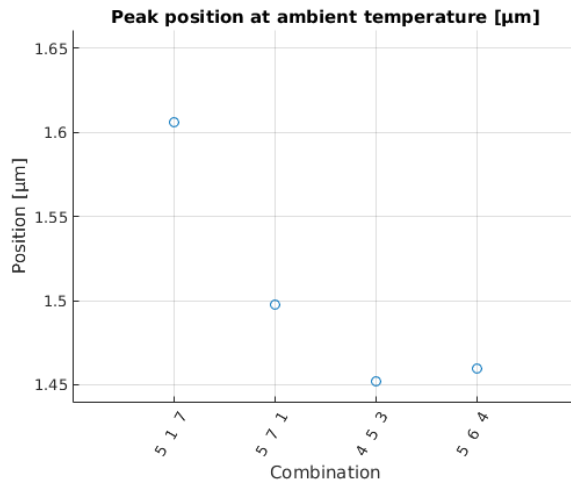
- ▶ Data extraction from comsol to matlab.
- ▶ Data classification (TE/TM, order).
- ▶ Data processing:
 - ▶ polynomial fit of λ and T_H .
 - ▶ evaluation of phase-mismatch (5) with (9) and (11) (12)

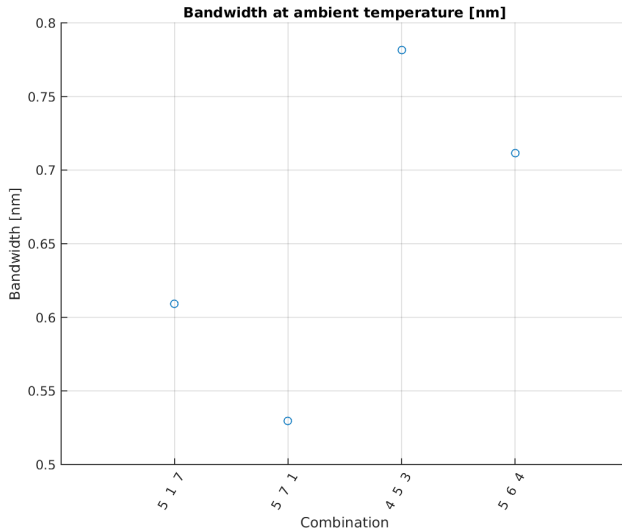
$$\Delta k = 2 \frac{2\pi}{\lambda_P} n_{\text{eff}}(\lambda_P, T_H) - \frac{2\pi}{\lambda_S} n_{\text{eff}}(\lambda_S, T_H) - \frac{2\pi}{\lambda_I} n_{\text{eff}}(\lambda_I, T_H)$$

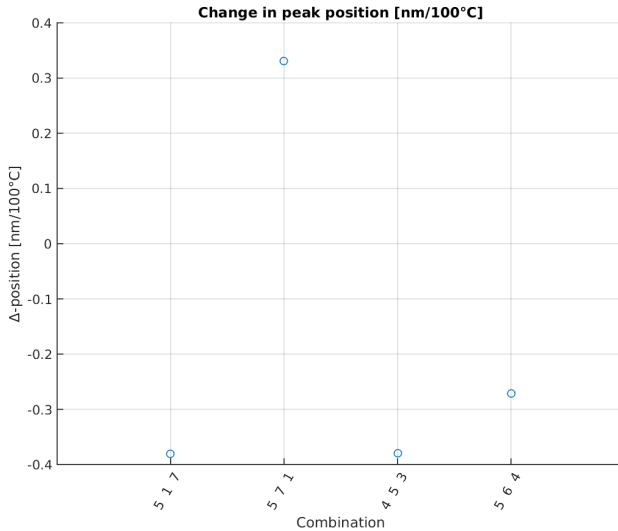
and coherence length $L_{\text{coh}} = \frac{2\pi}{|\Delta k|}$.

- ▶ Data selection: verify condition $L_{\text{coh}}/L_{\text{sam}} \geq 1$.
- ▶ Data aggregation.

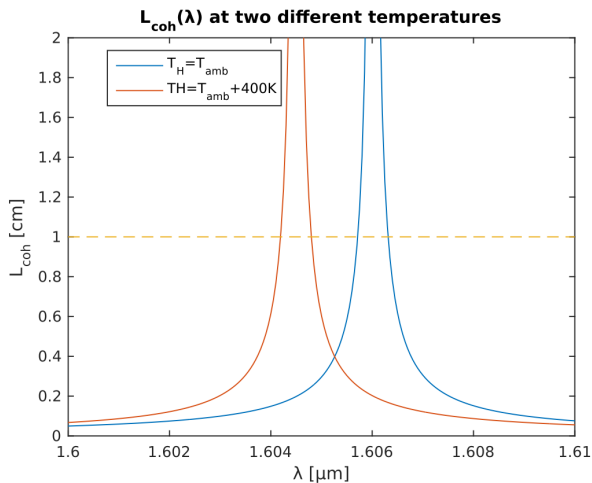
Results: symmetric configuration



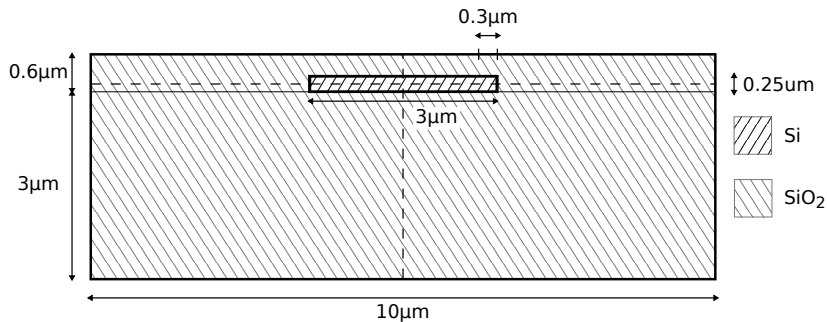


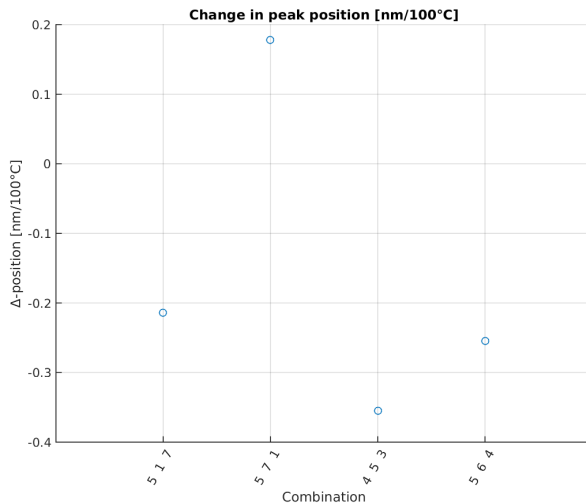


Combination TE 517, symmetric configuration.



Asymmetric configuration





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.
- ▶ Different core geometries should be studied.
- ▶ Develop the correlation also between temperature and efficiency of energy conversion.

Summary

- ▶ Configurations with a high difference between their orders are to be preferred.
- ▶ Limited interaction between the temperature of material and different modes is a constraint.
- ▶ Thermal tuning of the FWM phase-match is, in fact, possible.