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Some considerations on

Parametric up- and down-conversion in sub-wavelength waveguides: coherent sources in the UV and IR

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Buenos Aires, 2 Dec 2015

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A little issue

October 2005

Today

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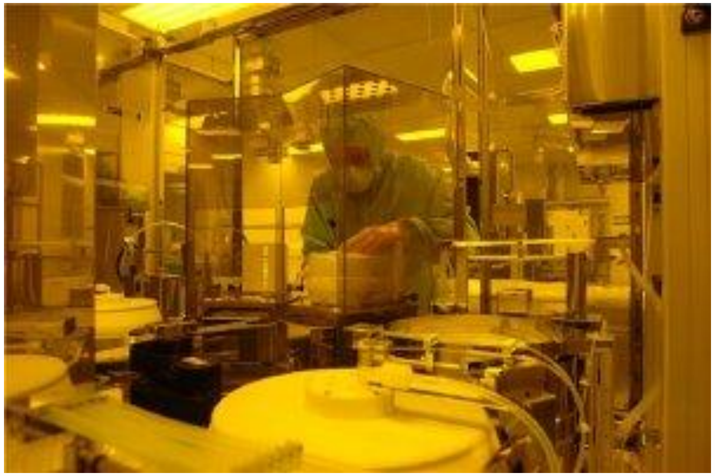
Research facilities



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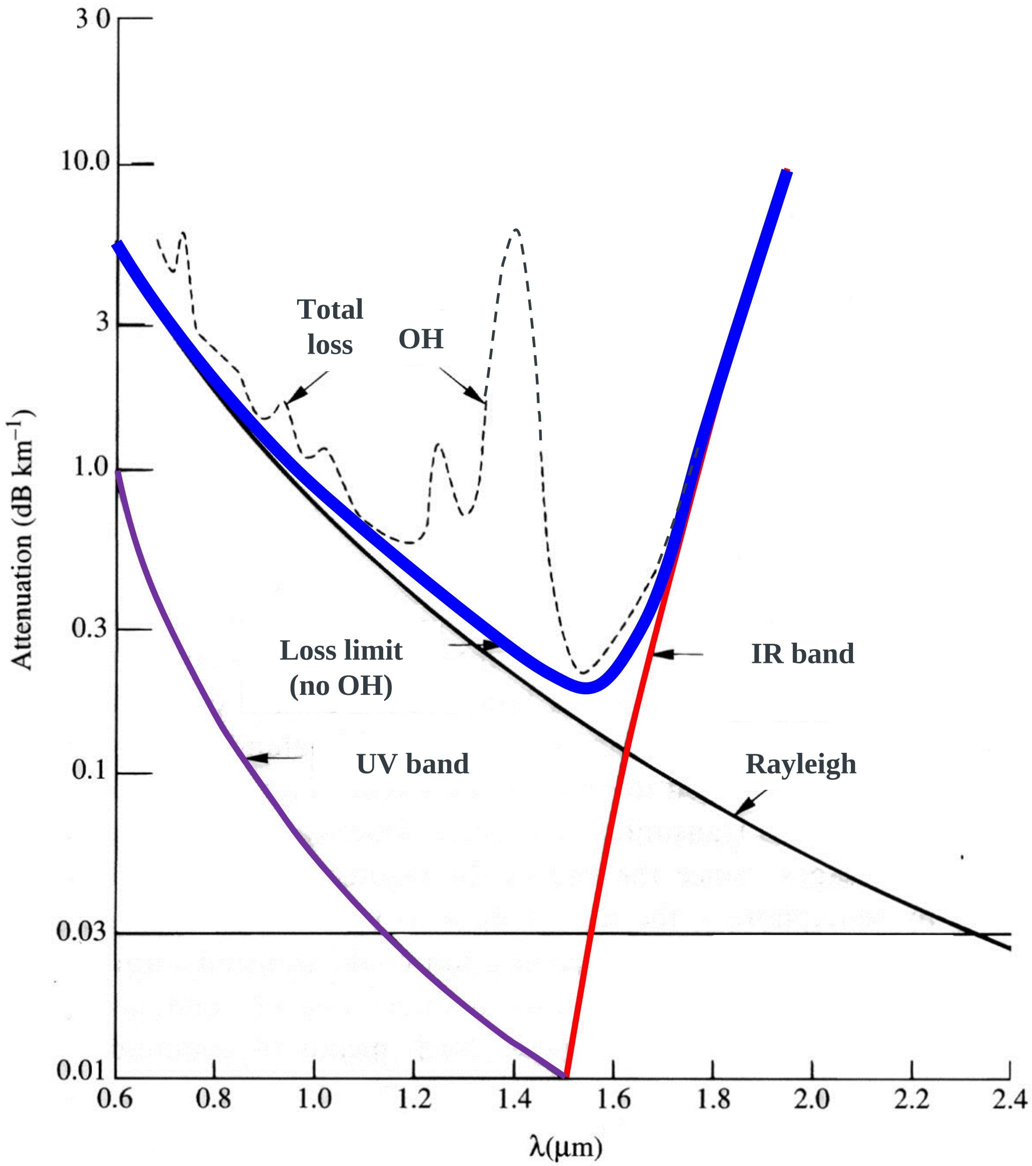
Outline

- Introduction
- $\chi^{(3)}$ nonlinear process
- Harmonic generation (up- and down- conversion)
- Resonators
- Conclusion

Introduction: optical fibre loss



Optical fibre lasers

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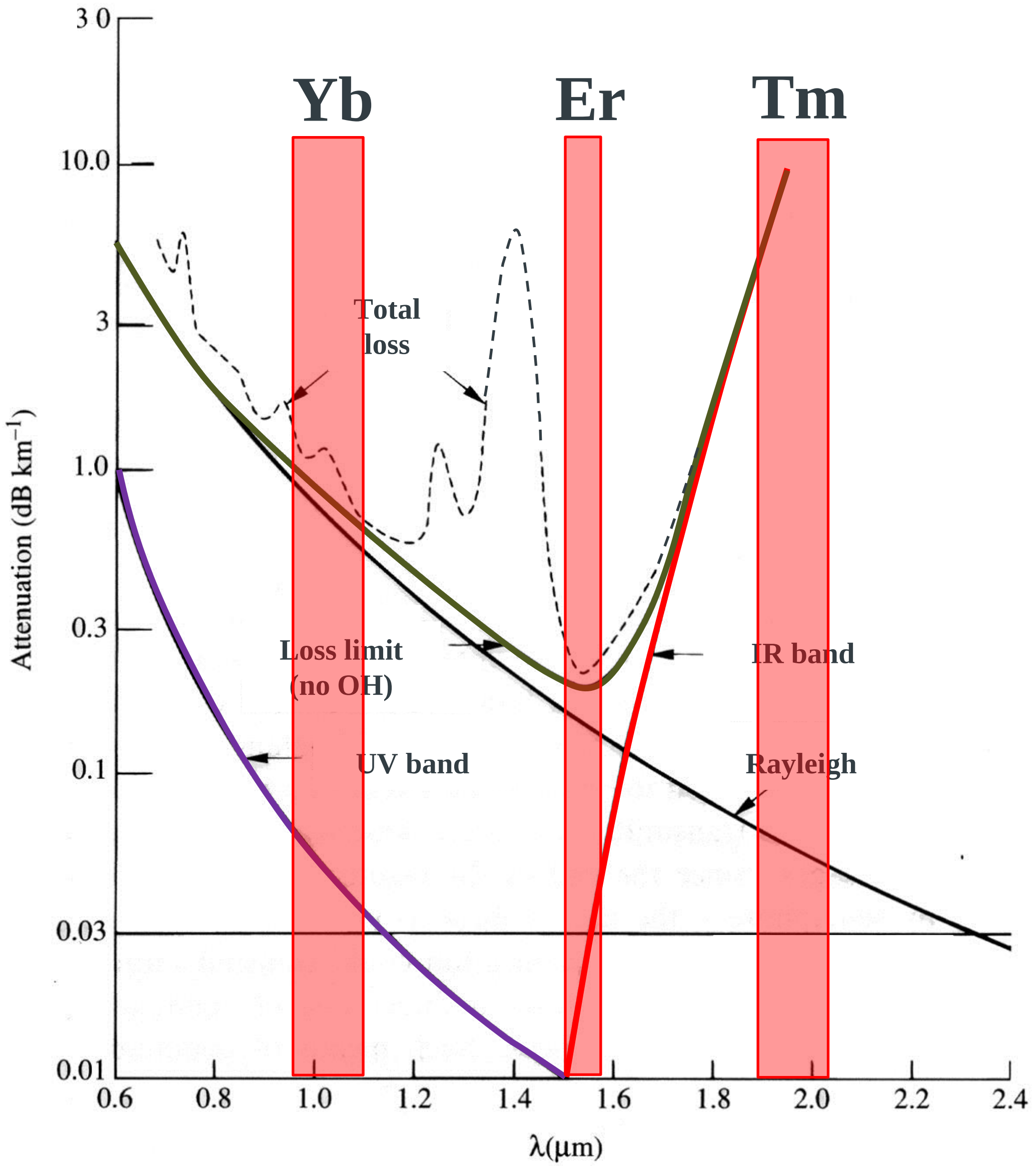

Introduction: optical fibre laser

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Advantages include:

- Efficient cooling: high surface to volume ratio
- Thus, no thermal lensing and high-quality optical beam: $M^2 \sim 1$
- High brightness
- High output power: active regions m long, thus very high optical gain
- Compact, reliable
- Light is already coupled into a flexible fibre

Optical fibre lasers

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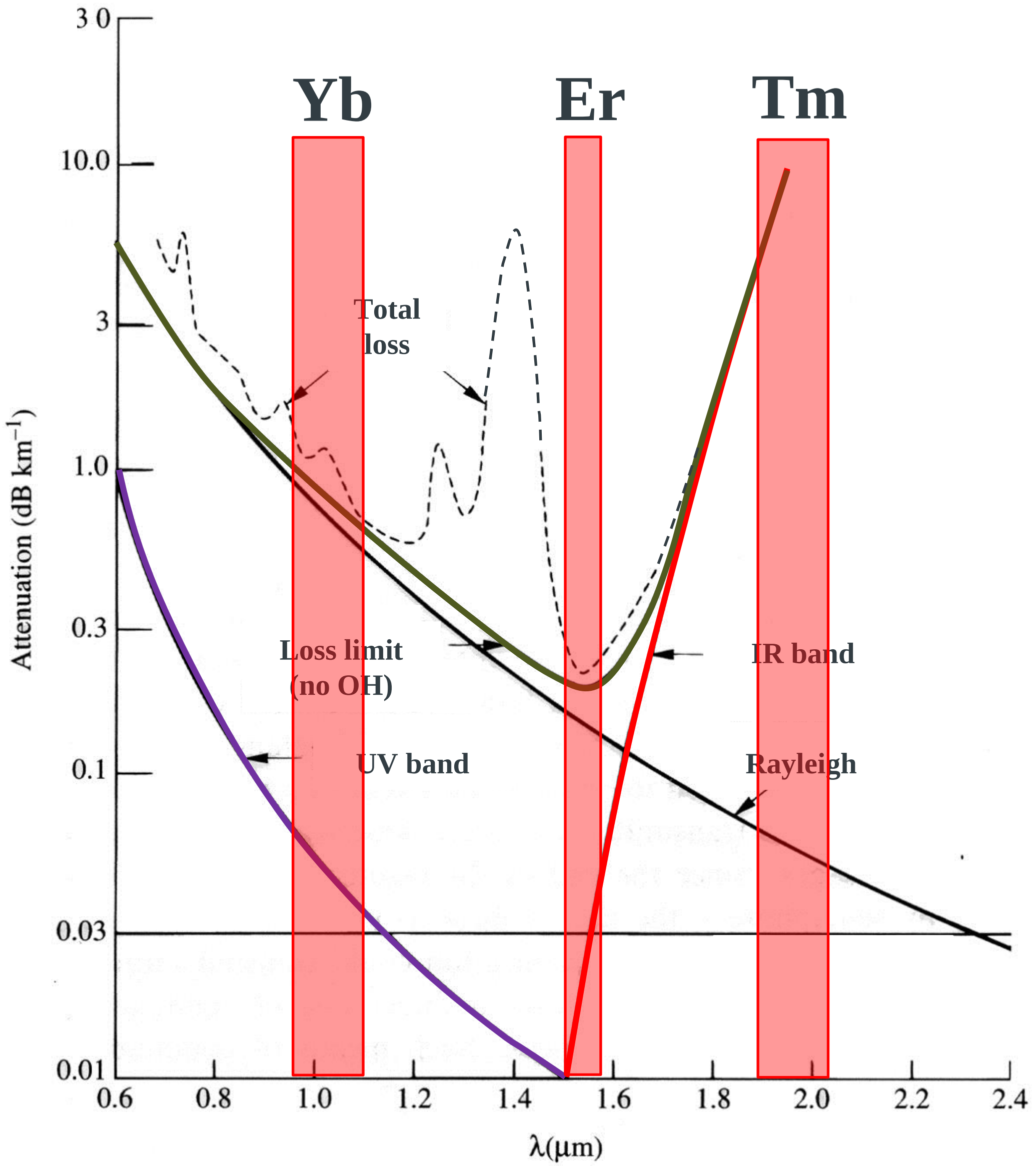
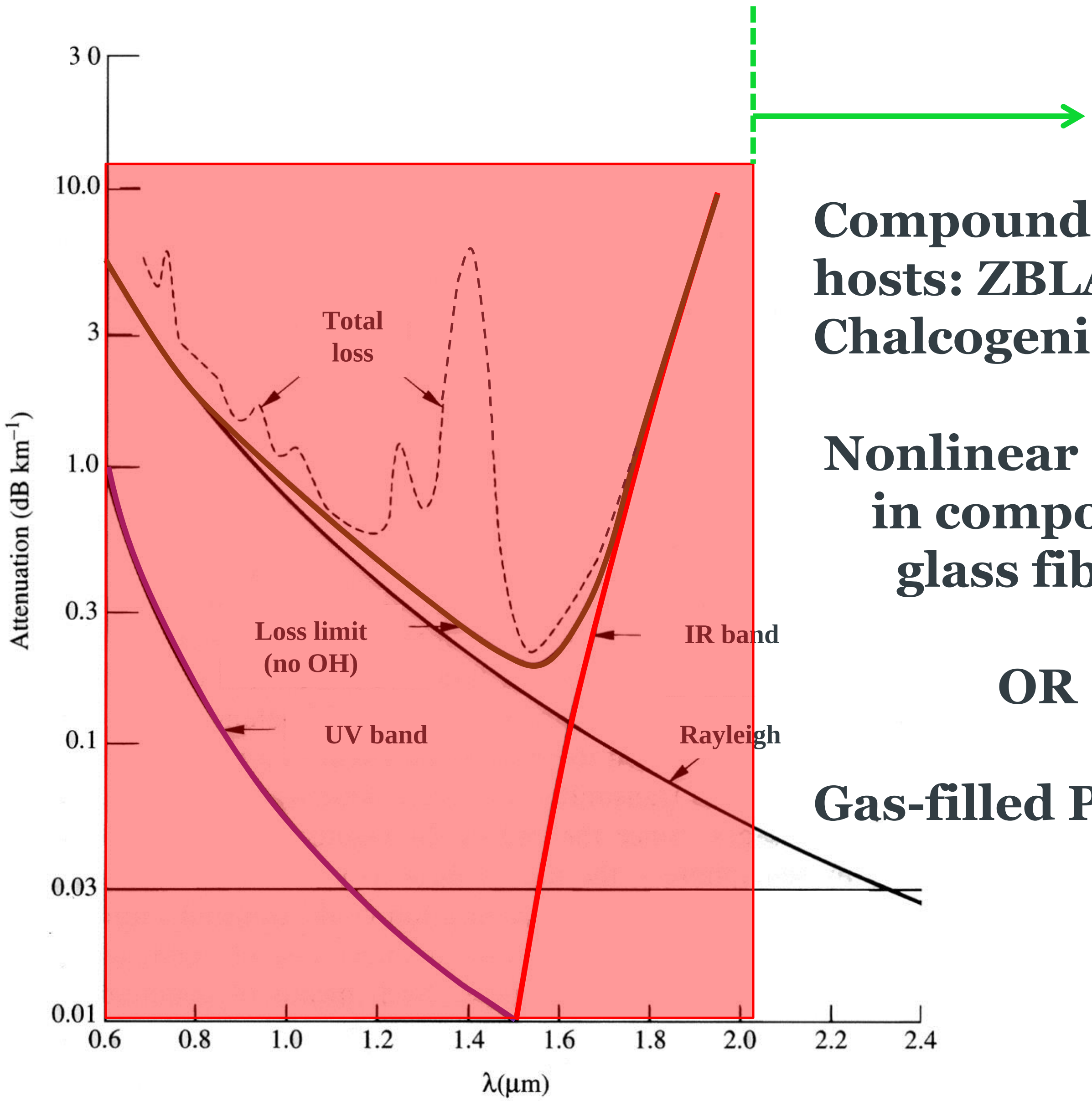


Optical fibre lasers



Compound glass hosts: ZBLAN, Chalcogenides

Nonlinear Optics in compound glass fibres

OR

Gas-filled PBGF

Laser applications

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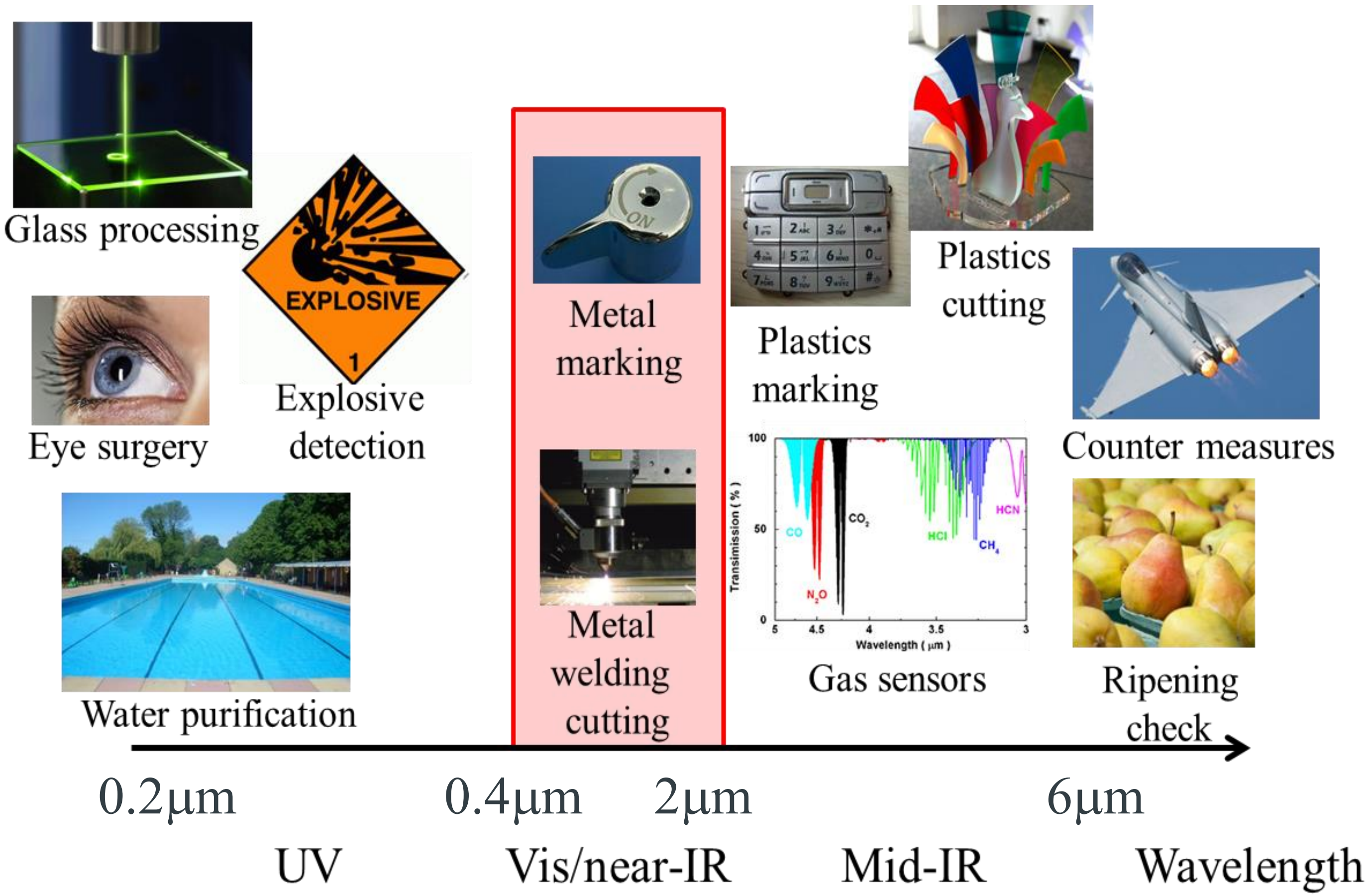

Silica loss: long λ

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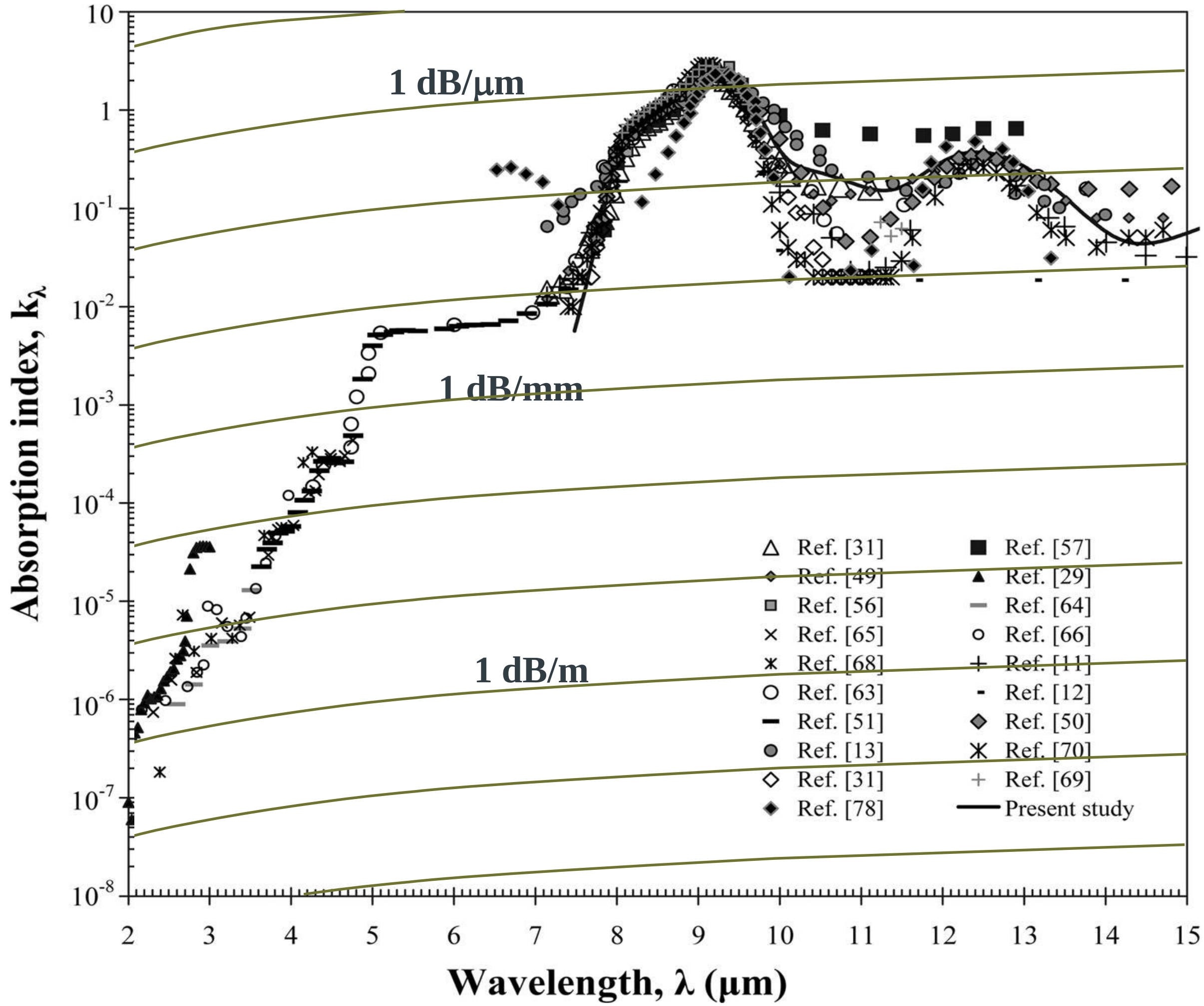

Kitamura, Appl. Opt 46(33),8118, 2007.

Silica loss: short λ

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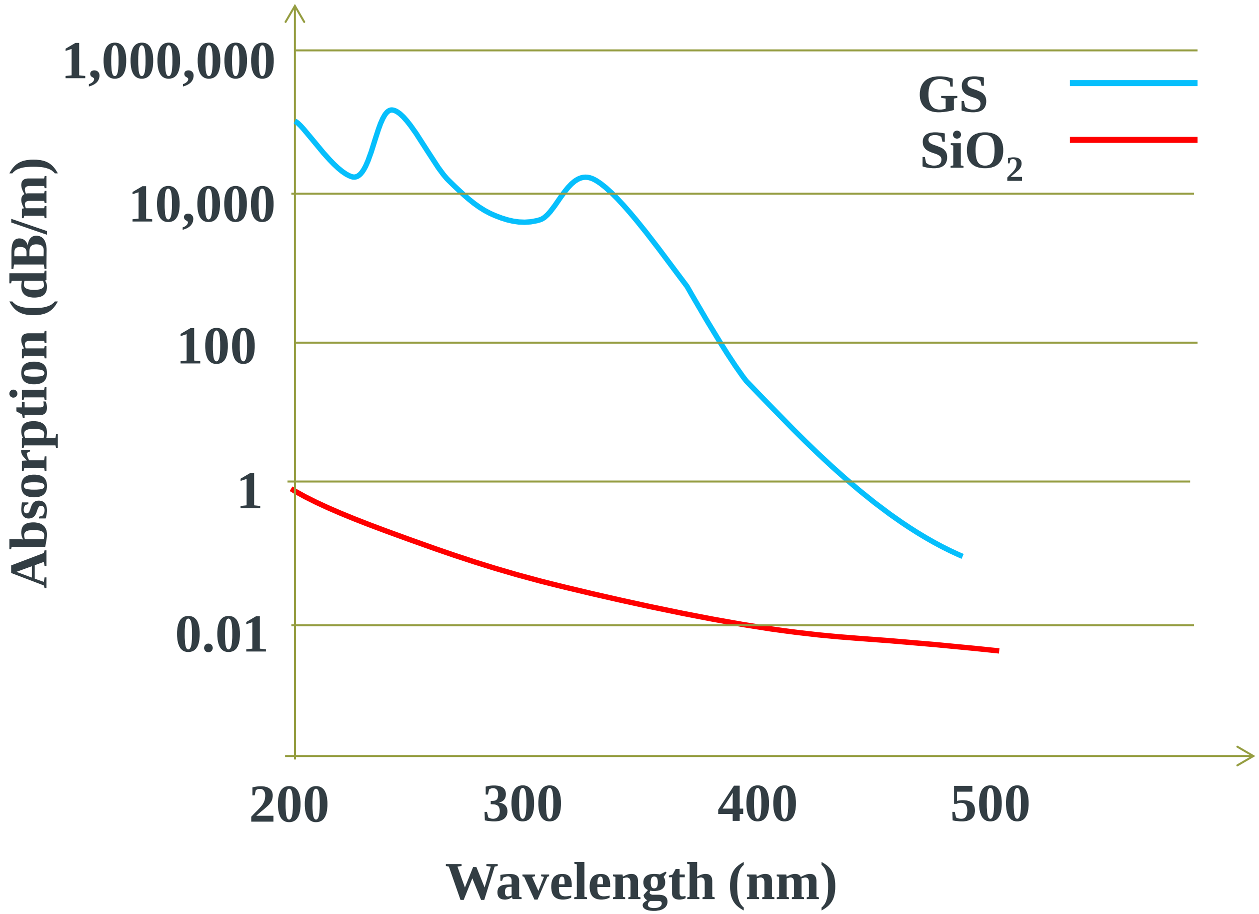
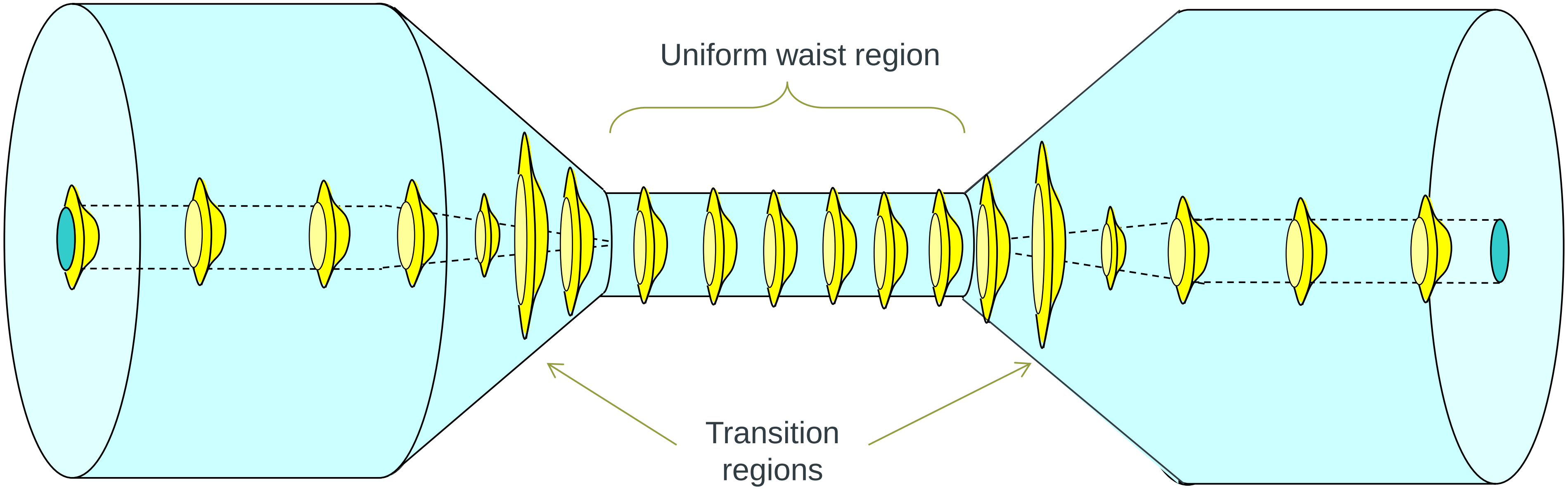


Nanofibers: Mode Propagation



Nonlinearity

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$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}}$$

Fiber Type	γ @1550nm
Standard SMF	1
Pure silica microfiber	~100
Lead Silicate microfiber (F2)	~1000
Bismuth Silicate microfiber	~6000
Chalcogenide microfiber	~100000

Strong confinement: Rayleigh length

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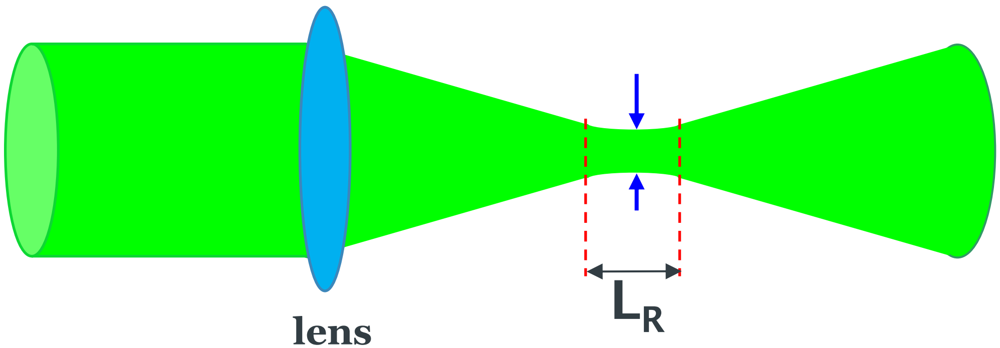
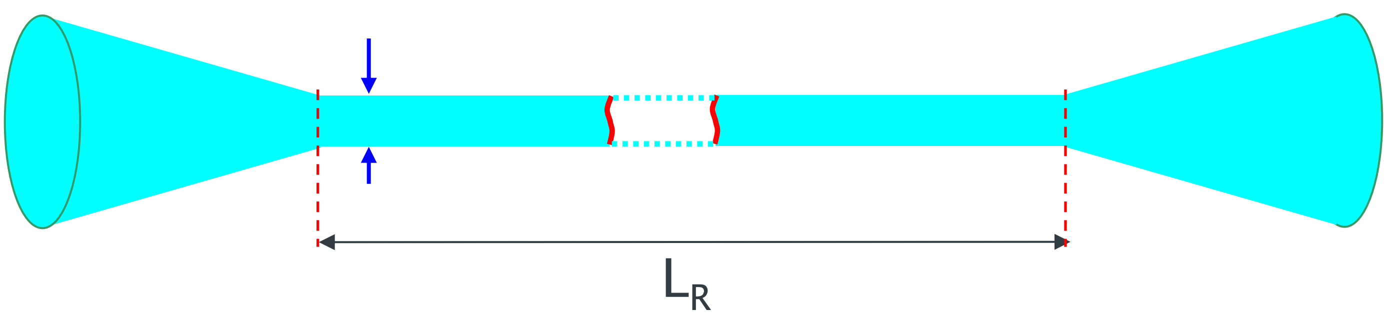
In free space, a Gaussian beam can be focused to the diffraction limit over the Rayleigh length L_r (few μm)



In OM: L_r limited only by loss



Nonlinearity

For low intensities, materials are assumed to have a linear response:

$$\mathbf{P} = \varepsilon_0 \chi^{(1)} \mathbf{E}$$

For high intensities, a dependence of polarization **P** on the electric field **E** strength is assumed:

$$\mathbf{P} = \varepsilon_0 \left[\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{EE} + \chi^{(3)} \vdots \mathbf{EEE} + \cdots \right]$$

~~SHG~~

~~$\mathbf{P}_{2\omega} \alpha \ \chi^{(2)} : \mathbf{EE}$~~

THG

$$\mathbf{P}_{3\omega} \alpha \ \chi^{(3)} \vdots \mathbf{EEE}$$

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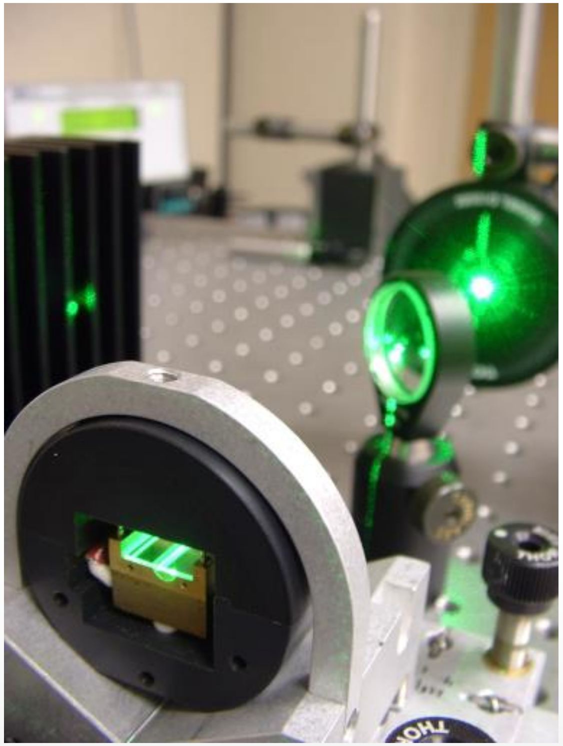
Third Harmonic Generation



- It uses $\chi^{(3)}$
- Pump is in the low loss wavelength region (500nm-2μm)
- Compatible with glass and fibre geometry.

One-third harmonic generation

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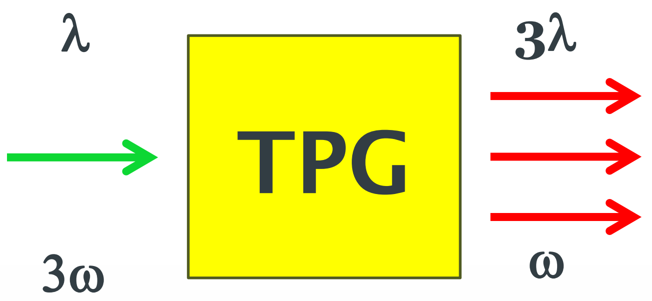
(Three Photon Generation)



- It uses $\chi^{(3)}$
- Pump is in the low loss wavelength region (500nm-2μm)
- Compatible with glass and fibre geometry.

OTHG/TPG: the big issue

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- THG has considerable pump (λ) at output
- THG and TPG would have comparable efficiency if input in TPG was the same as output at THG
- TPG does NOT have any signal at (3λ) at input
- TPG uses spontaneous photon generation from vacuum
- TPG generates 10 photons per W·m·s, but entangled.
- THG generates ~10^{17} photons per W·m·s.

THG - TPG

Third Harmonic / Three photon Generation

- Phase matching

  $\Delta\beta = \beta(3\omega) - 3\beta(\omega) \approx 0,$

  or $n_{eff}\,(2\pi/\lambda) = n_{eff}\,(2\pi/3\lambda)$

- High overlap between pump and third harmonic mode

Phase matching

n_{eff} depends

$$n_{eff} = \frac{\int_0^{2\pi}\int_0^{\infty} n(r,\vartheta) I(r,\vartheta)\, dr\, d\vartheta}{\int_0^{2\pi}\int_0^{\infty} I(r,\vartheta)\, dr\, d\vartheta}$$

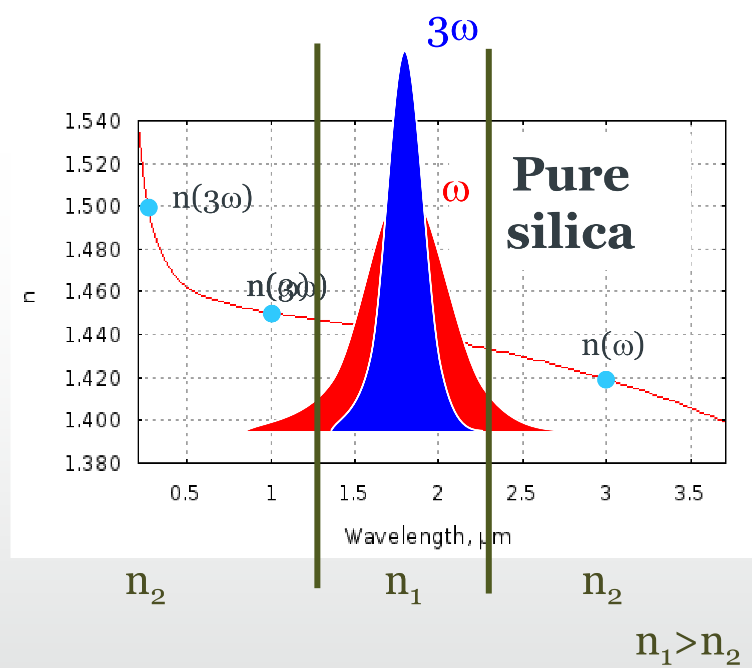
- Material dispersion

  $n_{eff}(3\omega) » n_{eff}(\omega)$

- Mode confinement

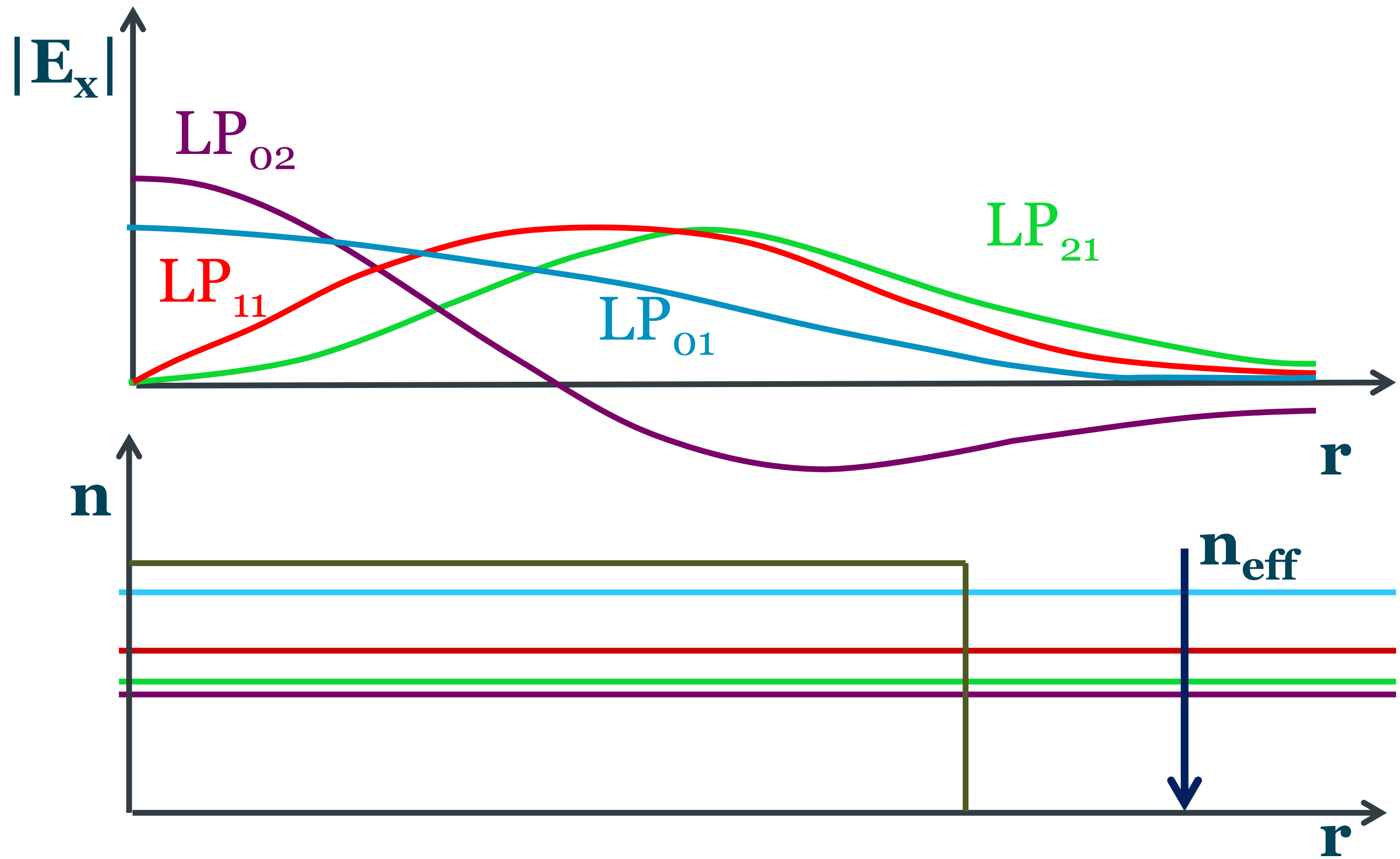
  for fundamental mode

  $n_{eff}(3\omega) » n_{eff}(\omega)$



BUT n_{eff} decreases for mode order

THG: high order mode n_{eff}



High order modes extend further in the low n medium they have a lower n_{eff}.

intermodal phase matching

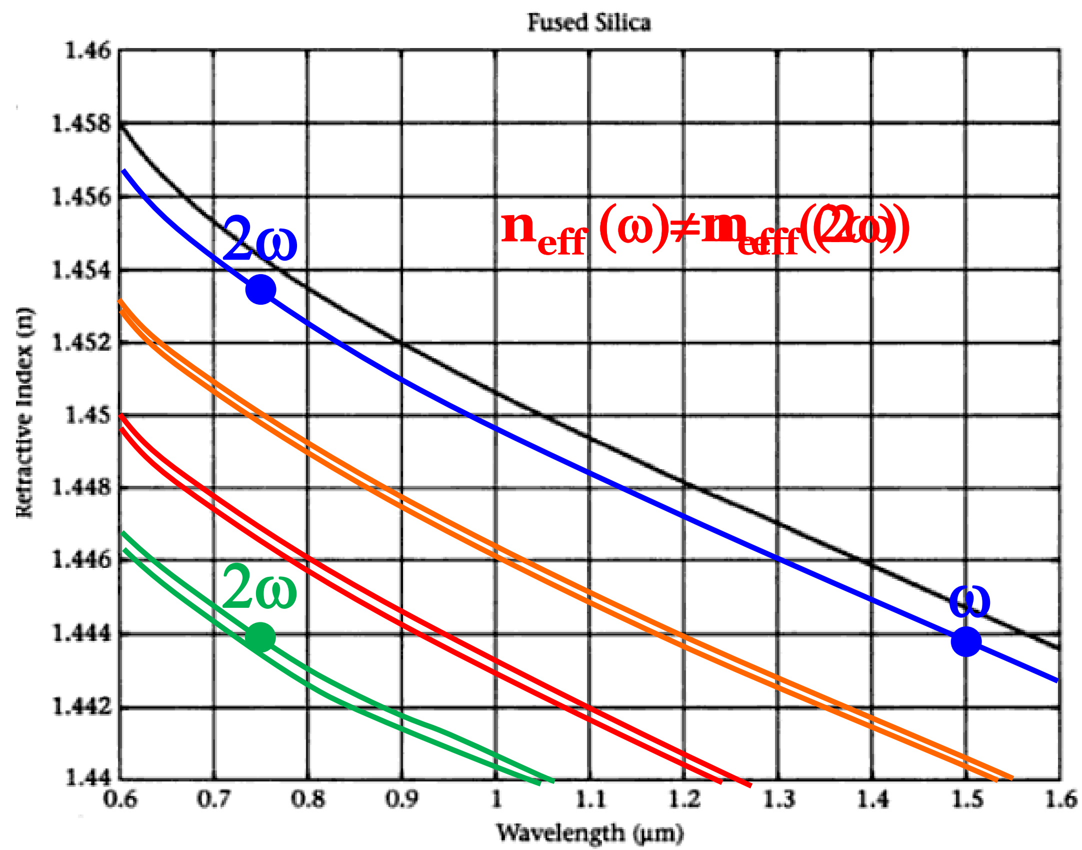
Grubsky, Opt. Lett., 2005

Intermodal Phase matching

Harmonic generation is efficient if

$\beta(\omega)=\beta(m\omega)$

or $n_{eff}\,(2\pi/\lambda)=n_{eff}\,(2\pi/m\lambda)$



Phase matching

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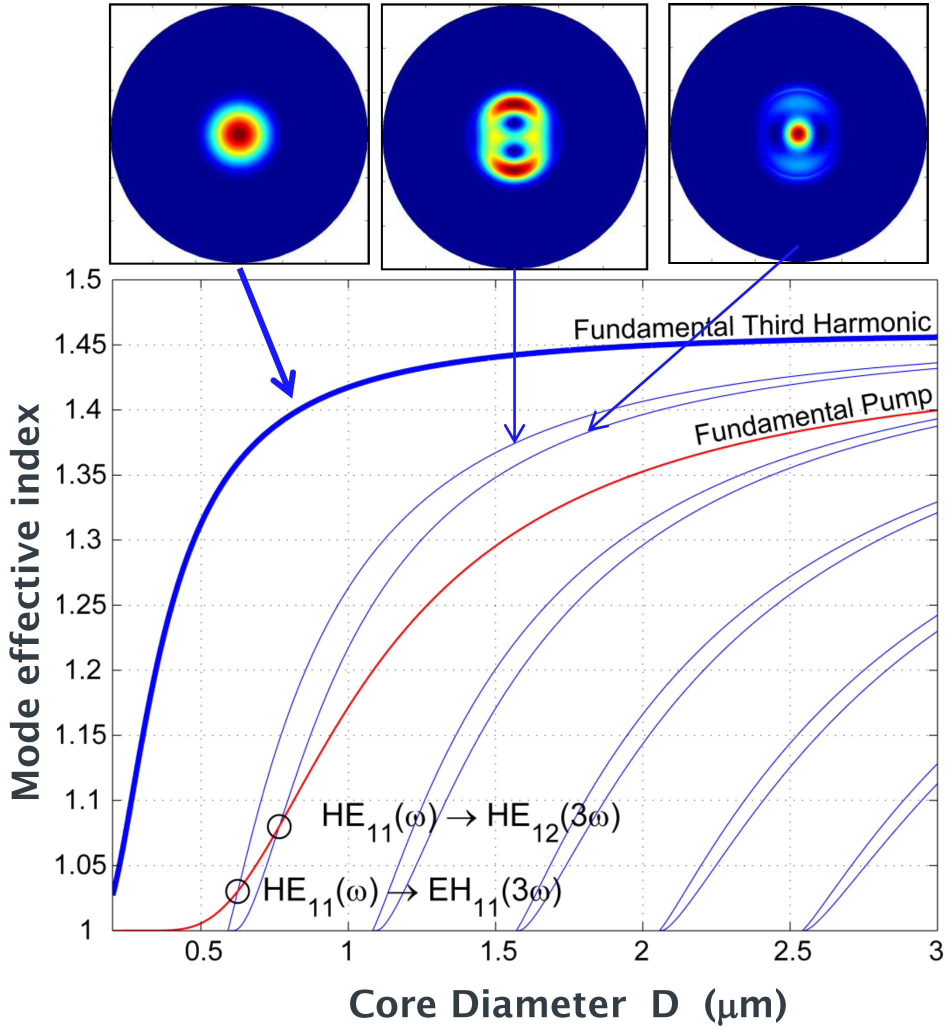
- Fundamental $HE_{11}(\omega)$ pump mode can be phase matched only to higher order third harmonic modes.

- For pump λ_p, critical diameters exist at $\sim\lambda_p/2$ for NA~1.



λ_p=1550nm

Phase matching

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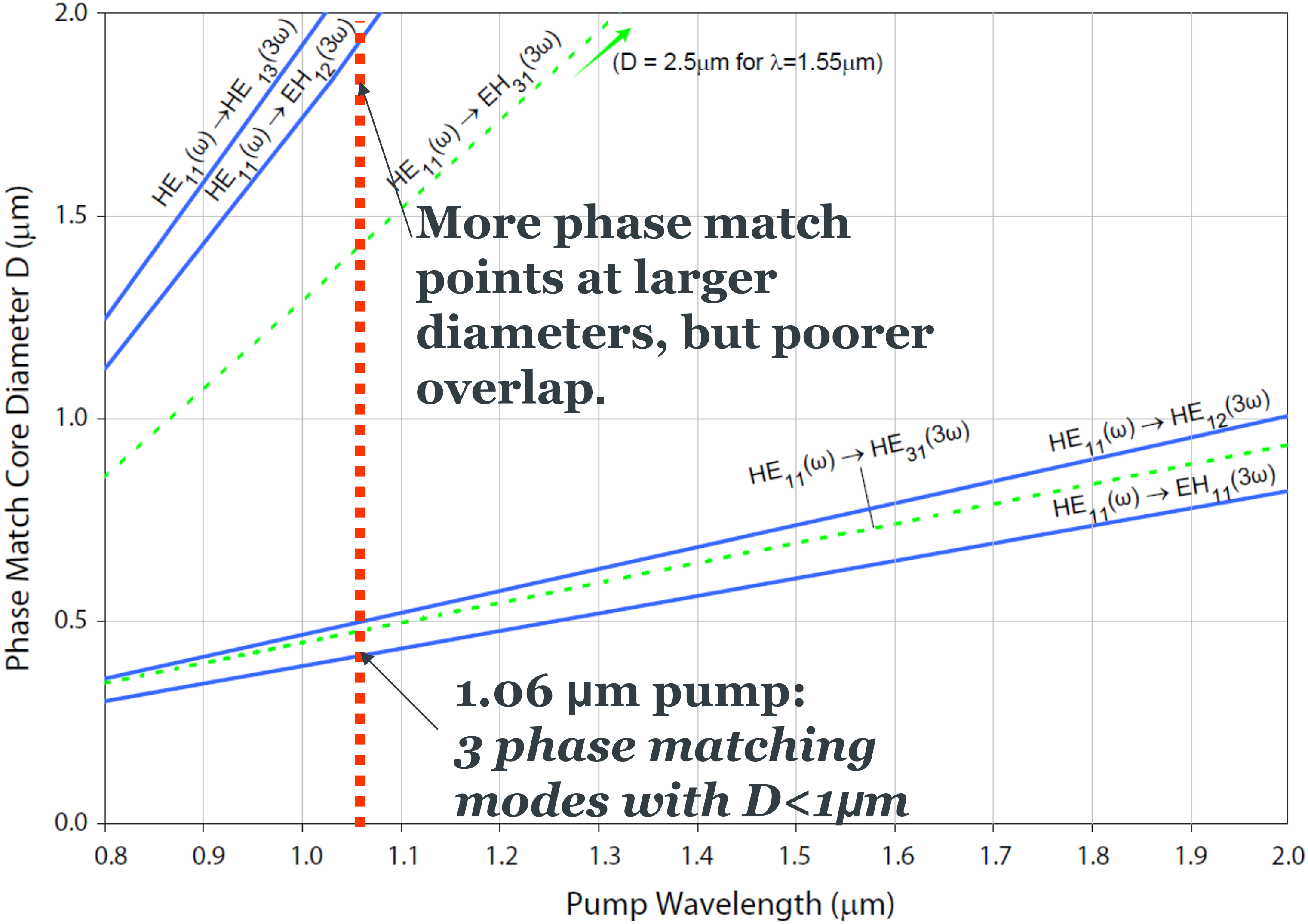
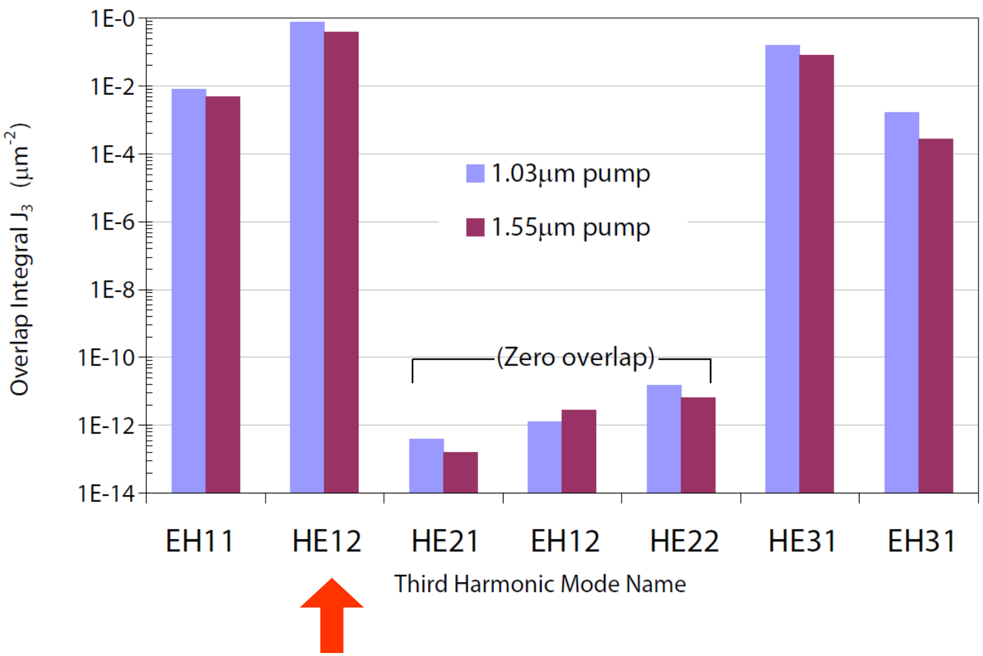
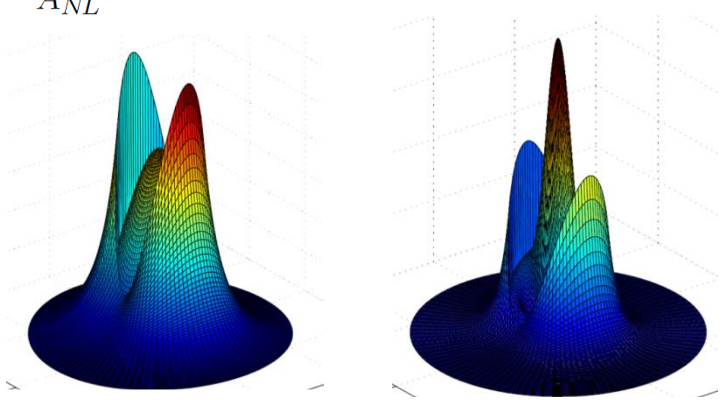


THG: Overlap

- Overlap between pump and TH mode governs efficiency.
- $HE_{12}(3\omega)$ overlap is greatest: 0.76 μm^{-2} for a 1.0 μm pump
- It increases for decreasing wavelengths (it is 0.38 μm^{-2} for 1.55 μm pump).
- Overlap is zero *TE*, *TM* and hybrid HE_{vm} EH_{vm} modes with even azimuthal mode order number *v*.



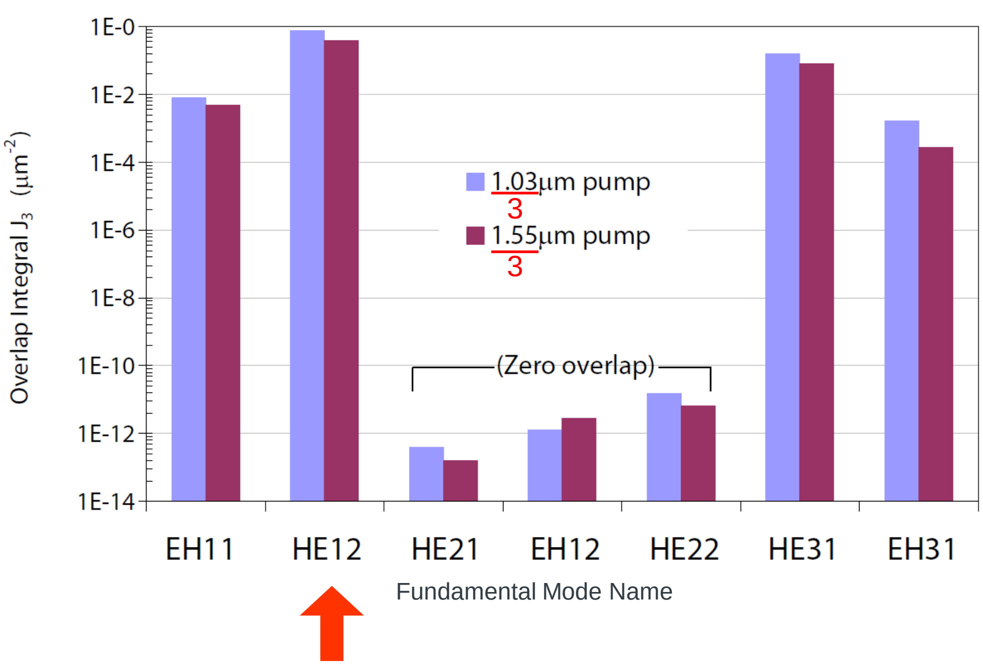
$$J_3 = \iint_{A_{NL}} \left((\boldsymbol{F}_1 . \boldsymbol{F}_3) |\boldsymbol{F}_1^*|^2 \right) dA$$



Pump $HE_{11}(\omega)$ ⟷ **Third Harmonic** $HE_{12}(3\omega)$

TPG: Overlap

- Overlap between pump and TP mode governs efficiency.
- $HE_{12}(\lambda)$ overlap is greatest.
- Pump is in high order mode!



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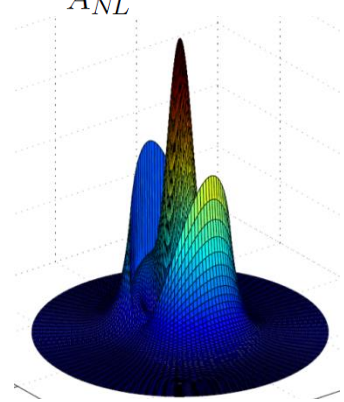

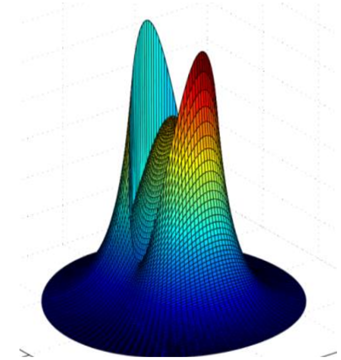

Pump ⟷ **Three photons**

$HE_{12}(\lambda)$ **$HE_{11}(3\lambda)$**

THG: experiment

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Taper

D = 0.78 μm,

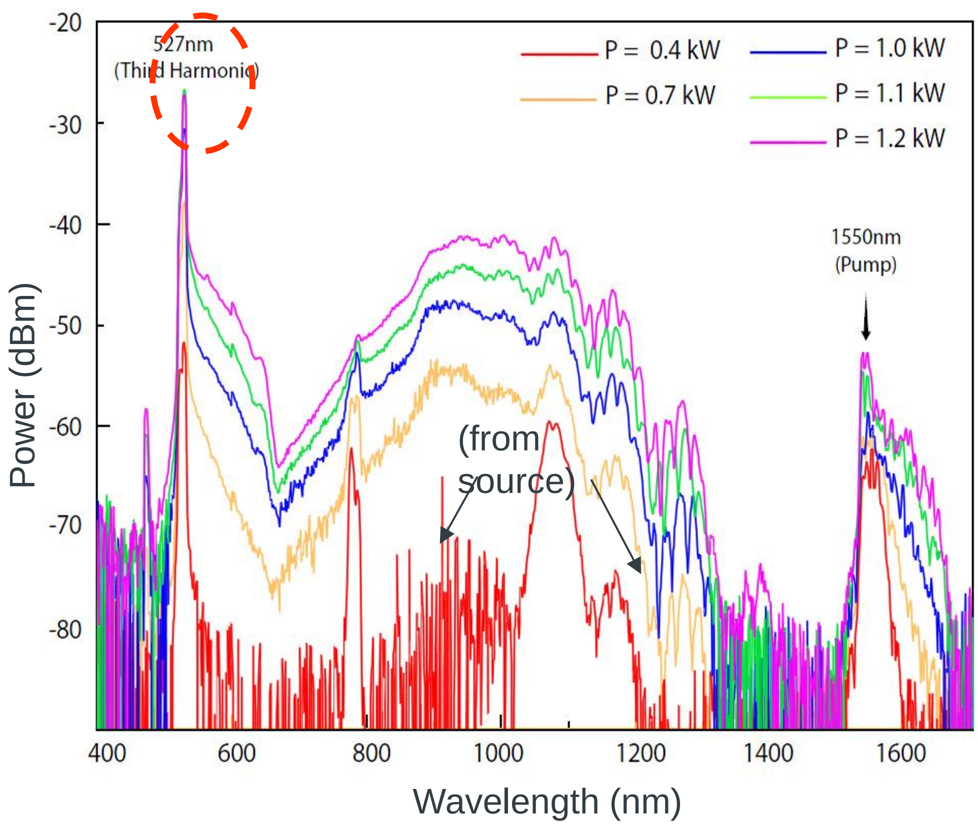
L ~200μm

- Diameter is closer to critical value.
- Peak at 527nm
- asymmetric TH spectrum.

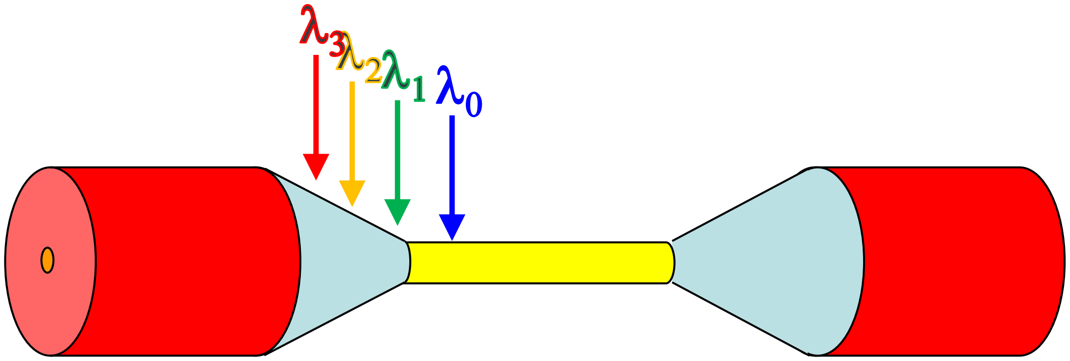
$\eta_{meas} \sim 10^{-3}$

$\eta_{th} = 2 \cdot 10^{-2}$

Spectrum recorded after shortpass filter:

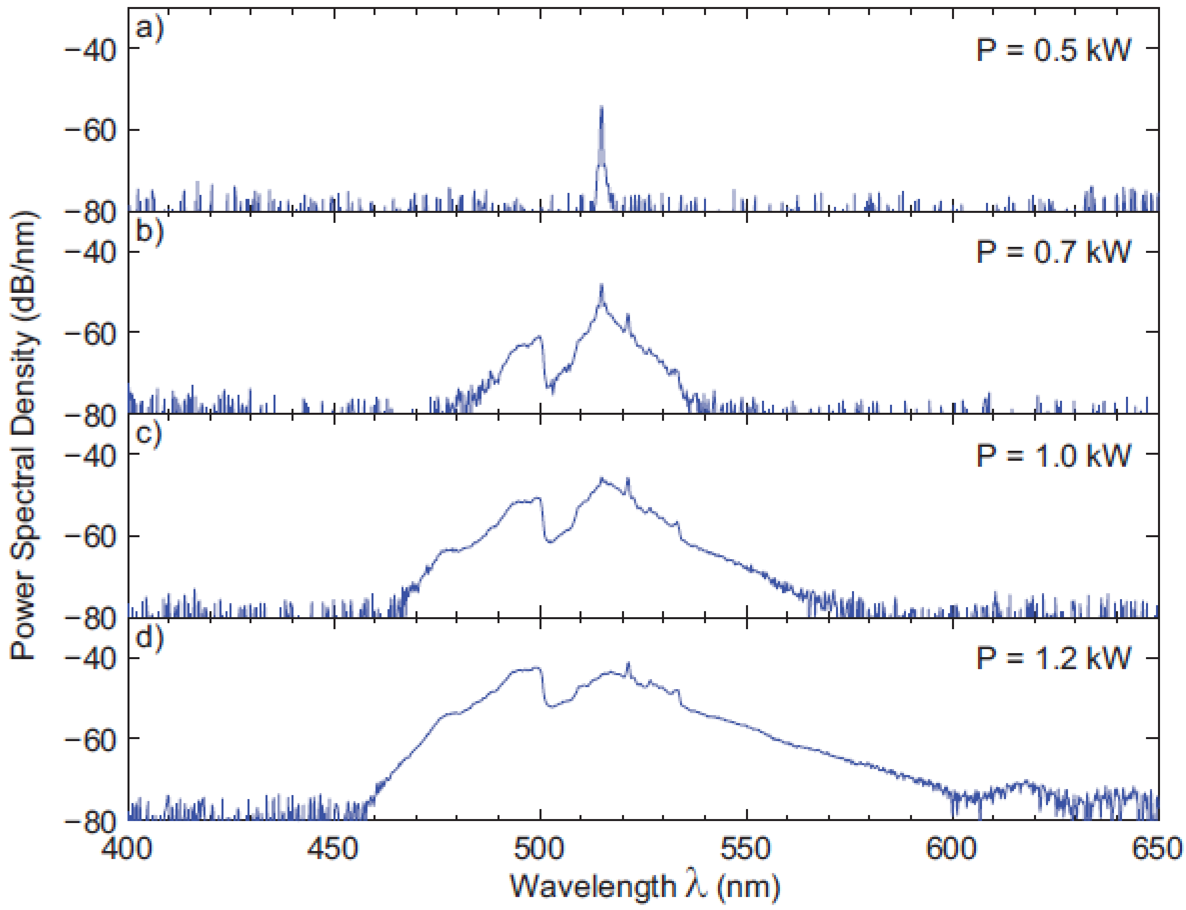


Broadband phase matching



Variable diameter ⟶ phase matching for different wavelengths

THG: broadband generation



THG: conversion efficiency

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- **THG differential equations:**

SPM XPM THG term with detuning

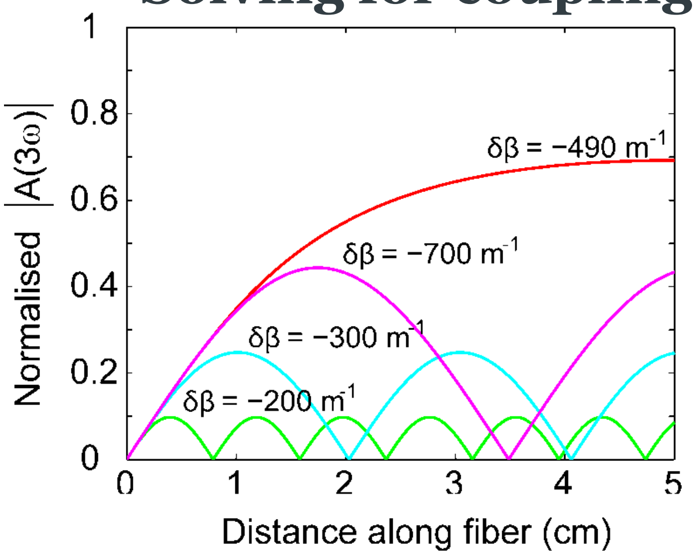
Pump:

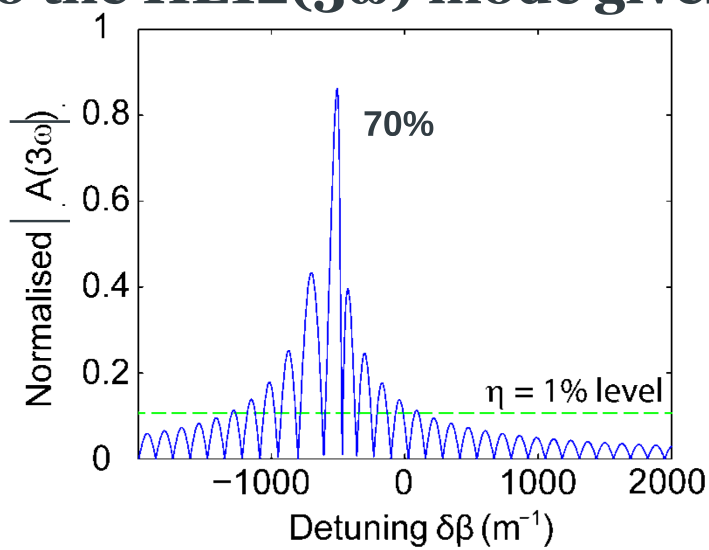
$$\frac{dA_1}{dz} = in^{(2)}k_1 \left\{ (J_1|A_1|^2 + 2J_2|A_3|^2)A_1 + J_3 A_1^{*2} A_3 e^{i\delta\beta z} \right\}$$

Third Harmonic:

$$\frac{dA_3}{dz} = in^{(2)}k_1 \left\{ (6J_2|A_1|^2 + 3J_5|A_3|^2)A_3 + J_3^* A_1^3 e^{-i\delta\beta z} \right\}$$

- **Solving for coupling to the HE12(3ω) mode gives:**





Parameters:

- **Length 5cm**
- **Diameter 0.77µm**
- **P_{in} = 1kW**

UV conversion efficiency: theory

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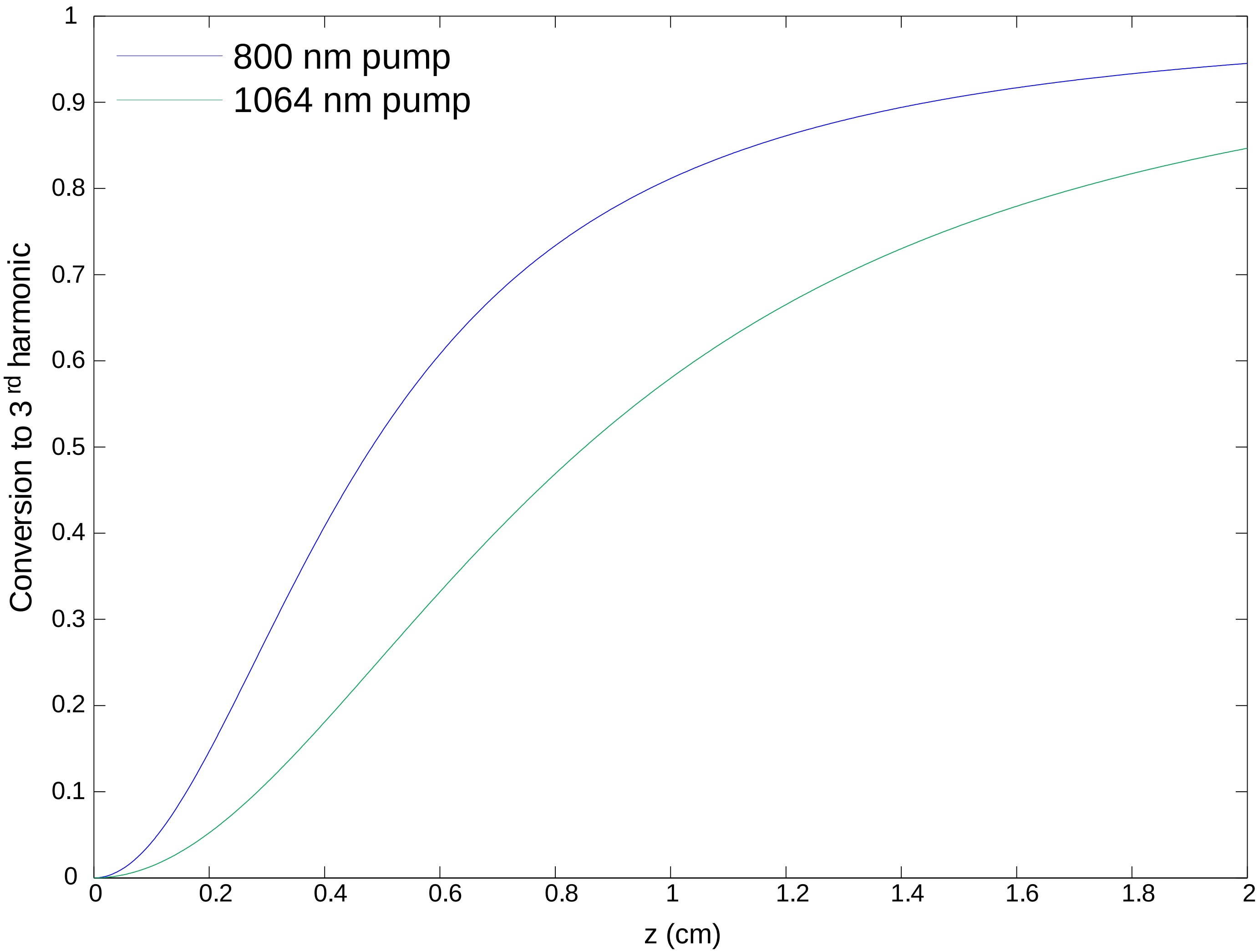
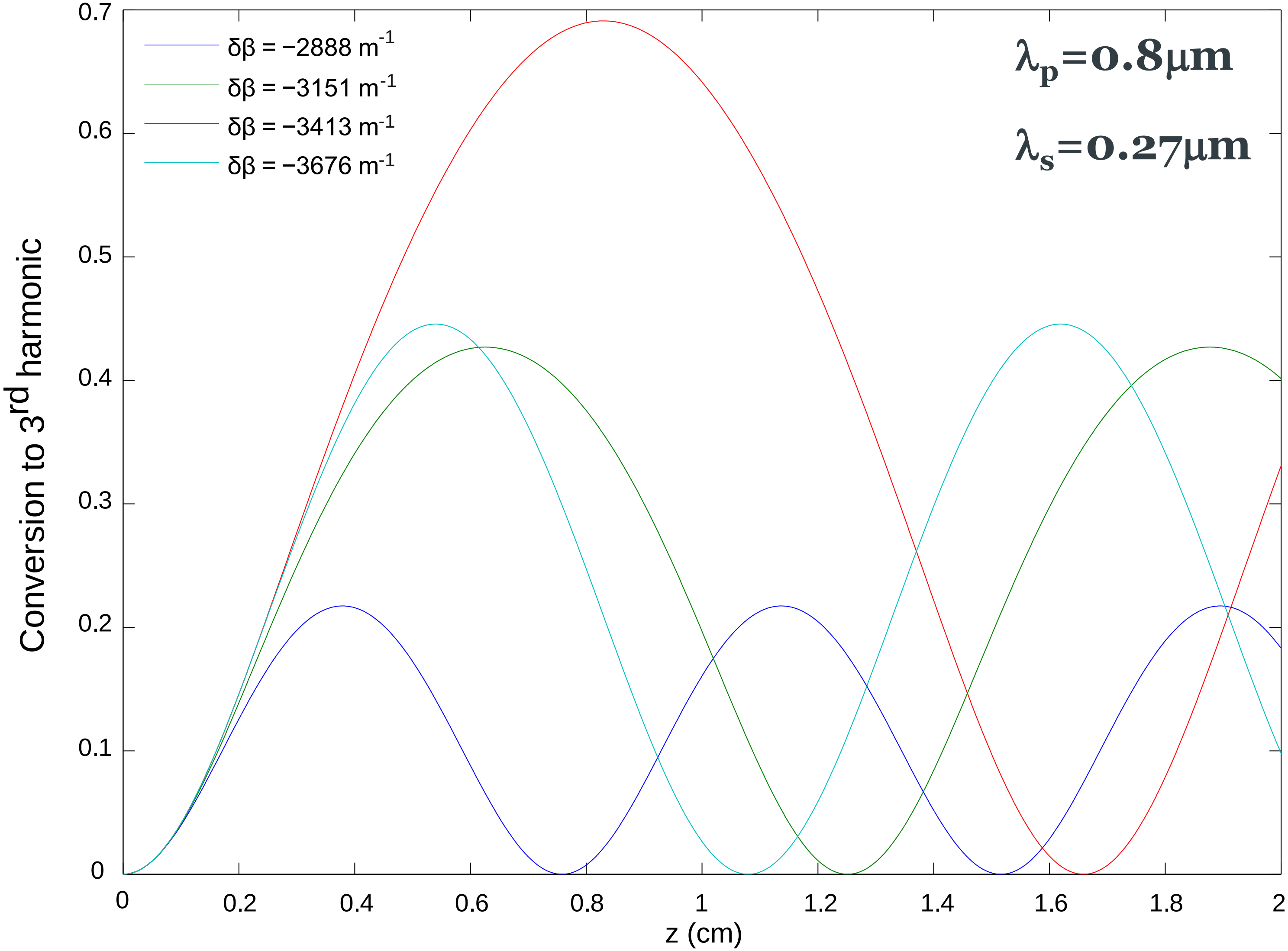


THG: detuning



THG: Effect of loss

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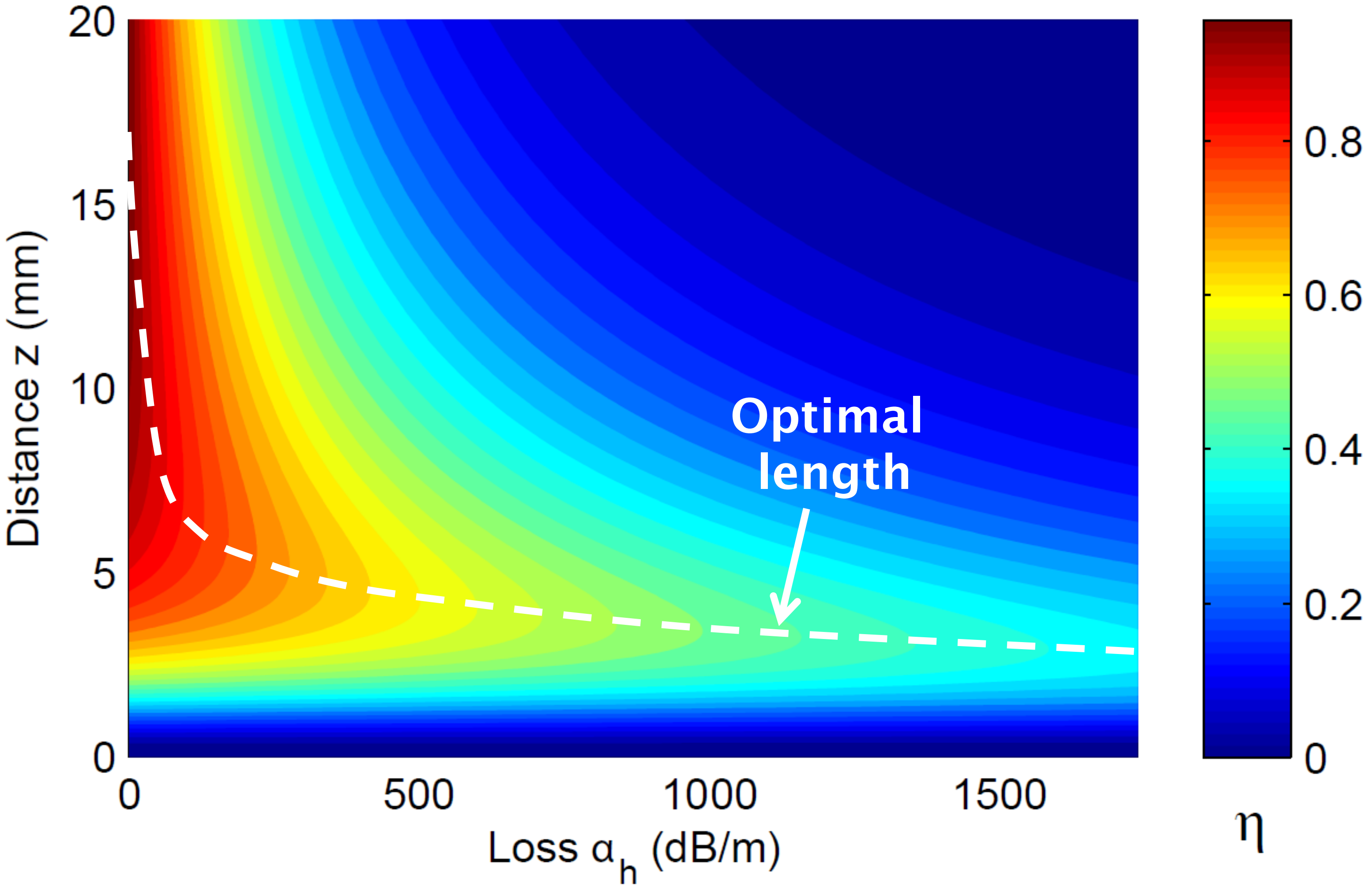

UV conversion efficiency: theory

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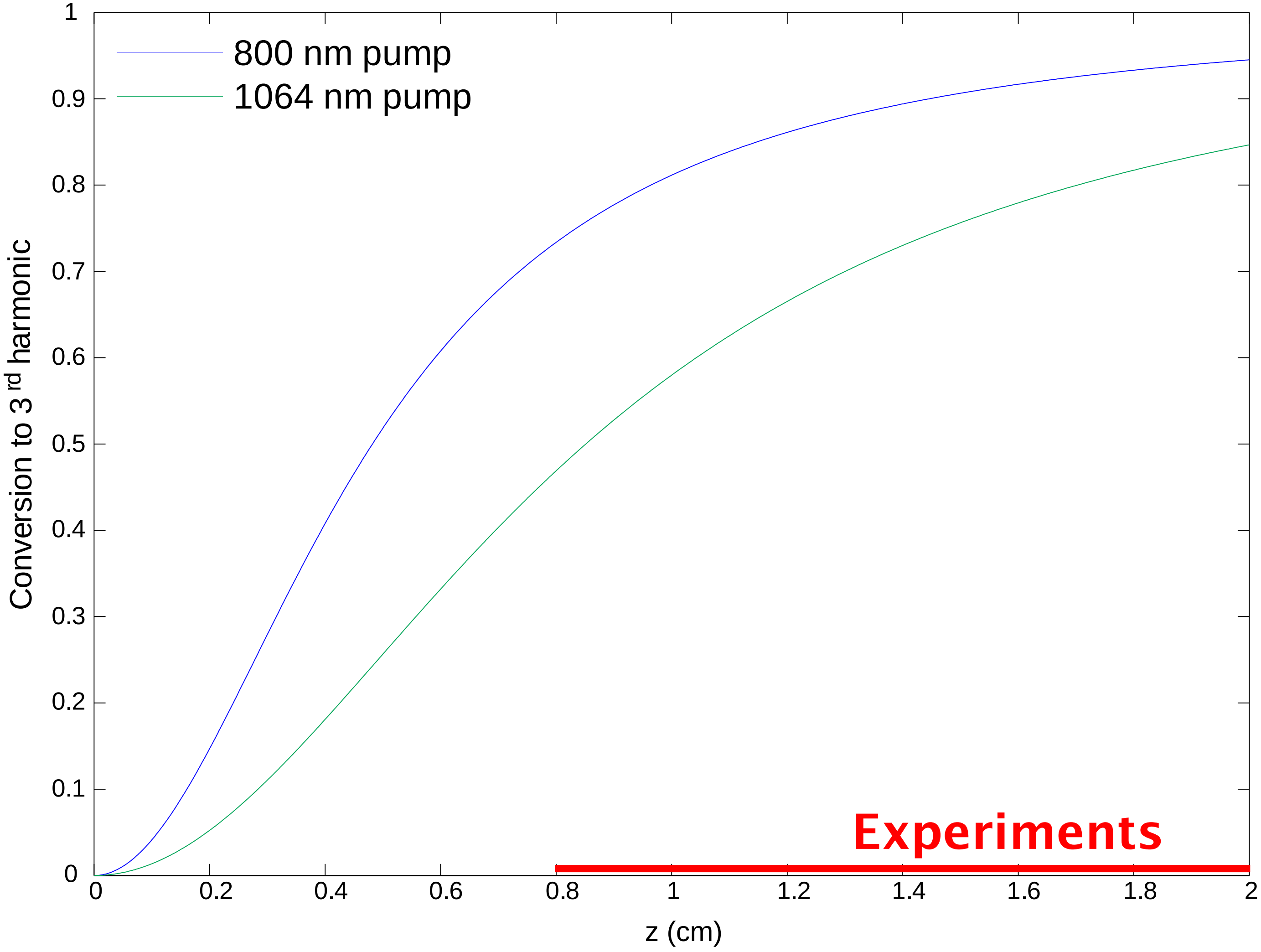

Towards higher efficiencies

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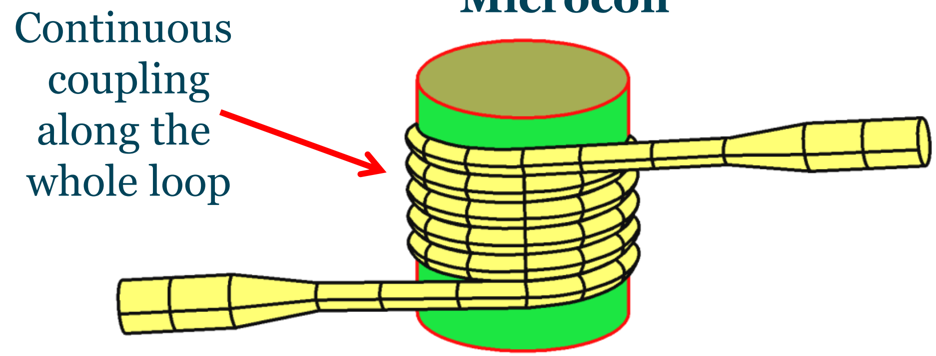
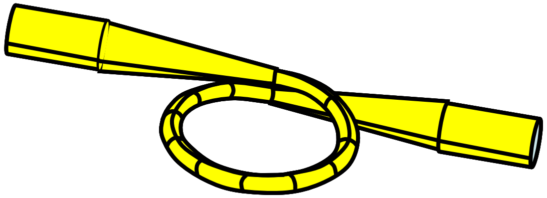
Resonators

- Extremely high Q-factors (10^9 predicted)
- Compact
- Robust/Portable

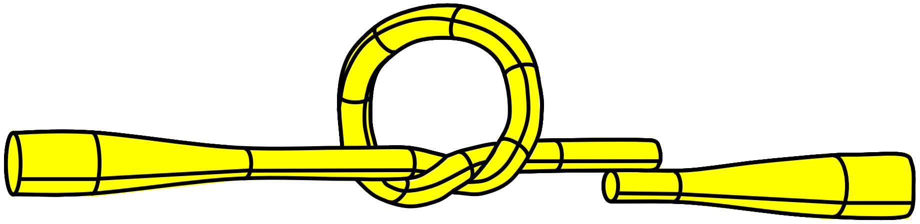
Microcoil



Loop



Knot



F. Xu, J. Lightwave Technology 25 (6), 1561-1567, 42, 2007.

THG: resonant effects

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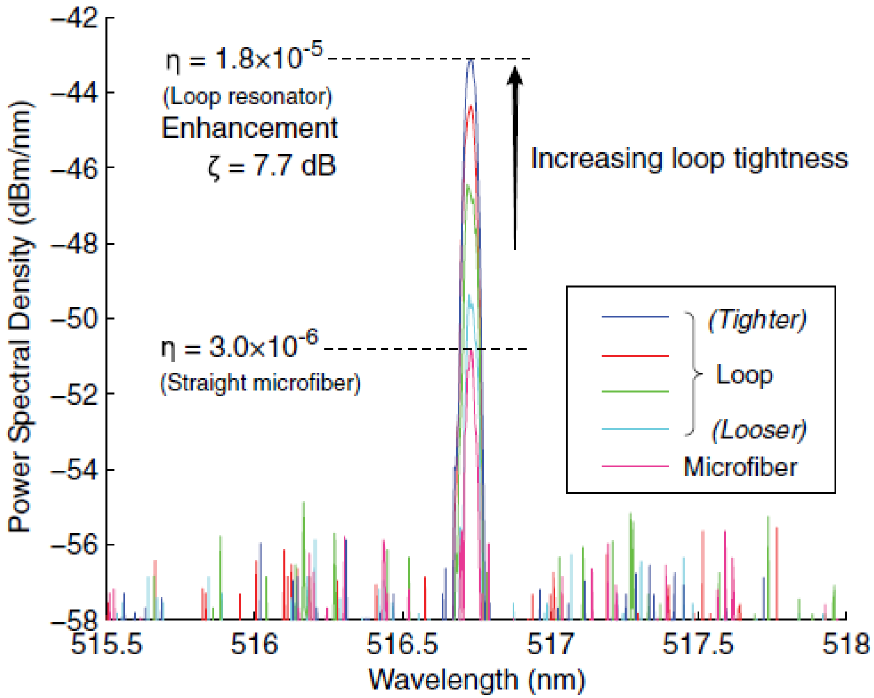

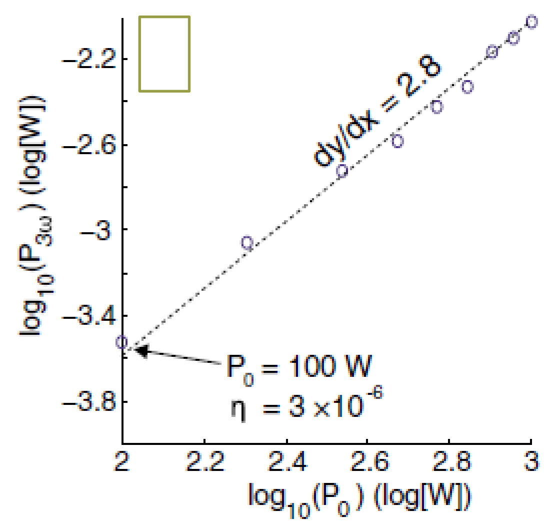

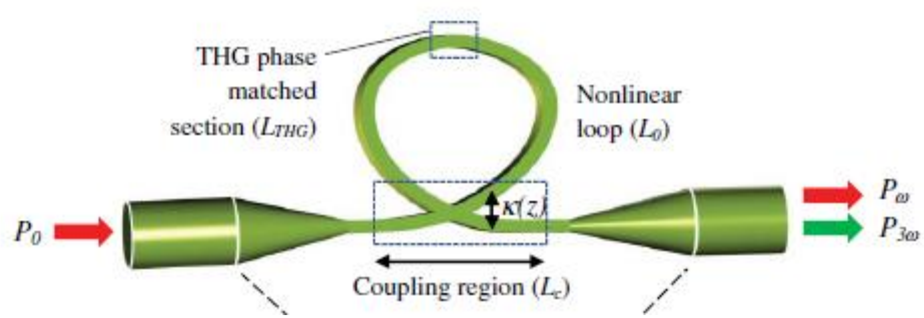

THG: experiment

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Taper

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L ~200µm

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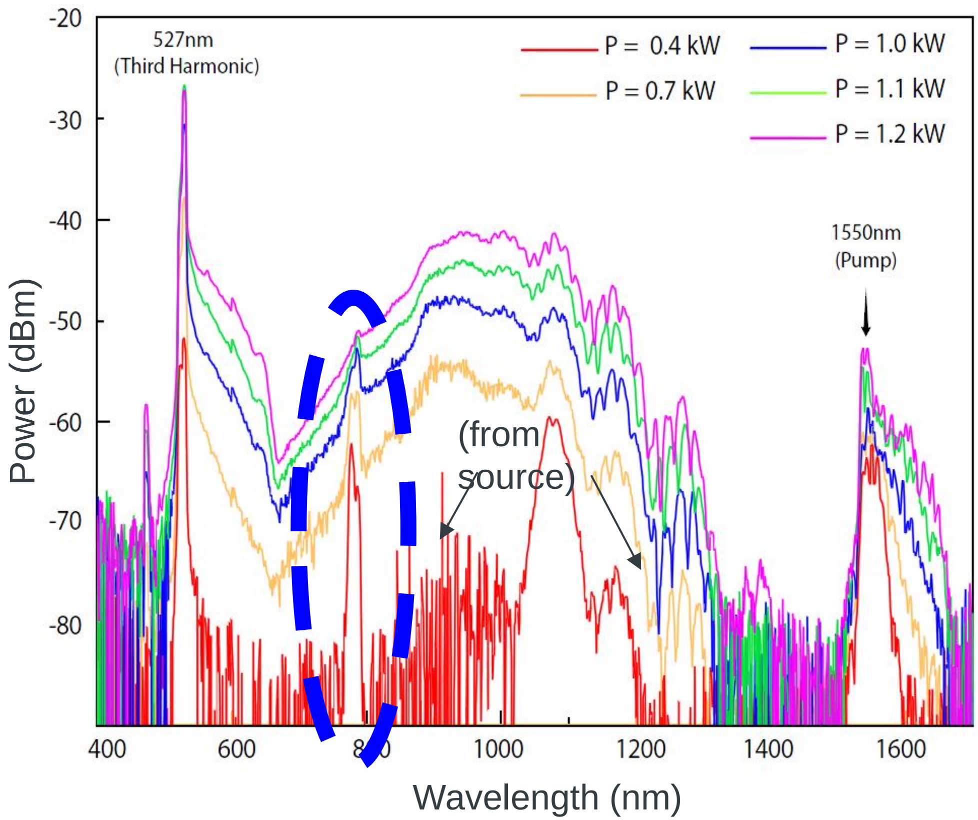
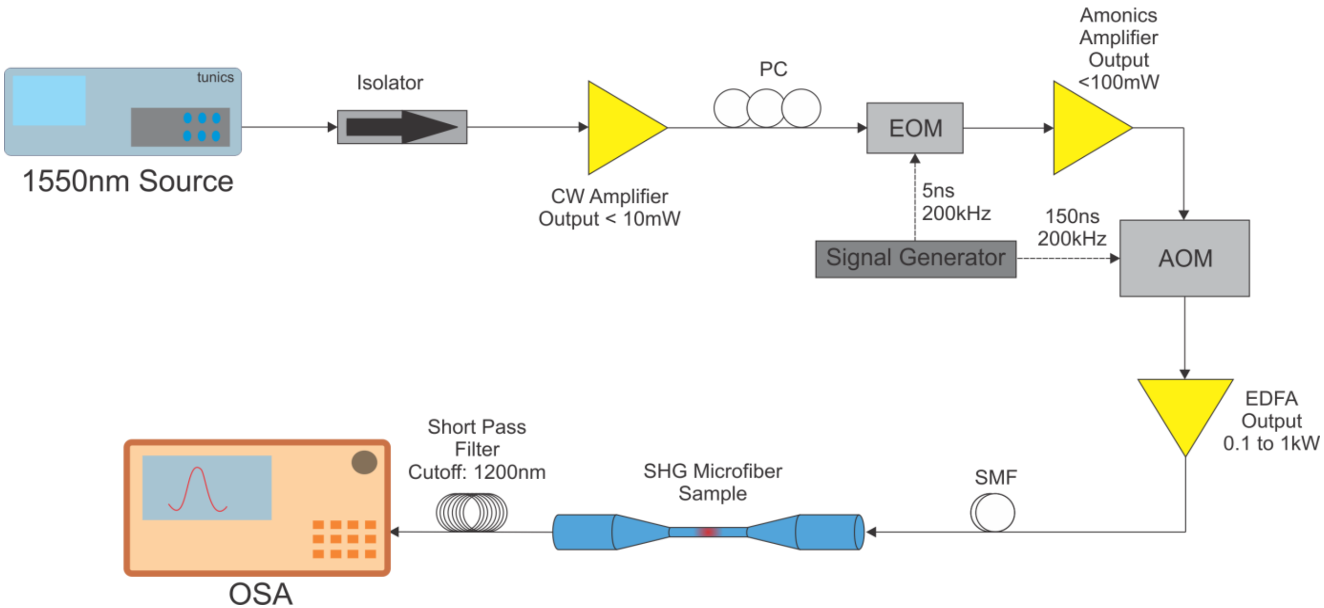
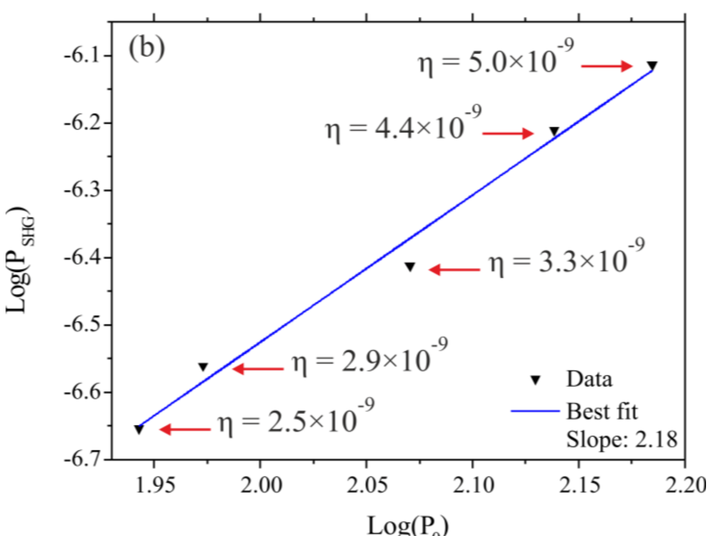
Spectrum recorded after shortpass filter:



Second harmonic generation





Gouveia, Appl. Phys. Lett. 102 (2013) 201120

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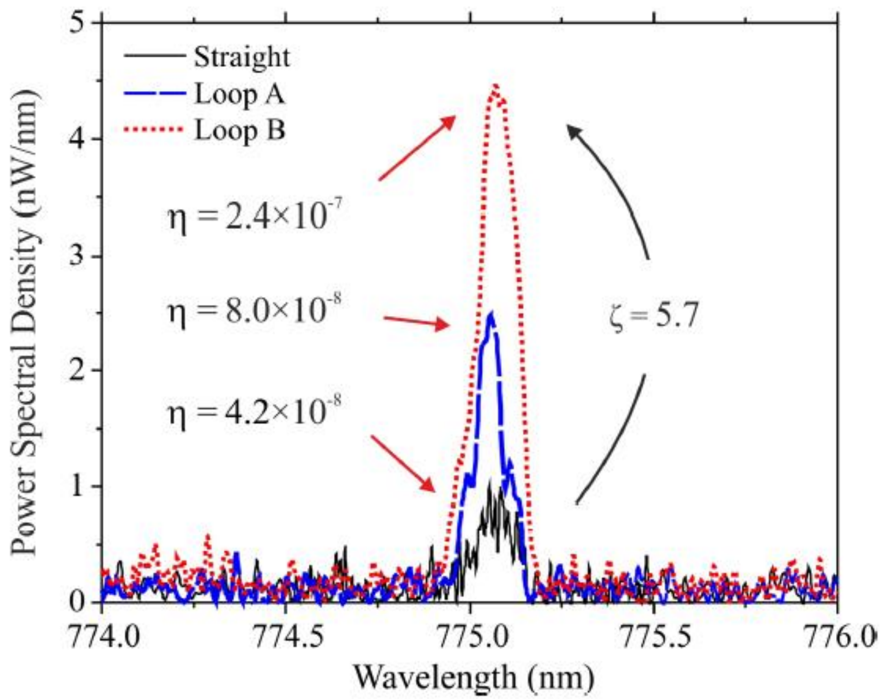
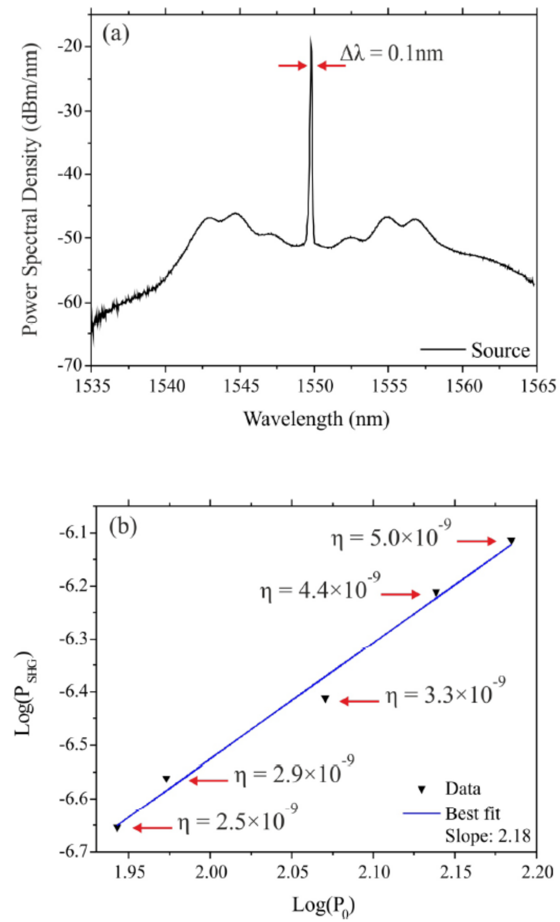
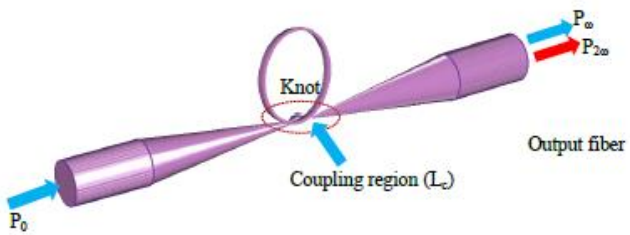
SHG: resonant effects





no $\chi^{(2)}$!



Gouveia, Appl. Phys. Lett. 102 (2013) 201120

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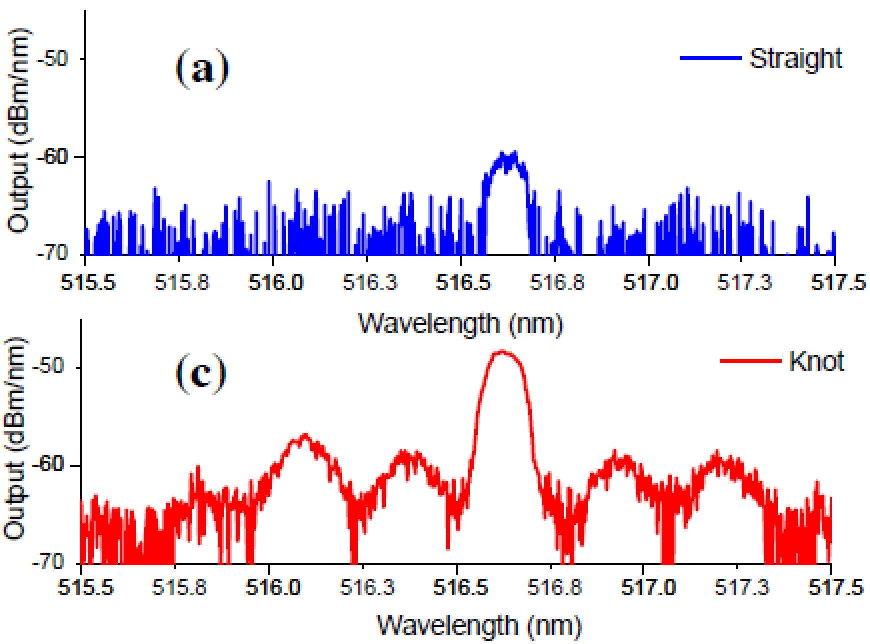
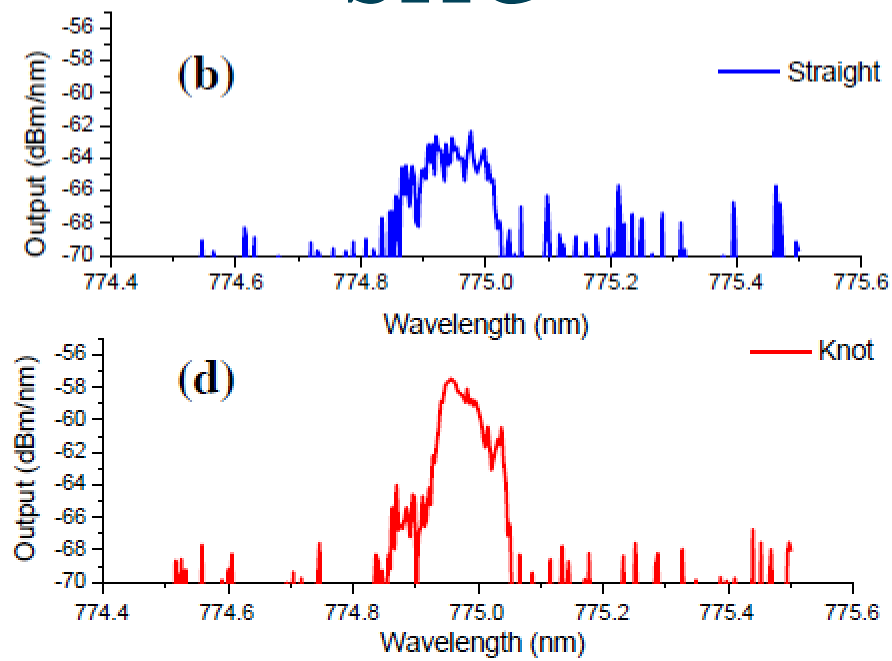
SHG and THG: resonant effects

THG

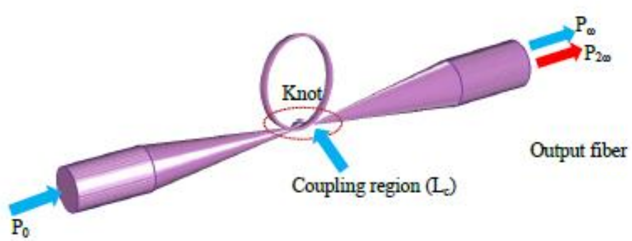


SHG



$\eta=3\cdot10^{-3}$

$\eta=3\cdot10^{-5}$



UV conversion efficiency: theory

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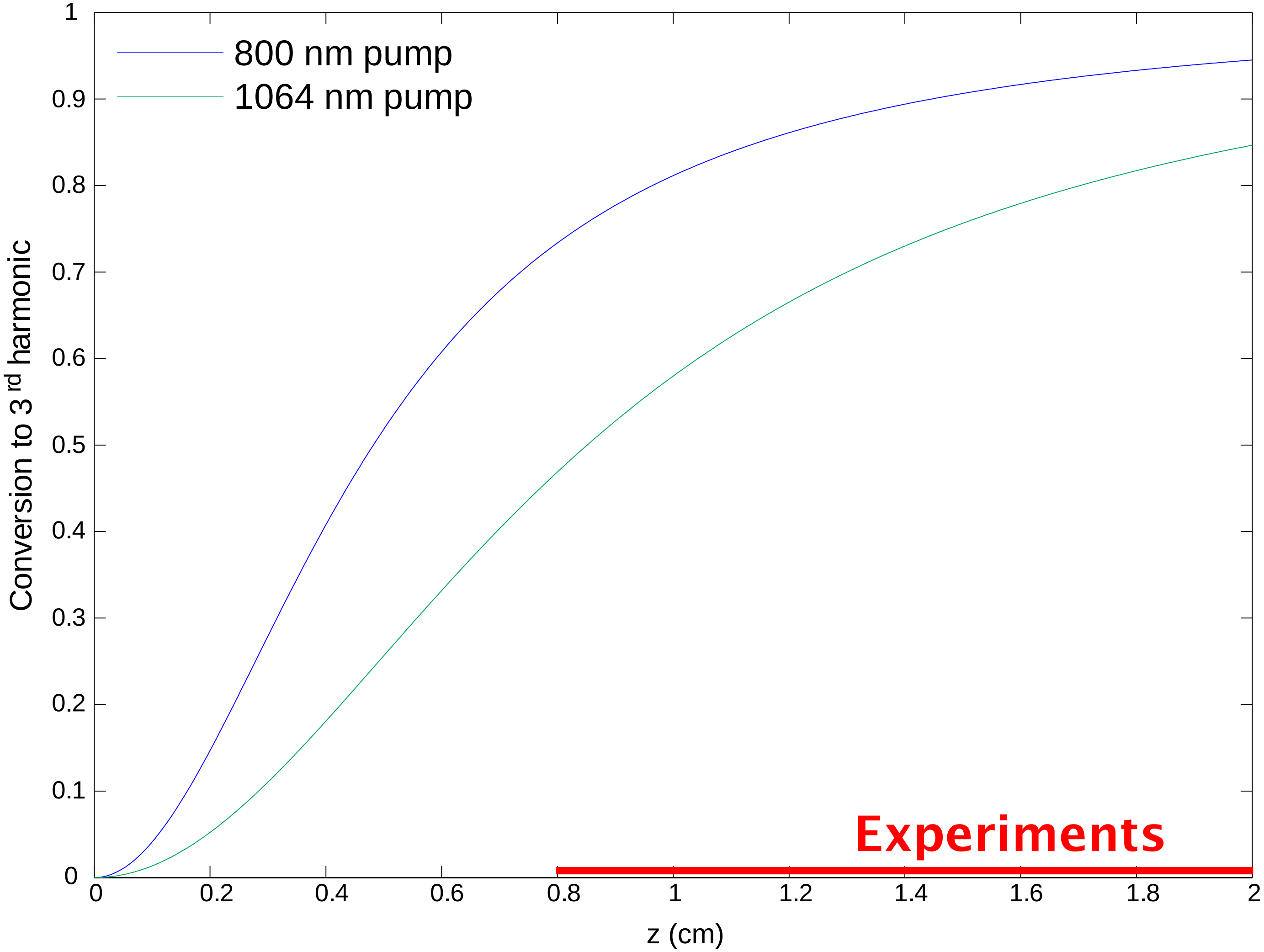
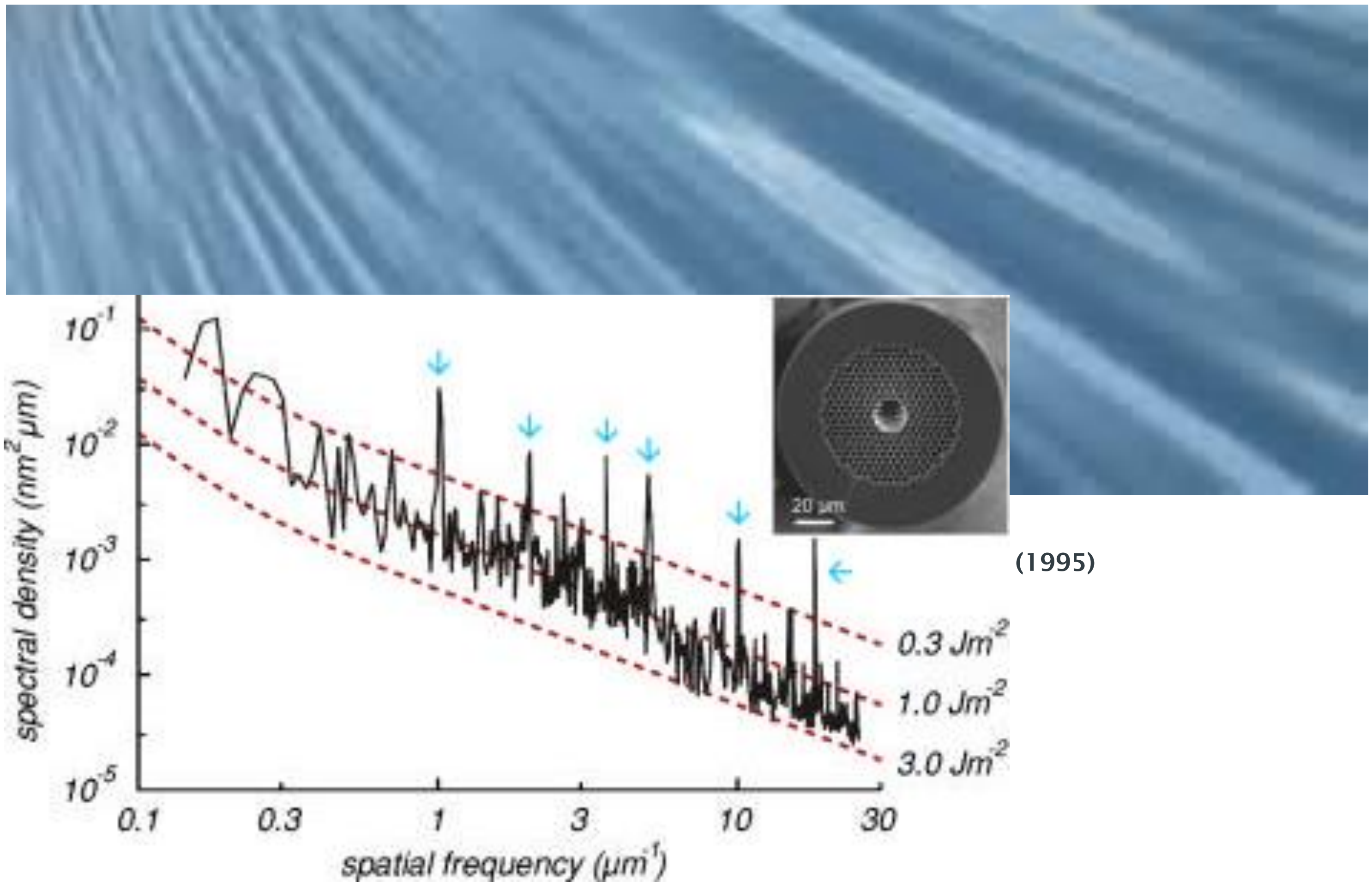


Intrinsic roughness: Surface waves?

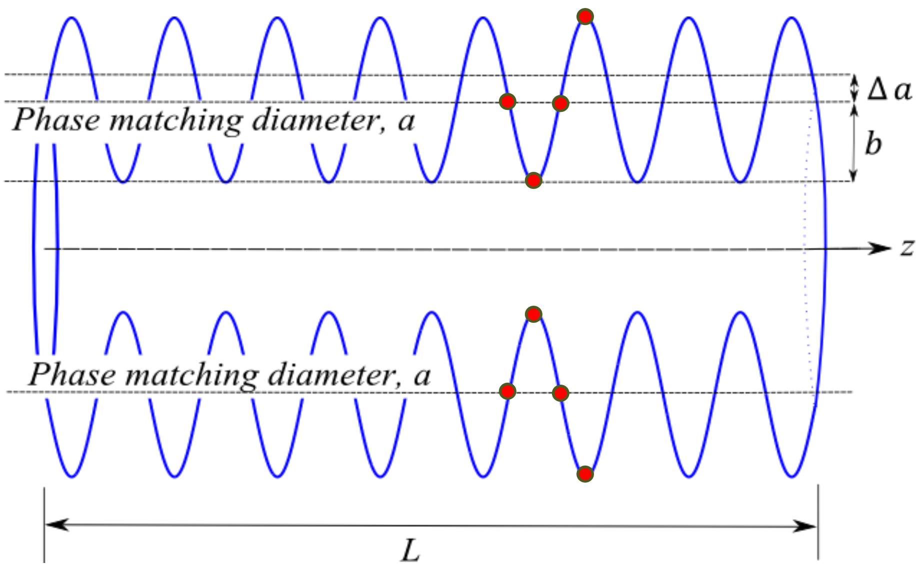
Diameter is not uniform!

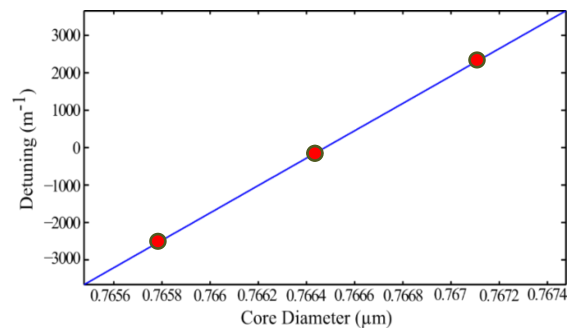


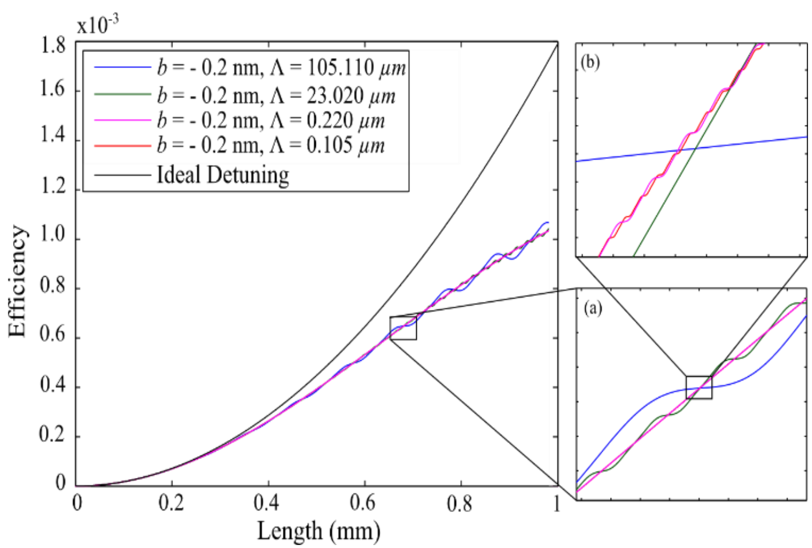
(1995)

Intrinsic roughness: Surface waves?

Diameter is not uniform!







Slow growth!

Intrinsic roughness: Surface waves?

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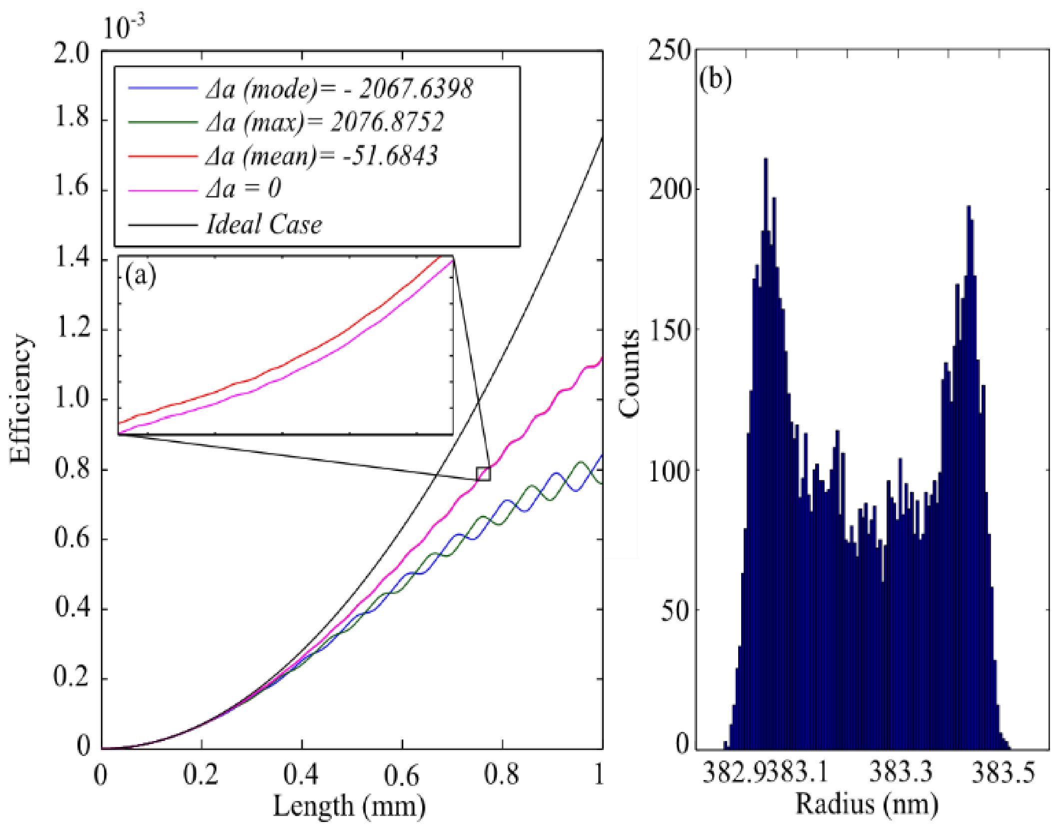

Efficiency smaller than experimental value

Three Photon Generation

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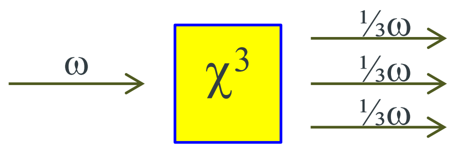
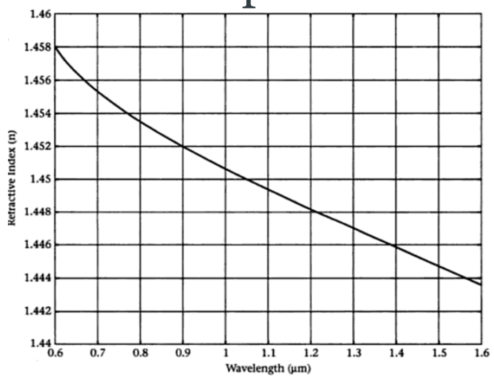


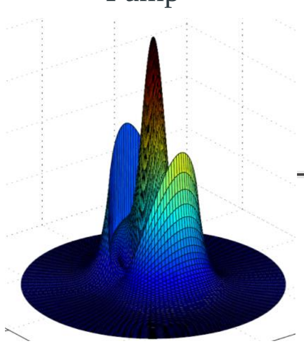
n dispersion



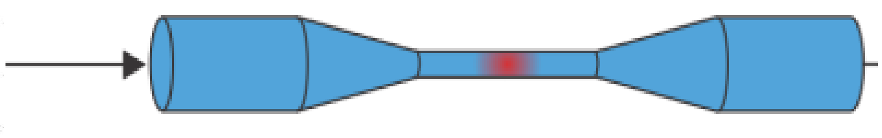
Phase matching does not occur with fundamental modes

Intermodal phase matching

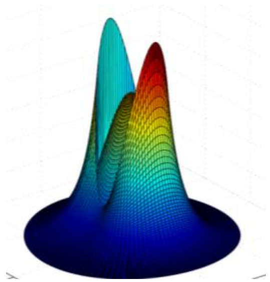
Pump



$HE_{12}(\omega)$



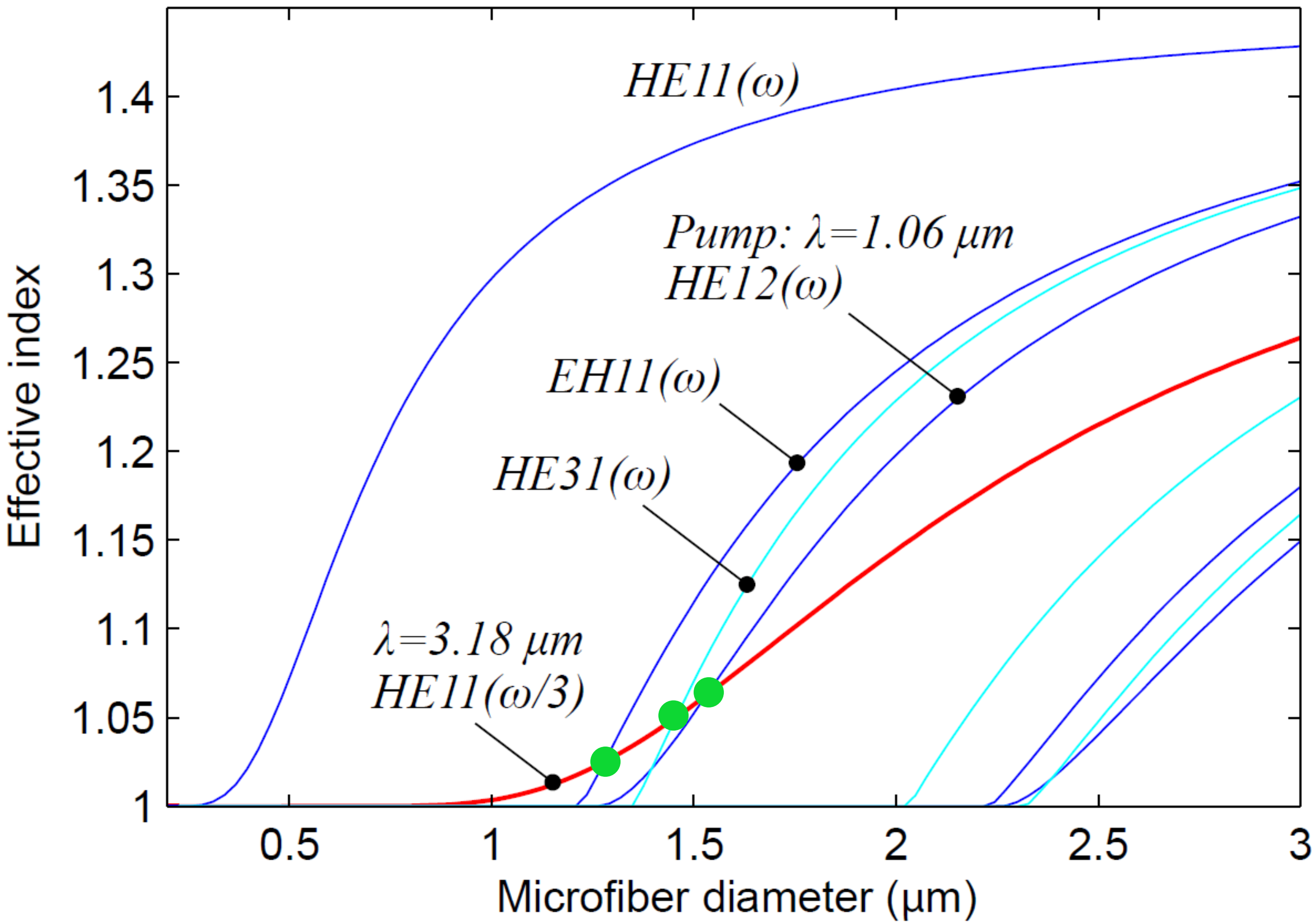
One Third Harmonic



$HE_{11}(1/3\omega)$

IR: Phase matching at λ=3.18μm

λ_p=1.06μm; λ_s=3.18μm



IR: Phase matching at λ=4.65μm

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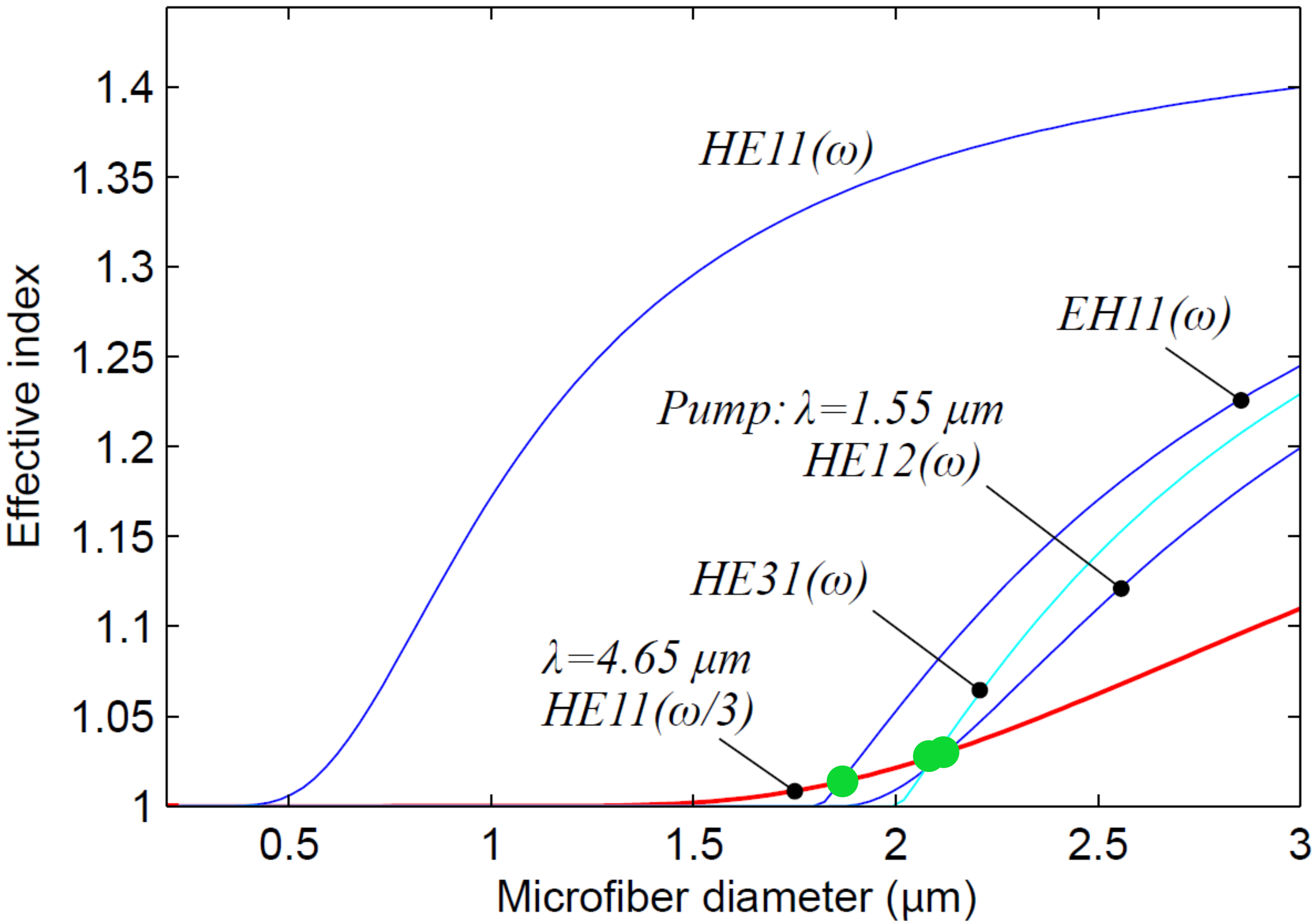
λ_p=1.55μm; λ_s=4.65μm

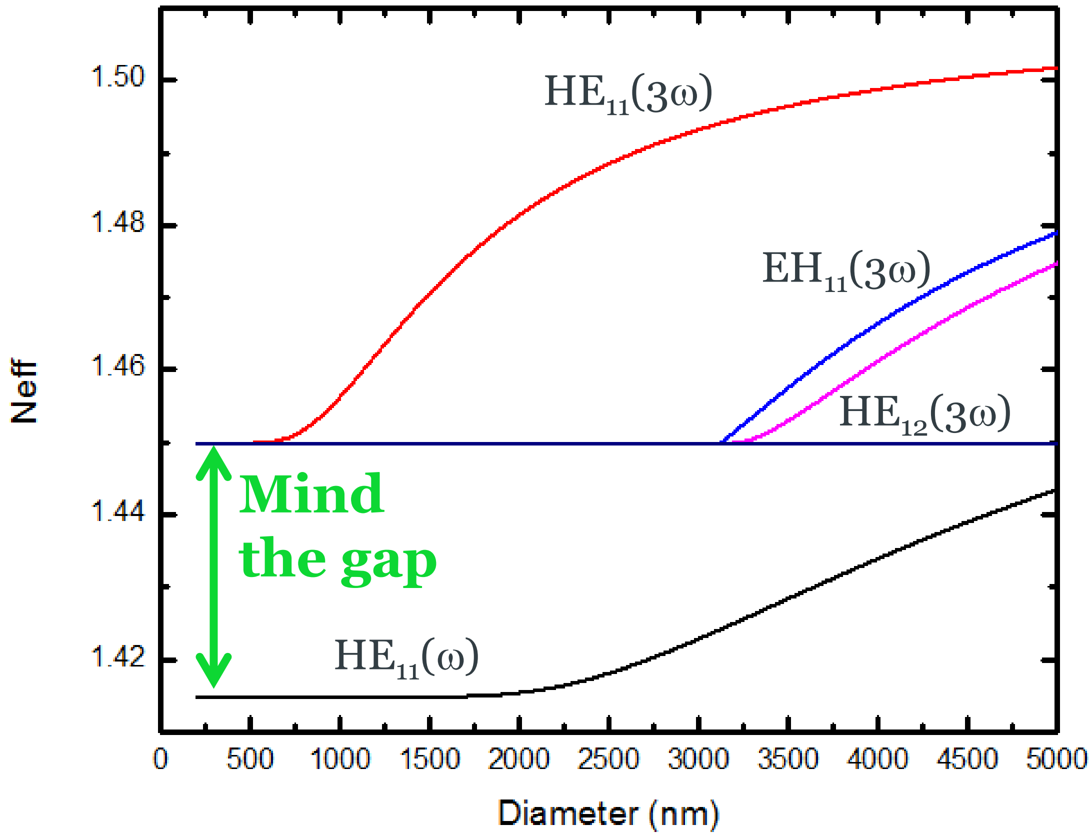


Fibres: Phase matching

λ_p=1.06μm; λ_s=3.18μm

Ge-doped silica fibre. [Ge]=40%

NA~0.42



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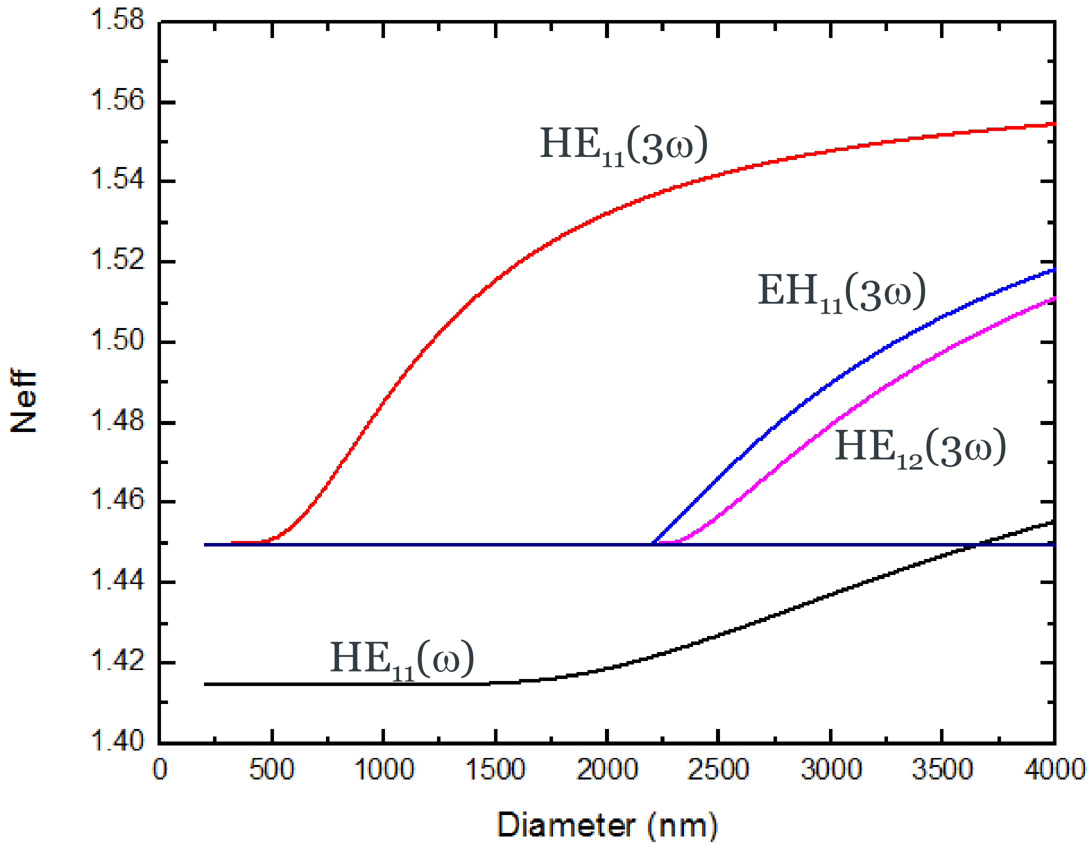
Fibres: Phase matching

λ_p=1.06μm; λ_s=3.18μm

Ge-doped silica fibre. [Ge]=60%

NA~0.52



Fibres: Phase matching

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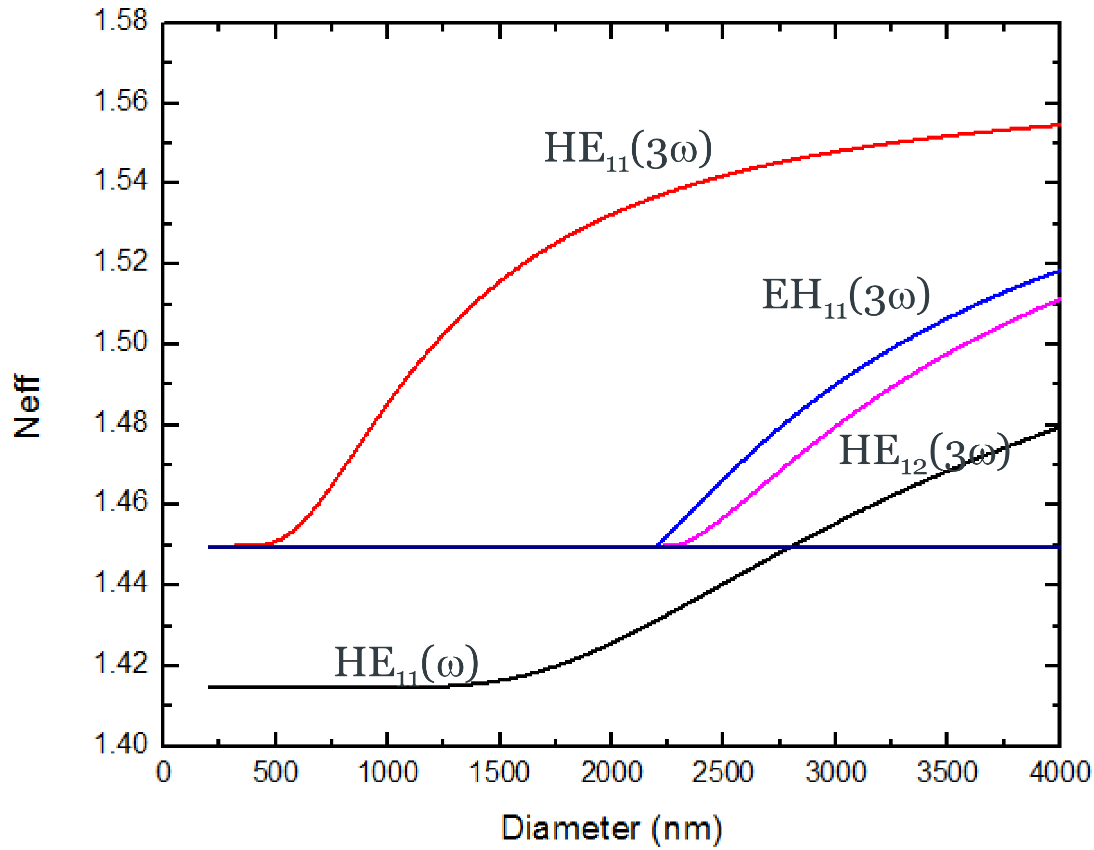
λ_p=1.06μm; λ_s=3.18μm

Ge-doped silica fibre. [Ge]=80%

NA~0.6



Fibres: Phase matching

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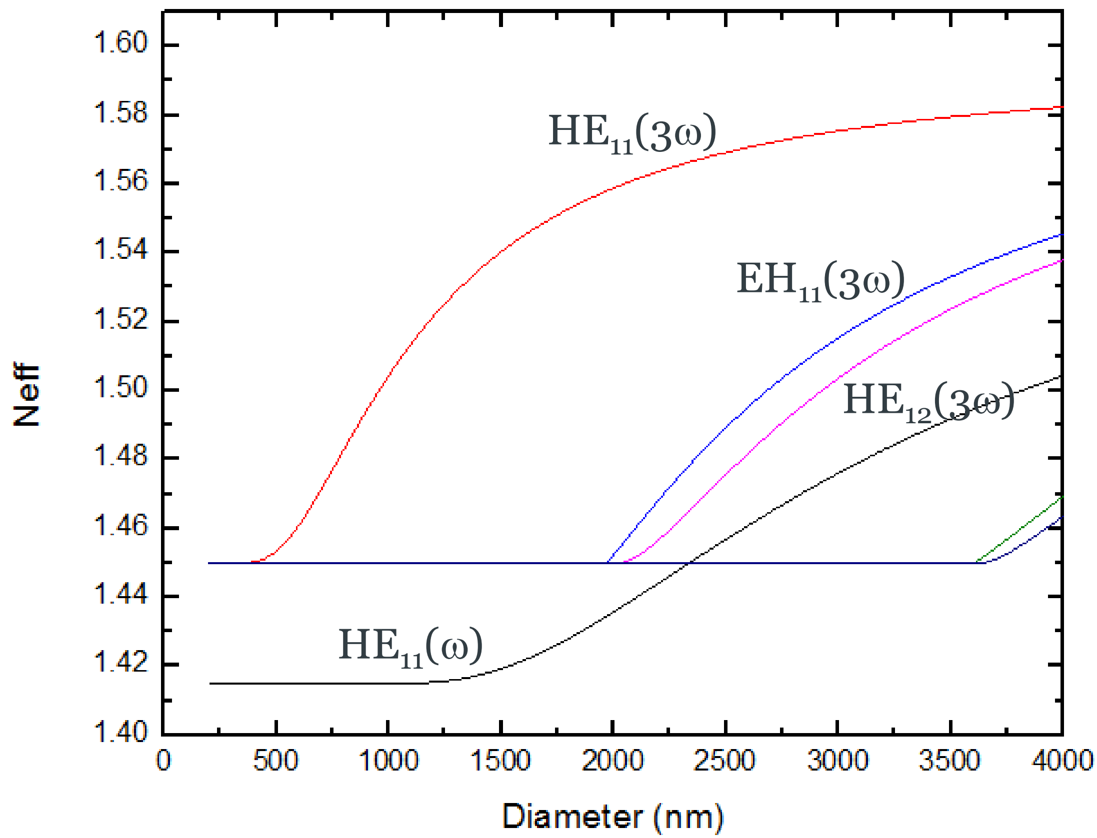
λ_p=1.06μm; λ_s=3.18μm

Ge-doped silica fibre. [Ge]=100%

NA~0.67



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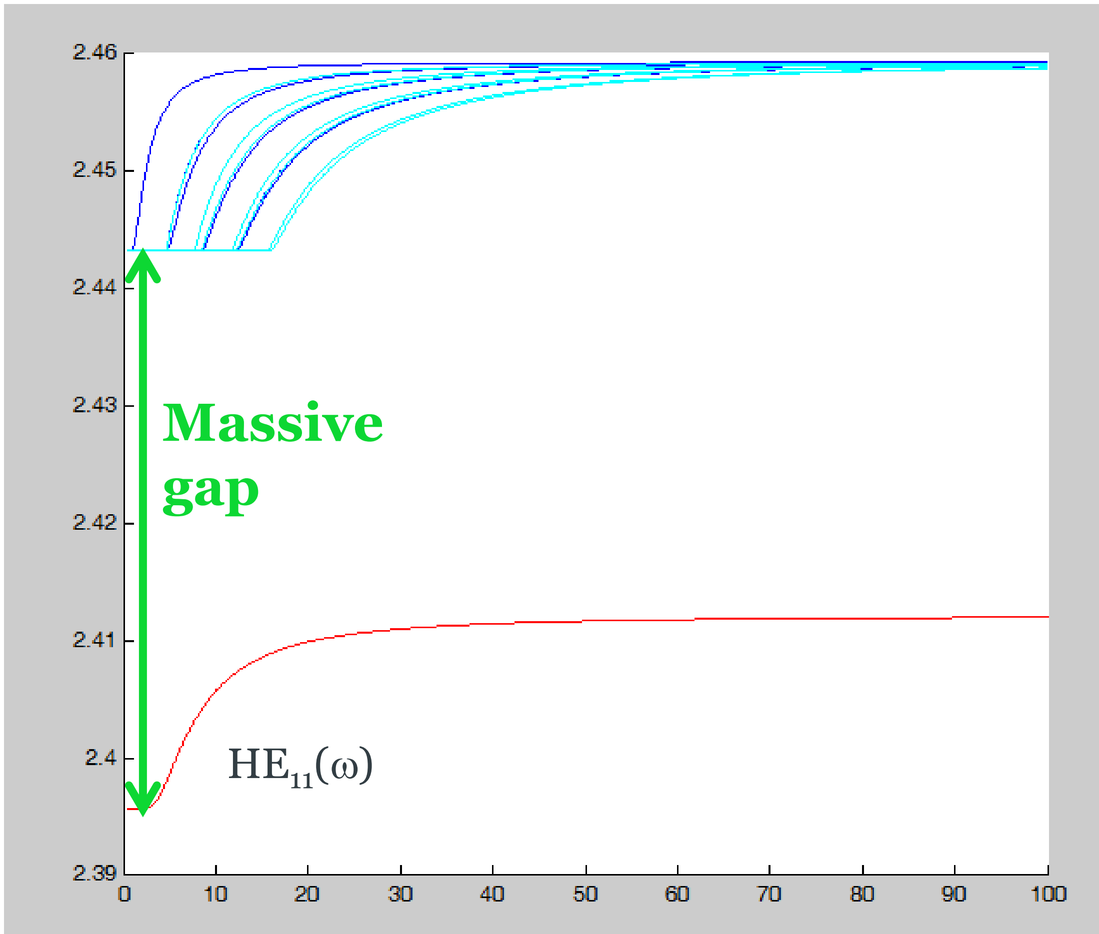
CHG fibres: Phase matching

λ_p=1.06µm; λ_s=3.18µm

NA=0.28

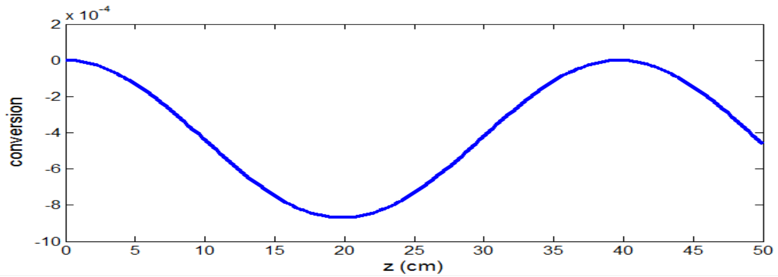


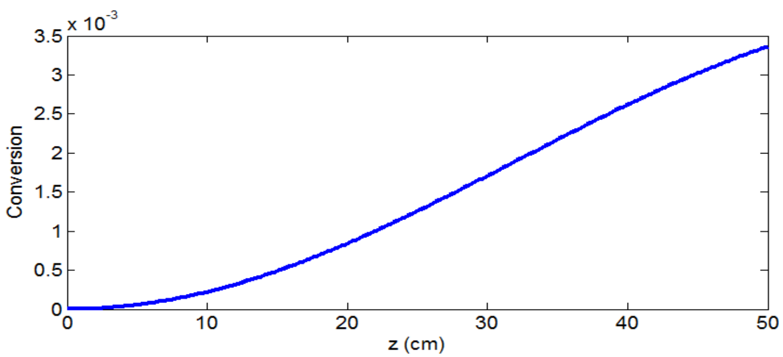
In high n materials refractive index dispersion compensation is much more difficult

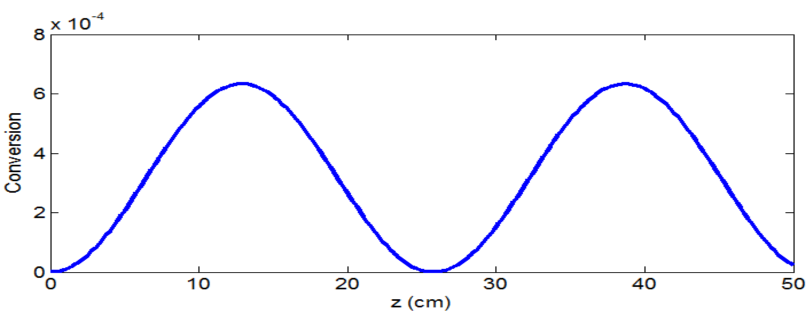
Fibres: detuning

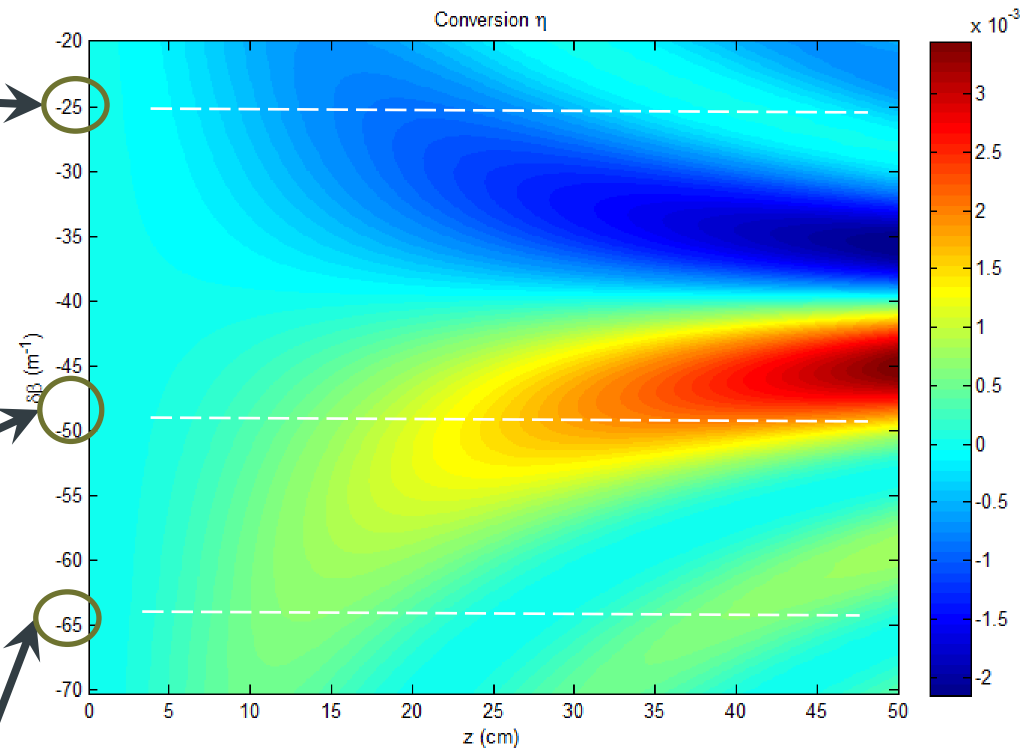
P_s=10W, P_p=1kW

$\eta=(P_{s\text{-}out}-P_{s\text{-}in})/P_{p\text{-}in}$





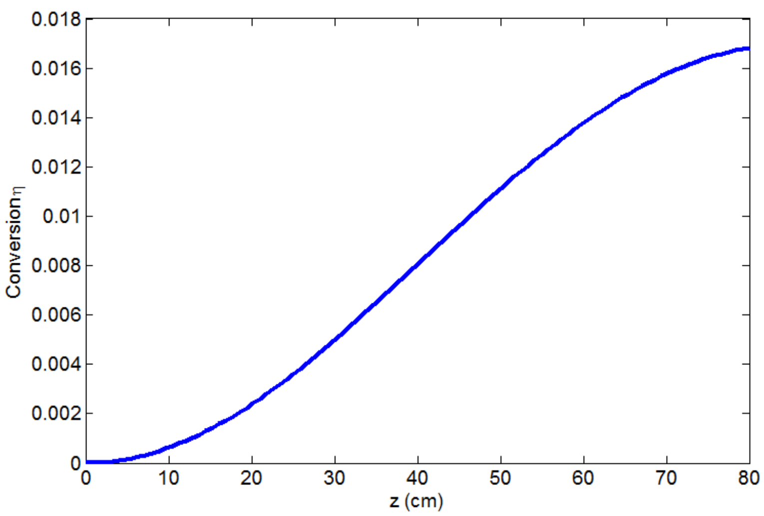


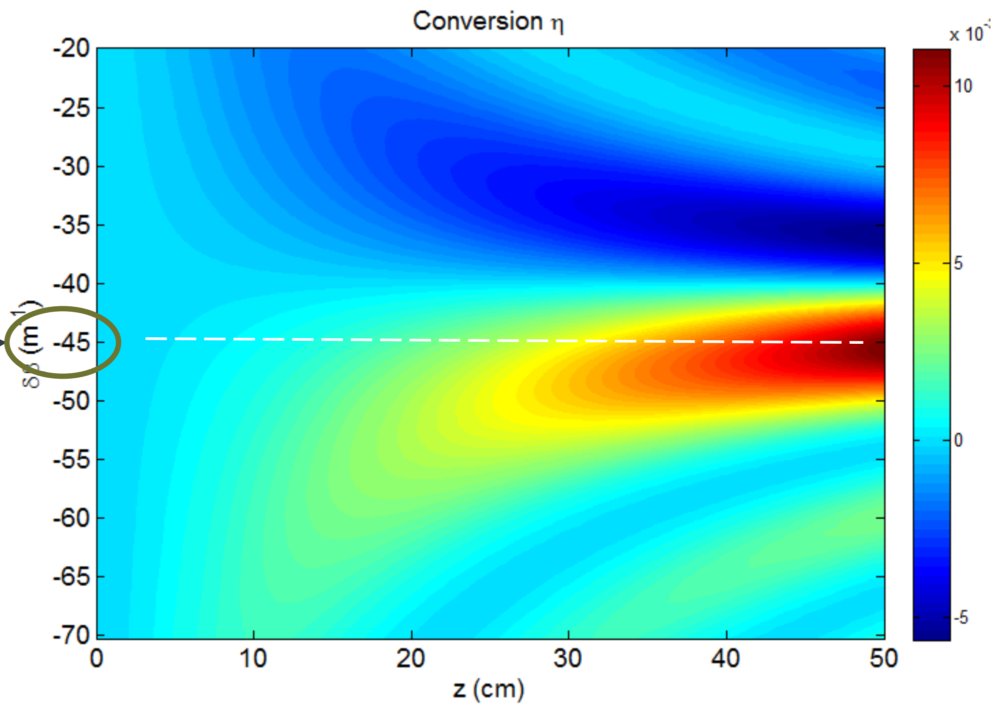


conversion efficiency

Fibres: detuning

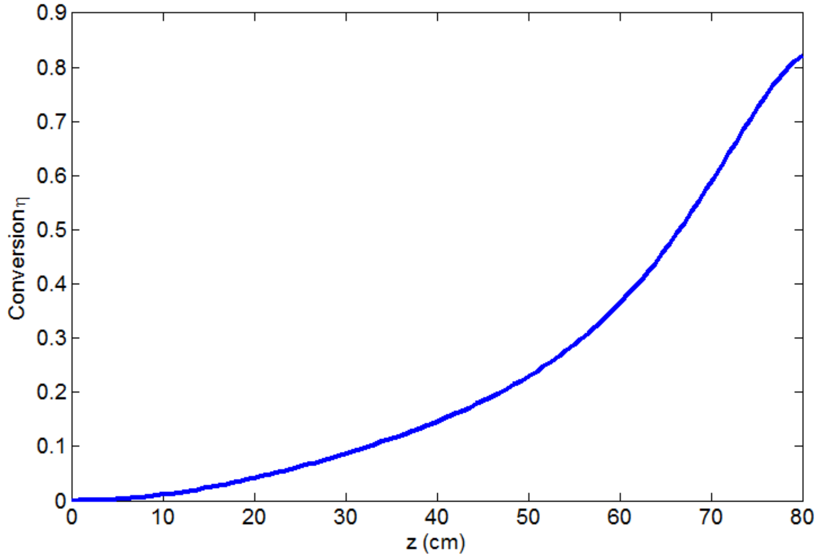
P_s=20W, P_p=1kW

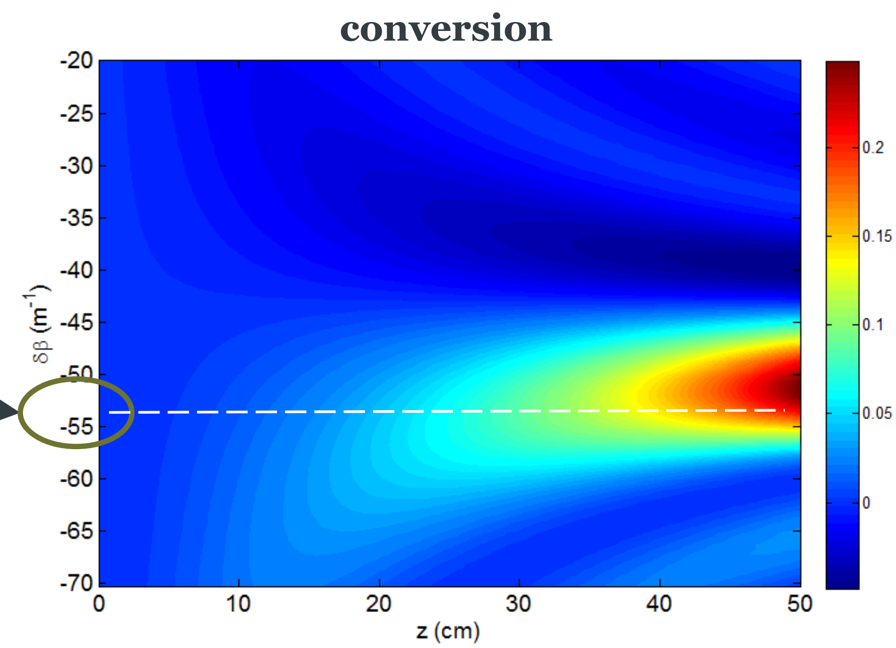




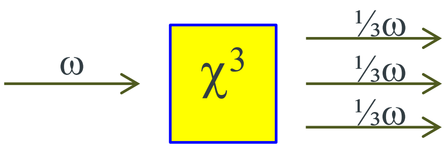
Fibres: detuning

P_s=100W, P_p=1kW

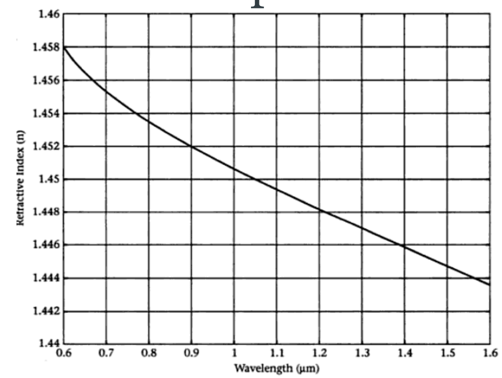




Three Photon Generation



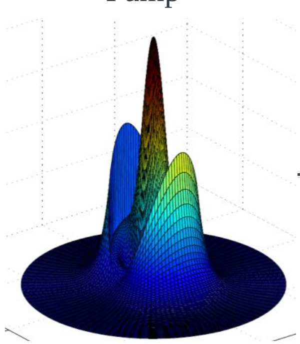
n dispersion



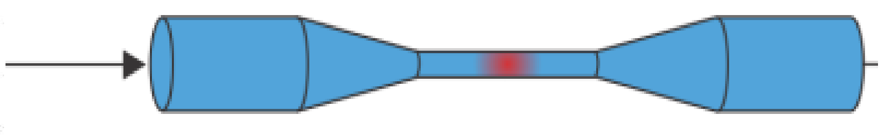
Phase matching does not occur with fundamental modes

Intermodal phase matching

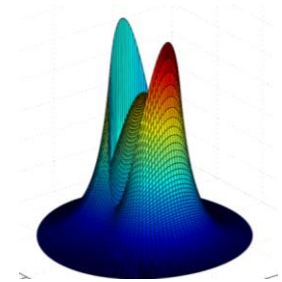
Pump



$HE_{12}(\omega)$



One Third Harmonic



$HE_{11}(1/3\omega)$

Intermodal coupler for pump launch

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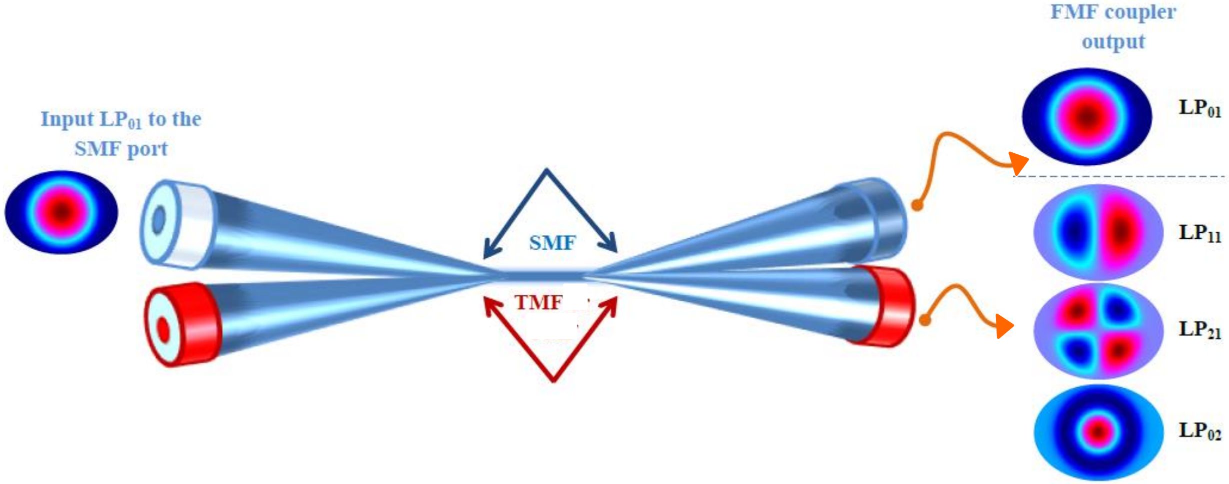
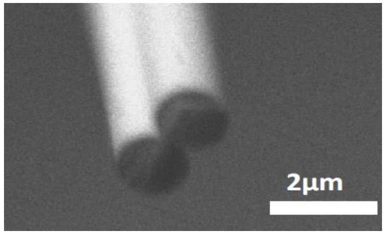
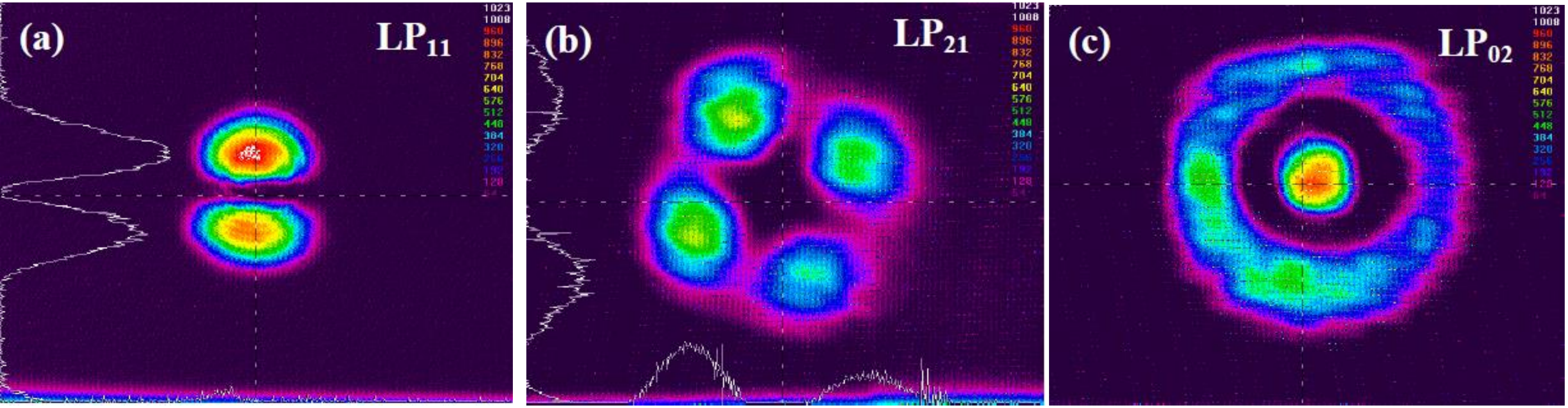
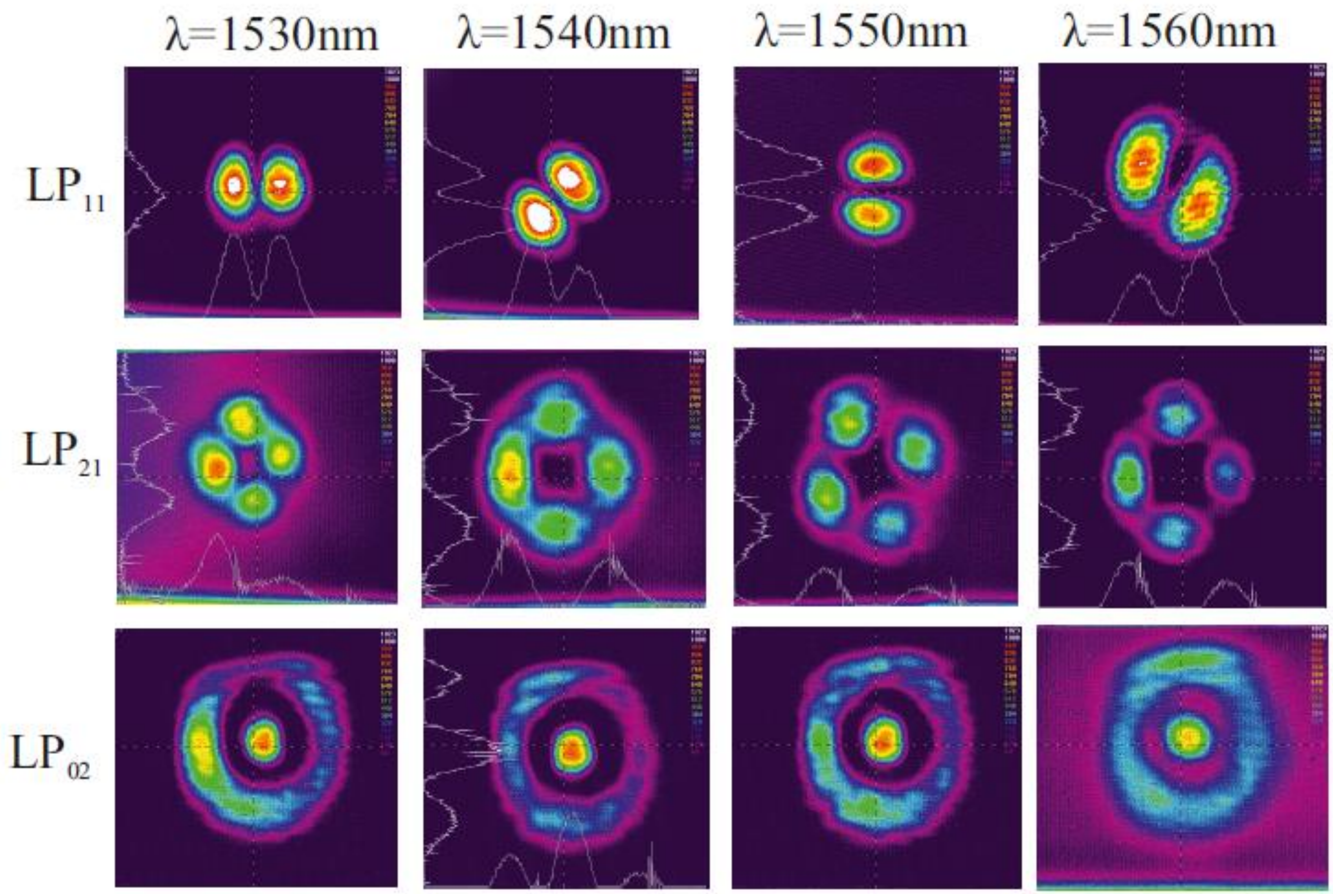
FMF couplers







Broadband operation



Broadband operation is strongly dependent on couple diameter.
Larger fibre diameters allow for broadband operation.

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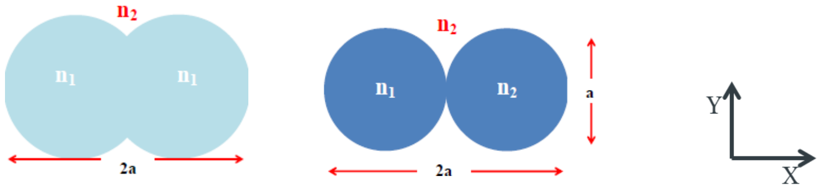
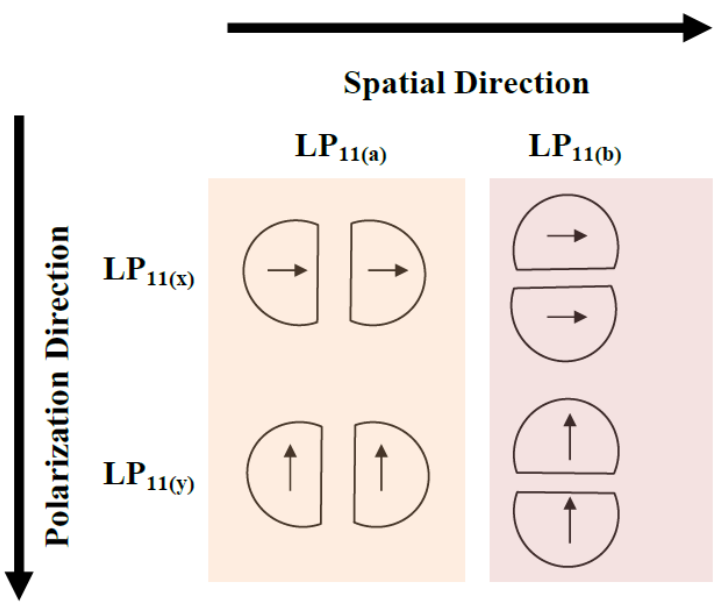
Polarization discrimination

For circularly symmetric waveguides high order modes are degenerate.

Couplers have ε=0.5.





Propagation constants in orthogonal directions X and Y are significantly different

can be discriminated

Polarization discrimination

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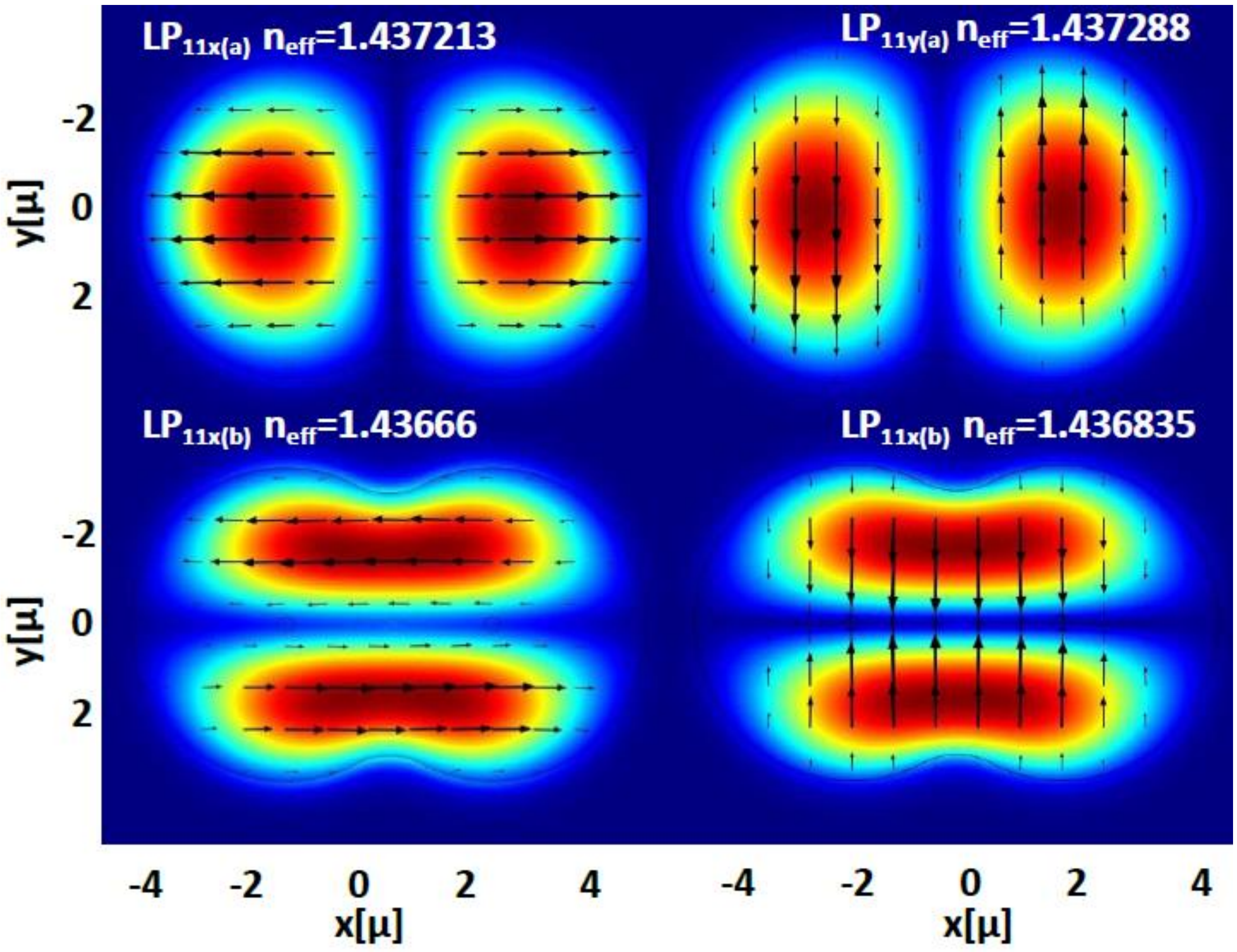
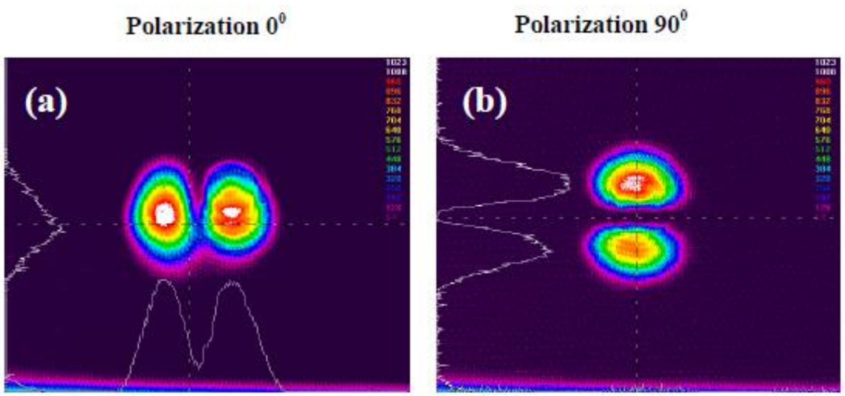


Polarization discrimination

L=20mm, small ε

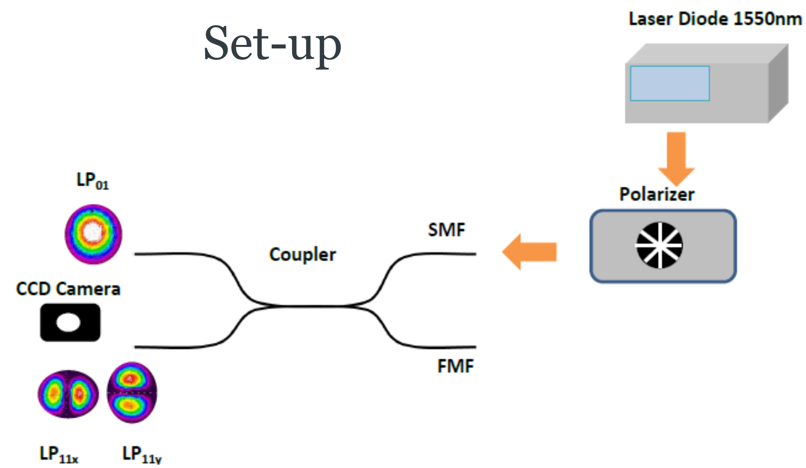


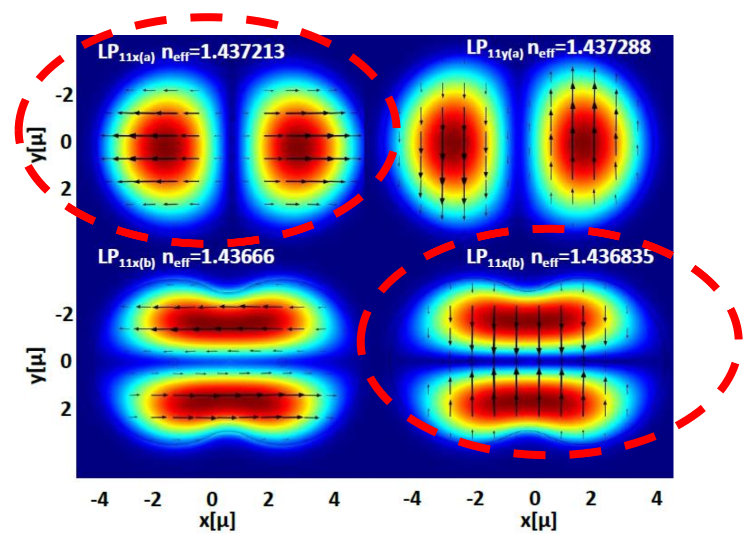
When polarization is rotated at the coupler entrance, the output intensity profiles follow.

Launch	Output
0^o	$LP_{11x(a)}$
90^o	$LP_{11y(b)}$

Coupler cannot discriminate $LP_{11(a)}$ from $LP_{11(b)}$

Set-up





Polarization discrimination

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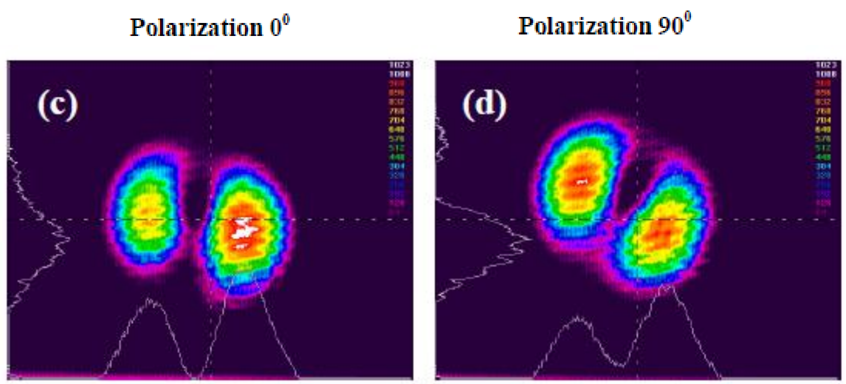
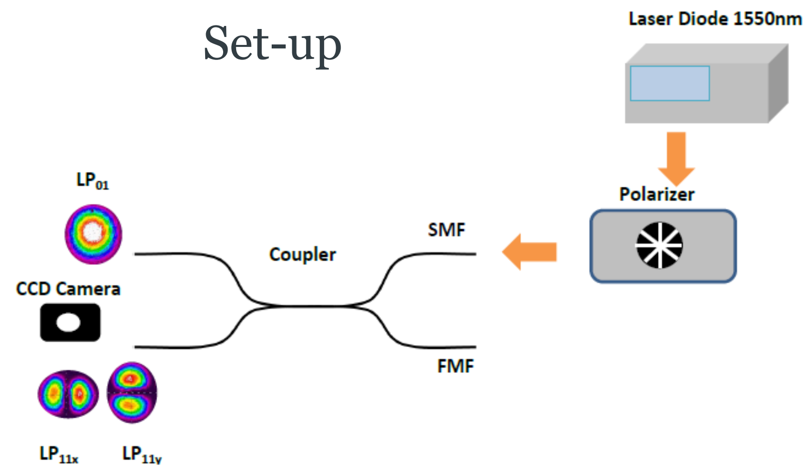
L=50mm, ε~0.5



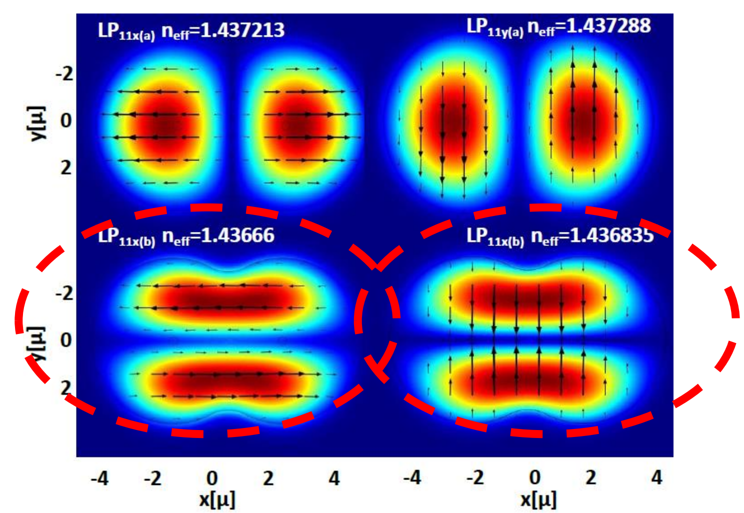
Set-up



Coupler discriminates $LP_{11(a)}$ from $LP_{11(b)}$

Launch	Output
0^o	$LP_{11x(a)}$
90^o	$LP_{11x(b)}$

Coupler selectively excites $LP_{11(b)}$



How to improve TPG efficiency?

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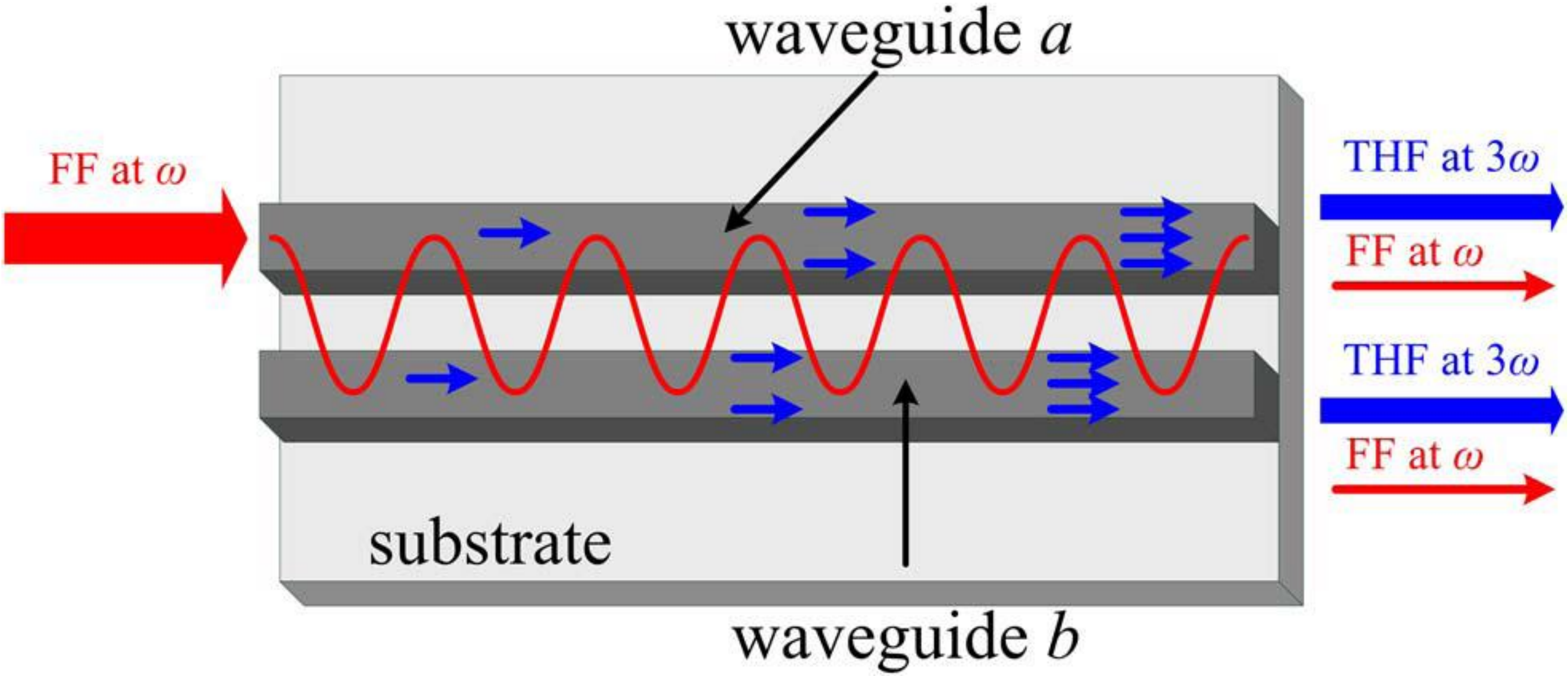
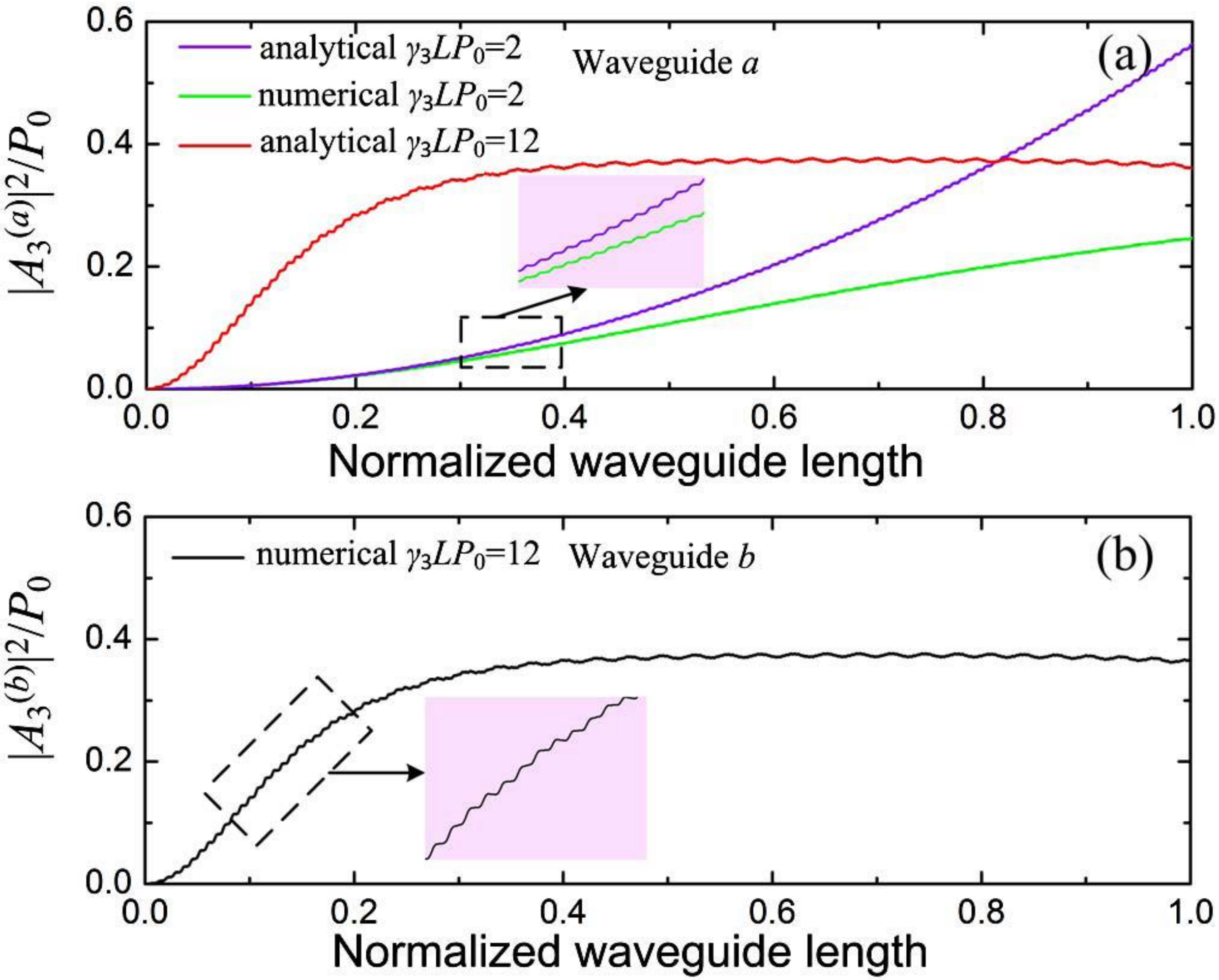
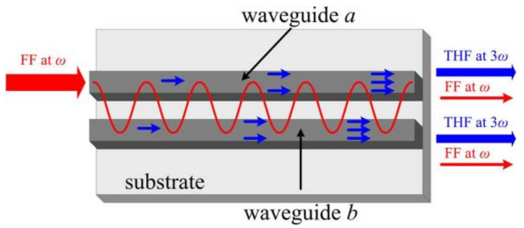


Huang, Opt. Lett. 40(6), 894, 2015

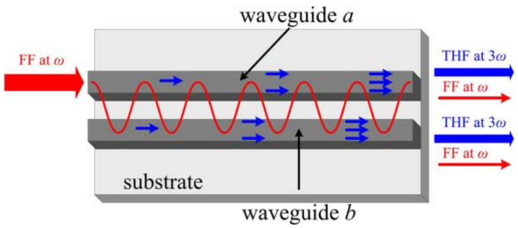
Coupling-length phase matching

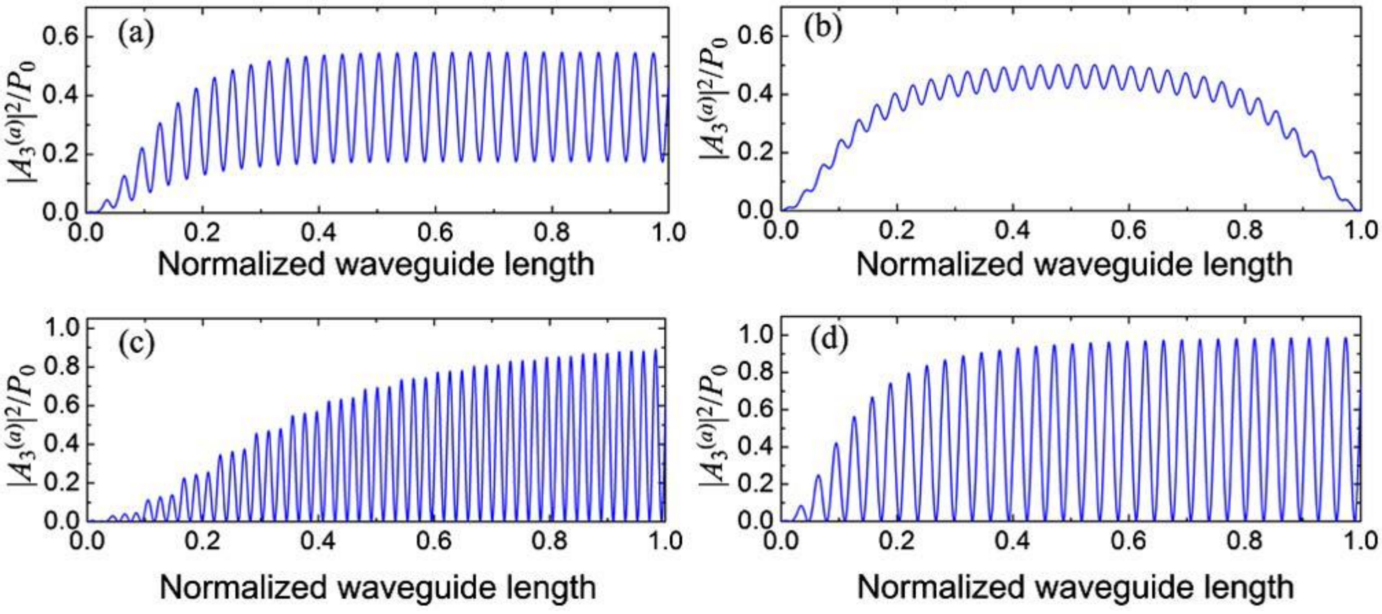




Huang, Opt. Lett. 40(6), 894, 2015

Coupling-length phase matching





Huang, Opt. Lett. 40(6), 894, 2015

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Conclusions

Microfibres can be used to generate light at short/long wavelengths

Up-conversion (THG) → UV generation

Down-Conversion (TPG) → IR generation

Efficiencies as high as 90% have been predicted for phase-matched optimised diameters, detuning and length.

Surface roughness limits the efficiency