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UV and IR generation in silica-based optical fibres and tapers

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Singapore, 1 July 2013

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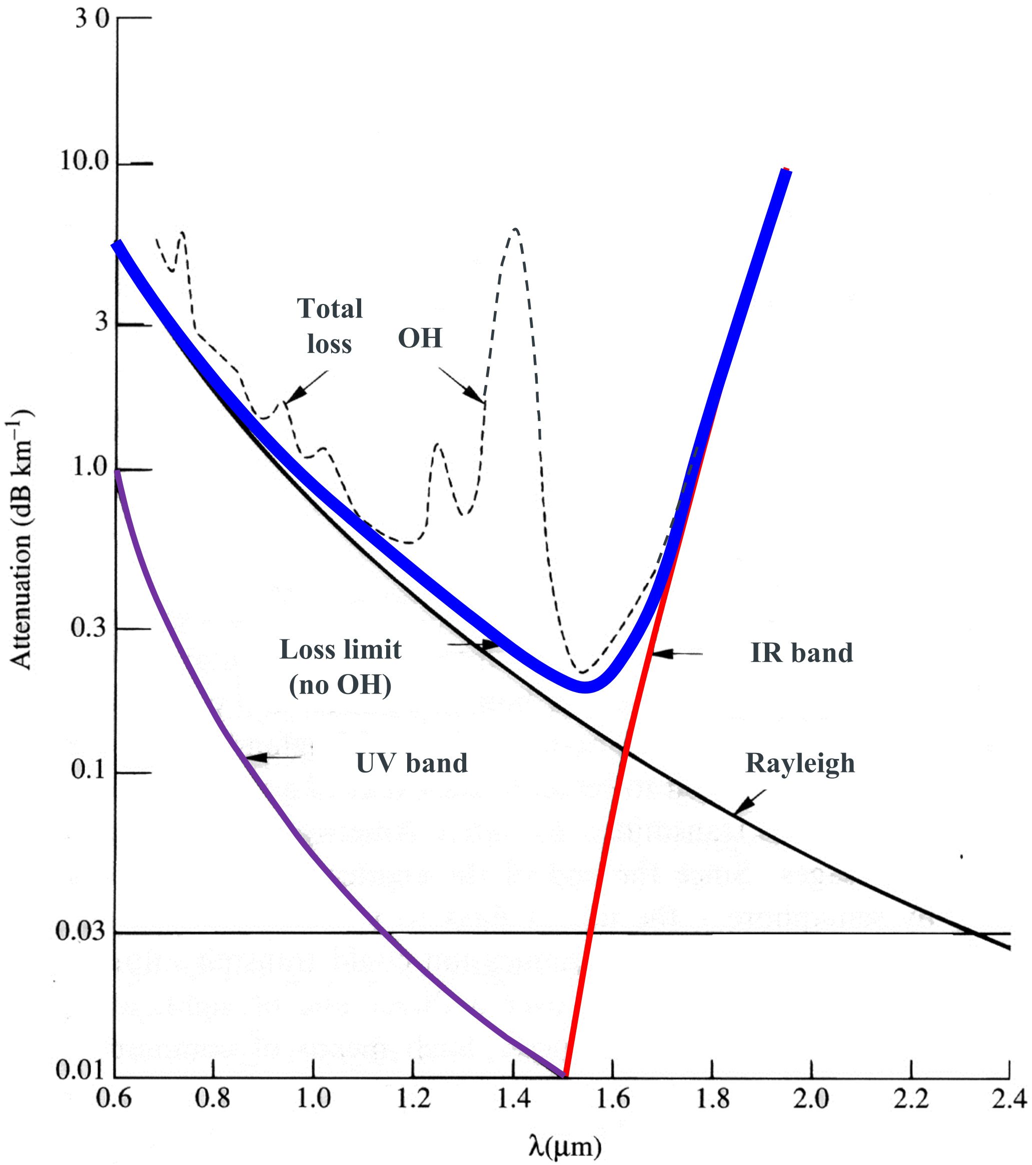
Outline

- Introduction
- χ^3 nonlinear process
- UV generation (THG)
- IR generation (TPG)
- Conclusion

Introduction: optical fibre loss



Optical fibre lasers

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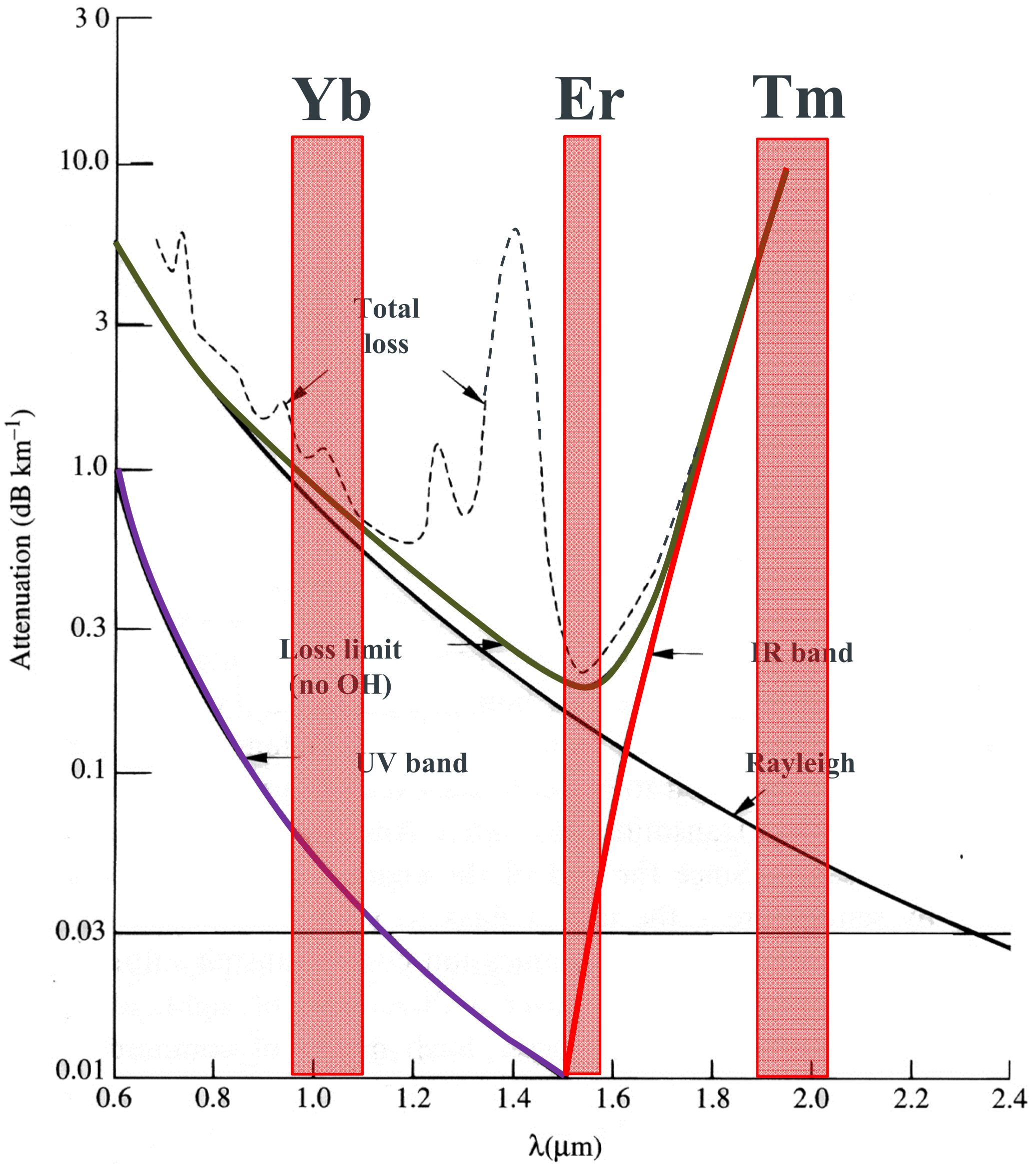

Introduction
Fibre lasers

Nonlinear processes

UV generation

IR generation

Conclusions

Introduction: optical fibre laser

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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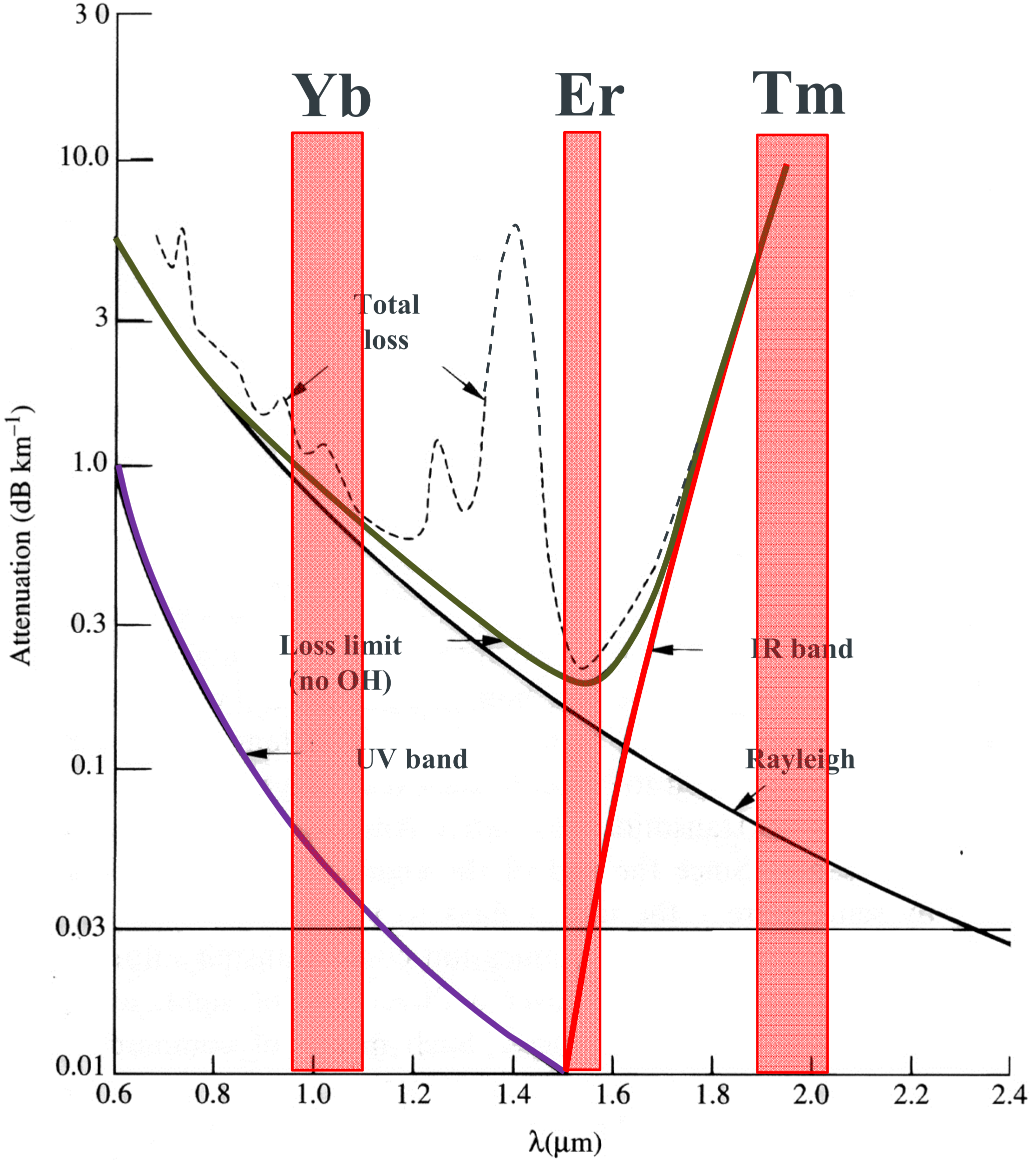

Optical fibre lasers

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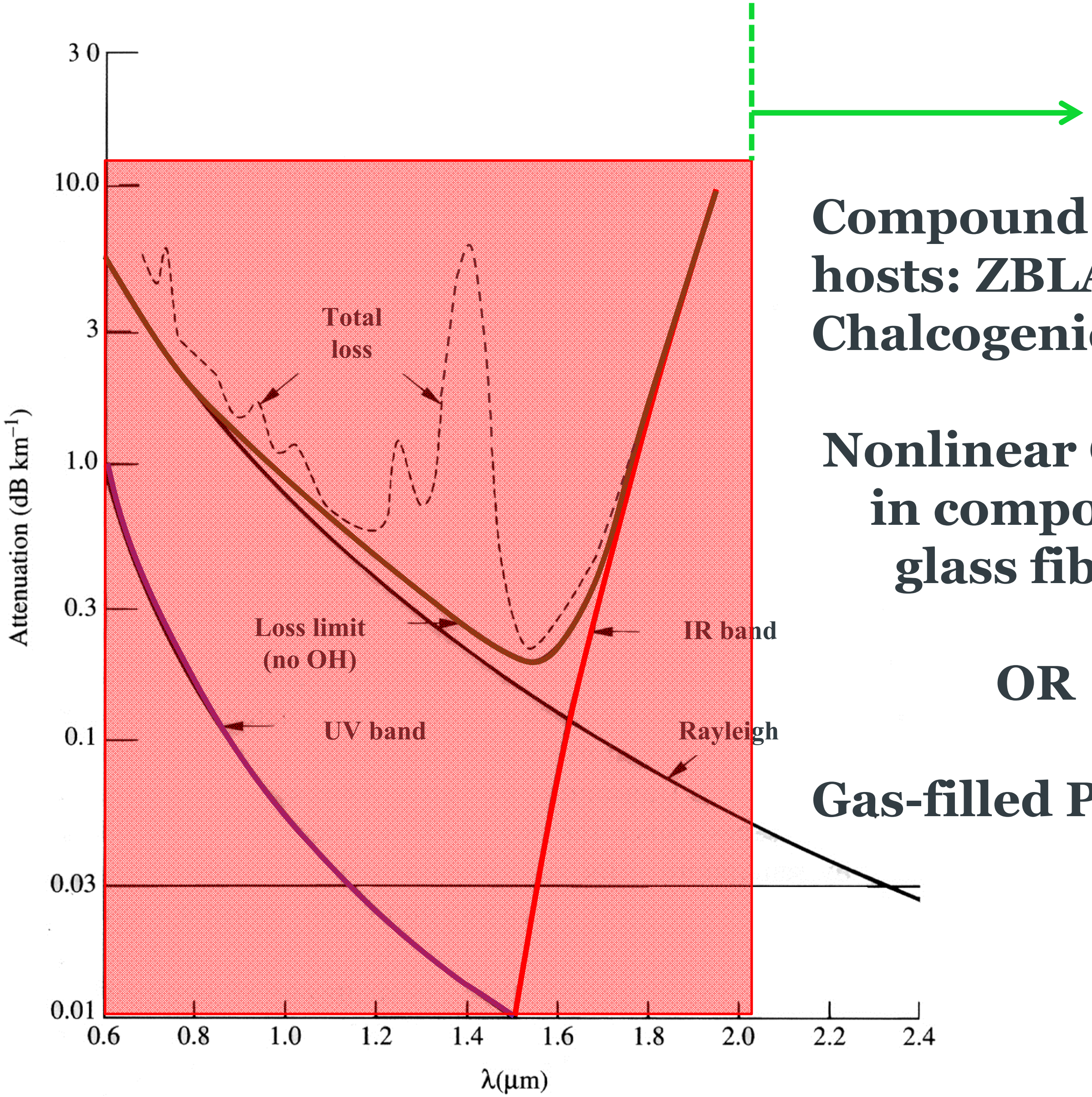

Compound glass hosts: ZBLAN, Chalcogenides

Nonlinear Optics in compound glass fibres

OR

Gas-filled PBGF

Laser applications

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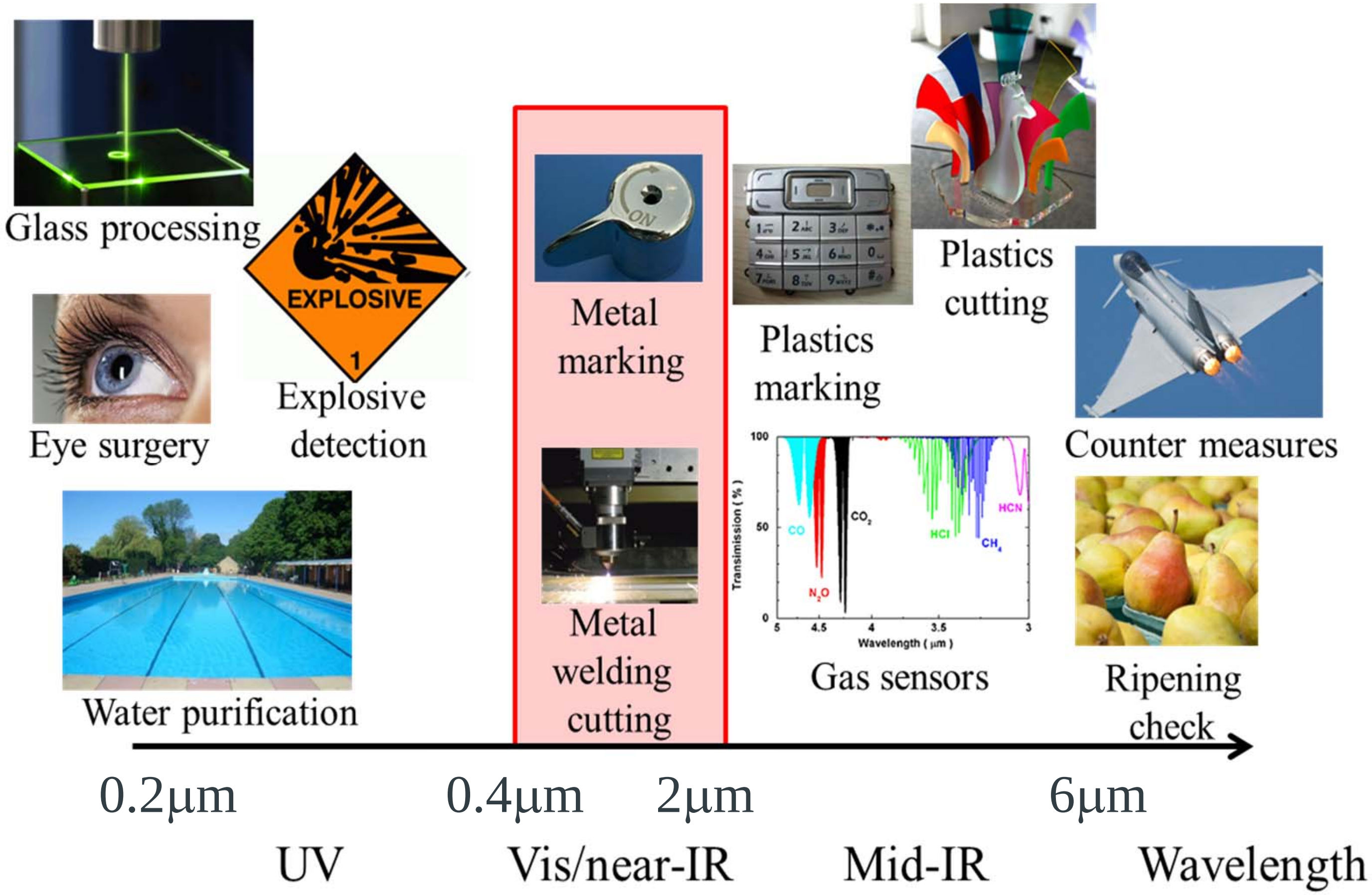


Introduction
Applications

Nonlinear processes

UV generation

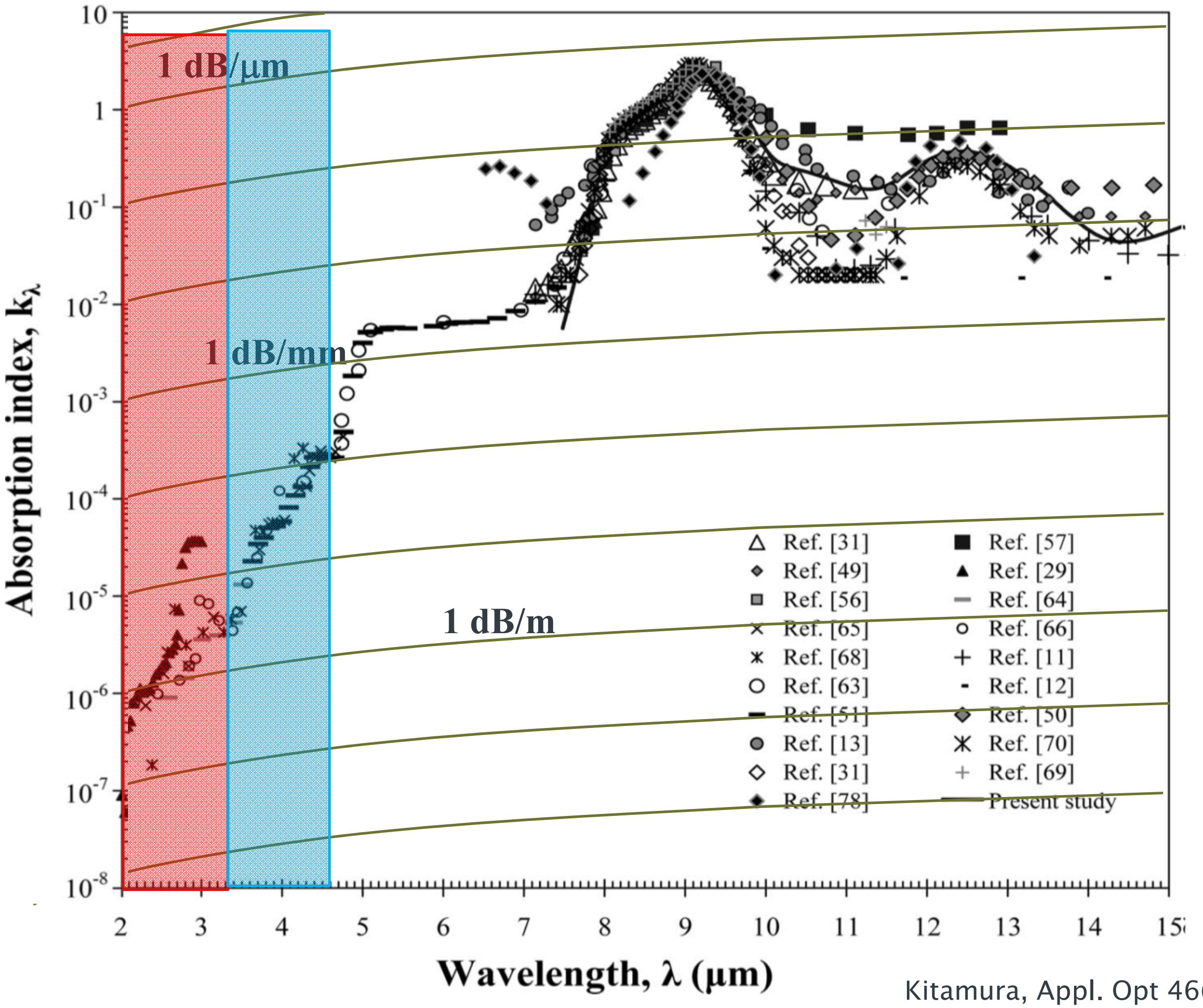
IR generation

Conclusions

Silica loss: long λ

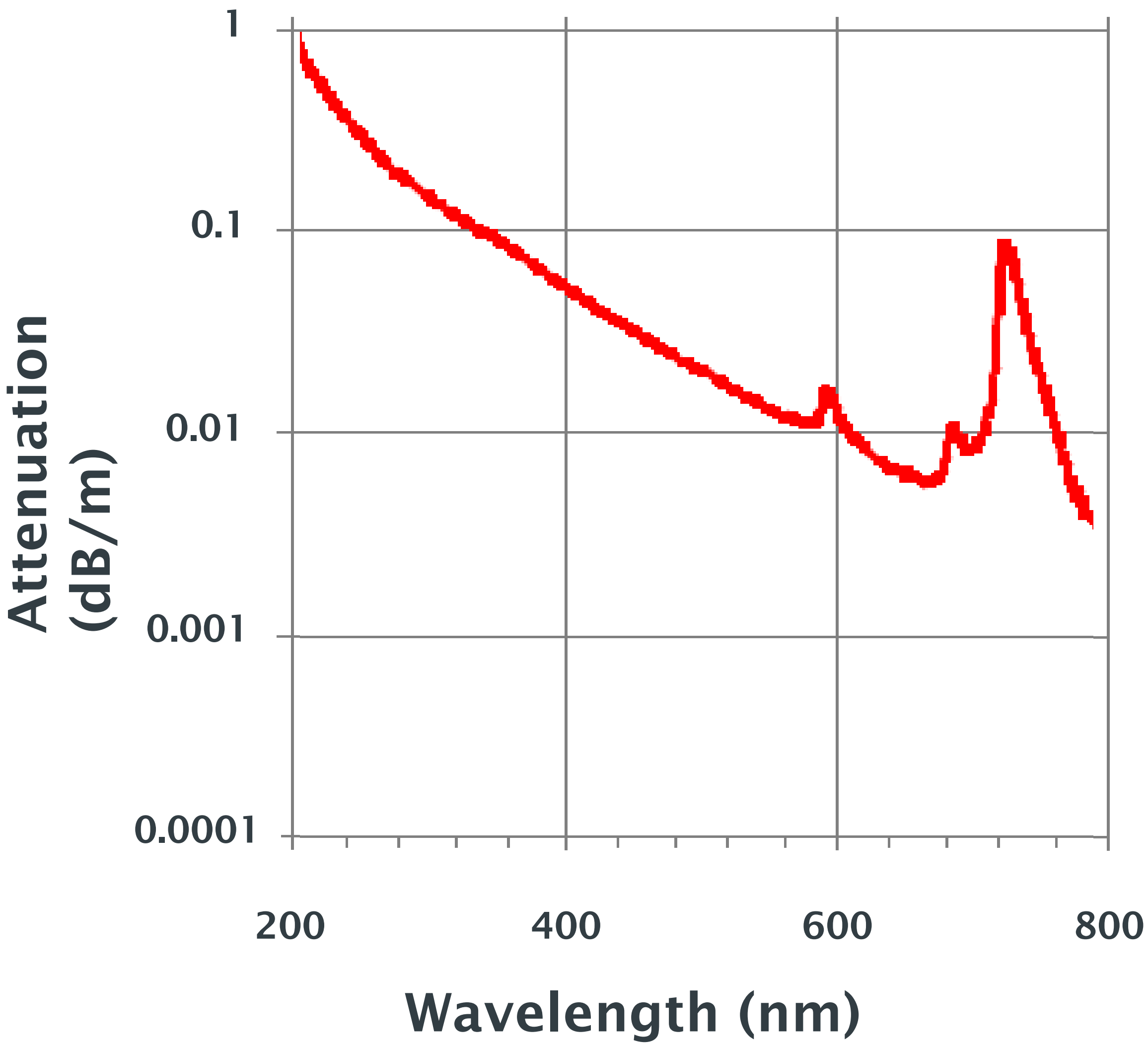
3 dB/m Active fibres

1 dB/cm Nonlinear processes



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

Silica loss: short λ



Nonlinear processes

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Requirements:

- **Efficient (few cm of fibre at most)**
- **Pump must be in low loss wavelength region (500nm-2μm)**
- **Compatible with fibre material (glass)**

  (no $\chi^{(2)}$).
- **Compatible with fibre geometry**

Nonlinear processes: UV

Third Harmonic Generation

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

Nonlinear processes: IR

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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.

THG - TPG

Third Harmonic / Three photon Generation

- **Phase matching**

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

- **High overlap between pump and third harmonic mode**

Third Harmonic Generation Phase matching

Third harmonic generation is efficient if

$\beta(\omega)=\beta(3\omega)$

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

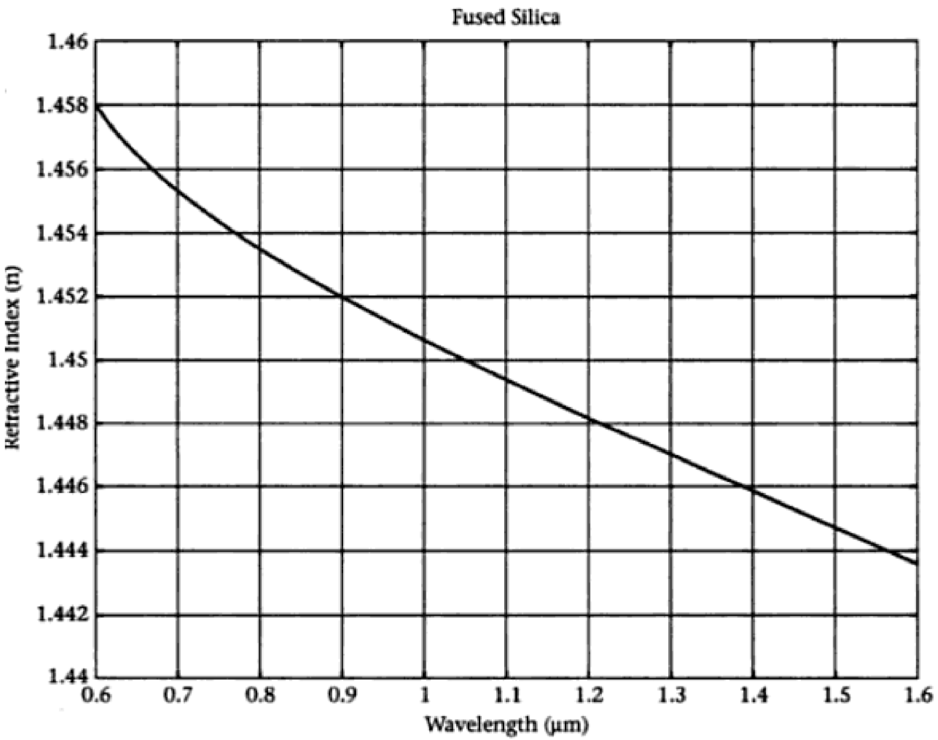
$$n_{eff}=\frac{\int_0^{2\pi}\int_0^{\infty} n(r,\vartheta)I(r,\vartheta)\,dr\,d\vartheta}{\int_0^{2\pi}\int_0^{\infty} I(r,\vartheta)\,dr\,d\vartheta}$$

refractive index → $n(r,\vartheta)$

mode intensity distribution → $I(r,\vartheta)$

radial coordinate → r

azimuthal coordinate → ϑ



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Phase matching

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n_{eff} depends

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

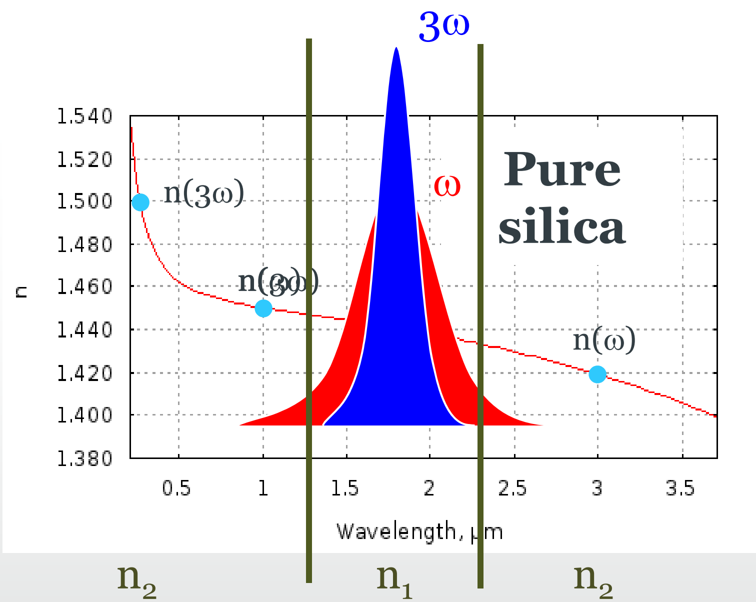
- Material dispersion

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

- Mode confinement

  for fundamental mode

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



$n_1 > n_2$

BUT n_{eff} decreases for mode order

THG: high order mode n_{eff}

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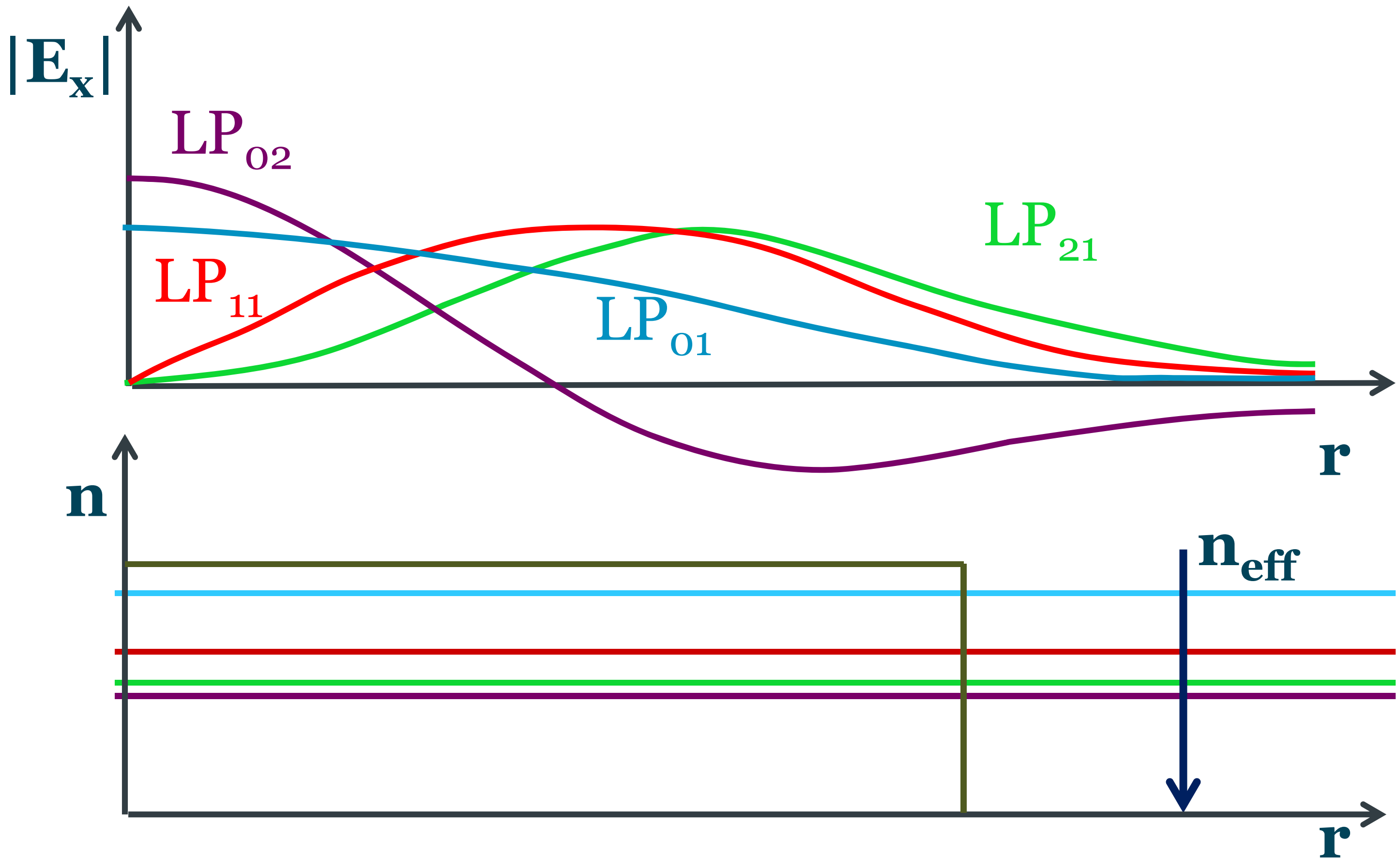

High order modes extend further in the low n medium they have a lower n_{eff}.

intermodal phase matching

Grubsky, Opt. Lett., 2005

Phase matching

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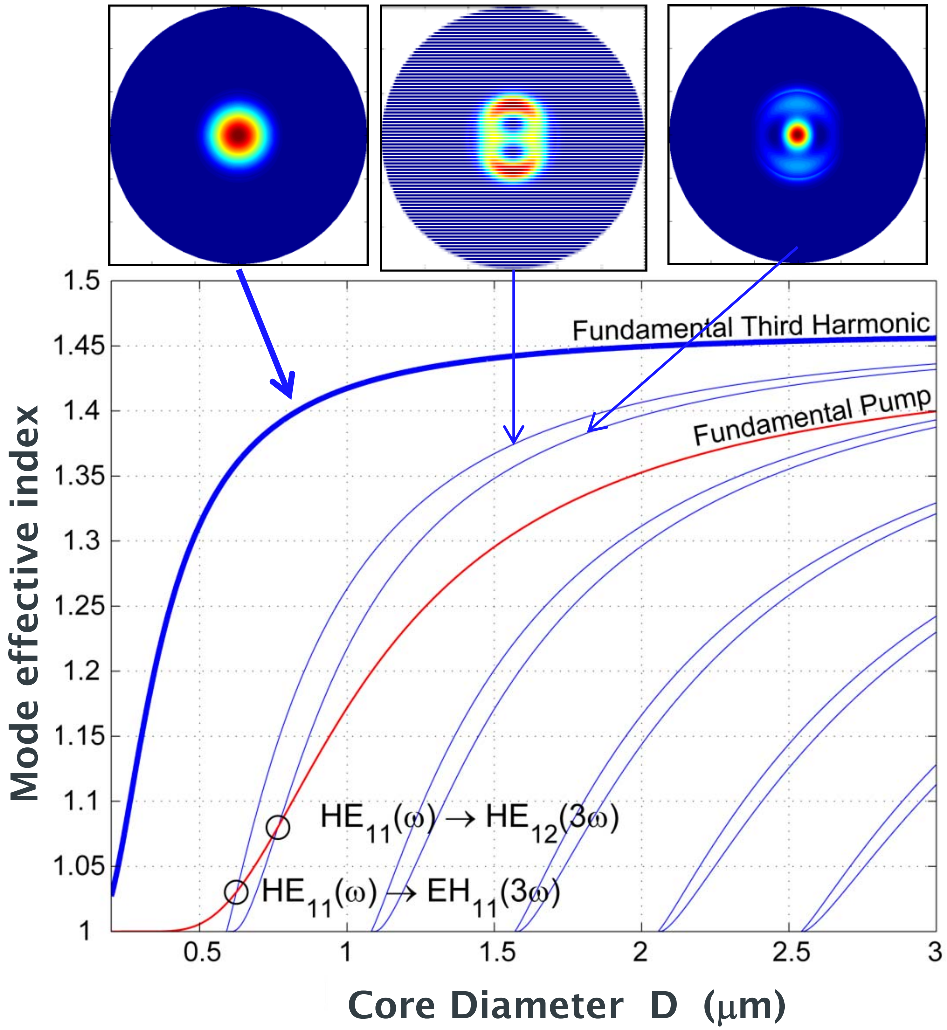
- **Fundamental $HE_{11}(\omega)$ pump mode can be phase matched only to higher order third harmonic modes.**
- **For pump λ_p, critical diameters exist at $\sim\lambda_p/2$ for NA~1.**



λ_p=1550nm

Phase matching

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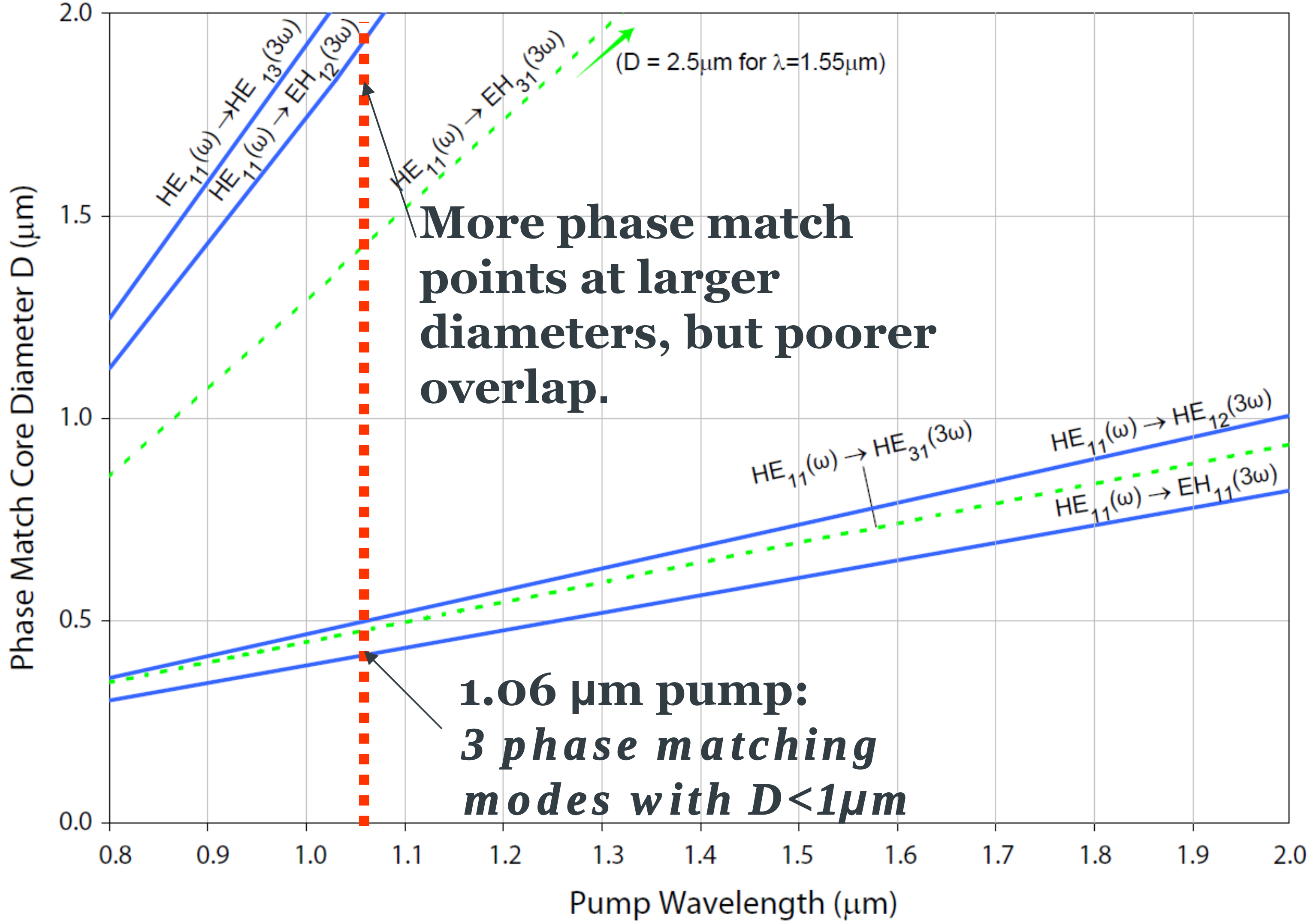

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THG: Overlap

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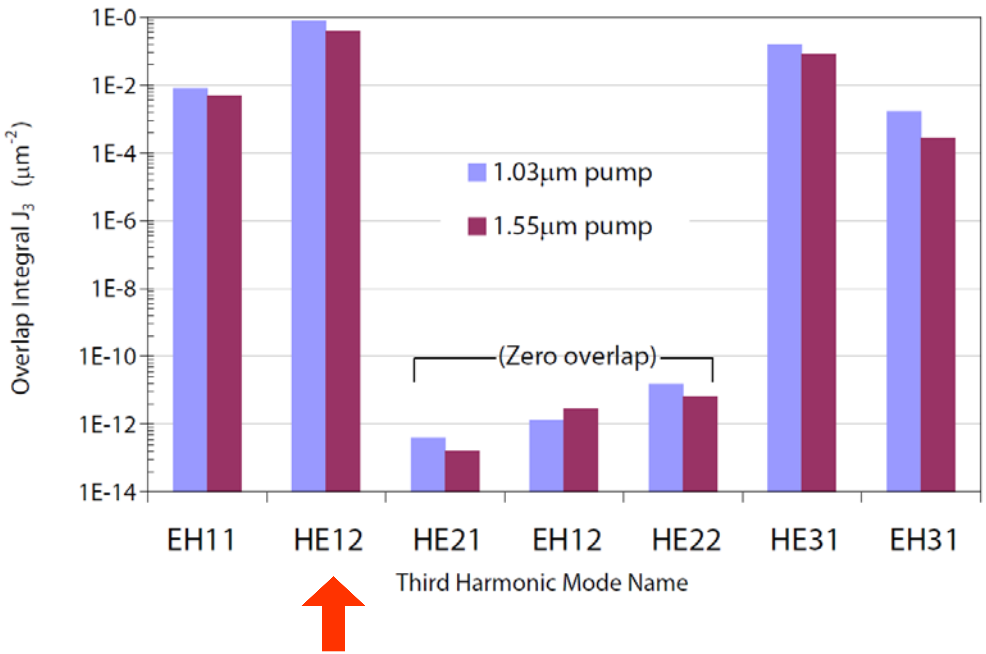
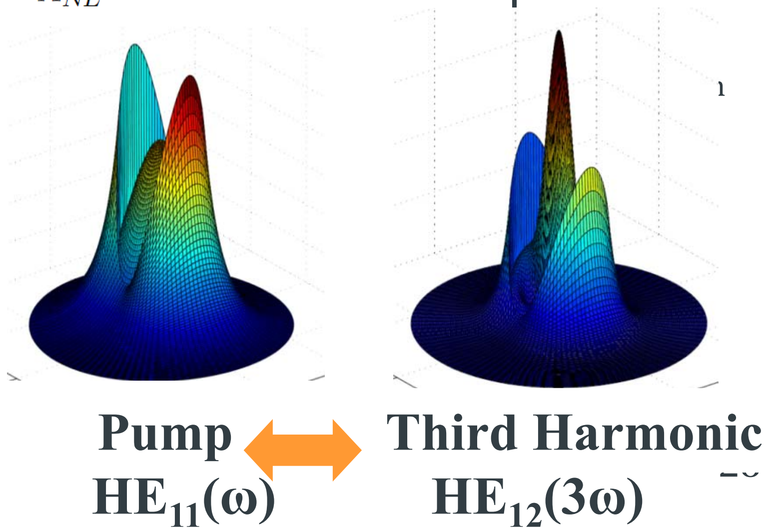
- Overlap between pump and TH mode governs efficiency.
- $HE_{12}(3\omega)$ overlap is greatest: 0.76 μm^{-2} for a 1.0 μm pump
- It increases for decreasing wavelengths (it is 0.38 μm^{-2} for 1.55 μm pump).
- Overlap is zero *TE*, *TM* and hybrid HE_{vm} EH_{vm} modes with even azimuthal mode order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

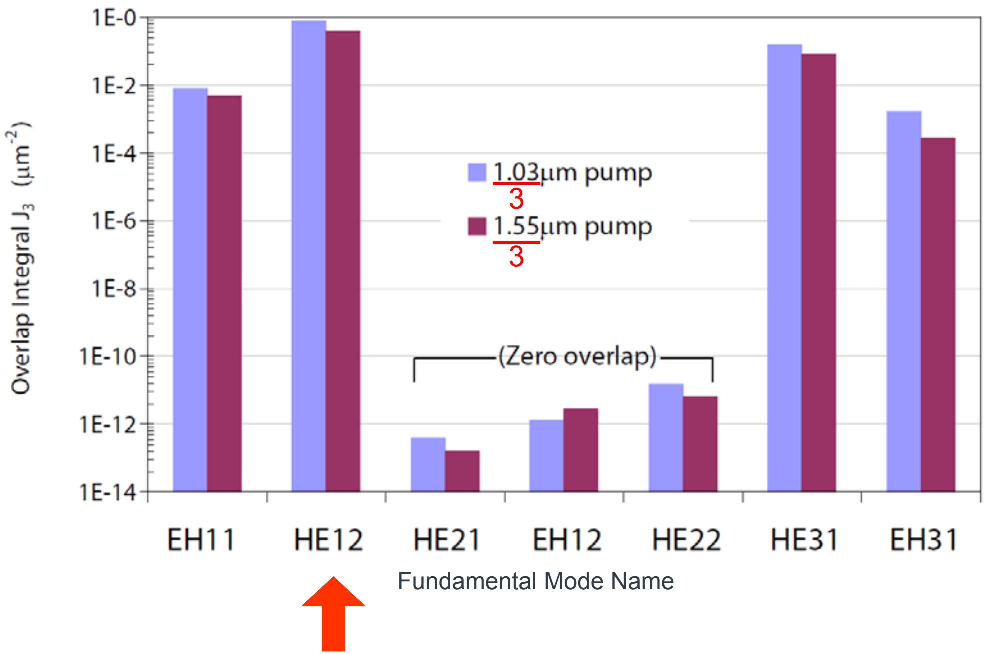
$$J_3 = \iint_{A_{NL}} \left((\boldsymbol{F}_1 . \boldsymbol{F}_3) |\boldsymbol{F}_1^*|^2 \right) dA$$



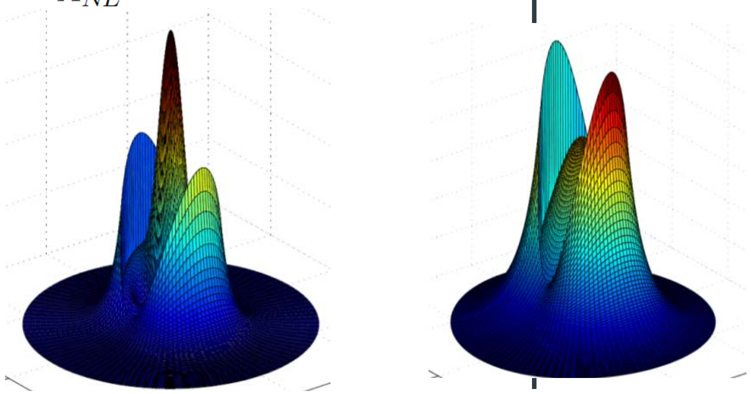


TPG: Overlap

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



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



Pump $HE_{12}(\lambda)$ ↔ **Three photons** $HE_{11}(3\lambda)$

THG: experiment

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Taper

D = 0.78 μm,

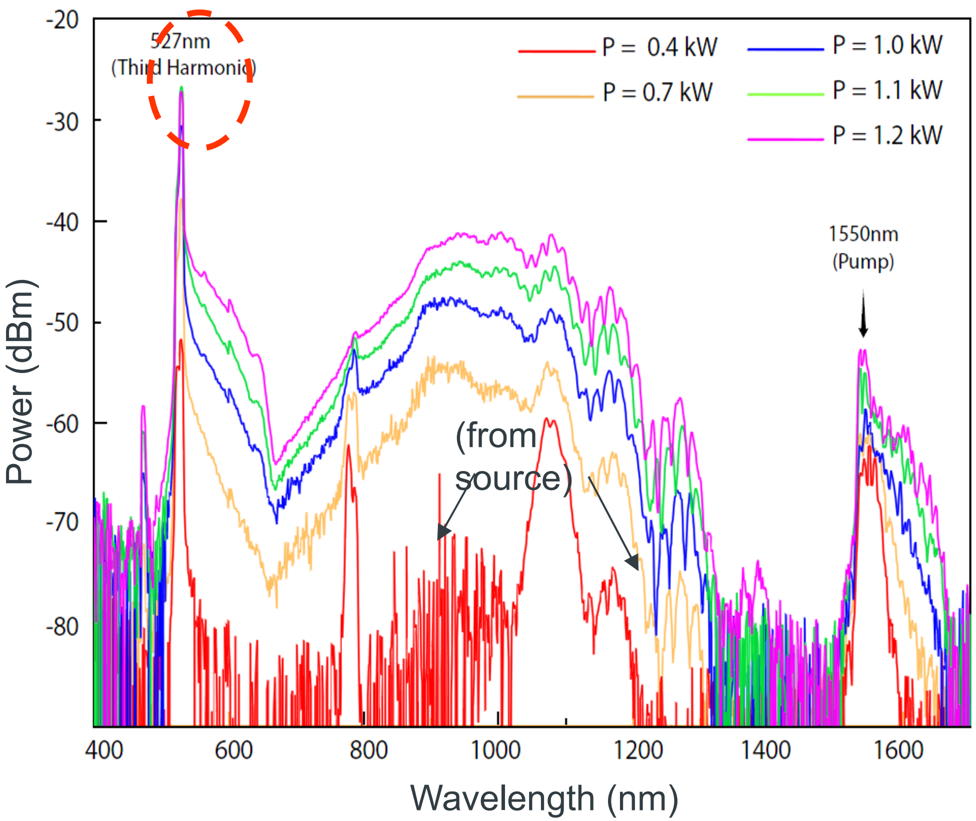
L ~200μm

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

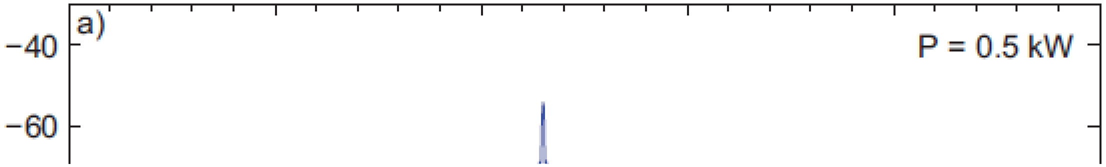
η_{meas}~10^{-3}

η_{th}=$2\cdot10^{-2}$

Spectrum recorded after shortpass filter:



THG: broadband generation



Broadband third harmonic generation in tapered silica fibres

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[2] *SPI Lasers, Southampton, SO30 2QU, United Kingdom*
[3] *Physics Department, University of Auckland, Private Bag 92019, Auckland, 1142, New Zealand*
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Abstract: Optical microfibres have recently attracted much attention for nonlinear applications, due to their tight modal confinement. Here, we report broadband third harmonic generation based on the intermodal phase matching technique in silica microfibres of several centimetres. The third harmonic signal is predominantly generated from the taper transition regions (rather than the waist), wherein the range of diameters permits phase matching over a wide bandwidth. Microfibres up to 4.5 cm long were fabricated with waist diameters below 2.5 μm to allow a $\lambda = 1.55$ μm pump to phase match with several higher order third harmonic modes; conversion rates up to 3×10^{-4} were recorded when pumped with 4 ns pulses at a peak power of 1.25 kW. Analysis of the third harmonic frequencies generated from the nonlinearly broadened pump components indicate a 5 dB conversion bandwidth of at least 36 nm, with harmonic power detected over a 150 nm range.

OCIS codes: (190.0190) Nonlinear optics; (190.2620) Harmonic generation and mixing; (190.4160) Multiharmonic generation; (190.4370) Nonlinear optics, fibers.

UV: Phase matching at λ=0.35μm

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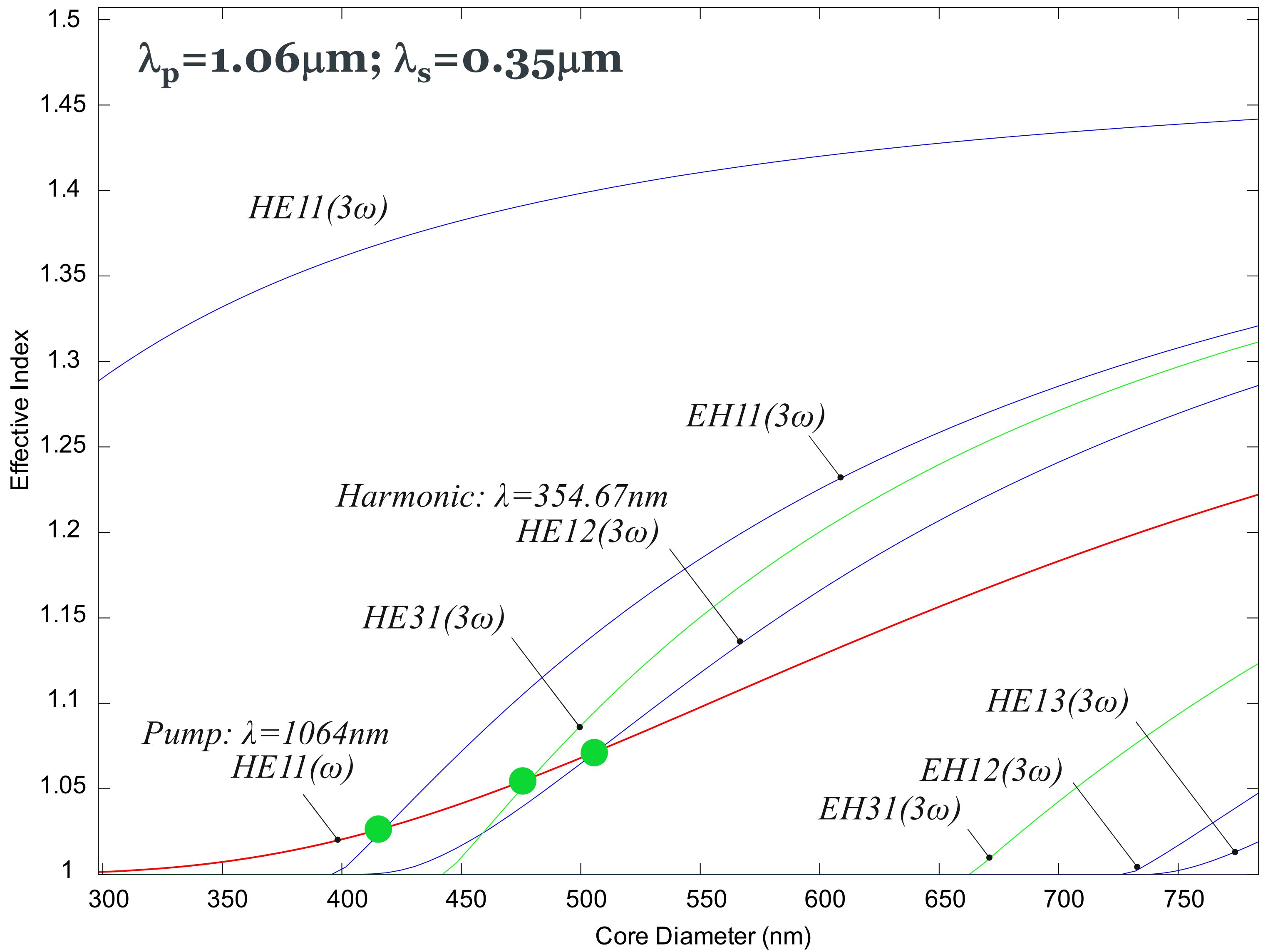

UV: Phase matching at λ=0.27μm

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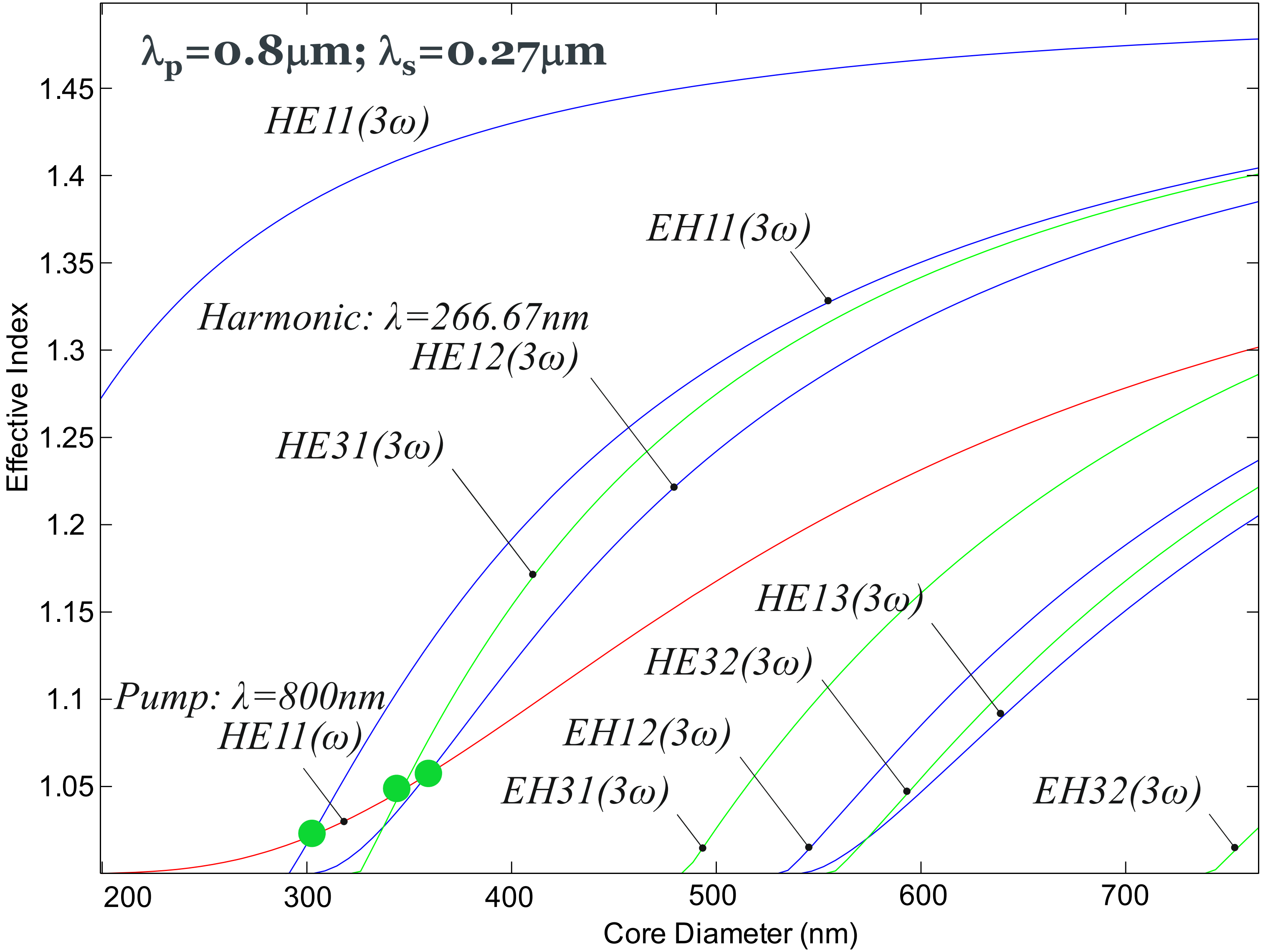


Introduction
Silica loss

Nonlinear processes

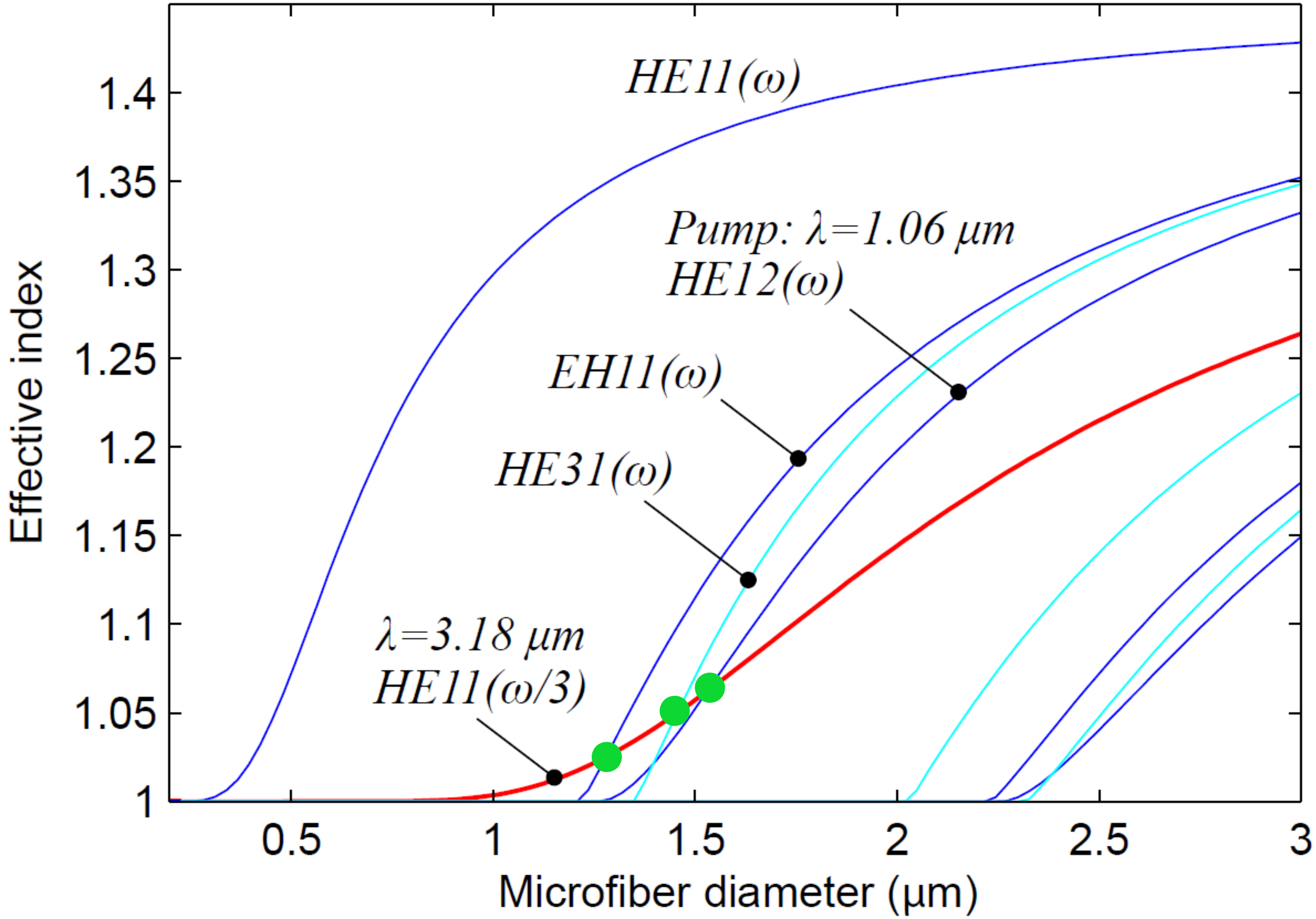
UV generation

IR generation

Conclusions

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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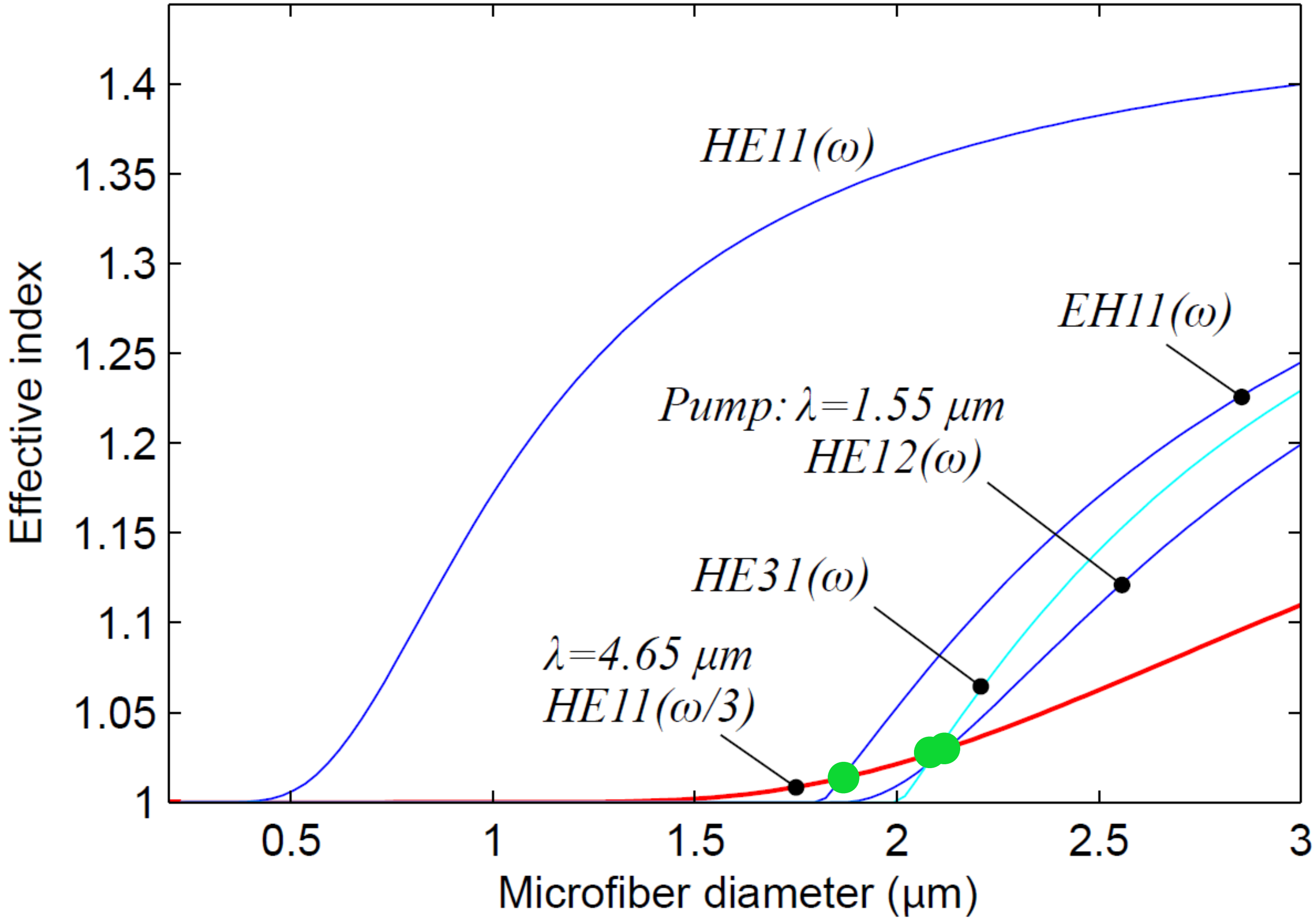
λ_p=1.55μm; λ_s=4.65μm



THG: conversion efficiency

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- **THG differential equations [1] :**

SPM XPM THG term with detuning

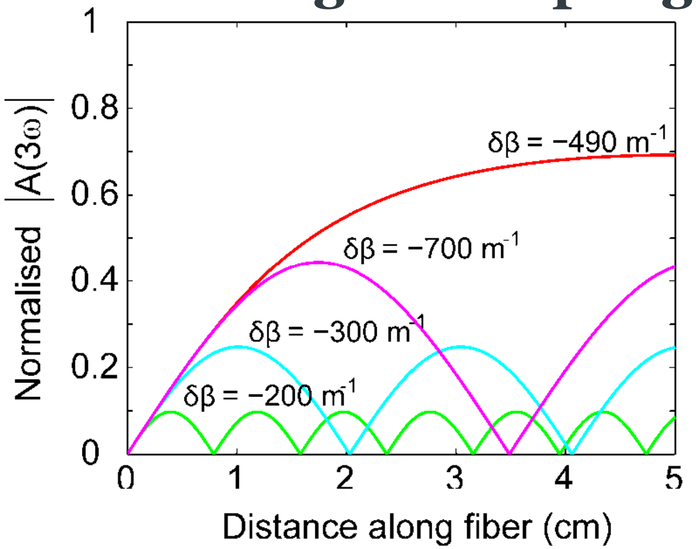
Pump:

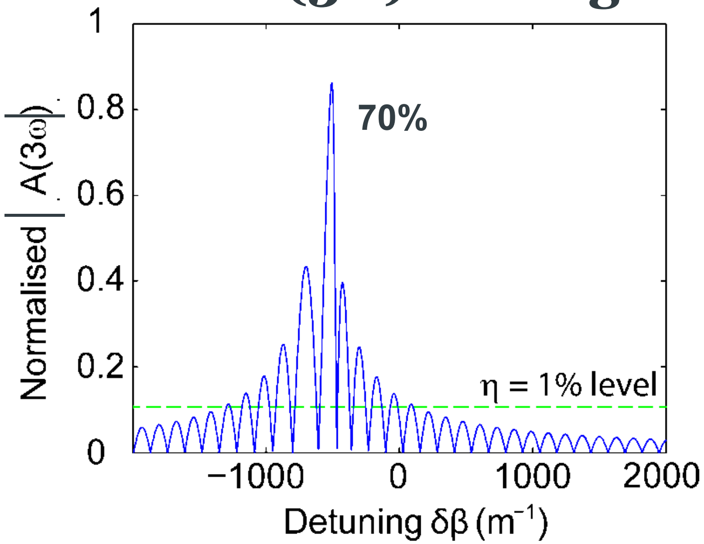
$$\frac{dA_1}{dz} = in^{(2)}k_1 \left\{ (J_1|A_1|^2 + 2J_2|A_3|^2) A_1 + J_3 A_1^{*2} A_3 e^{i\delta\beta z} \right\}$$

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**

[1] V. Grubsky and A. Savchenko, Opt. Expr. 13, 6798 (2006).

UV conversion efficiency

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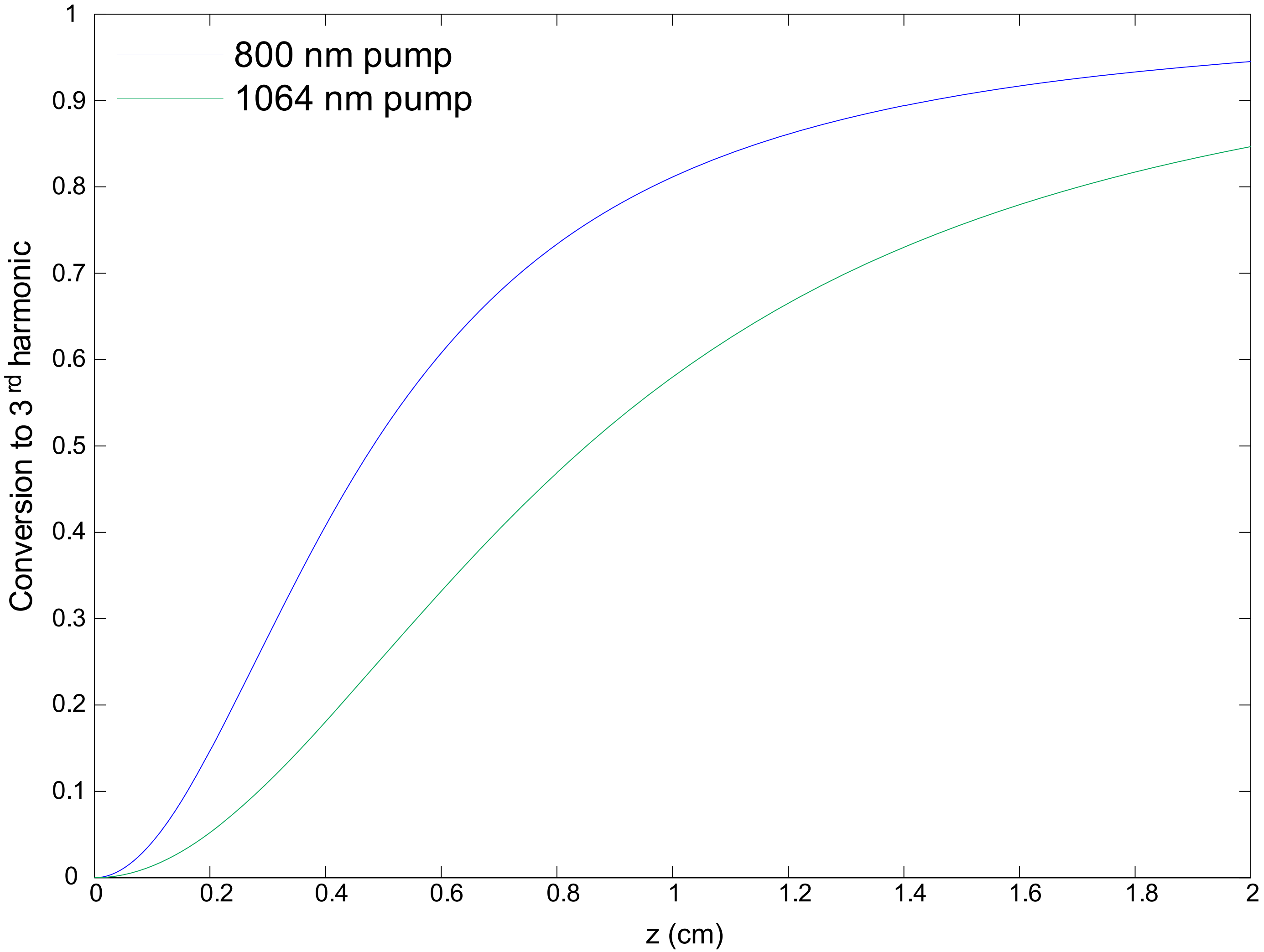

THG: detuning

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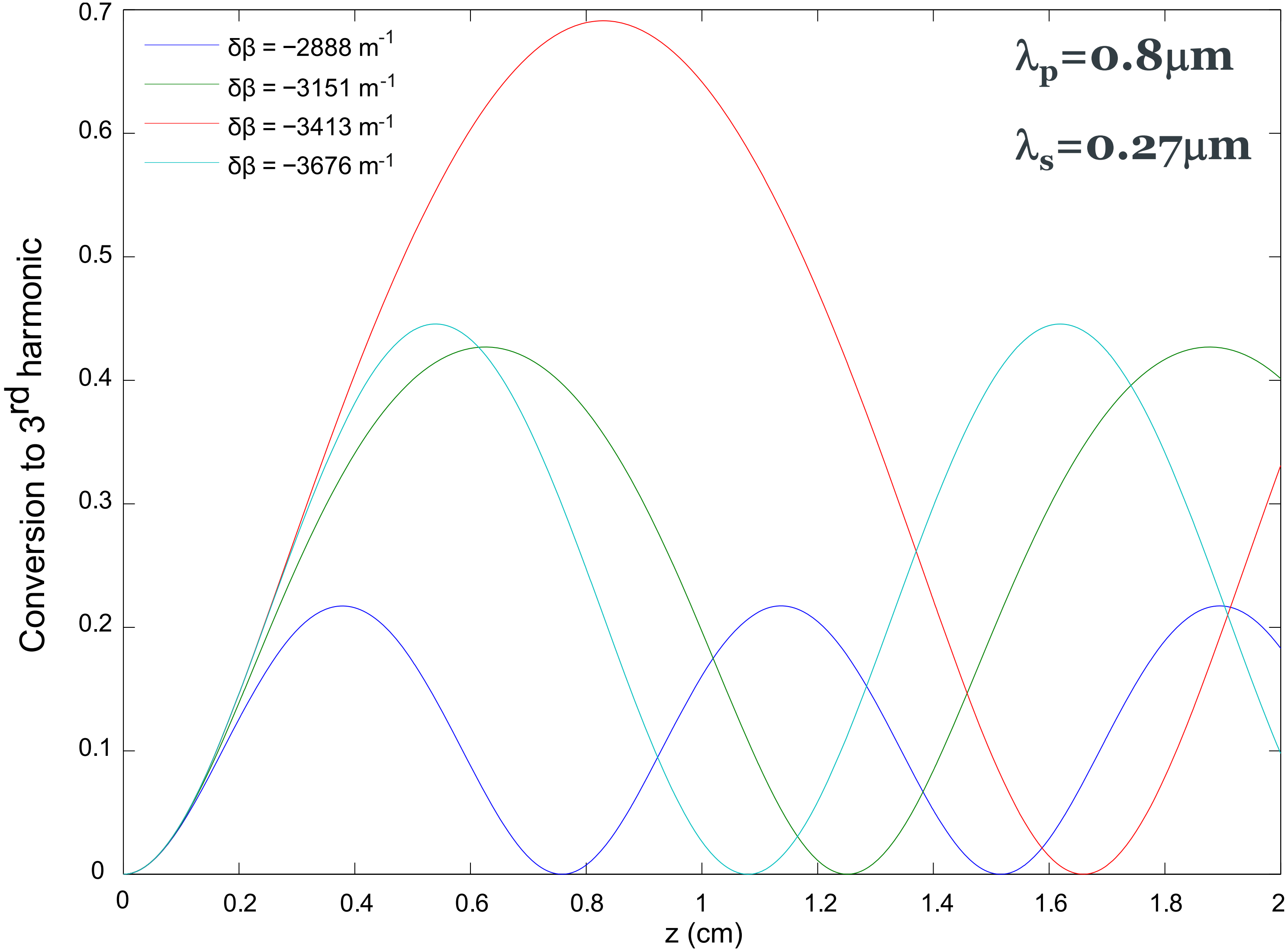
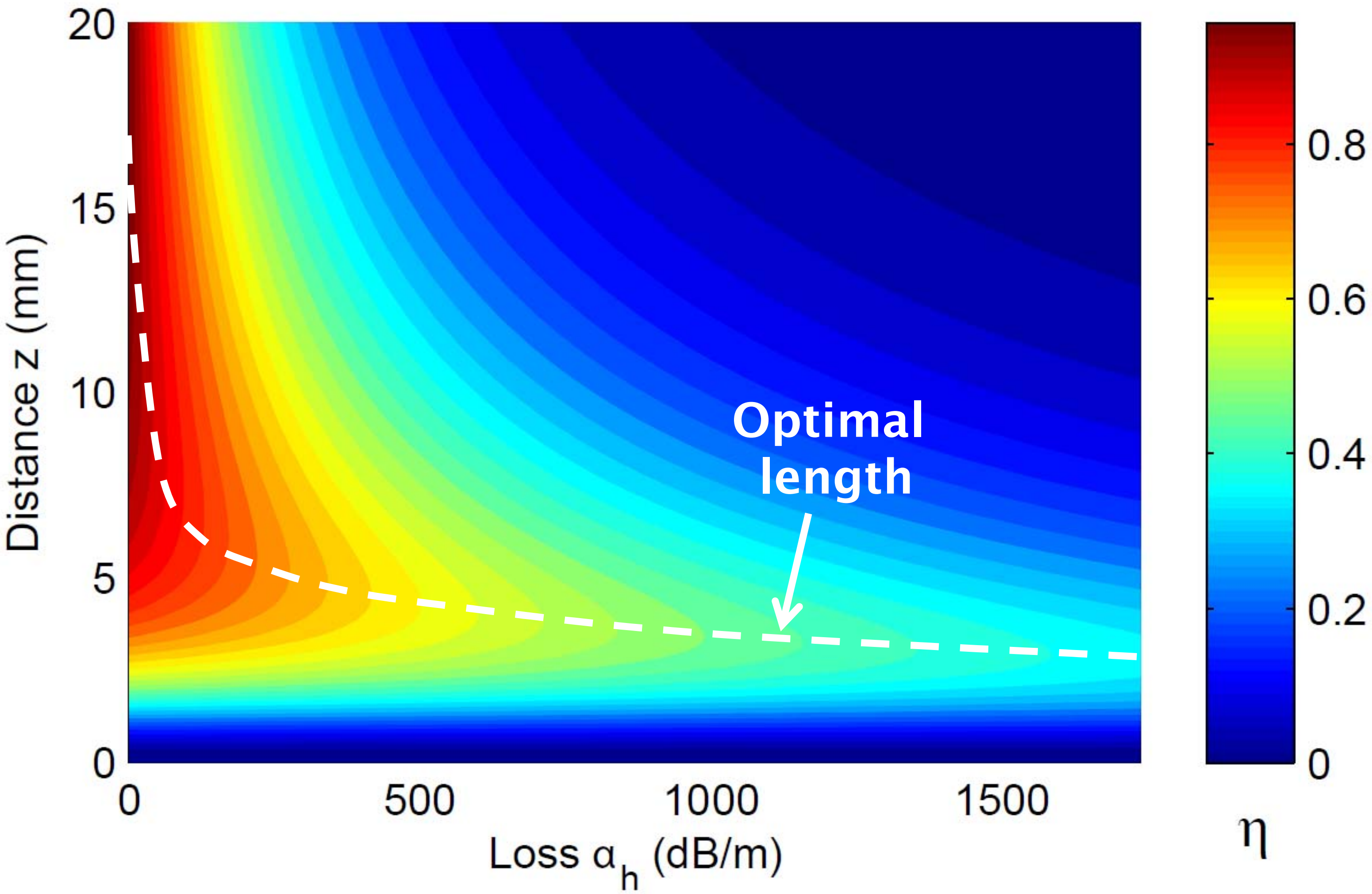


THG: Effect of loss



Fibres: Phase matching

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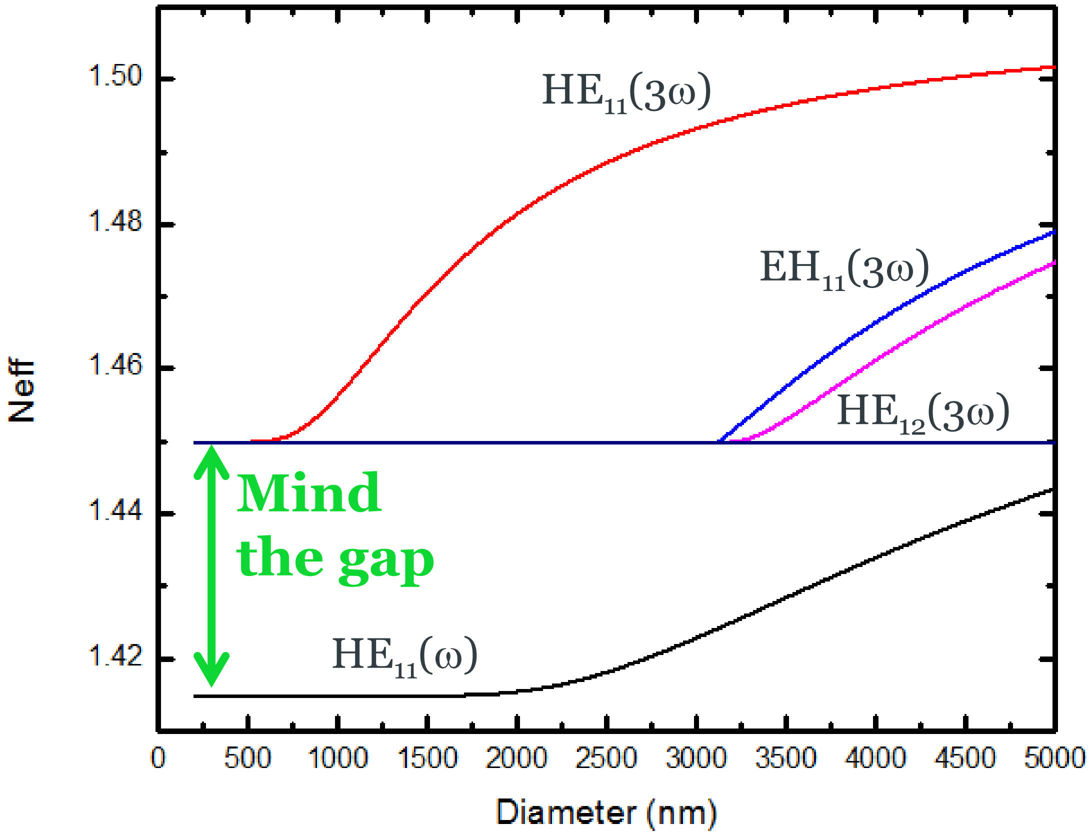
λ_p=1.06μm; λ_s=3.18μm

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

NA~0.42



Fibres: Phase matching

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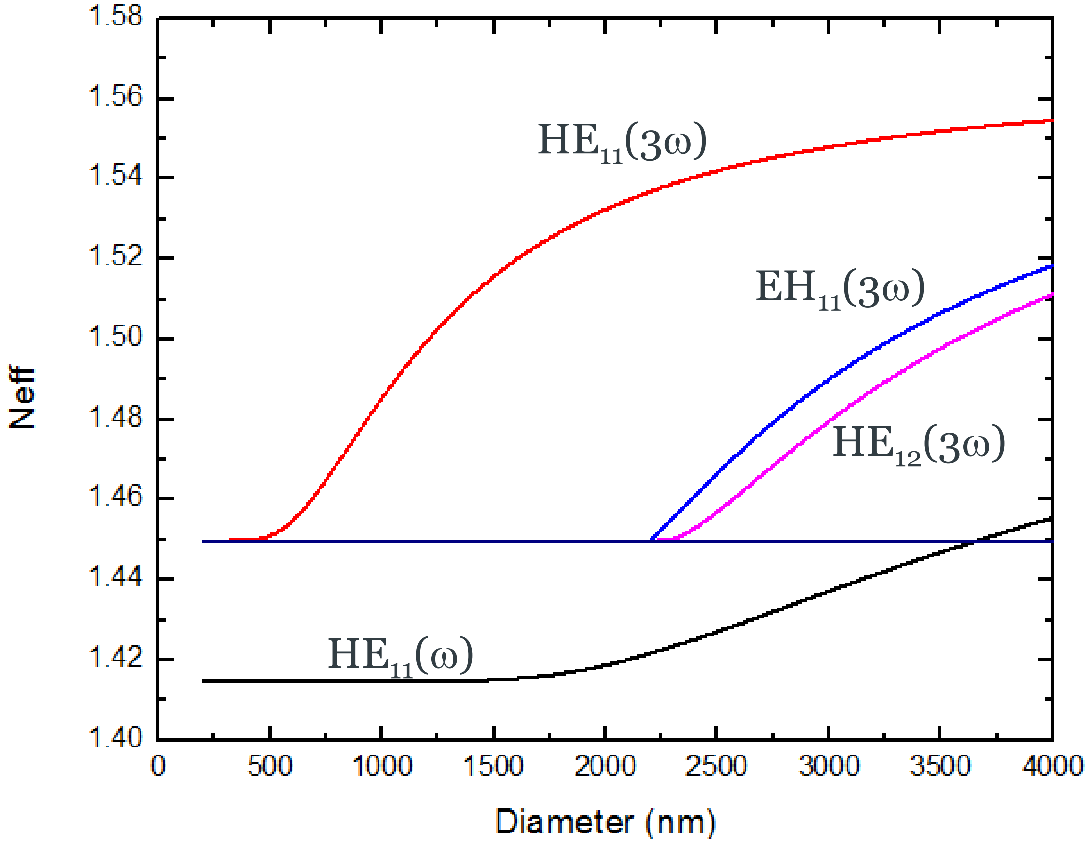
λ_p=1.06μm; λ_s=3.18μm

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

NA~0.52



Fibres: Phase matching

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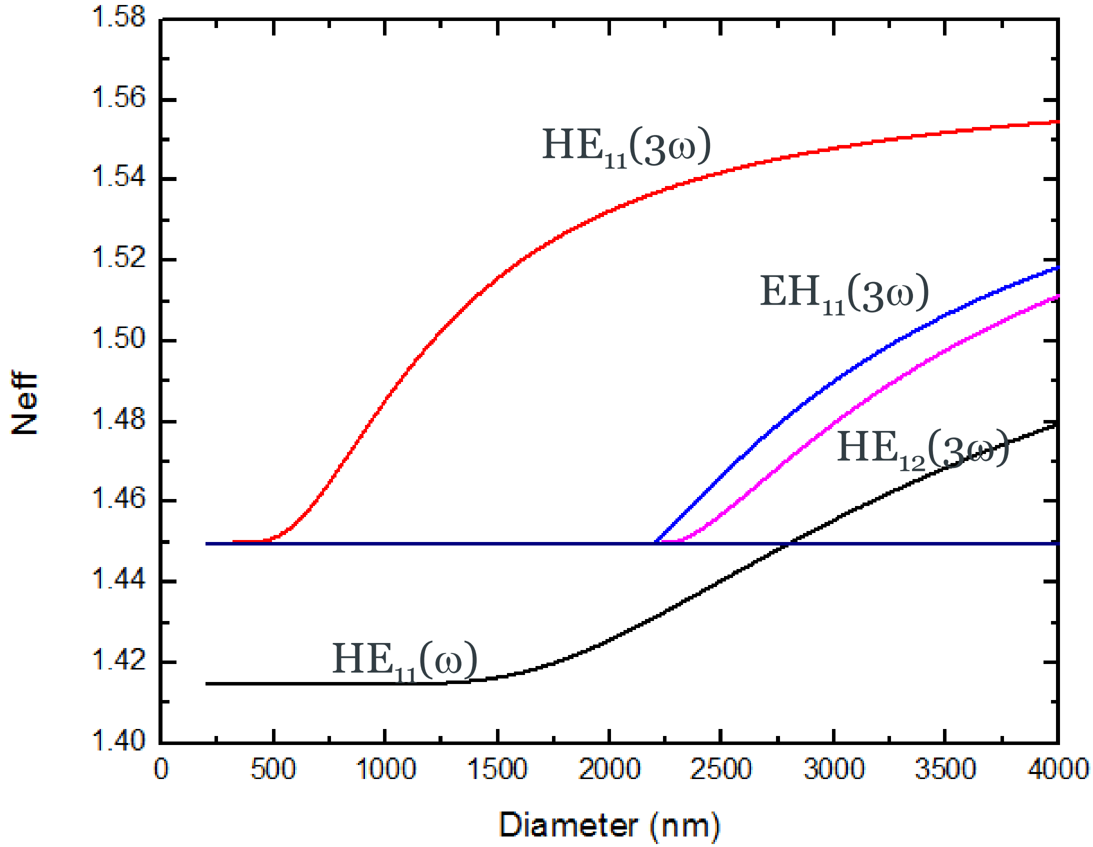
λ_p=1.06μm; λ_s=3.18μm

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

NA~0.6



Fibres: Phase matching

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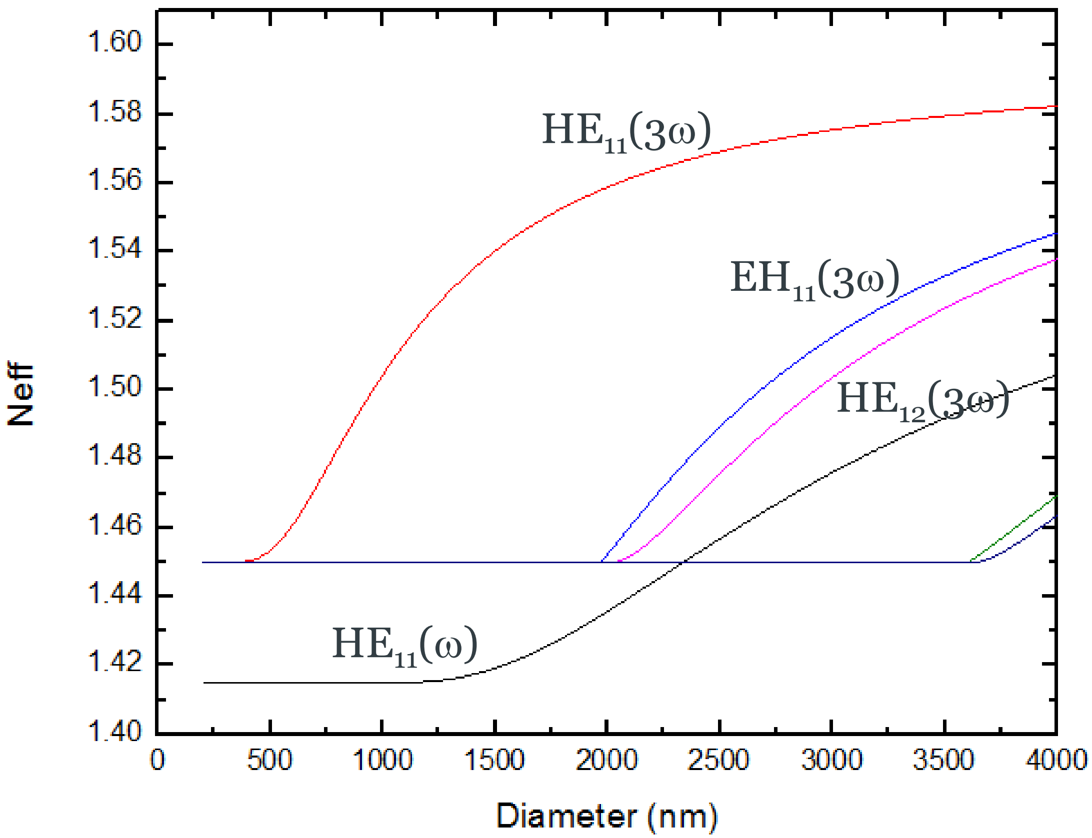
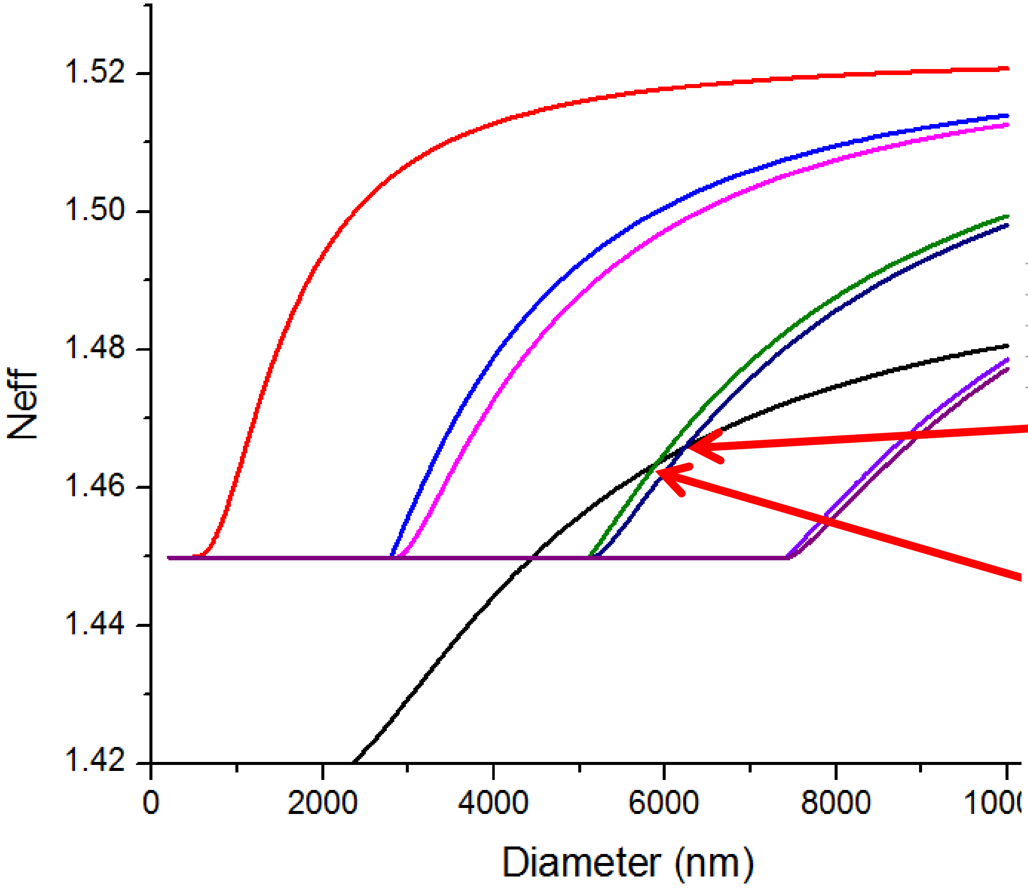
λ_p=1.06μm; λ_s=3.18μm

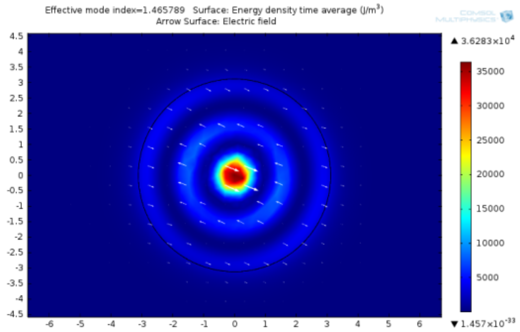
Ge-doped silica fibre. [Ge]=100%

NA~0.67

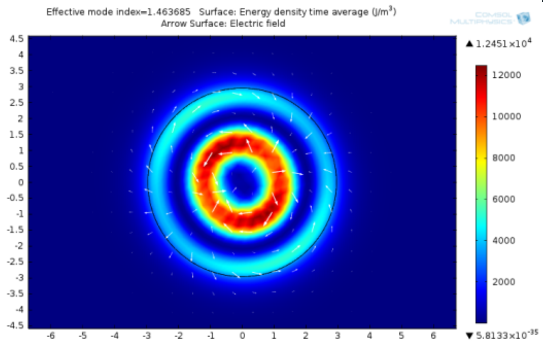


Fibres: Phase matching
The Good News





6232.5 nm-1.4658



5911.5 nm-1.4636

PM takes place at large core diameters

Nonlinearity

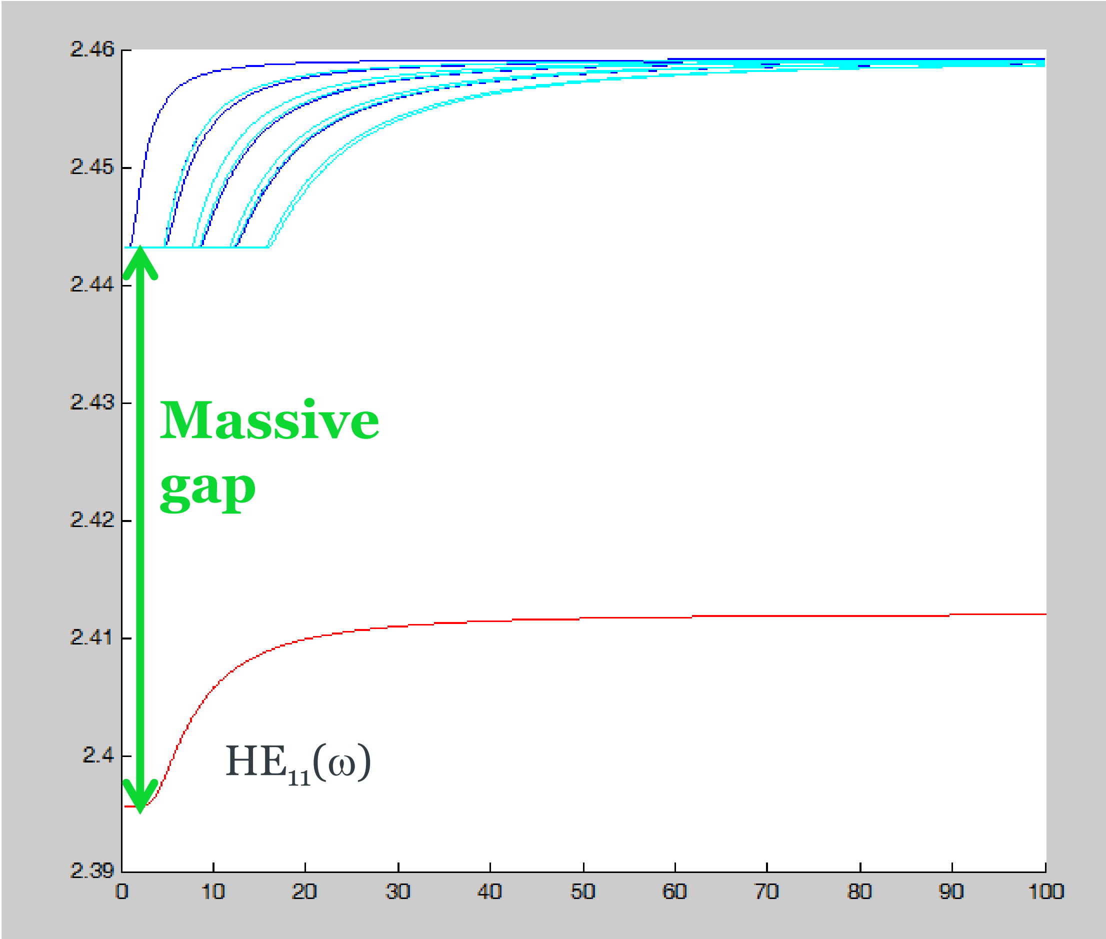
$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}}$$

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

CHG fibres: Phase matching

λ_p=1.06μm; λ_s=3.18μm

NA=0.28

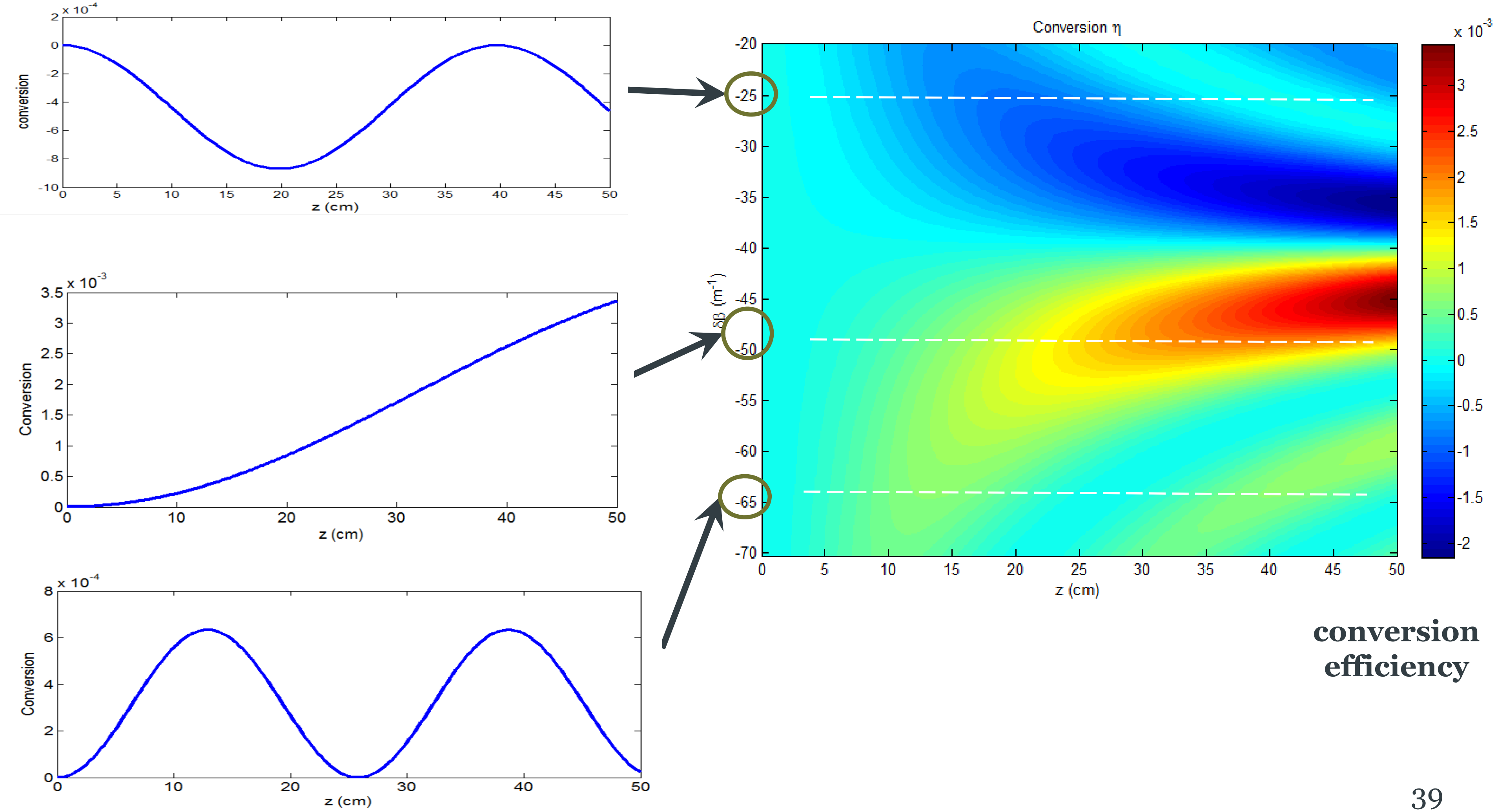


In high n materials refractive index dispersion compensation is much more difficult

Fibres: detuning

P_s=10W, P_p=1kW

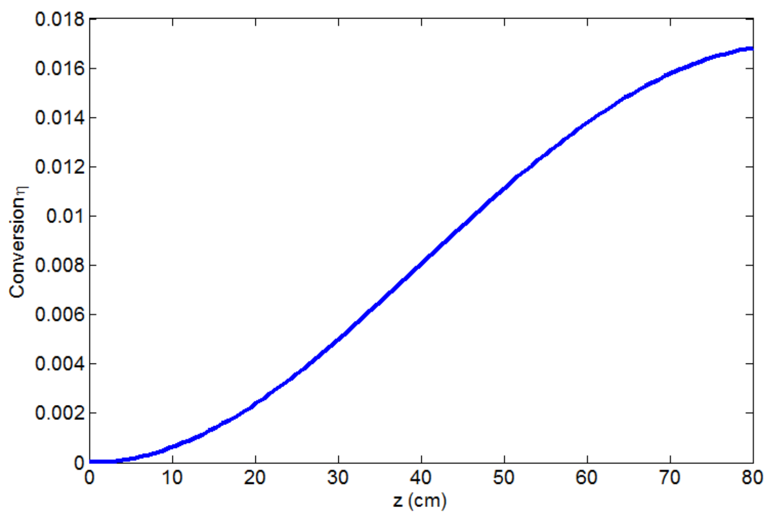
$\eta=(P_{s\text{-}out}-P_{s\text{-}in})/P_{p\text{-}in}$

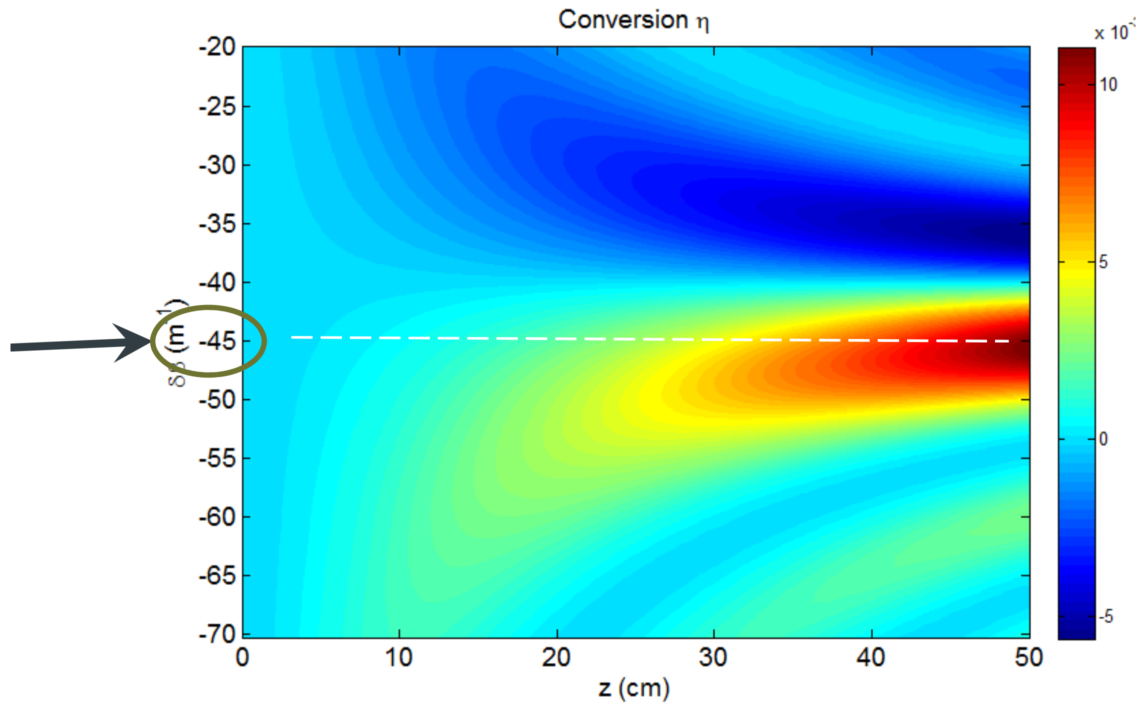


conversion efficiency

Fibres: detuning

P_s=20W, P_p=1kW

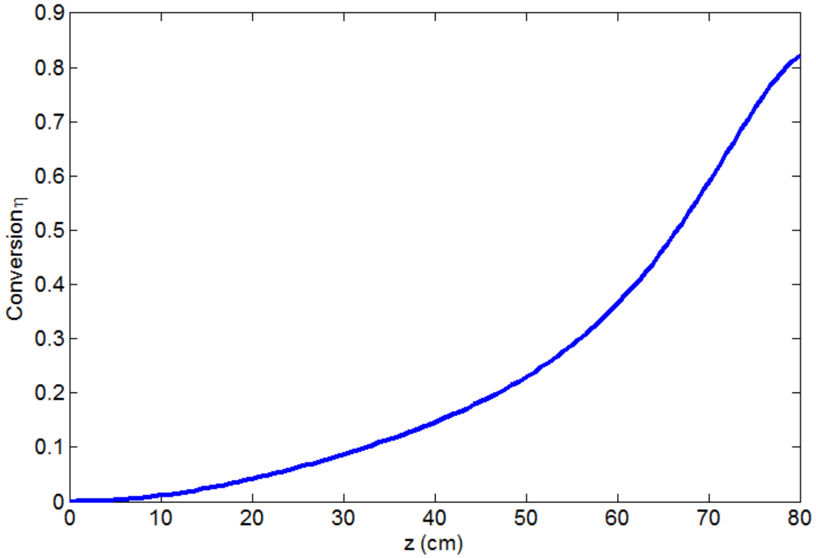


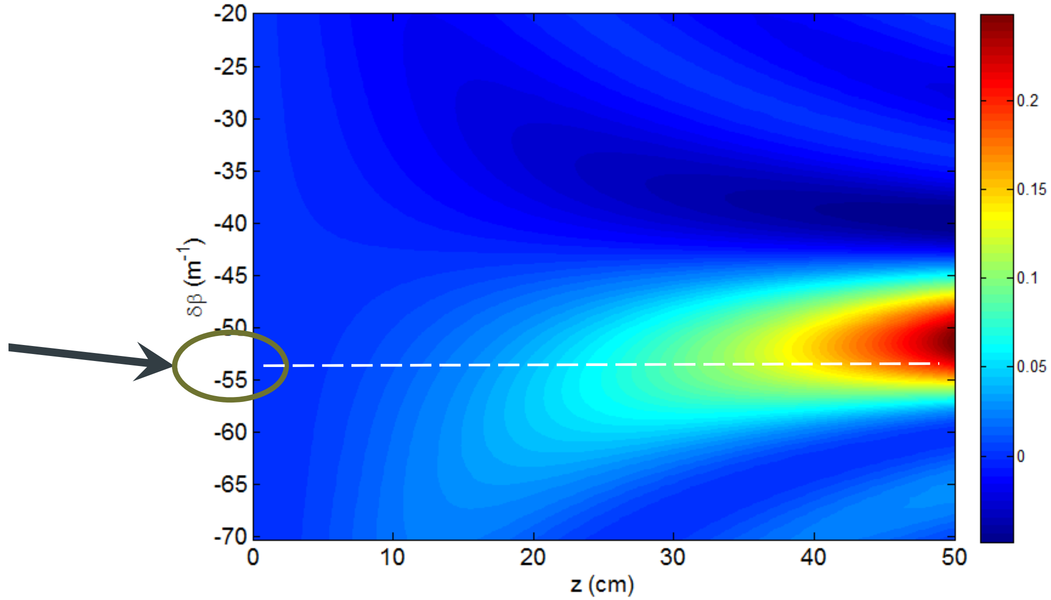


conversion

Fibres: detuning

P_s=100W, P_p=1kW





conversion

THG: resonant effects

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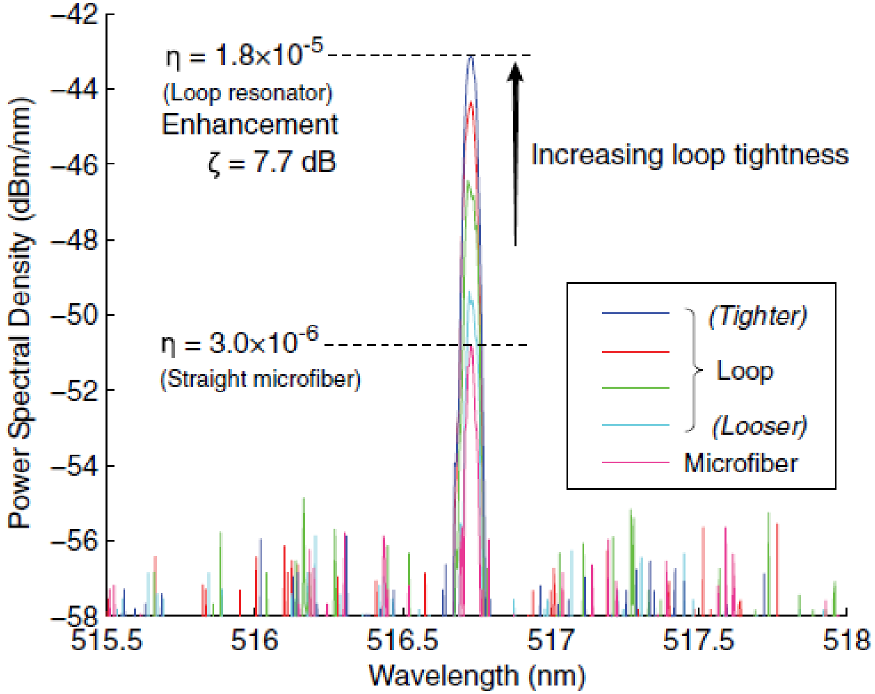

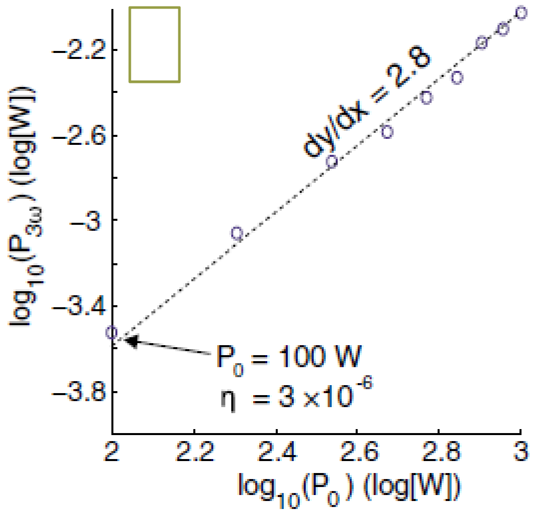

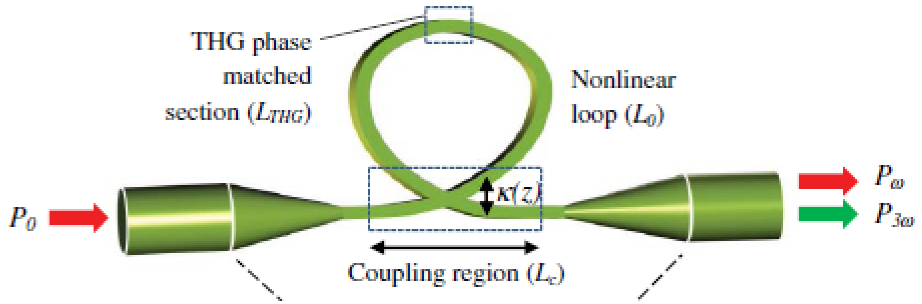

Conclusions

Silica has loss ,1dB/mm in the UV (200nm) and IR (up to 4.5μm)

Fibres and tapers can be used to generate light in the UV or IR

Up-conversion (THG) → UV generation

Down-Conversion (TPG) → IR generation

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

Aknowledgments

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Rand Ismaeel

Marcelo Gouveia

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Thank you

questions?