Efficient third harmonic generation: phase compensation using inter-fibre spacing

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14/12/2022

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Entangled photon pairs have held a paradigmatic place in physics for decades, but entangled triple photons has yet to be achieved.

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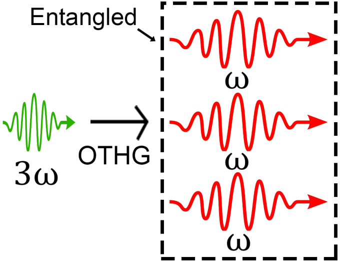

Figure: Photon splitting during One-Third Harmonic Generation.

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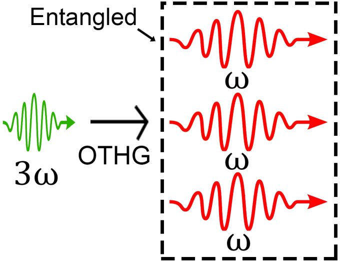

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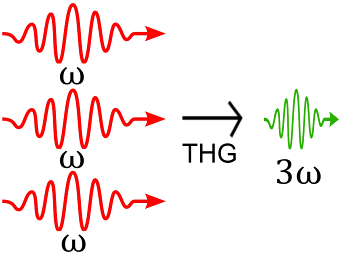

Figure: Photon merging during Third Harmonic Generation.

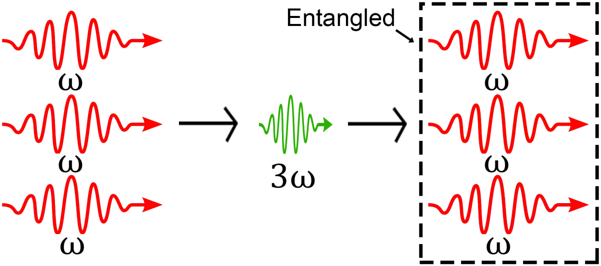

Figure: THG and stimulated OTHG as a full process.

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THG is a nonlinear parametric process, making it subject to the phase-matching condition.

$$\frac{\partial A_1}{\partial z} = i[(\gamma_1|A_1|^2 + \gamma_{13}|A_3|^2)A_1 + \gamma_c(A_1^*)^2 A_3 e^{i\delta\beta z}]$$
$$\frac{\partial A_3}{\partial z} = i[(\gamma_{31}|A_1|^2 + \gamma_3|A_3|^2)A_3 + \gamma_c A_1^3 e^{-i\delta\beta z}].$$

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Optical fibres are attractive platforms for THG due to the ability to induce inter-modal phase-matching.

$$\delta\beta = 3\beta_1 - \beta_3.$$

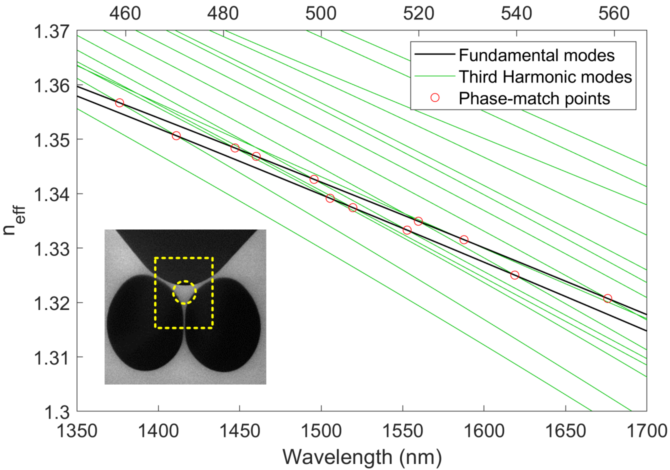

Figure: Effective nonlinear refractive index as a function of wavelength for the modes of a suspended core fibre.

Efficiencies reported in the literature

Publication	Efficiency (%)
X. Jiang *et al.* (2018)	≈ 0.00001
V. Grubksy, J. Feinberg (2006)	0.0002
A. Cavanna *et al.* (2016)	0.00026
S. C. Warren-Smith *et al.* (2016)	0.00045
T. Lee *et al.* (2012)	0.03
Y. Li *et al.* (2020)	0.05
T. Cheng *et al.* (2020)	0.068

Efficiencies for fibre based THG remain low, at considerably less than 1%. This has suggested there is a need for a 'scheme' to greatly improve the efficiency for the process.

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This theory derives from paper *Efficient third and one-third harmonic generation in nonlinear waveguides*[4].

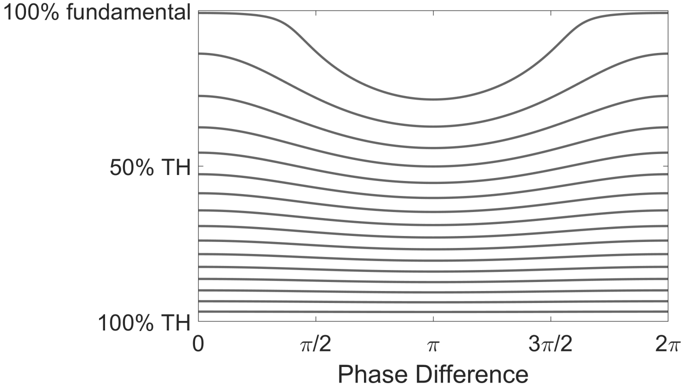

Figure: Phase space with constant energy contours

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Theoretical efficiency of THG

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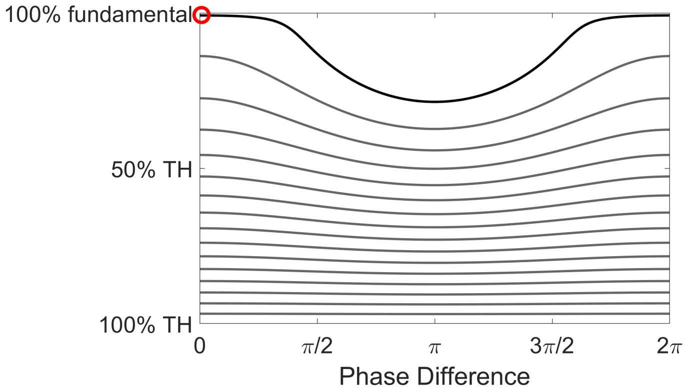

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Power transfer between frequencies

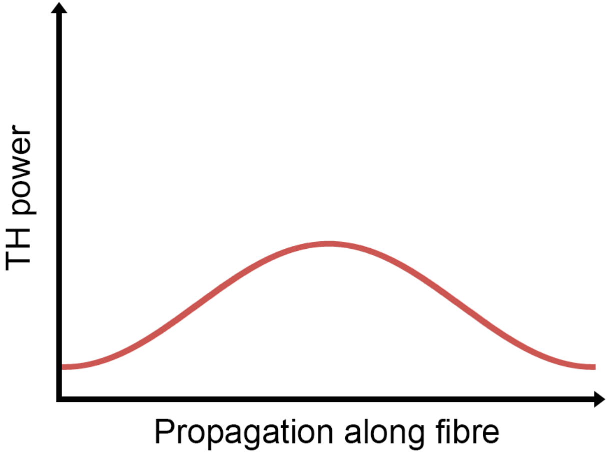

Figure: Oscillatory behaviour in the THG power as it propagates along the fibre.

Phase compensation using fibre spacing

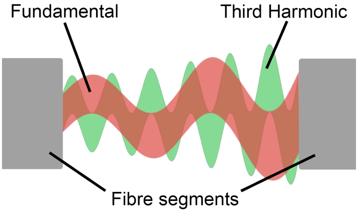

Figure: Coupling of the two frequencies of light between two fibre segments.

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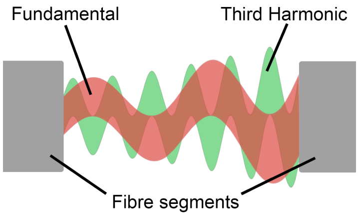

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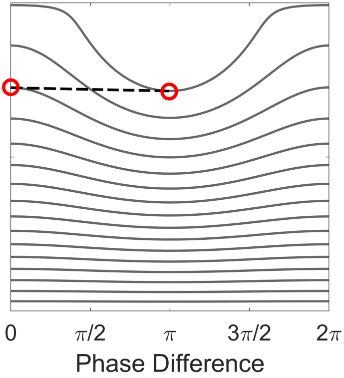

Figure: Result of this phase compensation in the phase space.

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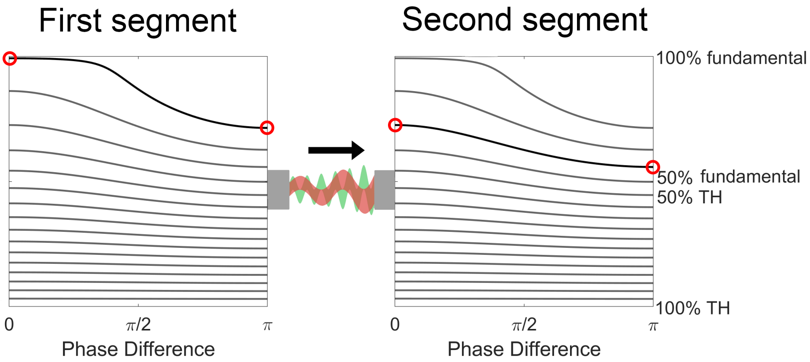

Figure: Depiction of the contours traced between the two segments of optical fibre.

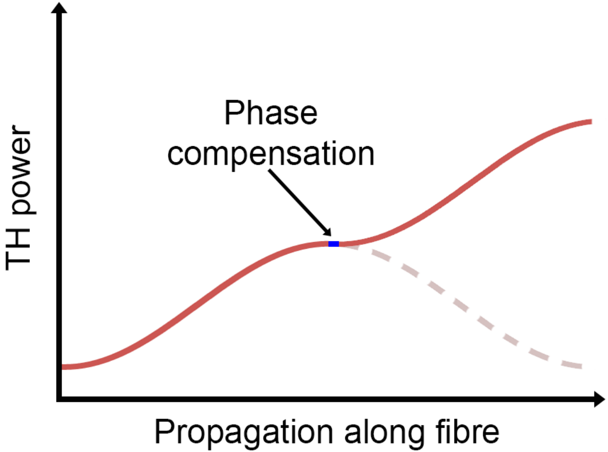

Figure: Monotonic power transfer from the fundamental to the third harmonic due to phase compensation.

Divergence of light during fibre gap

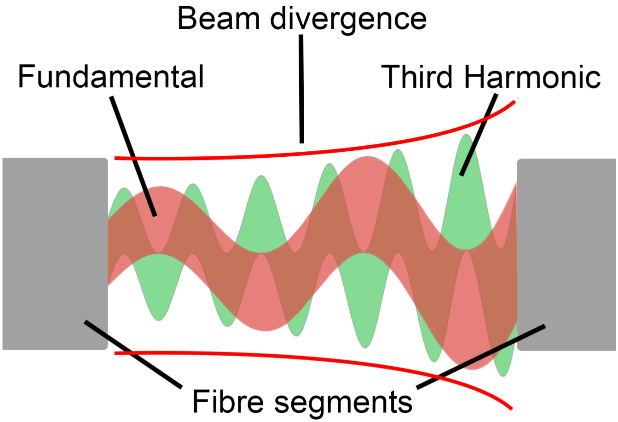

Figure: Divergence of the two frequencies as they propagate through free space.

In order to simulate properties of the fibre, COMSOL Multiphysics is used.

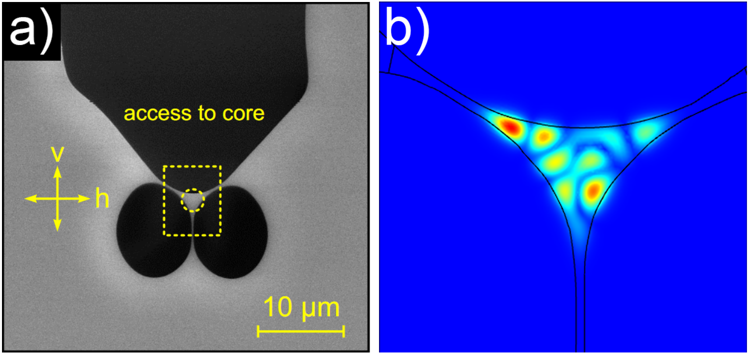

Figure: a) Electron microscope image of the suspended core fibre design[5]. b) Simulation of mode profile using COMSOL multiphysics.

[5] S. C. Warren-Smith et al., 'Third harmonic generation in exposed-core microstructured optical fibers', Opt. Express, vol. 24, no. 16, p. 17860, Aug. 2016, doi: 10.1364/OE.24.017860.

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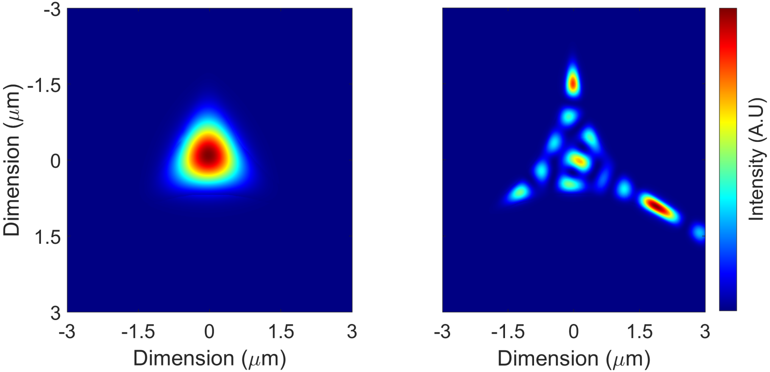


Figure: Intensity profile of the fundamental and higher-order phase-matched mode.

In order to simulate propagation in free-space, we follow a procedure adapted from the textbook *Fundamentals of optical waveguides* (2006)[6].

It uses the split-step Fourier method to solve the wave equation for an axial electric field profile. This, as well as simulation of the mode coupling, can be performed in MATLAB.

[6] K. Okamoto, Fundamentals of optical waveguides, 2nd ed. Amsterdam; Boston: Elsevier, 2006.

Free-space propagation

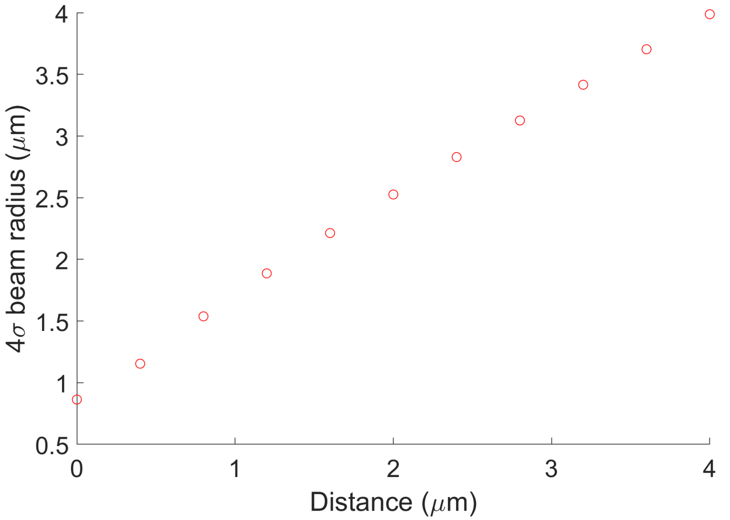


Figure: Beam radius as a function of propagation distance.

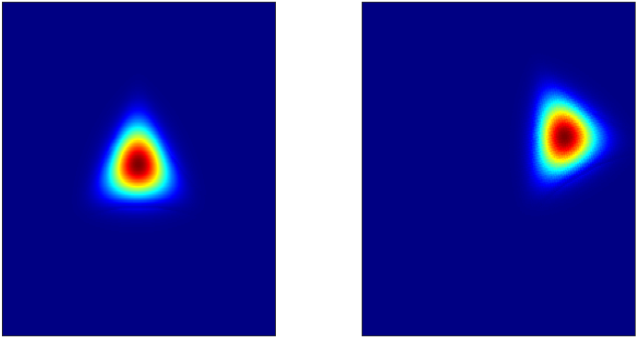
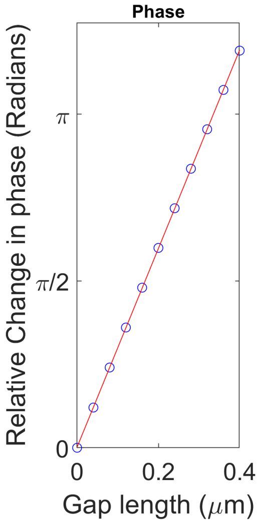


Figure: Relative misalignment between separate fibre segments.

Results


Phase
Relative Change in phase (Radians)
π
π/2
0
0
0.2
0.4
Gap length (μm)

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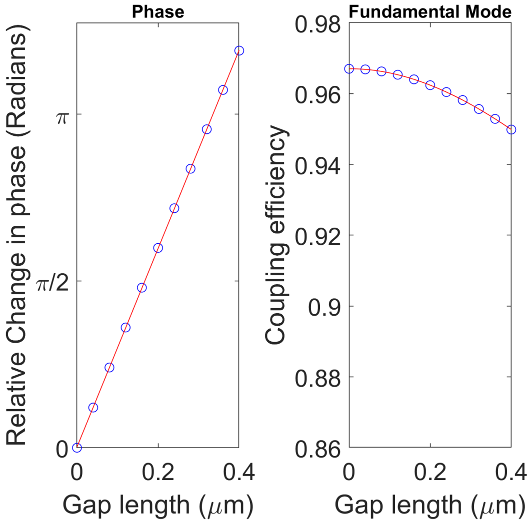

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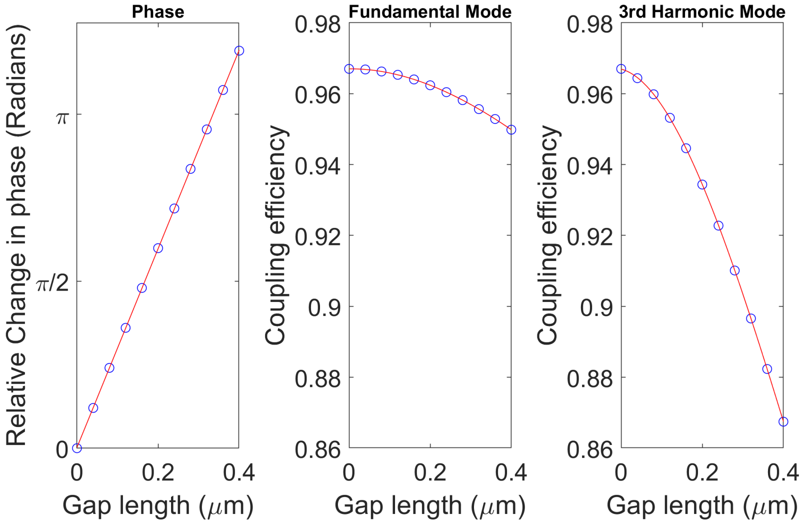

Conclusion

The results of these simulations show that the desired relative phase compensation can be achieved using a small gap of approximately 300nm.

However, the alignment between the fibres must be tightly controlled to avoid power loss.

Future research must empirically test these results, bringing us closer to efficient THG.

Acknowledgements

I would like to acknowledge Playford Trust for the generous scholarship which supported this research.

I would also like to acknowledge my supervisors for supporting me throughout the course of this research.

Any questions?