χ^3 Processes in High Numerical Optical Fibers and Fiber Tapers

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Abstract *Intermodally phase matched up- and down-conversion processes based on the third order nonlinearity can be used to efficiently generate UV and mid-IR wavelength regions in solid core silica optical fibers and optical fiber tapers. We theoretically study the waveguide parameters and practical considerations required for optimum conversion.*

Introduction

The third order $\chi^{(3)}$ nonlinearity in centrosymmetric amorphous media can be used for efficient nonlinear optical processes, including third harmonic generation (THG) and three-photon generation (TPG), which respectively generate light at a frequency triple or one third of the pump frequency. Both processes require the phase matching condition: $n_{eff}(\omega) \approx n_{eff}(3\omega)$, or $\beta(3\omega) - 3\beta(\omega) \approx 0$. However, due to material and waveguide dispersion, the pump and harmonic fundamental modes are phase mismatched, leading to extremely low efficiencies. On the other hand, as higher order modes show lower effective indices than the fundamental mode, intermodal phase matching has been proposed as means to achieve high conversion efficiency in a number of high contrast waveguides, including microstructured fibres[1], optical fiber nanowires[2-5] and high numerical aperture (NA) fibers[6]. Furthermore, the effective nonlinearity in waveguides with dimensions comparable to the wavelength is strongly enhanced by the tight modal confinement[7].

In this paper, the use of solid core optical fibers and optical fiber tapers for THG and TPG is discussed theoretically, with the specific aim of generating light in the UV and mid-IR wavelength regions.

Transparency

Optical fibers have long been perceived as being opaque to UV and mid-IR region and unsuitable for the generation of light in those wavelength regions because (1) the dopants used to increase the core refractive index (primarily germanium and phosphorous oxides) had a strong absorption below 350 nm; and (2) long lengths of fibers were considered, leading to a high cumulative absorption.

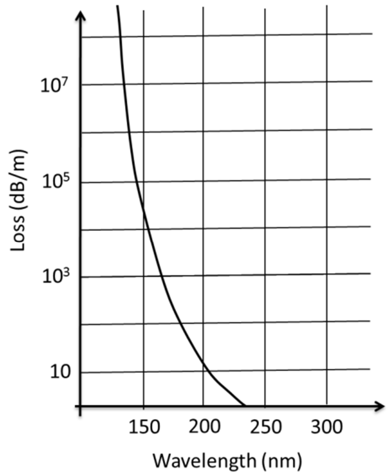

Fig. 1: Loss of pure silica in the UV[8-10].

Figures 1 and 2 present the absorption of pure silica in the UV and mid-IR wavelength regions, respectively. Losses are smaller than 1 dB/cm in the wavelength range 180 nm < λ < 4.7 μm and exceeds 1 dB/mm only at $\lambda > 6\mu$m. By using pure silica (as in the submarine telecom fibers or in optical fiber tapers) light generation and propagation in the UV or mid-IR can therefore be achieved over lengths of the order of a cm without incurring significant losses.

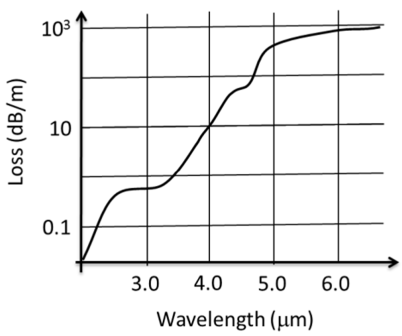

Fig. 2: Loss of pure silica in the mid-IR[11-12].

$\chi^{(3)}$ processes

The waveguide geometry and index contrast required to satisfy the phase matching condition can be easily found by solving the rigorous modal eigenvalue equations assuming a step index profile[13]. Although this might seem a coarse approximation for conventional telecom optical fibers, which traditionally experience strong diffusion during fiber pulling, it is accurate for optical fiber tapers, which have a distinct physical interface between the glass and surrounding, and also for the submarine telecom fibers, which have a pure silica core.

After determining the phase match diameters, the efficiency η can be evaluated from the propagation of the two frequencies' amplitudes[2]:

$$\frac{\partial A_p}{\partial z} = i\gamma_0 \left[\left(J_1 |A_p|^2 + J_2 |A_h|^2 \right) A_p + J_3 \left(A_p^* \right)^2 A_h e^{i\Delta\beta z} \right] - \alpha_p A_p \quad (1.1)$$

$$\frac{\partial A_h}{\partial z} = i\gamma_0 \left[\left(6J_2 |A_p|^2 + 3J_5 |A_h|^2 \right) A_h + J_3^* \left(A_p \right)^3 e^{-i\Delta\beta z} \right] - \alpha_h A_h \quad (1.2)$$

where A_p and A_h are the amplitudes of the pump and the third harmonic mode, J_i are the modal overlaps between the power-normalized electric field distributions, $\Delta\beta = \beta(3\omega) - 3\beta(\omega)$ is the detuning, $\gamma_0 = 2\pi n^{(2)}/\lambda$, $n^{(2)}$ is the nonlinear refractive index and α_p, α_h are the losses.

Firstly, Fig. 3 illustrates the phase matching conditions for TPG when pumping at 1.05 μm and 1.55 μm respectively using a higher order mode to generate the one-third (ω/3) harmonic in the mid-IR at the fundamental mode. To couple the $HE_{11}(\omega/3)$ and $HE_{12}(\omega)$ modes requires a diameter approximately half of the one-third harmonic's wavelength. This pair of modes seems to be most efficient for both THG and TPG in high NA waveguides, due to their large overlap J_3 with each other.

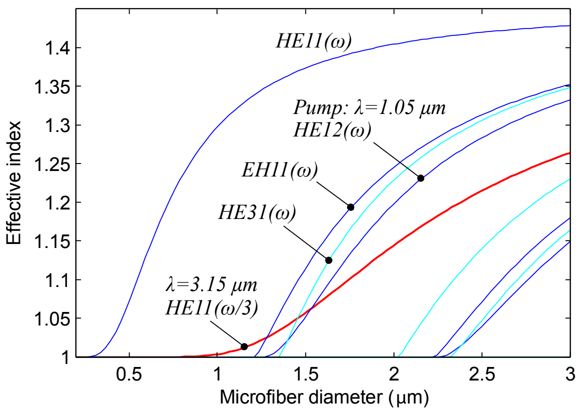

Fig. 3: Dependence of the effective indices of the pump and one-third harmonic modes against diameter for TPG in a silica microfiber in air. Pump wavelength is λ_p = 1.05 μm.

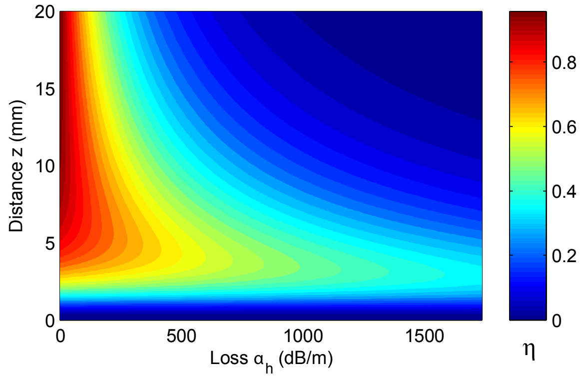

Fig. 4: Effect of UV absorption loss α_h on the efficiency η of THG using a λ_p = 0.8 μm pump, when coupled to the $HE_{12}(3\omega)$ mode with $\alpha_p = 0$ and P_p = 1 kW.

For THG, phase matching conditions for the different modes are reported in Table 1, when the pump is in the near–IR (λ_p = 0.8 μm) such that the harmonic is generated in the UV. When coupled with the $HE_{12}(3\omega)$ mode, it is possible to attain up to η = 80% conversion over several mm as shown in Fig. 4. For higher losses α_h around 1 dB/mm it is still possible to attain 50% conversion, but the harmonic signal falls with distance quickly and hence should be coupled out after ~5 mm. Shorter pumping wavelengths allows for higher efficiencies since the tighter maximum modal confinement increases the J_3 overlap.

Phase matching conditions change with the numerical aperture. Fig. 5 presents the phase matching conditions for THG using the

Tab. 1: Phase matching diameters, effective indices and maximum efficiencies for THG between fundamental pump mode and different third harmonic modes for a silica microfiber in air. Pump wavelength is λ_p = 0.8 μm and microfiber length was optimized to achieve maximum efficiency in each case.

Harmonic	D (μm)	n_{eff}	η (%)
EH_{11}	0.30	1.02	4.3×10^{-3}
HE_{12}	0.36	1.06	80
EH_{12}	1.13	1.38	4.5×10^{-3}
HE_{13}	1.24	1.39	7.2×10^{-2}
EH_{13}	2.10	1.43	1.9×10^{-4}
HE_{14}	2.17	1.43	9.3×10^{-2}
HE_{31}	0.35	1.05	47
EH_{31}	0.85	1.33	1.5×10^{-4}
HE_{32}	1.17	1.38	4.5×10^{-4}

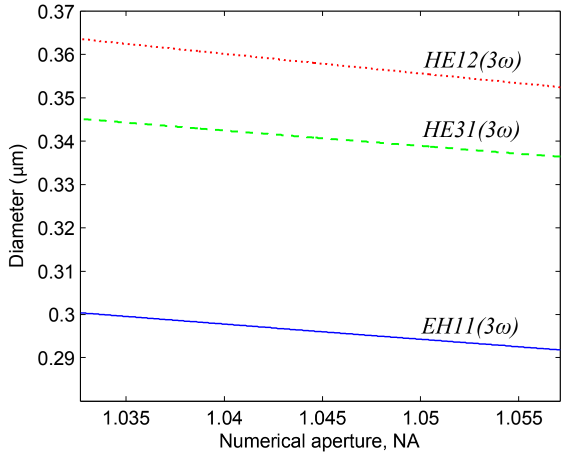

Fig. 5: Dependence of the THG phase matching diameter at different microfiber numerical apertures for different harmonic modes. Pump wavelength is λ_p = 775 nm and power is P_p = 1 kW.

$EH_{11}(3\omega)$, $HE_{12}(3\omega)$ and $HE_{31}(3\omega)$ harmonic modes for a microfiber numerical aperture in the region of 1.05. Here, the microfiber material is varied to simulate realistic Fluorine doping concentrations in the range 0 - 5%.

As before, phase matching between $HE_{11}(\omega)$ and $HE_{12}(3\omega)$ occurs at a diameter which is approximately half of the longest wavelength, and provides the greatest conversion compared to the other harmonic modes.

Finally, high NA optical fibers can be also used for THG and TPG. Intermodal phase matching remains applicable but is complicated by the fact that the cladding index is lower for longer wavelengths in silica. Since the n_{eff} of any guided mode must lie between n_{core} and n_{clad}, this necessitates the additional constraint $n_{core}(\omega) > n_{clad}(3\omega)$, otherwise the pump n_{eff} will always be lower than any third harmonic mode index regardless of core diameter. This is equivalent to ensuring that the core-cladding difference experienced by the pump is sufficient to compensate the index difference of the cladding caused by material dispersion. For this reason, there exists a minimum NA below which intermodal phase matching is impossible. For example, a 1 μm pump for THG in a core with $n_{clad}(\omega)$ = 1.48 requires an NA of at least 0.29, corresponding to a core-cladding difference of 0.03 which would be realistically achievable in practice.

Figure 6 shows the diameter for phase matching to the $HE_{13}(3\omega)$ for THG using a 1.0 μm pump. Note that the peak appears due to the proximity of the phase match point to the $HE_{13}(3\omega)$ mode cutoff; for higher NA values the phase matching

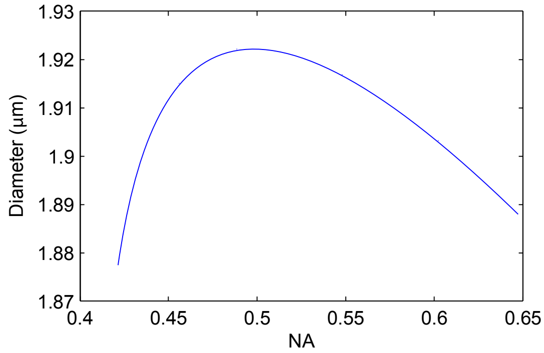

Fig. 6: The required phase matching diameter for THG in a silica high NA fiber, for matching the $HE_{11}(\omega)$ and $HE_{13}(3\omega)$ modes. The NA is varied by altering n_{core} whilst keeping n_{clad} constant. λ_p = 1.0 μm.

diameter will fall monotonically according to the increased modal confinement.

In conclusion, it is possible to exploit $\chi^{(3)}$ processes in silica to generate wavelengths within the UV and mid IR. In microfibers the tight confinement allows high efficiencies over short distances, whereas high NA fibers benefit from improved robustness and much longer possible interaction lengths limited by loss or walkoff rather than fabrication constraints.

Acknowledgements

G. Brambilla gratefully acknowledges the Royal Society (London) for his University Research fellowship.

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