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Parametric χ^3 Light Generation in Subwavelength Waveguides

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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.

OCIS codes: 190.0190, 190.2620, 190.4160, 190.4370

1. Introduction

Third order χ^3 nonlinearity in centrosymmetric amorphous media can be used for efficient generation of light via third harmonic generation (THG) and Parametric Amplification (PA). These two processes require the phase matching condition where the effective refractive index of the pump (ω) and harmonic (3ω) wavelengths is the same ($n_{eff}(\omega) \approx n_{eff}(3\omega)$). Normally, the material and waveguide dispersion caused the pump and harmonic fundamental modes phase mismatched, leading to extremely low efficiencies. However, due to the fact that 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] and optical fiber nanowires [2–5]. Furthermore, the effective nonlinearity in waveguides with dimensions comparable to the wavelength is strongly enhanced by the tight modal confinement [6]. In this paper, we consider the generation of UV and mid-IR radiation using In this paper, we consider the generation of UV and mid-IR radiation by intermodal phase matching up-conversion and down-conversion.

2. Phase Matching Condition, Efficiency and Detuning

The phase matching condition required for the two $\chi^{(3)}$ processes discussed here can be achieved by tailoring the waveguide geometry and index contrast, discovered by solving the rigorous modal eigenvalue equations of a step index profile waveguide [7]. THG generation in microfibres require phase matching between the fundamental and harmonic modes of the two wavelengths. The phase matching conditions for the different modes are shown in Figure 1a, where a near-IR pump is employed ($\lambda_p = 0.8\mu\text{m}$) such that the harmonic is generated in the UV.

Following the determination of the phase match diameters, the efficiency η can be evaluated from the propagation of the two frequencies' amplitudes by the following equations [2],

$$\frac{\partial A_p}{\partial z} = i\gamma_0[(J_1|A_p|^2 + J_2|A_h|^2)A_p + J_3(A_p^*)^2A_h e^{i\Delta\beta z}] - \alpha_p A_p \quad (1)$$

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

where the subscripts p and h refer to pump and harmonic signals, A_p and A_h are the amplitudes of the pump and the third harmonic mode, J_i are the modal overlaps between different modes of the power-normalized electric field

Fig. 1: (a) Phase matching diameters for THG of a silica microfiber for pump wavelengths of 800 nm. (b) Efficiency, η , of the THG process at various loss values with a pump power $P_p = 1\text{ kW}$

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.

The efficiency of this process to each mode is obtained by simultaneously solving equations 1 and 2, with the transfer of power from one wavelength to another is given by the J_3 term. It was discovered that the HE_{12} mode provides the highest modal overlap and is therefore the most efficient mode in this process. Calculating the efficiency for a pump power of 1 kW in an ideal microfiber with different absorption values, shown in Figure 1b. It is clear that the process can be highly efficient even at relatively large amount of losses, and therefore is feasible in microfibres.

Mode	$D_{\lambda=0.53\mu\text{m}}$	$D_{\lambda=0.8\mu\text{m}}$
EH11	657.84	975.90
HE12	807.24	1188.70
HE31	751.97	1116.50

Fig. 2: Phase matching conditions of PA from 800 nm to $2.4\text{ }\mu\text{m}$. The inset table lists the phase matching diameters for various modes for two different harmonic wavelengths, namely, $\lambda_h = 0.53\text{ }\mu\text{m}$ and $\lambda_h = 0.8\text{ }\mu\text{m}$.

The reverse procedure allows the transfer of power from shorter to longer wavelengths. This process is known as Parametric Amplification (PA) as it requires a pump seed at the desired wavelength, which is a consequence of the multiplication of the amplitudes of the two frequencies with the J_3 modal overlap in equation 1. The phase matching conditions for a PA at $2.4\text{ }\mu\text{m}$ with a harmonic pump at $0.8\text{ }\mu\text{m}$ is given in Figure 2.

One consideration which has not been discussed is the detuning present in the transfer process. This arises from the fact that there are self-phase (SPM) and cross phase modulation (XPM) effects present in the calculations, whose modal overlaps are represented in J_1 and J_5 for SPM and J_2 for XPM. To investigate this, the effect of detuning on the PA (515 nm to 1545 nm) efficiency is given in figure 3 in the top-most inset, which showed the details for a microfiber with three different detuning values (-280 m^{-1} , -386.4 m^{-1} and -460 m^{-1}). From the inset, it can be seen that the process is extremely sensitive to changes in detuning. In practice, the detuning can only be varied by varying the diameter slightly or by employing a tunable source.

Fig. 3: A comparison between two different detunings for a realistic microfiber from the HE_{12} pump mode (shorter wavelength) to the HE_{11} harmonic seed mode (longer wavelength) for a pump wavelength of $0.53 \mu\text{m}$ and seed wavelength of $1.59 \mu\text{m}$. Three different detunings are shown in the inset. Calculations were made at the phase matching diameter for a pump power $P_p = 1 \text{ kW}$ and seed power of $P_s = 50 \text{ W}$

In addition to microfibres, we have also theoretically explored the use of asymmetric plasmonic slot waveguides for third harmonic generation from $2.25 \mu\text{m}$. The phase matching condition of the waveguide is fulfilled between the zeroth-order mode of the pump wavelength and the first-order mode of the harmonic wavelength [8]. The asymmetrical nature of the geometry investigated allowed significant enhancement of the overlap between the two modes, increasing the efficiency of the THG process. It was shown that a theoretical efficiency of 1.4% can be obtained for a relatively low pump power of 1 W.

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