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Tuning Quadratic Nonlinear Photonic Crystal Fibers for Zero Group-Velocity Mismatch

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Relying on quadratic nonlinearities, second harmonic generation (SHG) is widely used for efficient wavelength conversion devices in order to extend the spectral range of laser sources and to do all optical wavelength multiplexing. Efficient conversion from the fundamental to the second harmonic (SH) mode requires a small phase mismatch between them. Phase matching to the lowest order is typically achieved through a quasi phase matching (QPM) technique [1] whereby the group velocity mismatch (GVM) sets the limits to device length and bandwidth for pulsed SHG. In conventional fibers, SHG with near zero GVM was found for restricted wavelengths [2] while zero GVM was predicted using mode matching [3]. For bulk media zero GVM was found for restricted wavelengths by spectrally noncritical phase matching [4] and by combining noncollinear QPM with a pulse front tilt [5].

Here we investigate efficient pulsed SHG in a poled silica photonic crystal fiber (PCF) having a standard index guiding triangular design with a single rod defect in the center. The main design parameters of the PCF are the pitch A and the relative hole diameter D=π Δ. The nonlinearity is induced e.g. by thermal poling as has recently been demonstrated in PCFs [6]. We tune the phase matching properties of SHG by exploiting the flexibility that PCFs offer in designing the dispersion properties [7]. Previous investigations [8] of SHG in PCFs considered the scalar case and found large bandwidths and strong modal overlaps for selected parameter values. Instead we perform a detailed vectorial analysis over a continuous parameter space and show zero GVM for any fundamental wavelength λ1> 80 nm by merely adjusting λ and D. This is a much simpler way of removing GVM compared to previous methods [3, 5]. It promises very large bandwidths due to its flexibility and it is very efficient.

A fiber mode can be described by an effective index n_eff=νβ/c, ie. the ratio of the speed of light c to the phase velocity of the mode νβ which is the propagation constant of the mode. The dispersive character of β gives a phase velocity mismatch between the fundamental (ω0) and SH (ω2=2ω0) modes which we classify through the index mismatch Δn=ε{νδ(ω0)}1-ε{νδ(ω2)}=c(β0 , ω0 β2 , ω2) related to the phase mismatch Δβ=2β , Δs=Δβλ / 2π The group velocity is instead defined as 1/νc=β c giving a GVM (walk off) parameter d12=1 νδ(ω1) 1 νδ(ω2)

Fig 1: (a) GVM and (b) index mismatch in D and λ1 space keeping A=λ1 fixed. The solid contour in (a) indicates zero GVM. (c) shows zero GVM contours for different λ1 (upper) and the corresponding index mismatch along the zero GVM contour (lower). (d) shows the D value as function of A that gives zero GVM for some selected pump wavelengths as well as the corresponding SHG bandwidth for a 10 cm fiber.

We calculated the dispersion with the MIT Photonic Bands (MPB) package [9]. A perturbative approach [10] was used to introduce chromatic dispersion allowing us to calculate data once over a large parameter space for A unity and perturbatively calculate the changes as A was varied. The result of the dispersion calculations is shown in Fig 1. The GVM and index mismatch are shown in Fig 1(a,b) in the (D λ1) parameter space keeping the pitch fixed at λ1=1 μm. Along the the solid contour d12=0 thus zero GVM is possible for any λ1>1 μm by choosing a proper D. Fig 1(c) underlines that this is a general trend: there the zero GVM contour is shown for selected pitches and we found d12=0 can be achieved for any λ1> 80 nm. Figure 1(b) shows that zero index mismatch can never be achieved even with zero GVM. This holds also for other pitches so efficient SHG will require additional phase matching.

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such as QPM (typical QPM grating periods 2L_{m1}=2\pi \Delta |\mu|=\lambda_1 2\Delta m \text{ range from 5}\ 100\ \mu m) \ Figure 1 (c) shows the values of the index mismatch as the zero GVM contour is traversed \ For \ \Lambda=0\ 0\ 1\ 0\ \text{ and } \ 1\ \mu m \ \text{ a cusp appears around } \lambda_1=\Lambda \ \text{ after which } \lambda m \ \text{ increases with } \lambda_1. \ This \ is \ because \ the \ fundamental \ mode \ is \ no \ longer \ well \ confined \ in \ the \ core \ while \ the \ SH \ having \ a \ smaller \ wavelength \ is \ still \ well \ confined \ Conversely \ for \ the \ considered \ wavelengths \ the \ modes \ are \ always \ well \ confined \ for \ larger \ pitches \ explaining \ why \ a \ small \ \lambda m \ \text{is observed there.} 

Focusing on the telecom Nd: AG and Ti:Sapphire operating wavelengths (\lambda_1=55 \ \mu m \ \text{ and } \ 0\ 8 \ \mu m \ \text{ respectively}) \ Fig 1 (d) shows the D value required to get zero GVM as \ \Lambda \ is \ changed \ For \ \lambda_1=0\ 80 \ \mu m \ \text{ zero GVM requires very large } D \ \text{ values e g } D=0\ 9 \ \text{ for } \ \Lambda=0\ 0 \ \mu m \ \text{ For such } D \ \text{ values deviations from the ideal circular holes must be expected which might influence the results. We still highlight the results because SHG with zero GVM for \ \lambda_1=0\ 80 \ \mu m \ \text{ is not obtainable in standard nonlinear materials For } \ \lambda_1=0\ 0 \ \mu m \ \text{ the lowest required } D \ \text{ values are in a range where the ideal round holes should be preserved. The curves stop for larger } \ \Lambda \ \text{ because it is no longer possible to get } d_2=0 \ \text{ (it would require } D>1 \ \text{ which is unphysical.) For } \ \lambda_1=55 \ \mu m \ \text{ a large } D \ \text{ can be found for both large and small pitches but } \ \Lambda<2 \ \mu m \ \text{ is preferred because the core is smaller leading to higher intensities. In Fig 1(d) we calculate the SHG bandwidth \ \Delta \ \text{ by expanding } \Delta \ \text{ around } \ \lambda_1 \ \text{ up to third order and assuming that a QPM grating compensates the lowest order term (as in conventional fibers [2]). Since we have } d_2=0 \ \text{ the } 2 \ \text{ order dispersion dominates yielding very large bandwidths Moreover because } d_2=0 \ \text{ the bandwidth of a fiber with length } L_f \ \text{ scales as } \Delta \lambda \sim \lambda_f^{-1/2} \ \text{ (instead of } \Delta \lambda \sim \lambda_f^{-1} \ \text{ when } d_2>0) \ \text{ so a longer device can be created without loosing too much bandwidth. Note also in Fig 1(a) the turn of the zero GVM contour around } D=0\ 43 \ \text{ and } \ \lambda_1=55 \ \mu m \ \text{ implying that the } 2 \ \text{ order contributions to the bandwidth term vanish giving an increasing bandwidth as observed in Fig 1(d).} 

Using the reductive perturbation method [11] and assuming that the dimensionless (DL) propagating fields \ u_1(x,t) \ can be decoupled from the DL transverse MPD modes \ e(x) \ the DL nonlinear equations for SHG are

\begin{equation}
\begin{aligned}
\left( \partial_x - iD_1 \partial_t^2 \right) \upsilon_i &= \frac{i\alpha_1 u_2 e^{-i\Delta \beta}}{\tau} \\
\left( \partial_x - d_2 \partial_t^2 \right) \upsilon_2 &= \frac{i\alpha_1 u_2 e^{-i\Delta \beta}}{\tau} \\
\sigma &= \rho l_f \sqrt{2h \omega_0^2 \alpha_2} \eta_{PH} \upsilon_2 (\Delta \beta \partial_t^2 - \tau^{-1} \partial_x - \partial_x \partial_t) \upsilon_1 \upsilon_2 \\
\rho &= \int \left| \upsilon_1(x) \upsilon_2(x) \upsilon_2^{(2)}(\Delta \lambda) \upsilon_1^{(2)}(\Delta \lambda) \right|^2 \\
\eta &= \pi l_f \eta_{PH} \upsilon_2 (\Delta \beta \partial_t^2 - \tau^{-1} \partial_x - \partial_x \partial_t) \upsilon_1 \upsilon_2 \\
\eta_{PH} &= \pi l_f \eta_{PH} \upsilon_2 (\Delta \beta \partial_t^2 - \tau^{-1} \partial_x - \partial_x \partial_t) \upsilon_1 \upsilon_2 \\
\end{aligned}
\end{equation}

z is scaled to \ L_f \ \text{ is the input pulse length } \tau \ \text{ and } \ x=(x,y) \ \text{ to the pitch } \ \lambda \ \text{ Integrating } u_1(x,t)^0 \ \text{ over time gives the photon number of the mode The DL nonlinear coefficient } \sigma \ \text{ was found to scale as } \sigma \sim D \ \text{ because a large } D \ \text{ gives a better mode confinement and a large overlap integral } \rho \ \text{ and decreasing } \Lambda \ \text{ gives a smaller core and thus a larger } \rho \ \text{ Integrating Eqs (1) under assumption of a continuous wave and undepleted fundamental the SHG efficiency is } \eta = P_2 / P_1 = \sigma \eta_{PH} \upsilon_2 (\Delta \beta \partial_t^2 - \tau^{-1} \partial_x - \partial_x \partial_t) \upsilon_1 \upsilon_2 \text{ and the mode power in Table 1 i some designs are then shown for selected } \lambda_1 \ \text{ values assuming a realistic poling strength of 1 pm V in the main direction of the } \chi^{(2)} \text{ tensor (the xxx direction) \ We find bandwidths large enough to convert down to } \upsilon_{\text{in}}=21 \ \text{ fs pulses and very high effective efficiencies } \eta_{\text{eff}} = \eta P_1 L_f \ \text{ ranging from 5 } 250 \ \% \text{ (W cm)}

Table 1: Efficient SHG with zero GVM Input pulse length \upsilon_{\text{in}}=1 \ \text{ ps } L_e=10 \ \text{ cm main component of } \chi^{(2)} \text{ tensor } 1 \ \text{ pm V}

<table>
<thead>
<tr>
<th>\lambda_1 [\mu m]</th>
<th>\Lambda [\mu m]</th>
<th>D</th>
<th>\Delta m [\text{n m}]</th>
<th>\upsilon_{\text{in}} [\text{fs}]</th>
<th>\upsilon_{\text{out}} [\text{fs}]</th>
<th>\sigma \times 10^4</th>
<th>\eta P_1 [% \text{ mW}]</th>
<th>\eta_{\text{eff}} [% \text{ (W cm)}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>0 0 0</td>
<td>9 13</td>
<td>3 21</td>
<td>112</td>
<td>25</td>
<td>250</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1.0</td>
<td>0 85 0</td>
<td>21</td>
<td>3 498</td>
<td>0.5</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.55</td>
<td>1 0 0 43</td>
<td>1 21</td>
<td>14 115</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Summarizing silica index guiding PCFs can be designed for efficient SHG with zero GVM for any fundamental wavelength above 80 nm simply by tuning the pitch and relative diameter of the air holes. The design examples focused on important wavelengths of optical components: we found very high bandwidths (large enough for 21 fs pulse conversion) and very high efficiencies [5 250 % (W cm)] giving great promise for frequency conversion of short pulses with fibers Puling of PCFs have already been demonstrated [1] so such fibers can readily be made once the QPM grating techniques have been successfully transferred from standard fibers to PCFs.