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Group-Velocity Matched Nonlinear Photonic Crystal Fibers
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Abstract A quadratic nonlinear index-guiding silica PCF is optimized for efficient second-harmonic generation through dispersion calculations. Zero group-velocity mismatch is possible for any pump wavelength above 780 nm. Very high conversion efficiencies and bandwidths are found.

Introduction
Second-harmonic generation (SHG) is widely used for efficient wavelength conversion devices enabling the spectral range of laser sources and all-optical wavelength multiplexing. Efficient conversion from the fundamental to the second-harmonic (SH) only occurs close to phase matching. To lowest order it is typically achieved through a quasi-phase matching (QPM) technique, so the group-velocity mismatch (GVM) limits the device length and bandwidth for pulsed SHG. For fiber SHG, zero GVM for restricted wavelengths was predicted by changing the core radius [1], and by using mode-matching [2]. In bulk media zero GVM was found for restricted wavelengths by spectrally noncritical phase matching [3] and by combining non-collinear QPM with a pulse-front tilt [4]. Here [5] we investigate efficient pulsed SHG in a silica index-guiding photonic crystal fiber (PCF) with a triangular air-hole pattern and a single-rod core defect (Fig. 1). The PCF design parameters are the pitch $\Lambda$ and the relative hole size $D/d$. We assume a quadratic nonlinearity from thermal poling of the PCF [6]. We tune the phase-matching properties of SHG by exploiting the flexibility that PCFs offer in designing the dispersion properties [7] and maximizing the nonlinear strength. 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 $\lambda_1$>780 nm by merely adjusting $\Lambda$ and $D$. This method is much simpler than previous methods [2-4], it shows very large bandwidths, and high efficiency.

Dispersion calculations
We describe a fiber mode by an effective index $n=c\beta/v_p$, i.e., the ratio of the speed of light $c$ to the phase velocity of the mode $v_p=\omega/\beta$, ($\beta$ is the propagation constant of the mode.) The dispersive character of $\beta$ gives a phase-velocity mismatch between the fundamental ($\omega_1$) and SH ($\omega_2=2\omega_1$) modes, which we classify through the index mismatch $\Delta n=n_1-n_2=[1/\sqrt{\varepsilon_1(\omega_1)}-1/\sqrt{\varepsilon_2(\omega_2)}]$, related to the phase mismatch $\Delta \omega=2\beta_1-\beta_2$ as $\Delta \omega=\Delta \lambda/4\pi$. The group velocity is instead defined as $1/v_g=\partial \beta/\partial \omega$, giving a GVM (walk-off) parameter $d_{12}=1/v_g(\omega_1)-1/v_g(\omega_2)$. We calculated the fiber modes with the MIT Photonic-Bands (MPB) package [9]. First $\omega_1$ and $v_g(\omega_1)$ were calculated, followed by iterations of the SH until $|\omega_2-2\omega_1|<10^{-8}$. Material dispersion, parameterized by the silica Sellmeier equation, was then included using a perturbative technique [10], whose advantage is that many different $\Lambda$ values can be calculated perturbatively from the MPB data (where $\Lambda$ is unity.)

Fig. 1: (a) Zero GVM contours in $(\lambda, D)$-space for $\Lambda$ fixed, and (b) $|\Delta n|$ along these contours. Inset: PCF with pitch $\Lambda$ and air-hole diameter $D$.

Fig. 2: (a) Zero GVM contours in $(\Lambda, D)$-space and fixing $\lambda_1$, (b) and (c) $\Delta \lambda$ and $l_{QPM}$ along these contours. The calculated GVM parameter $d_{12}$ is shown in Fig. 1(a) as a zero GVM contour ($d_{12}=0$) for 0.65$\lambda_1$<2.0 $\mu$m and 0.3$\mu$m, while keeping the pitch $\Lambda$ fixed. The examples show that the design parameters can be tuned over a continuous range to achieve zero GVM for any $\lambda_1$>0.78 $\mu$m. In Fig. 1(b) we show that the corresponding index mismatch $\Delta n$ is never zero. This is a general trend, even with non-zero GVM, so a QPM method is needed to achieve lowest order phase-matching. In Fig. 1(b) we also note that for
Effective nonlinearity

Using the reductive perturbation method [11], and assuming that the dimensionless (DL) propagating fields $u_j(z,t)$ can be decoupled from the DL transverse MPB modes $e(x)$, the DL Schrödinger equations are

\[
\begin{aligned}
\partial_z u_1 + iD_1 \partial_{\Omega}^2 u_1 &= i\alpha \Delta \Omega u_1 e^{i\Delta \beta_1}, \\
\partial_z u_2 - i D_2 \partial_{\Omega} u_2 &= i\alpha \Delta \Omega u_2 e^{i\Delta \beta_2}, \\
D_j &= \left(\frac{\partial^2}{\partial x^2}\right)^2 \beta_j,
\end{aligned}
\]

\[
\begin{aligned}
\sigma &= \rho \left[\frac{\hbar c^2}{\lambda} \alpha \Delta \Omega / \gamma_i^2 \gamma_t e^3 / \epsilon_0^3 \right], \\
\rho &= \left| \int dx e_j^*(x) \cdot \tilde{Z} \left(2 \cdot \mathbf{e}_j^* (x)e_j(x) \right) / (\epsilon_0 \alpha \Omega_0^2 z)^{1/2},
\end{aligned}
\]

$z$ is scaled to $l_0$, $t$ to the input pulse length $\tau$, and $x=\lambda(x,y)$ to $\Lambda$. Integrating $|u_j(z,t)|^2$ over time gives the mode photon number. Fig. 3 shows the nonlinear strength $\sigma$ for $\Lambda$ and $\Omega$ fixed (note that these curves are not zero-GVM contours.) A 2/π reduction of $\chi^{(2)}$ is included because we assume lowest order phase matching through a QPM grating. We found that $\sigma$ scales as $D/\Lambda$, which is due to a smaller core when $\Lambda$ is reduced and a better core confinement when $D$ is increased. $\sigma$ peaks when $\Lambda$ takes values around $\Lambda_1$, and drops for $\Lambda>\Lambda_1$ because the fundamental mode has maximum core confinement at the peak [Fig. 3(2)]. It becomes more poorly confined when $\Lambda<\Lambda_1$, while the SH stays better confined [cf. Fig. 3(1)], resulting in a poor modal overlap (controlled by the $\rho$ parameter). The SHG efficiency is $\eta=P_{\text{SHG}}/P_{\text{in}}$, where $P_j$ is the mode power. Depending on the chosen $\Lambda_1$, we found very large relative efficiencies of 5-180%/(W cm²), assuming a realistic $\chi^{(2)}=1 \text{ pm}/V$.

**Conclusions**

Tuning the pitch and relative hole size of an indexing-guiding silica PCF, SHG with zero GVM could be achieved for any $\lambda_1>780$ nm. The method holds great promise due to its simplicity, and fs pulse-conversion should be feasible. The SHG nonlinear strength was optimized when the fundamental was maximally confined, and it was inversely proportional to the pitch and proportional to the relative hole size. We found up to 180%/(W cm²) relative conversion efficiencies.

**References**