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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 for extending 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 $D=d/\Lambda$. 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 $n=c/v_g$, i.e., the ratio of the speed of light $c$ to the phase velocity of the mode $v_g=\omega/\beta$, ($\beta$ 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 $\Delta n=n_1-n_2=\varepsilon[1/v_g(\omega_1)-1/v_g(\omega_2)]=\varepsilon[\beta/\omega_1-\beta/\omega_2]$, related to the phase mismatch $\Delta \beta=2\beta_1-\beta_2$ as $\Delta n=\Delta \beta \lambda_1/4\pi$. 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 ($\lambda_1$,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$t_\text{core}$=2.0 $\mu$m and 0.3$s_r$=1, 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 SL propagating fields \( u_j(z,t) \) can be decoupled from the DL transverse MPB modes \( e(x) \), the DL Schrödinger equations are

\[
\begin{align*}
(\partial_z - i \mu D_1^2) u_1 &= i \alpha u_1 e^{i \Delta k y} \\
(\partial_z - i D_2^2) u_2 &= i \alpha_2 e^{i \Delta k y} \\
D_j &= \left( l_F / (2\pi)^2 \right)^{1/6} \beta_j \\
\sigma &= \rho l_F \sqrt{\hbar \omega_2 \omega_1 / n_1 n_2 e_e c^3} \\
\rho &= \frac{1}{\int dx} \left( \partial_z e_j^*(x) \cdot \vec{F}^{(2)} : e_j(x) e_j(x) \right) / (\Lambda a_1 d_1^2),
\end{align*}
\]

where \( z \) is scaled to \( l_0 \), \( t \) to the input pulse length \( \tau \), and \( x=x_0(y) \) to \( \Lambda \). Integrating \( u_j(z,t)^2 \) over time gives the mode photon number. Fig. 3 shows the nonlinear strength \( \sigma \) for \( \lambda_1 \) and \( D \) fixed [note that these curves are not zero-GVM contours.] A 2/\( \pi \) 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 \( \eta = P_{out} / P_{in} \), where \( P \) is the mode power. Depending on the chosen \( \lambda_1 \), we found very large relative efficiencies of 5-180 \( \%/(W \text{cm}^2) \), assuming a realistic \( \chi^{(2)}=1 \text{ pm/V} \).

References