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 $n=c/\nu_g$, i.e., the ratio of the speed of light $c$ to the phase velocity of the mode $\nu_g=\omega/\beta$, (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 $\Delta n=n_1-n_2=c(1/\nu_{g1}(\omega_1)-1/\nu_{g2}(\omega_2))=c(\beta_1/\omega_1-\beta_2/\omega_2)$, related to the phase mismatch $\Delta \phi=2\beta_1-\beta_2$ as $\Delta n=\Delta \phi\lambda/4\pi$. The group velocity is instead defined as $1/\nu_g=2\beta/\omega$, giving a GVM (walk-off) parameter $d_{12}=1/\nu_g(\omega_1)-1/\nu_g(\omega_2)$. We calculated the fiber modes with the MIT Photonic-Bands (MPB) package [9]. First $\omega_1$ and $\nu_g(\omega_1)$ 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.)

The calculated GVM parameter $d_{12}$ is shown in Fig. 1(a) as a zero GVM contour ($d_{12}=0$) for $0.68\lambda_1\leq2.0$ µm and $0.35D\leq5.0$, 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 $\lambda_1>0.78$ µm. 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 \( u_j(\rho,z,t) \) can be decoupled from the DL transverse MPB modes \( e(x) \), the DL Schrödinger equations are

\[
(\partial_z - i D_j \partial_{\rho}^2) u_j = i a_{j1} e_j e_{-j} e_{\pm j} \\delta(\rho),
\]

\[
(\partial_z - D_j - i D_j \partial_{\rho}^2) u_2 = i a_{j1}^2 e_j e_{-j} e_{\pm j} / 2,
\]

\[
D_j = l_j / (2\tau)^2 \partial_{\rho}^2 a_j,
\]

\[
\sigma = \rho l_j \sqrt{\hbar \omega_0^2 / n_j^2 e_0^2 c^3},
\]

\[
\rho = \left| \int d\eta \ e_1^*(\eta) \ (2) \cdot e_2(\eta) e_1(\eta) \right| / (\Lambda \Lambda z d_j^2 / 2),
\]

\[
a_j = \left| \int d\eta \ e_j(\eta) \right|^2.
\]

\( z \) is scaled to \( l_0 \), \( t \) to the input pulse length \( \tau \), and \( \omega_0(x,y) \) to \( \Lambda \). Integrating \( |u_j(\rho,z,t)|^2 \) over time gives the mode photon number. Fig. 3 shows the nonlinear strength \( \sigma \) for \( \Lambda \) 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 \( \eta = P_{2,\text{out}} / P_{1,\text{in}} \), where \( P \) is the mode power. Depending on the chosen \( \Lambda_1 \), we found very large relative efficiencies of 5-180 \%/Wcm\(^2\) and drops for \( \Lambda=\Lambda_1 \) because the fundamental mode has maximum core confinement at the peak [Fig. 3(2)].

**References**