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

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Abstract: A nonlinear index guiding silica PCF is optimized for efficient second harmonic generation through dispersion calculations ero group velocity mismatch is possible for any pump wavelength above 80 nm Very high conversion efficiencies and bandwidths are found
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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 non collinear 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 Λ and the relative hole diameter $D=d/\Lambda$ The nonlinearity is induced e g by thermal poling as has recently been demonstrated in PCFs [ ] We tune the phase matching properties of SHG by exploiting the flexibility that PCFs offer in designing the dispersion properties [ ] 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 $\lambda_1 > 80$ 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 $n_{eff}=c/v_{ph}$ i e the ratio of the speed of light c to the phase velocity of the mode $v_{ph}=\omega/\beta$ with β the propagation constant of the mode The dispersive character of β gives a phase velocity mismatch between the fundamental (ω_1) and SH ($\omega_2=2\omega_1$) modes which we classify through the index mismatch $\Delta n=c[1/v_{ph}(\omega_1) 1/v_{ph}(\omega_2)]=c(\beta_1/\omega_1 \beta_2/\omega_2)$ 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 $d_{12}=1/v_g(\omega_1) 1/v_g(\omega_2)$

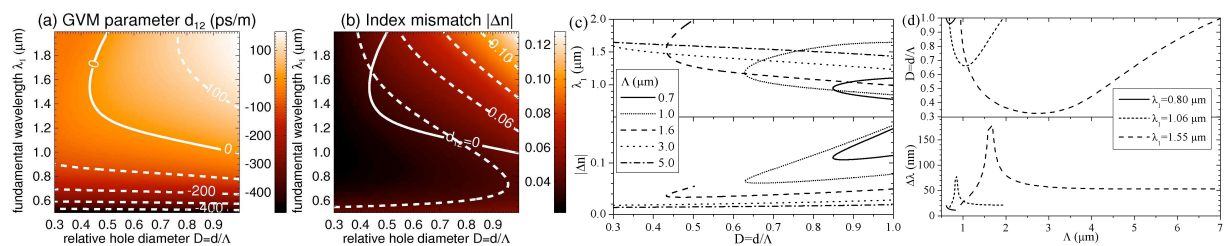Fig 1 (a) GVM and (b) index mismatch in D and λ_1 space keeping $\Lambda=1$ μm fixed The solid contour in (a) indicates zero GVM (c) shows zero GVM contours for different Λs (upper) and the corresponding index mismatch along the zero GVM contour (lower) (d) shows the D value as function of Λ that gives 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 Λ unity and perturbatively calculate the changes as Λ 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 λ_1) parameter space keeping the pitch fixed at $\Lambda=1$ μm Along the the solid contour $d_{12}=0$: thus zero GVM is possible for any $\lambda_1>1$ 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 $d_{12}=0$ can be achieved for any $\lambda_1> 80$ nm Figure 1(b) shows that zero index mismatch can never be achieved even with non zero GVM This holds also for other pitches so efficient SHG will require additional phase matching

such as QPM (typical QPM grating periods $2|l_{coh}|=2\pi\ |\Delta\beta|=\lambda_1\ 2|\Delta n|$ range from 5 100 µm) Figure 1 (c) shows the values of the index mismatch as the zero GVM contour is traversed For Λ=0 0 1 0 and 1   µm a cusp appears around $\lambda_1{\sim}\Lambda$ after which $|\Delta n|$ increases with λ_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 $|\Delta n|$ is observed there

Focusing on the telecom Nd: AG and Ti:Sapphire operating wavelengths (λ_1=1 55 1 0   and 0 8 µm respectively) Fig 1 (d) shows the D value required to get zero GVM as Λ is changed For λ_1=0 80 µm zero GVM requires very large D values e g D=0 9 for Λ=0 0 µm For such D 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 λ_1=0 80 µm is not obtainable in standard nonlinear materials For λ_1=1 0   µm the lowest required D values are in a range where the ideal round holes should be preserved The curves stop for larger Λ because it is no longer possible to get d_{12}=0 (it would require D>1 which is unphysical) For λ_1=1 55 µm a large D can be found for both large and small pitches but Λ<2 µm is preferred because the core is smaller leading to higher intensities In Fig 1(d) we calculate the SHG bandwidth $\Delta\lambda$ by expanding $\Delta\beta$ around λ_1 up to third order and assuming that a QPM grating compensates the lowest order term (as in conventional fibers [2]) Since we have d_{12}=0 the 2 order dispersion dominates yielding very large bandwidths Moreover because d_{12}=0 the bandwidth of a fiber with length l_F scales as $\Delta\lambda\propto l_F^{-1\ 2}$ (instead of $\Delta\lambda\propto l_F^{-1}$ when $|d_{12}|$>0) 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 and λ_1=1 55 µm implying that the 2 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 $u_j(z,t)$ can be decoupled from the DL transverse MPB modes $\mathbf{e}(\mathbf{x})$ the DL nonlinear equations for SHG are

$$(\partial_z - iD_1\partial_t^2)\,u_1 = i\sigma u_1^* u_2 e^{-i\Delta\beta z l_F} \qquad (\partial_z - d_{12}l_F\tau^{-1}\partial_t - iD_2\partial_t^2)\,u_2 = i\sigma u_1^2 e^{i\Delta\beta z l_F}\ \ 2 \qquad D_j = l_F\ \ (2\tau^2)\partial_\omega^2\beta_j$$

$$\sigma = \rho l_F\sqrt{2\hbar\omega_1^2\omega_2\ \ n_1^2 n_2\varepsilon_0 c^3\tau} \qquad \rho = \left|\int d\mathbf{x}\,\mathbf{e}_1^*(\mathbf{x})\cdot\tilde{\chi}^{(2)}:\mathbf{e}_2(\mathbf{x})\mathbf{e}_1^*(\mathbf{x})\right|\ \ (\Lambda a_1 a_2^1\ \ 2) \qquad a_j = \int d\mathbf{x}\,|\,\mathbf{e}_j(\mathbf{x})\,|^2$$

$$(1)$$

z is scaled to l_F t to the input pulse length τ and $\mathbf{x}$=($x\ y$) to the pitch Λ Integrating $|u_j(z\ t)|^2$ over time gives the photon number of the mode The DL nonlinear coefficient σ was found to scale as $\sigma\propto D\ \Lambda$: a large D gives a better mode confinement and a large overlap integral $\propto\rho$ and decreasing Λ gives a smaller core and thus a larger ρ Integrating Eqs (1) under assumption of a continuous wave and undepleted fundamental the SHG efficiency is

$\eta = P_2\ \ P_1 = P_1\tau\sigma^2\text{sinc}^2(\Delta\beta l_F\ \ 2)\ \ 2\hbar\omega_1 \propto P_1\rho^2 l_F^2\text{sinc}^2(\Delta\beta l_F\ \ 2)$ where $P_j=\hbar\omega_j|u_j|^2\ \tau$ is the mode power In Table 1 some designs are then shown for selected λ_1 values assuming a realistic poling strength of 1 pm V in the main direction of the $\chi^{(2)}$ tensor (the xxx direction) We find bandwidths large enough to convert down to τ_{lim}=21 fs pulses and very high relative efficiencies $\eta'{=}\eta\ P_1 l_F^2$ ranging from 5 250 % (W·cm^2)

Table 1 Efficient SHG with zero GVM Input pulse length τ=1 ps l_F=10 cm main component of $\chi^{(2)}$ tensor 1 pm V

λ_1 [µm]	Λ [µm]	D	$\Delta\lambda$ [nm]	τ_{lim} [fs]	$|l_{coh}|$ [µm]	$\sigma\cdot 10^4$	$\eta\ P_1$ [% mW]	$\eta'{=}\eta\ P_1 l_F^2$ [% (W·cm^2)]
0 80	0 0	0 9	13	3	2 1	112	25	250
1 0	0 85	0 2		21	3	49 8	3	3
1 55	1 0	0 43	1 0	21	14 4	11 5	0 5	5 0

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^2)] giving great promise for frequency conversion of short pulses with fibers Poling of PCFs have already been demonstrated [ ] so such fibers can readily be made once the QPM grating techniques have been successfully transferred from standard fibers to PCFs

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