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Temporal switching induced by cascaded third order nonlinearity

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We investigate the impact of cascaded third harmonic generation and the intrinsic n_4 material nonlinearity on the propagation of ultrashort pulses in noble-gas filled Kagome fibers. We show that the pressure tunability of the cascade allows for the implementation of temporal switching. We also investigate the relative strengths of both effects and show their ratio to be pressure tunable.   © 2012 Optical Society of America
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Processes using the $\chi^{(3)}$ nonlinearity interacting with dispersion are the workhorses of nonlinear optics. They are used to generate supercontinua [1], and for all-optical signal processing [2]. For very short pulses effects which were previously discarded start to become important. Among them is the generation of third harmonic (TH), which is phase-mismatched and seemingly of no impact, unless $f - 3f$ interference takes place [3]. The nonlinearity is thus usually assumed to be Kerr-effect only.

However, it was shown [4,5] that even mismatched TH fields affect the fundamental wave (FW) by generation and consecutive down-mixing back into the FW (see Fig. 1). This process is comparable to cascaded second harmonic generation (SH) in $\chi^{(2)}$ media [6–9] and thus termed cascaded TH generation. Here we show that the TH cascade acts like a noninstantaneous fifth order nonlinearity, whose sign, magnitude, and delay depend on the dispersion of the FW and the TH. This effective nonlinearity adds to the n_4 term of the intrinsic nonlinearity of the medium, which produces a nonlinear refractive index modulation $\delta n = n_2 I + n_4 I^2 + \ldots$ and is subject to self-steepening (SS). The origin and magnitude of n_4 are currently under strong debate [10]. We show that the TH cascade yields effects on the same scale.

It was demonstrated that noble gas filled Kagome fibers [11] exhibit pressure-tunable TH generation. They are ideal for the investigation of TH cascading and support solitons due to anomalous dispersion. It is particularly interesting to characterize the impact of the noninstantaneousness of the cascaded TH. The overall effect is similar to stimulated Raman scattering (SRS) and SS [12], but with tunable delay. Because noble gases do not exhibit SRS, a signature of related effects is a clear sign of TH cascading and occurs only when it is significant with respect to the material n_4 and SS.

In this Letter we will show how this tunable response influences the propagation dynamics of high order solitons and propose a temporal switching scheme. This choice was made because high order solitons are susceptible to SS triggered fission [13].

In contrast to previous works [11] we analyze the influence of coupling to multiple TH modes [14] of the gas filed Kagome fiber, with individual dispersion. We assume filling with Xe gas, being more nonlinear with a reduced relative impact of n_4 than Ar. Finally we assume a fundamental wavelength of 1550 nm due to reduced gas dispersion, higher phase and group velocity matching pressures and thus reduced power requirements.

The pulse propagation equations for a single FW mode A and a multimode TH field $B^{(l)}$ influenced by the Kerr effect with SS, without cross phase modulation are:

$$\left(i\frac{\partial}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2}{\partial \tau^2} + i\alpha_A \right) A$$
$$+ \left[1i\omega_0^{-1}\frac{\partial}{\partial \tau} \right](\Gamma_A |A|^2 + \tilde{\Gamma}_A |A|^4)A$$
$$+ \left[1 + i\omega_0^{-1}\frac{\partial}{\partial \tau} \right] A^{*2}\sum_l \Gamma_B^{(l)} B^{(l)} e^{i\Delta\beta_0^{(l)} z} = 0, \qquad (1)$$

$$\left(i\frac{\partial}{\partial z} - i\Delta\beta_1^{(l)}\frac{\partial}{\partial \tau} - \frac{\beta_2^{(l)}}{2}\frac{\partial^2}{\partial \tau^2} + i\alpha_B^{(l)} \right) B^{(l)}$$
$$+ \left[1 + 3i\omega_0^{-1}\frac{\partial}{\partial \tau} \right]\Gamma_B^{(l)} A^3 e^{-i\Delta\beta_0^{(l)} z} = 0. \qquad (2)$$

The dispersion of each mode is characterized by its wave number $\beta(\omega)$, which is expanded into a Taylor series around its respective central frequency ω_0 or $3\omega_0$. The Taylor coefficients are β_m for the FW and $\beta_m^{(l)}$ for the TH modes. The equations are in the frame of reference traveling with the FW group velocity $v_g = 1/\beta_1$, giving rise to the group-velocity mismatch (GVM) $\Delta\beta_1^{(l)} = \beta_1 - \beta_1^{(l)}$. The phase mismatches are $\Delta\beta_0^{(l)} = \beta_0^{(l)} - 3\beta_0$. Loss is accounted for by α_A and $\alpha_B^{(l)}$. It is 1.1 dB/m for the FW mode, allowing a few meters of propagation [11].
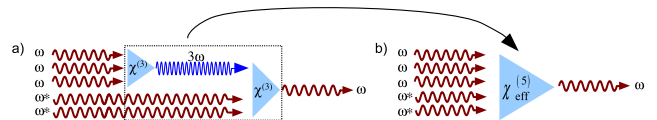

Fig. 1.   (Color online) The TH cascade. (a) Three FW photons generate a TH photon. It mixes with two more FW photons into a phase shifted FW photon. (b) If the intermediate step is mismatched the process acts like a quintic nonlinearity.

The Kerr constant is defined as $\Gamma_A = n_2\omega/(cA_{\text{eff}})$. The quintic nonlinearity constant is $\tilde{\Gamma}_A = n_4\omega_0/(c\tilde{A}_{\text{eff}})$ with $\tilde{A}_{\text{eff}} = (\int |a|^2 dx^2)^3/\int |a|^6 dx^2$. The nonlinearity constant related to the cascading is $\Gamma_B^{(l)} = n_2\omega/(cA_{\text{eff}}^{(l)})$ with $A_{\text{eff}}^{(l)} = (\int |a|^2 dx^2)^{3/2}(\int |b^{(l)}|^2 dx^2)^{1/2}/\int aa^{*2}b^{(l)} dx^2$. All constants are defined by the modal fields $a(\mathbf{x})$ of the FW and $b^{(l)}(\mathbf{x})$ of the TH modes, respectively [13]. Eqs. (1) and (2) can be expanded to account for higher order dispersion, which is neglected for simplicity.

Mode properties are calculated from the modal wave-numbers of a Xe [15–18] filled Kagome fiber of 25 μm radius with $n_2 = 93 \cdot 10^{-24}$ m^2/W/bar and $n_4 = 32 \cdot 10^{-42}$ m^4/W^2/bar (note erroneous factor of 10^3 in C_1 for Xe in [16]). Results are plotted in Figs. 2(a) and 2(b).

Figure 2(c) displays the relative impact $L_{\text{Kerr}}/L_{n4} = \Gamma_B^{(l)2}P_0/(\Delta\beta_0^{(l)}\Gamma_A)$ of each TH mode compared to the FW Kerr nonlinearity in the cascaded limit as discussed below. The calculation is made for an $N = 3$ soliton with a dispersion length $L_D = 0.25$ m ($\tau_0 \approx 25$ fs pulse width) and the corresponding launch power, where L are characteristic length scales. The solid line is the same quantity for the n_4 nonlinearity $L_{\text{Kerr}}/L_{n4} = \Gamma_A P_0/\Gamma_A$. All quantities are weak perturbations to the Kerr effect. It can be seen that material n_4 dominates at low pressures. Close to the phase matching pressure $p^{\text{PM}} \approx 5.6$ bar interaction with HE$_{13}$ is enhanced. At high pressures HE$_{11}$ is dominant. We emphasize that the difference in the ratio of the cascaded and intrinsic nonlinearity by pressure tuning is a unique feature of guided wave geometries.

Equations (1) and (2) can be dramatically simplified for mismatched TH fields and if SS is neglected. Then the shape of the cascading response [19] is calculated with the enslaving approach [20–22] as $B^{(l)}(z,t) = \phi^{(l)}(t)e^{-i\Delta\beta_0^{(l)}z}$. Equation (2) is then solved in frequency domain:

$$\phi^{(l)}(\omega) = \frac{\Gamma_B^{(l)}}{i\alpha^{(l)} - \Delta\beta_0^{(l)} + \Delta\beta_1^{(l)}\omega - \frac{1}{2}\beta_2^{(l)}\omega^2}\mathcal{F}[A^3(z,t)]. \quad (3)$$

Back transformation into time domain and insertion into Eq. (1) yields an evolution equation in terms of the FW $A(z,t)$ only. The last term is replaced by a convolution with the cube of the FW with a response function $R(\tau)$:

$$\sum_l \Gamma_B^{(l)} B^{(l)} e^{i\Delta\beta_0^{(l)}z} = \int_{-\infty}^{\infty} R(\tau)A^3(z,t-\tau)d\tau, \quad (4)$$

where the frequency domain representation of the response function in $R(\omega)$ is taken from Eq. (3):

$$R(\omega) = \sum_l \frac{\Gamma_B^{(l)2}}{i\alpha^{(l)} - \Delta\beta_0^{(l)} + \Delta\beta_1^{(l)}\omega - \frac{1}{2}\beta_2^{(l)}\omega^2}. \quad (5)$$

If the incident pulse's spectrum is narrower than the response function we can simplify the equations and get a nonlinear refractive index $n_{4,\text{casc}} = -\sum \Gamma_B^{(l)2}/\Delta\beta_0^{(l)}$, adding to the material n_4 [19]. In general, however, $R(\omega)$ is spectrally asymmetric and non-instantaneous. The cascaded response thus competes with the intrinsic SS. For a single TH mode the location ω_{max} for the largest value of $\Re e[R(\omega)]$ is $\omega_{\text{max}} = \Delta\beta_1^{(l)}/\beta_2^{(l)}$. A symmetry flip of $R(\omega)$ thus coincides with a flip of the group velocity mismatch $\Delta\beta_1^{(l)}$. If more TH modes are present ω_{max} can be evaluated numerically, with a sign flip still attributed to a symmetry flip of the aggregated response function. The above discussed geometry yields a symmetry flip at $p^{\text{GVA}} \approx 2.7$ bar.

With these properties we choose $N = 3$ solitons as test objects for the TH cascade induced dynamics. More specifically we investigate how the pressure tunable asymmetry of the response function $R(\omega)$ influences the soliton's decay. We solved Eqs. (1) and (2) for pressures from 1 bar to 6 bar and for a fiber of 3 m length.

Figure 3(a) displays the pulse at the fiber's end if the intrinsic n_4 and SS is neglected. The white line denotes the symmetry flip pressure p^{GVA}. The shapes of $R(\omega)$ below, at, and above p^{GVA} are depicted below to underline the response's symmetry flip. For all pressures the pulse has decayed into a first order soliton containing roughly two thirds of the total energy and residual radiation. The temporal symmetry of the fission process depends on pressure, with a shift of the output pulse from $t \approx -20$ fs to $t \approx 20$ fs, occurring at $p \approx p^{\text{GVA}}$, clearly indicating the direction of the soliton decay is determined by the symmetry of the response function. Note the switching process is attributed to a change in sign of a SS-like term, leading to a change in the shock front and thereby to the asymmetry in the frequency spectrum. Thus, this change in the frequency spectrum content is different from the well-known Raman-like frequency shift, and in fact we observed a very small frequency shift in connection with the switching. If material n_4 and SS are also considered [see Fig. 3(b)] the result is only quantitatively different. SS has lead to a shift of the overall timing and the
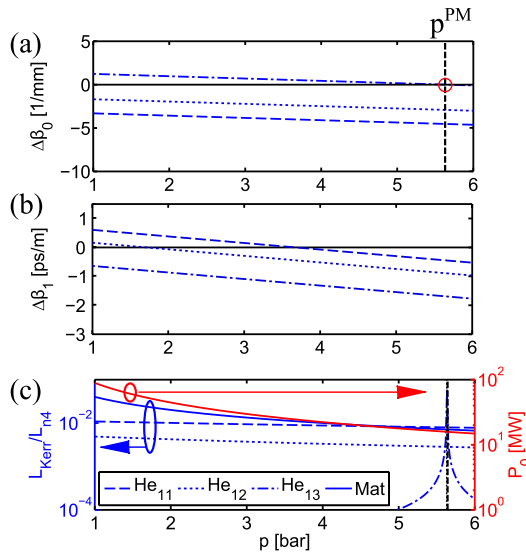

Fig. 2. (Color online) Dispersion properties of TH modes for a Kagome fiber with FW at 1550 nm. (a) Phase $\Delta\beta_0^{(l)}$ mismatch. (b) Group velocity mismatch $\Delta\beta_1^{(l)}$. (c) Relative impact (blue) of the cascade and the n_4 nonlinearity on the FW evolution for an $N = 3$ soliton with a dispersion length $L_D = 0.25$ m and corresponding peak power (red). Black lines denote phase or group velocity matching pressures.
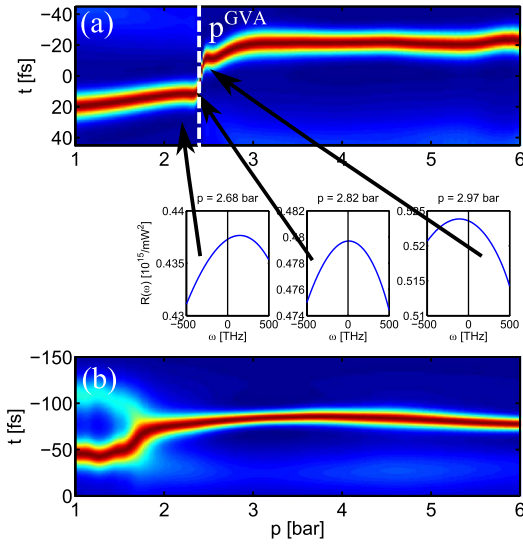
Fig. 3. (Color online) Pulse shape of the FW after the fiber. (a, top) $|A(t)|^2$ if material n_4 and SS is neglected. The dotted line denotes the symmetry flip pressure p^{GVA}. Media 1 displays the pulse evolution. (a, bottom) $\Re e[R(\omega)]$ for pressures close to p^{GVA} (b) $|A(t)|^2$, if n_4 nonlinearity and SS are considered, too. Media 2 displays the pulse evolution.

combined action of the intrinsic higher order material nonlinearity and SS have shifted the switching pressure to $p \approx 1.75$ bar. The general switching character is, however unaffected, clearly indicating that the TH cascade has significant impact on nonlinear pulse evolution. This is especially interesting to note as the intrinsic n_4 nonlinearity is the dominating perturbation for the pressures where switching is observed [see Fig. 2(c)]. The amount of energy in the resulting solitary wave is roughly 65%, the rest is contained in the dispersive waves.

We have shown that the TH cascade in noble gas filled fibers affects the propagation of ultrashort pulses significantly. It is of similar strength as the intrinsic n_4 nonlinearity. The effect it has on propagation is governed by the tunable symmetry and noninstantaneousness of the response function $R(\omega)$ and thus competes with the intrinsic SS. We have further shown that this tunable, nonlinear response is an interesting candidate for switching and retiming. The interaction of the TH cascade with the intrinsic n_4 nonlinearity was shown to vary from that encountered in homogeneous materials, providing a system in which various contributions to fifth order nonlinearities could be investigated separately.

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