Competing nonlinearities in quadratic nonlinear waveguide arrays

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We demonstrate experimentally the existence of competing focusing and defocusing nonlinearities in a double resonant system with quadratic nonlinear response. We use an array of periodically-poled coupled optical waveguides and observe inhibition of the nonlinear beam self-action independent on power. This inhibition is demonstrated in both regimes of normal and anomalous beam diffraction.

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Nonlinear optics is a broad field of research that explores wave phenomena at high light intensities. Particular interest is devoted to spatial nonlinear effects arising due to intensity-dependent phase shifts accumulated with propagation in the medium. Typically, beam focusing or defocusing is observed for positive or negative sign of the nonlinearity, respectively. If an optical system, however, exhibits so-called *competing nonlinearities* a laser beam can experience simultaneously focusing and defocusing, depending on the light intensity. The competition of focusing and defocusing for different parts of the beam can lead to a rich variety of effects, such as stable vortex beams [1] and liquid light [2]. However, such competing type nonlinearities, where the focusing and defocusing nonlinear phase shifts can cancel each other, are difficult to achieve in natural materials.

One possible approach is to combine fast and slow nonlinear responses, such as quadratic and photorefractive nonlinearities [3]. However, this combination requires a subtle balance between pulse peak and average beam powers, and no experimental demonstration of nonlinear phase shift cancellation has been reported, so far. Other approaches have focused on the implementation of competing cubic-quintic [4] or quadratic-cubic nonlinearities [5]. The latter system provides a realistic way to achieve competing nonlinearities due to the fact that a combined $\chi^{(2)} - \chi^{(3)}$ response appears intrinsically in inhomogeneous quasi phase matching (QPM) gratings [6]. Theoretical studies of this system have shown that its behaviour is qualitatively different from media with a pure quadratic response, due to the presence of nonlinear phase cancellation [7]. Still experimental results demonstrating the effect of nonlinear phase cancellation due to competing nonlinearities are missing. Here, we employ a periodic system with a dual-resonant quadratic type nonlinearity and report on the observation of nonlinear phase shift cancellation due to competition. By using the diffraction engineering of the periodic structure [8] we show that nonlinear phase cancellation is possible in both regimes of normal and anomalous diffraction.

The competing nonlinearities are realized in an array of periodically-poled waveguides in a z-cut lithium niobate crystal [9]. The waveguides support multiple second harmonic (SH) modes at wavelengths of $\sim 750\,\mathrm{nm}$, which are coupled to the fundamental wave (FW) of a wavelength of $\sim 1500\,\mathrm{nm}$ by quadratic nonlinear interactions. The presence of several SH modes is crucial for observation of competing nonlinearities since it provides various second harmonic generation (SHG) resonances. We show that as a result of these multiple resonances spatial effects that arise due to nonlinear phase shifts are strongly modified in a certain wavelength range.

The used waveguide array is periodically poled to fulfill the phase matching (PM) condition: $\Delta\beta = 2\beta^{\mathrm{FW}} - \beta^{\mathrm{SH}} + 2\pi/\Lambda^{\mathrm{QPM}} = 0$, where $\beta^{\mathrm{FW/SH}}$ are the propagation constants of the participating waveguide modes, $\Delta\beta$ is the phase mismatch, and $\Lambda^{\mathrm{QPM}} = 16.803\ \mu\mathrm{m}$ is the period of the QPM grating.

For nonzero phase mismatches, nonlinear phase shifts of the dominant FW component occur due to cascading of different frequency-mixing processes [10, 11]. In a single waveguide, the phase shift induced by a single FW-SH-interaction can be approximated by $\phi_{\mathrm{NL}}(z) = \int_0^z n_2^{\mathrm{eff}}(z')\,\beta P dz'$ with the wavenumber β and the guided power P. The effective nonlinear refractive index n_2^{eff} is determined as [12]

$$n_2^{\mathrm{eff}} = \frac{\chi_{\mathrm{eff}}^2}{(\omega/c)\,\Delta\beta}\frac{\left[1-\cos\left(\Delta\beta z\right)\right]}{\left[1-(4\chi_{\mathrm{eff}}^2 P/\Delta\beta^2)\sin^2\left(\Delta\beta z/2\right)\right]}, \quad (1)$$

where χ_{eff} is the effective nonlinearity of the quadratic interaction and ω is the frequency of the FH component. This approximation holds if $\left(4\chi_{\mathrm{eff}}^2 P/\Delta\beta^2\right) \leq 1$, which is true if the PM condition is not exactly met. The effective Kerr-type nonlinearity induced by the nonlinear phase shift of the FW wave is focusing/defocusing for wavelengths above/below a SHG resonance. In waveg-

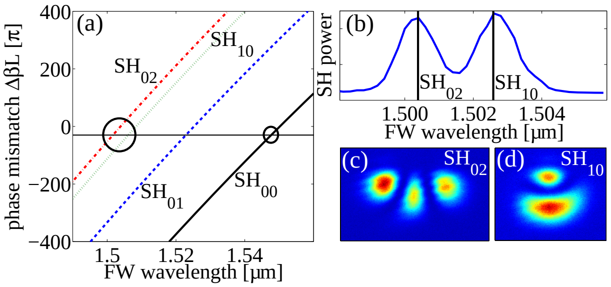

Fig. 1. (Color online) (a) Calculated phase mismatch for the FW_{00} mode in a sample of $L = 71$mm. The circles show the interaction with the SH fundamental mode and the double resonance considered here. (b) Measurement of the SH output power of a single waveguide in dependence on the FW input wavelength and profiles of the (c) SH_{02} and (d) SH_{10} modes intensity distributions.

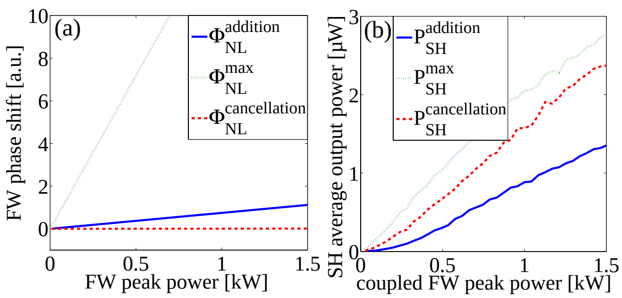

Fig. 2. (Color online) (a) Calculated FW phase shift corresponding to wavelengths of cancellation ($\Phi^{\mathrm{cancellation}}$), the maximum phase shift at the SH_{10} resonance (Φ^{max}), and at a wavelength 2 nm above this resonance where the two phase shifts are added (Φ^{addition}). (b) Measured SH output power at wavelengths corresponding to (a), showing strong nonlinear interaction at the cancellation wavelength.

uide arrays with only one SHG resonance this effective nonlinearity supports quadratic spatial solitons [13, 14].

As shown earlier some PM resonances with higher order SH modes can be in close proximity to each other at wavelengths around 1500 nm [15]. This was also confirmed for our system by numerical calculations of the PM condition [Fig. 1(a)] and measurements of the SH signal versus the FW wavelength, shown in Fig. 1(b). We find two SH resonances of equal strength, where the FW (FW_{00}) is phase matched to the higher order SH modes SH_{10} [Fig. 1(d)] and SH_{02} [Fig. 1(c)] at wavelengths of $\lambda_{\mathrm{FW}} = 1502.6$ nm and 1500.5 nm, respectively.

Since the two participating orthogonal SH modes do not interact directly with each other, they both independently impose phase shifts on the FW wave. In the wavelength region between the two resonances, these phase shifts possess different signs, because the wavevector mismatch has different signs for both interactions. This leads directly to competition of the two effective nonlinearities induced by the SHG resonances. In Fig. 2(a) we show the sum of the phase shifts affecting the FW in dependence on the input power for three different wavelengths. Since the nonlinear resonances in our sample are of equal strength the phase shifts induced by both resonances have the same absolute value but different signs in the middle of the wavelength interval between the QPM wavelengths. Here the sum of the phase shifts is zero for all input powers. In Fig. 2(b) we show that at the wavelength of phase shift cancellation we still see strong SHG stemming from both resonances although we are not in the phase matched regime.

For different strengths of the nonlinear interactions the wavelength of smallest phase shift moves towards the weaker resonance. However, absolute cancellation of the phase shifts can only be achieved for longer and not exactly phasematched propagation. Then the oscillating and power dependent terms of Eq. 1 can be neglected.

We note that the nonlinear phase shift could also be trivially suppressed either for large phase mismatch or at the PM wavelength. In the former scenario the nonlinearity is totally absent, while in the latter one no phase shifting process happens due to the lack of back conversion to the FW component. Hence, in these cases the absence of nonlinear phase shifts is not due to competing nonlinearities.

The considerations presented above neglect the coupling between the waveguides of a waveguide array. However, the given predictions are still correct since the nonlinear coupling will be the dominating effect for our experimental parameters.

To show the effect of the vanishing nonlinear phase shift experimentally, we excite the array with 7 ps pulses of an elliptical FW beam, approximately 4 waveguides wide, polarized along the c-axis of the crystal. We then monitor the output intensity patterns of the array for different wavelengths and peak powers. Peak powers are defined as the sum of the peak powers in the individual waveguides. As a representative parameter to describe the beam we chose the width of the output pattern, which was calculated as the transverse second moment from the intensities of the waveguides. In Fig. 3(a) the measured beam width is plotted as a function of wavelength and peak power coupled into the array. The SHG-resonances are indicated by the two lines at 1500.5 nm and 1502.6 nm. Similar to earlier studies on single resonant quadratic interaction [14], we observe a narrowing of the beam due to the formation of discrete quadratic solitons at wavelengths above both resonances. In this wavelength region the two nonlinearities are focusing. In contrast both nonlinearities are defocusing at wavelengths below the resonances, leading to nonlinear broadening of the beam. For wavelengths between the two SHG resonances, the induced nonlinearities have different signs, enabling competition and cancellation of phase shifts. Hence we observe the inhibition of the nonlinear self-action of the beam and consequently the beam width stays the same for all experimentally accessible powers. In Fig. 3(b) the output intensity profiles at a wavelength of 1501.6 nm are plotted as a function of power to confirm the constant beam profile.

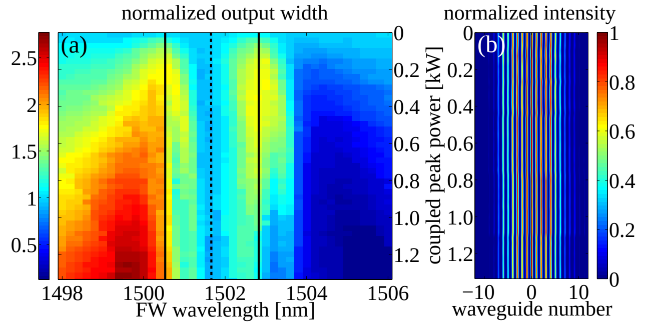

Fig. 3. (Color online) (a) Output beam width for normal excitation, normalized to the linear output at 1498 nm. The PM wavelengths are indicated by solid lines. (b) Power independent output pattern at 1501.6 nm [dotted line in (a)].

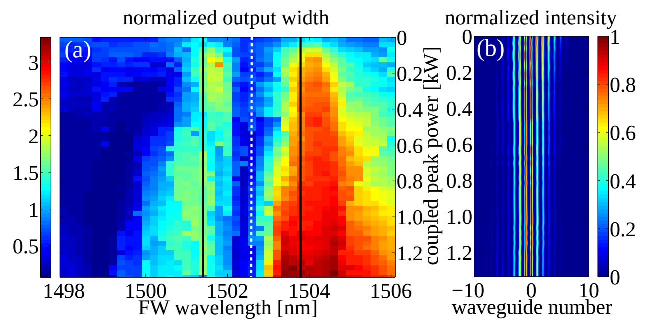

Fig. 4. (Color online) (a) Output beam width for staggered excitation, normalized to the linear output at 1498 nm. The PM wavelengths are indicated by solid lines. b) Power independent output pattern at 1502.3 nm [dotted line in (a)].

An important feature of the waveguide array is the change of sign of diffraction when the input beam is inclined to the Bragg angle [8, 16]. However, even though the diffraction is inverted for this type of excitation, we observe a qualitatively similar situation [see Fig. 4(a)]. In this case, the QPM wavelengths are shifted due to the curvature of the transmission bands. In the wavelength regions above and below the two resonances, the changes of the beam width have a reversed sign compared to the findings in Fig. 3(a). Between the resonances, however, we again observe a region of power independent propagation, as seen in Fig. 4(b). The small deviations of the beam width and the shift of the cancellation region with increased power are caused by additional phase shifts. These are generated by the excitation of the FW_{01} mode and the resulting weak nondegenerated mixing of FH_{00} and FH_{01} to the SH_{03} modes.

In conclusion, we have proved experimentally the cancellation of nonlinear phase shifts due to competing nonlinearities in a system with double resonant quadratic nonlinearity. At the regime of phase shift cancellation the propagation of the FW beam is independent on power over the experimentally available power levels. We believe, that a similar effect may occur in other double-resonant system, such as a two-dimensional QPM structure with non-collinear phase matching [17]. In such a system, however, the beam would also experience strong transverse shifts at the output.

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