Observation of competing quadratic nonlinearities in lithium niobate waveguide arrays

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Abstract
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 lithium niobate optical waveguides and observe inhibition of nonlinear beam self-action, independent on power. This inhibition is demonstrated in both regimes of normal and anomalous beam diffraction.

Keywords: second harmonic generation; quadratic nonlinearity; waveguide arrays

Introduction
Spatial effects in nonlinear optics have triggered significant interest in the last four decades, with important effects such as self-focusing and defocusing. In all current experiments, however the sign of the nonlinearity has been considered constant. On the other hand, theoretical studies have shown that a variety of new nonlinear phenomena can be present in a system with competing focusing and defocusing nonlinearity. Important possibility to engineer the nonlinear response of a system has been offered by the quasi phase matching (QPM) in periodically poled crystals. In QPM structures one can achieve competing nonlinearities due to the fact that a combined $\chi^{(2)} - \chi^{(3)}$ response appears intrinsically in inhomogeneous QPM gratings [1]. 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 [2]. Experimental results demonstrating the effect of nonlinear phase cancellation due to competing nonlinearities, however are missing. Here, we employ a periodic system with a dual-resonant quadratic type nonlinearity and report, for the first time to our knowledge, on the observation of nonlinear phase shift cancellation due to competition. By using the diffraction engineering of the periodic structure [3], we show that nonlinear phase cancellation is possible in both regimes of normal and anomalous diffraction.

Experimental arrangement
The competing nonlinearities are realized in an array of periodically-poled waveguides ($\Lambda^{\mathrm{QPM}} = 16.803\ \mu$m) in a z-cut lithium niobate crystal [4]. The waveguides support multiple second harmonic (SH) modes at wavelengths of ~ 750 nm, which are nonlinearly coupled to the fundamental wave (FW) of a wavelength of ~ 1500 nm. The presence of several SH modes is crucial for observation of competing nonlinearities since it provides various second harmonic generation (SHG) resonances. As a result of these multiple resonances, spatial effects that arise due to nonlinear phase shifts are strongly modified in a certain wavelength range.

For nonzero phase mismatches, nonlinear phase shifts of the dominant FW component occur due to cascading of different frequency-mixing processes [5, 6]. The effective Kerr-type nonlinearity induced by the nonlinear phase shift of the FW wave is focusing or defocusing for wavelengths above or below the SHG resonance, respectively. In general, however some phase matching (PM) resonances with higher order SH modes can be in close proximity to each other [8]. This is also the case for our system as seen by the PM conditions shown in Fig. 1(a). We find two SH resonances of equal strength [Fig. 1(b)], 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. 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. For different strengths of the two resonances, the wavelength of smallest phase shift moves towards the weaker resonance. 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 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.

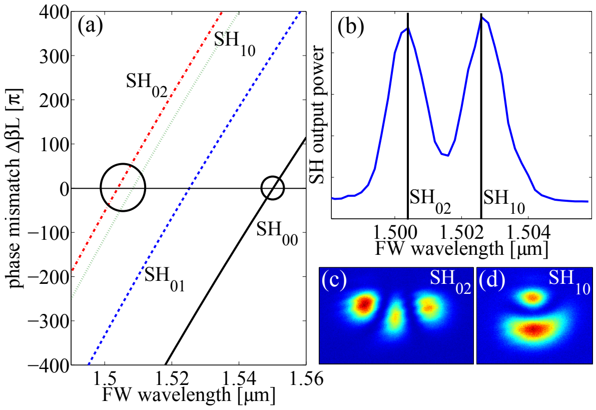

Figure 1: (a) Phase mismatch for the FW_{00} mode in our sample. Circles – interactions with the SH_{00} mode and the double resonance considered here. (b) Measured SH output power vs. FW wavelength. Profiles of the SH_{02} (c) and SH_{10} (d) modes.

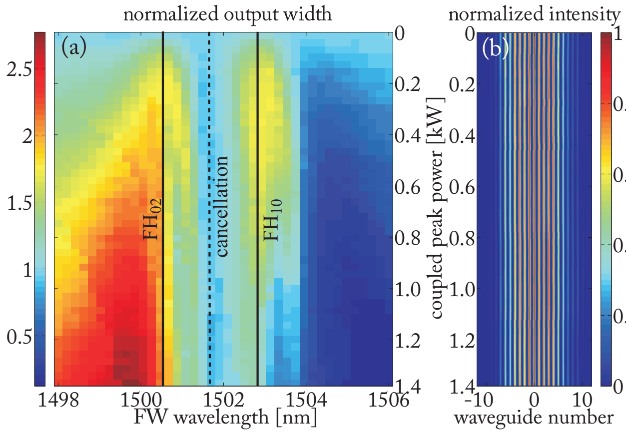

Figure 2: (a) Output beam width for normal excitation, normalized to the linear output at 1498 nm. The solid lines indicate the PM wavelengths. (b) Power independent output pattern at 1501.6 nm [dotted line in (a)].

Results and Discussion

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. 2(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 [7], 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 the phase shifts. There we observe inhibition of the nonlinear self-action of the beam and consequently the beam width stays the same for all experimentally accessible powers. In Fig. 2(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.

An important feature of the waveguide array is the change of the sign of diffraction when the input beam is inclined to the Bragg angle [3, 9]. However, even if the diffraction is inverted, we again observe a phase shift cancellation due to competition of two nonlinearities. 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. 2(a). Between the resonances, however, we again observe a region of power independent propagation.

Conclusions

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 [10]. In such a system, however, the beam would also experience strong transverse shifts at the output.

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