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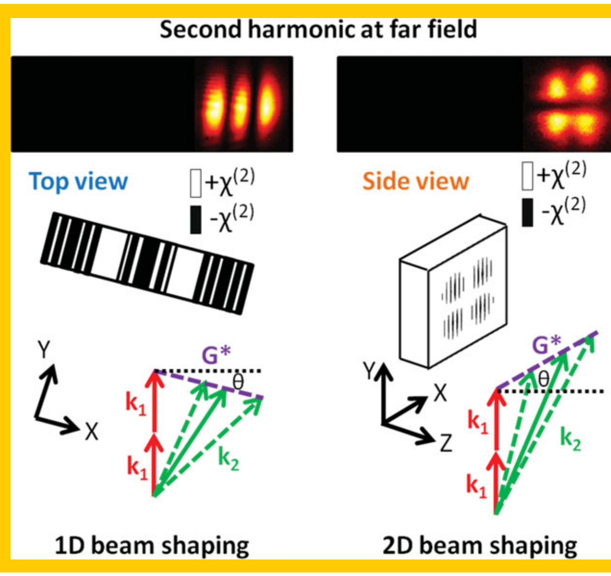
Abstract A method is proposed for nonlinear beam shaping, employing a non-collinear quasi phase-matched interaction in a crystal whose nonlinear coefficient is encoded by a computer generated hologram pattern. In this method the same axis is used for both satisfying the phase-matching requirements and encoding the holographic information, the result is a single shaped beam in the generated frequency. This allows to shape beams in one-dimension using a very simple method to fabricate patterned nonlinear crystals and to shape beams in two-dimensions with high conversion efficiency. The one-dimensional case is experimentally demonstrated by converting a fundamental Gaussian beam into Hermite-Gaussian beams at the second harmonic in a $KTiOPO_4$ crystal. The two-dimensional case is demonstrated by generating Hermite-Gaussian and Laguerre-Gaussian beams in a stoichiometric lithium tantalate crystal. The suggested scheme enables broad wavelength tuning by simply tilting the crystal.



Tunable nonlinear beam shaping by non-collinear interactions

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Optical diffraction occurs when a light beam encounters a periodic structure. Nonlinear diffraction takes place when this periodicity is in a nonlinear coefficient, for example, a periodically altered second order nonlinear coefficient impinged by a pump beam will result in a diffraction pattern in the second harmonic (SH). Usually the pump propagates perpendicularly with respect to the grating, thereby leading to a symmetric diffraction pattern from both sides of the propagation direction. Schemes for symmetric nonlinear diffraction were extensively studied in recent years, for the cases of Raman-Nath [1], Cerenkov [2–4] and Bragg [5, 6]. Breaking the symmetry, i.e. entering the nonlinear crystal at an angle can enlarge the operational bandwidth [7, 8] and in this case, the resulting diffraction pattern is also asymmetrical.

Shaping the generated beams in nonlinear interactions is of great interest, since it can save both cost and space compared with the alternative approach of first frequency converting the beam and then manipulating it. In addition, such shaping techniques open new possibilities for all-optical control of beam parameters that cannot be achieved in linear optics [9]. Several approaches for one-dimensional beam shaping where studied, including shaping of the generated amplitude [10, 11] or phase [12–16]. Arbitrary shaping of both amplitude and phase was demonstrated by us, implementing the concept of computer generated hologram in the nonlinear regime [17]. A common disadvantage to all the above mentioned schemes is that they require two-dimensional modulation of the nonlinear coefficient – usually one axis is used for quasi phase-matching and the second axis for beam shaping. This complicates the design and crystal fabrication, and in addition it poses a limitation when working with some of the more efficient crystals, e.g. $KTiOPO_4$. Two-dimensional beam shaping was also studied recently [18, 19] by working in a transverse setting of the nonlinear crystal, where both transverse axes are used for encoding the desired pattern and phase-matching is partially obtained using the nonlinear Raman-Nath [1] scheme. The disadvantage of this setup is the resultant low nonlinear conversion efficiency, owing to the partial phase-matching.

In this letter we propose, for the first time to our knowledge, a shaping scheme that provides a solution to both of the above mentioned problems: It enables 1D beam shaping by 1D modulation of the nonlinear coefficient, and it enables fully phase matched, and hence efficient scheme for 2D beam shaping. The suggested method is based on a non-collinear quasi phase-matched interaction, where a binary holographic pattern [20] is encoded on the same crystal axis used for quasi phase-matching. The diffraction is of an asymmetric nature and hence results with a single

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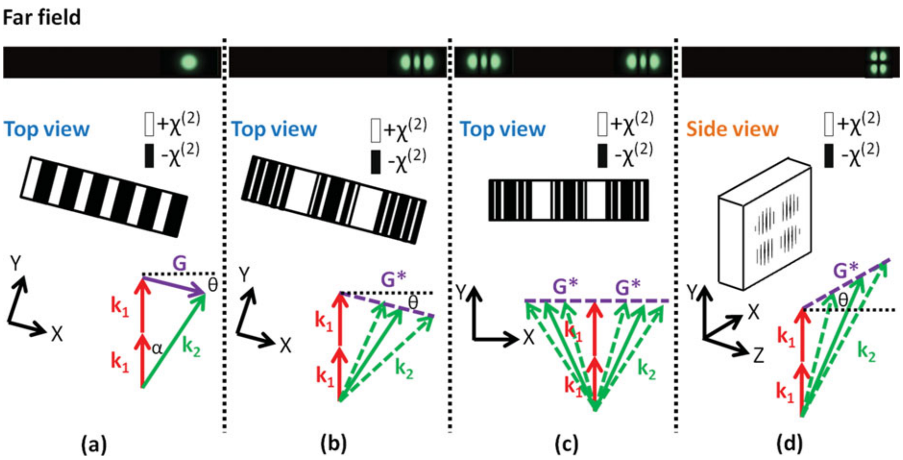

Figure 1 Shaping nonlinear diffraction – setup schematic illustration. Asymmetric nonlinear diffraction for a periodic crystal (a), a crystal encoded with one-dimensional information (b) and with two-dimensional information (d). Symmetric nonlinear diffraction in a crystal encoded with one-dimensional information (c). G* – local reciprocal crystal vector.

generated beam, separated from the fundamental frequency (FF). In the two-dimensional case the X-axis of the crystal is used for both quasi phase-matching and encoding the holographic information, whereas the Y-axis is used only for the holographic information. The general expression for the modulation of the nonlinear coefficient, in this case, is given by,

$$d_{NLO}(x, y) = d_{ij} sign\{\cos[xG - \varphi(x, y)] - \cos[\pi q(x, y)]\}, \qquad (1)$$

where d_{ij} is an element of the quadratic susceptibility $\chi^{(2)}$ tensor, G is the reciprocal vector in the X direction required for quasi phase-matching, $q(x, y) = 1/\pi \times \text{asin}\{A(x, y)\}$, and $A(x, y)\exp(i\varphi(x, y))$ is the Fourier transform of the desired wave-front in the first diffraction order [20]. For the process of SH generation $G = k_2 \sin(\alpha)/\cos(\theta)$, where k_2 is the wave-vector of the SH beam, α is the angle of separation between the fundamental frequency (FF) and SH beams and θ is the angle of FF beam propagation inside the crystal in respect to the normal to the crystal facet. θ can be either positive or negative, depending on phase-matching requirements. This differs from previous schemes [18, 19], where the full vectorial phase-matching condition was not fulfilled and the result of the nonlinear interaction was a symmetrical diffraction pattern with a low conversion efficiency.

In the one-dimensional case only the X-axis is employed, for both phase-matching and pattern encoding and the modulation is described by omitting the Y dependence in Eq. (1). This implementation differs from a previously presented technique [17], where continuous encoding was implemented with two-dimensional patterning, the propagation axis was used for collinear phase-matching and the perpendicular axis for imposing the desired phase on the generated SH. The method suggested here results with a much simpler 1D poling process, hence working with efficient nonlinear crystals with highly non-isotropic poling behavior, such as $KTiOPO_4$, becomes possible. Moreover, the suggested implementation for both one- and two-dimensional shaping can be employed for a wide range of wavelengths by simply tilting the crystal.

Figure 1 shows a schematic illustration of the suggested setups, in the one-dimensional case, the FF beam is propagating in a tilt with respect to the Y axis of the crystal. The k-vector diagram is presented to explain the quasi phase-matching scheme. Part (a) in the figure shows the output SH at far field for a simple one-dimensional periodic modulation, part (b) shows the result for encoding an Hermite-Gaussian (HG) beam, HG_{20} [21], with the one-dimensional version of Eq. (1). It is important to note that this technique can also be implemented for a zero tilt angle, as shown in part (c) of Figure 1. Whereas in the first two cases a single beam is generated, in the latter case two beams are generated symmetrically with respect to the optical axis. Part (d) in the figure illustrates how the concept of asymmetrical diffraction can be employed for two-dimensional beam shaping, showing a result for encoding HG_{11} [21] with Eq. (1). Symmetrical diffraction pattern with respect to the optical axis in a two-dimensional case is usually not feasible since this configuration requires sub-micron patterning [22] of the nonlinear crystal for phase-matching.

To demonstrate the one-dimensional concept we fabricated a crystal aimed to generate two beams of the Hermite-Gaussian family [21], HG_{10} and HG_{20} in the process of SH generation. The two-dimensional concept was demonstrated by second harmonic generation of the Hermite-Gaussian HG_{11} and the Laguerre-Gaussian LG_{20} [23] beams. The latter beam is a vortex beam with a topological charge of +2.

The experimental demonstration for the one-dimensional shaping was performed on a one-dimensionally poled $KTiOPO_4$ crystal with a carrier frequency, $G/2\pi$, of 0.1176 μm^{-1}. This frequency phase-matches an o-eo SH generation of an 1064.5 nm Nd:YAG laser, with the crystal tilted by 0.206 rad [24] (related with θ through Snells' law). Due to encoding, domain widths in the poled crystal varied between 1.6 μm and 4 μm. The length of the crystal in the Y direction was 2 mm. The FF source used was a Nd:YAG laser producing 10 ns pulses at a 2 kHz repetition rate at a wavelength of 1064.5 nm. The laser beam was focused to the center of the crystal with a

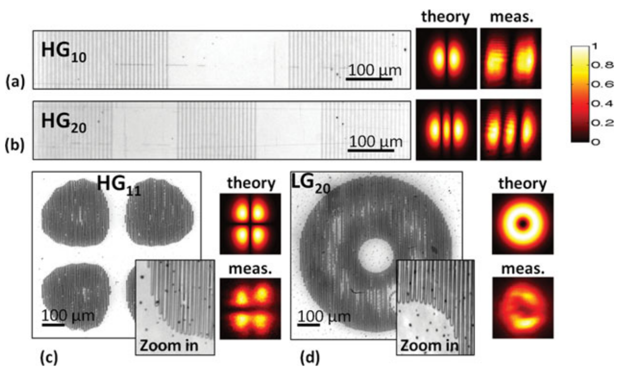

Figure 2 Fabricated poling patterns and a comparison between theoretical and measured SH beam profiles.

Table 1 A comparison between predicted and measured conversion efficiencies and beam profile correlation for the measured beams.

	prediction	measurement	
	conv. eff. [$\%W^{-1}$]	conv. eff. [$\%W^{-1}$]	spatial correlation
HG_{10}	1.39×10^{-5}	7.3×10^{-6}	0.96
HG_{20}	9.78×10^{-6}	7.17×10^{-6}	0.96
HG_{11}	7.48×10^{-8}	4.85×10^{-8}	0.93
LG_{20}	1.03×10^{-7}	5.43×10^{-8}	0.87

cylindrical lens, creating a waist radius of approximately 70 μm and 1 mm in the crystallographic z- and x-directions, respectively. An additional cylindrical lens was placed at the output of the crystal. Two-dimensional shaping was demonstrated on a two-dimensionally poled stoichiometric lithium tantalate (SLT) nonlinear crystal. 2D poling is also possible in $KTiOPO_4$ [25] but is much more difficult owing to the large anisotropy of the crystal. The carrier frequency in the X direction was 0.125 μm^{-1}, aimed to phase-match an e-ee SH generation of a 1550 nm pump at room temperature, with the crystal tilted by 0.86 rad [26]. Working in this tilted setting allows to use d_{33} in the nonlinear interaction, the fraction of FF power taking part in such interaction is $\cos^2(\theta)$, where θ is the FF angle. The processes of o-oo and o-eo SH generation result with negligible contribution to the total SH power because in SLT d_{33} is larger by more than an order of magnitude with respect to d_{22} and d_{24} [26]. Domain widths in the poled crystal varied between 2 μm and 4.5 μm. The length of the crystal in the Z direction was 0.5 mm. The FF source in this experiment was the signal of an optical parametric oscillator (OPO) producing 4.5 ns pulses at a 10 kHz repetition rate at 1550 nm. The beam was focused to the center of the crystal creating a waist radius of approximately 500 μm.

Microscopic pictures of the poling structures on the crystals are presented in Figure 2, parts (a), (b), (c) and (d). The high quality of the poling process is evident from the pictures. The desired HG and LG modes were obtained at the far field of the SH and a comparison between theoretical and measured beam shapes is also presented in Figure 2. It should be noted that the largest variation between measured and theoretical beam shapes is seen for the vortex beam, which most probably originates from fabrication variations in this poled structure.

A comparison between experimental and predicted conversion efficiencies for the generated beams in both crystals was conducted, the results are summarized in Table 1. Numerical simulations were performed based on the split-step Fourier method, with physical parameters identical to those in the experiment and assuming $d_{15} = 3.7$ pm/V [24] for $KTiOPO_4$ and $d_{33} = 12.9$ pm/V [26] for SLT. Simulations took into account the larger interaction length and reduced effective nonlinear coefficients caused by the tilted setup of the crystals. We can estimate the reduction in efficiency owing to the modulation by comparing with standard periodically poled crystals. The expected external conversion efficiency for a periodically poled $KTiOPO_4$ crystal, such as presented in Figure 1 part (a), is $2.88 \times 10^{-5}\%W^{-1}$, i.e. 2–3 times larger than the predicted efficiency for generating HG_{10} and HG_{20} beams. A similar reduction in efficiency is obtained in SLT, in which the efficiency of a periodically poled crystal is $2.34 \times 10^{-7}\%W^{-1}$. The observed reduction in efficiency due to modulation is expected since both modulation and phase-matching are implemented on the same axis in both crystals. In addition, Table 1 also summarizes the spatial correlation between measured and theoretical beam shapes.

An advantage of the suggested scheme in $KTiOPO_4$ is the wide range of temperatures in which this device operates, since the temperature change only leads to a small change in the angle of the generated beam. The device exhibits an almost constant output power in the examined range of 25°C – 150°C. In both crystals, the advantage of working with an asymmetric scheme is the flexibility of the chosen work point, i.e. phase-matching is achieved for different crystal tilt angles at different pump wavelengths. This flexibility is demonstrated in Figure 3, where the required crystal tilt angle versus FF wavelength is presented for the two materials, $KTiOPO_4$ and SLT, at room temperature, for two different poling periods. Tunability of more than 200 nm is achieved in both cases, by simply changing the tilt angle.

It's important to note that the suggested technique is not limited only to Hermite-Gaussian or Laguerre-Gaussian beams and any arbitrary one- and two-dimensional modulation can be generated in the SH, e.g Airy beam [12], Parabolic beam [27], etc. Also, it is now possible to implement a two-dimensional lens in the nonlinear process, previously demonstrated only in one dimension [13, 14].

A comparison between measured conversion efficiency for one-dimensional shaping in the presented method and the previously presented technique [17], when taking into account the different interaction lengths and different nonlinear coefficients, shows an improvement by a factor of 2.

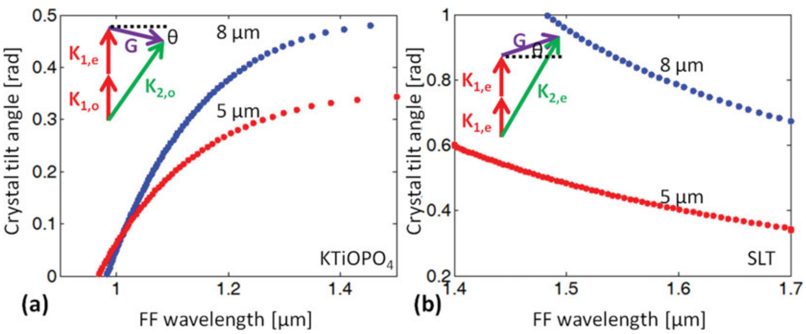

Figure 3 Possible work points in asymmetrical diffraction in an o-eo SH generation in $KTiOPO_4$ at two different carrier periods (a) and e-ee SH generation in SLT (b).

The improvement is due to the fact that in the present method SH power is only concentrated in the shaped diffraction order. A comparison for the two-dimensional shaping case, comparing results in this letter and reported results in Ref. 18, taking into account the different FF beam waist, shows a dramatic improvement of 5 orders of magnitude. This emphasizes the advantage of the asymmetrical diffraction scheme. An additional option for achieving efficient two-dimensional beam shaping is working with two-dimensionally patterned nonlinear slanted crystals [28]. In this case the nonlinear interaction would be collinear, the propagation axis would serve for both phase-matching and encoding holographic information and the perpendicular axis for encoding only.

The nonlinear process described here is non-collinear and the pattern described in Eq. (1) does not depend on the tilt angle of the crystal. It is hence important to state the geometrical limitations of the chosen work point in terms of tilt angle, crystal length and the beam waist of the pump. We studied the influence of the above parameters by examining the simulated spatial correlation for the case of generating an HG_{20} beam in $KTiOPO_4$. We empirically derived the following condition, set for a spatial correlation higher than 90%, $L \times \tan(\theta) \leq 0.45w_0$, where L is the length of the crystal in the direction of propagation, θ is the angle of the pump beam propagation inside the crystal (related with the crystal tilt angle through Snells' law) and w_0 is its' waist. The experiments we report in this letter fulfill this condition – for SLT $L \times \tan(\theta)/w_0$ is 0.38, and for $KTiOPO_4$ it is 0.23.

In conclusion, we have presented and experimentally demonstrated a scheme for one- and two-dimensional beam shaping in nonlinear wave mixing based on non-collinear phase-matching. This is achieved by introducing both phase-matching and encoded information on the same crystal axis. The concept was demonstrated by converting a fundamental HG_{00} Gaussian beam light into HG_{10}, HG_{20}, HG_{11} and LG_{20}, beams at the second harmonic. In the one-dimensional case the scheme requires a simple one-dimensional poling pattern to efficiently shape the result of the interaction. In the two-dimensional case the scheme offers a major improvement in conversion efficiency of the shaping process. In both cases, working with a wide range of pump wavelengths is possible by changing the tilt angle of the crystal.

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References

[1] S. M. Saltiel, D. N. Neshev, W. Krolikowski, A. Arie, O. Bang, and Y. S. Kivshar, Opt. Lett. **34**, 848–850 (2009).
[2] S. M. Saltiel, Y. Sheng, N. Voloch-Bloch, D. N. Neshev, W, Krolikowski, A. Arie, K. Koynov, and Y. S. Kivshar, Quantum Electron. **45**, 1465–1471 (2009).
[3] Y. Zhang, Z. D. Gao, Z. Qi, S. N. Zhu, and N. B. Ming, Phys. Rev. Lett. **100**, 163904–163907 (2008).
[4] H. Ren, X. Deng, Y. Zheng, N. An, and X. Chen, Phys. Rev. Lett. **108**, 223901–223905 (2012).
[5] I. Freund, Phys. Rev. Lett. **21**, 1404–1406 (1968).
[6] A. Shapira and A. Arie, Opt. Lett. **36**, 1933–1935 (2011).
[7] S. Moscovich, A. Arie, R. Urneski, A. Agronin, G. Rosenman, and Y. Rosenwaks, Opt. Exp. **12**, 2236–2242 (2004).
[8] T. Ellenbogen and A. Arie, Opt. Comm. **277**, 423–426 (2007).
[9] I. Dolev, T. Ellenbogen, and A. Arie, Opt. Lett. **35**, 1581–1583 (2010).
[10] G. Imeshev, M. Proctor, and M. M. Fejer, Opt. Lett. **23**, 673–675 (1998).
[11] X. Q. Yu, P. Xu, Z. D. Xie, J. F. Wang, H. Y. Leng, J. S. Zhao, S. N. Zhu, and N. B. Ming, Phys. Rev. Lett. **101**, 233601–233605 (2008).
[12] T. Ellenbogen, N. Voloch-Bloch, A. Gannay-Padowicz, and A. Arie, Nature Photon. **3**, 395–398 (2009).
[13] J. R. Kurz, A. M. Schober, D. S. Hum, A. J. Saltzman, and M. M. Fejer, Selec. Top. in Quant. Elec. **8**, 660–664 (2002).
[14] Y. Qin, C. Zhang, Y. Zhu, X. Hu, and G. Zhao, Phys. Rev. Lett. **100**, 063902–063905 (2008).
[15] H. Y. Leng, X. Q. Yu, Y. X. Gong, P. Xu, Z. D. Xie, H. Jin, C. Zhang, and S. N. Zhu, Nature Communications **2**, 429 (2011).
[16] J. P. Torres, A. Alexandrescu, S.a Carrasco, and L. Torner, Opt. Lett. **29**, 376–378 (2004).

[17] A. Shapira, I. Juwiler, and A. Arie, Opt. Lett. **36**, 3015–3017 (2011).
[18] A. Shapira, R. Shiloh, I. Juwiler, and A. Arie, Opt. Lett. **37**, 2136–2138 (2012).
[19] N. Voloch-Bloch, K. Shemer, A. Shapira, R. Shiloh, I. Juwiler, and A. Arie, Phys. Rev. Lett. **108**, 233902–233906 (2012).
[20] W. H. Lee, Appl. Opt. **18**, 3661–3669 (1979).
[21] B. E. A. Saleh and M. C. Teich, Fundamentals of Photonics (John Wiley and Sons, 1991).
[22] C. Canalias and V. Pasiskevicius, Nature Photon. **1**, 459–462 (2007).
[23] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A **45**, 8185–8189 (1992).
[24] I. Shoji, T. Kondo, A. Kitamoto, M. Shirane, and R. Ito, JOSA B **14**, 2268–2294 (1997).
[25] C. Canalias, M. Nordlöf, V. Pasiskevicius, and F. Laurell, Appl. Phys. Lett. **94**, 081121–081123 (2009).
[26] I. Dolev, A. Ganany-Padowicz, O. Gayer, A. Arie, J. Mangin, and G. Gadret, Applied Physics B **96**, 423–432 (2009).
[27] M. A. Bandres, Opt. Lett. **33**, 1678–1680 (2008).
[28] D. S. Hum, R. K. Route, and M. M. Fejer, Opt. Lett. **32**, 961–963 (2007).