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Review

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Nonlinear optical holograms for spatial and spectral shaping of light waves

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Abstract Shaping either the spatial or the spectral output of a nonlinear interaction is accomplished by introducing basic concepts of computer-generated holography into the nonlinear optics regime. The possibilities of arbitrarily spatially shaping the result of a nonlinear interaction are presented for different phase-matching schemes allowing for both one- and two-dimensional shaping. Shaping the spectrum of a beam in nonlinear interaction is also possible by utilizing similar holographic techniques. The novel and complete control of the output of a nonlinear interaction opens exciting options in the fields of particle manipulation, optical communications, spectroscopy and quantum information.

Keywords Nonlinear optics · Beam shaping · Spectral shaping · Computer-generated holograms

1 Introduction

The scheme for nonlinear wave mixing is based on interaction between laser beams having a Gaussian profile. The generated beam is then shaped by various additional elements such as lenses, filters and holograms. However, as we will describe in this paper, it is now possible to realize these shaping tasks within the nonlinear converter, by suitable modulation of its nonlinear coefficient. The motivation for beam shaping comes from the fact 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 [1]. Nonlinear optical shaping can be done not only in the spatial domain but also in the spectral domain, and in some cases, both spatial shaping and spectral shaping are possible, thereby enabling the realization of interesting wave functions such as light bullets [2].

One-dimensional shaping of the generated beam in a nonlinear process was first suggested by Imeshev et al. [3]. The generation of a flat top beam at the output of the crystal, i.e., near field, was achieved by changing the interaction length along the profile of the incoming Gaussian beam. This technique can be used for various one-dimensional manipulations on the amplitude of the generated beam. Ellenbogen et al. [4] proposed a two-dimensional structure satisfying non-collinear phase matching, implementing an all-optical deflector. At the output of the crystal, two Gaussian beams were generated and their relative location could be controlled by different parameters in the experiment.

Manipulating the phase of the output was suggested by Kurtz et al. [5] and demonstrated for linear phase arrays and lenses. In another study, Ellenbogen et al. [6] proposed using the transverse axis to the propagation direction to impose a cubic phase on the generated beam, when such a beam undergoes an optical Fourier transform and the resulting beam is a self-accelerating Airy beam [7]. This is a unique feature of this specific beam since other beams Fourier transform cannot necessarily be expressed in terms of a Gaussian beam multiplied by some defined phase function. A nonlinear structure that generated multiple focal points at the converted frequency was presented by Qin et al. [8].

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Two common characteristics exist in all of the above-mentioned devices. First, they all allow manipulating the output beam of a nonlinear interaction only in a single dimension. A theoretical device for two-dimensional manipulation—in order to nonlinearly generate vortex beams—was previously proposed by Bahabad and Arie [9], but due to the fact that the main fabrication process for modulating the nonlinear coefficient, electric field poling of ferroelectric crystals [10], is a planar technique, it cannot yet be realized in practice. The second, and very important, common feature is the fact that none of the mentioned studies proposed a general approach for arbitrary shaping of the output beam; i.e., each study suggested a specific ad hoc type of solution for a specific type of desired beam.

In recent years, arbitrary shaping of beams in a nonlinear process was demonstrated, by bringing the concept of computer-generated holography into nonlinear optics, first for one-dimensional beam shaping [11] and later for two-dimensional beam shaping [12, 13]. This concept was further extended for spectral shaping of the generated signal in a nonlinear three-wave mixing process [14, 15].

In this review, we present an overview of new research in the field of spatial and spectral shaping based on exploiting holographic techniques in nonlinear crystals. First, a theoretical background of nonlinear interactions is presented, followed by an introduction to basic concepts of holography. Next, different shaping schemes are described and evaluated.

2 Theoretical background

2.1 Three-wave mixing process and quasi-phase matching

In a three-wave mixing process, two input beams of frequencies, ω_1 and ω_2, can generate a new wave of frequency ω_3. The generated wave may be equal to the sum or the difference of the two input waves, or the second harmonic of each one of them. In this review, we will mainly focus on the nonlinear process of second-harmonic generation SHG, where both incoming beams have the same fundamental frequency (FF), ω_1, and the generated second-harmonic (SH) beam has a frequency of $\omega_2 = \omega_1 + \omega_1$, although all the concepts we present here can also be utilized with other nonlinear optical interactions.

The interaction taking place inside a nonlinear crystal between the two frequencies in SHG can be described in terms of two coupled-wave equations. These equations are derived from the wave equation using the slowly varying amplitude approximation [16]. The resulting equations are,

$$\frac{\mathrm{d}A_1}{\mathrm{d}z} = \frac{2\mathrm{i}\omega_1^2 d_{\mathrm{eff}}}{k_1 c^2} A_2 A_1^* \mathrm{e}^{-\mathrm{i}\Delta k z}, \tag{1}$$

$$\frac{\mathrm{d}A_2}{\mathrm{d}z} = \frac{\mathrm{i}\omega_2^2 d_{\mathrm{eff}}}{k_2 c^2} A_1^2 \mathrm{e}^{\mathrm{i}\Delta k z}, \tag{2}$$

where A_1 and A_2 are the amplitudes of the two waves, k_1 and k_2 are the wave vectors, d_{eff} is the nonlinear susceptibility coefficient and $\Delta k = 2k_1 - k_2$. In the process of SHG, the annihilation of two photons with energy $\hbar\omega_1$ is followed by a generation of a single photon with energy $\hbar\omega_2$; energy is conserved. Achieving momentum conservation is more complicated due to dispersion. The parameter Δk is defined to asses this phenomena and is termed phase mismatch. As a result of phase mismatch, $\Delta k \neq 0$, different dipoles in the nonlinear crystal oscillate in different phases and this destructive interference results with a low conversion efficiency of the SHG.

Under the assumption of an un-depleted pump beam, which occurs if $A_2 \ll A_1$ throughout the entire process, an exact solution to the coupled equations, for a crystal with length l, is given by [16],

$$A_2(z = l) = -\frac{\mathrm{i}\omega_1 d_{\mathrm{eff}}}{n_2 c} A_1^2 l \frac{\sin\left(\frac{\Delta k l}{2}\right)}{\frac{\Delta k l}{2}} \mathrm{e}^{\mathrm{i}\Delta k l/2}. \tag{3}$$

The effect of phase mismatch is clearly seen in the above expression.

The two well established possible solutions to the phase-mismatch problem are using the natural birefringence existing in many nonlinear crystals or quasi-phase matching (QPM) [17]. Birefringence is the dependence of the refractive index on the direction of polarization of the optical radiation. Finding the polarization combination allowing for phase matching is sometimes possible with angle tuning, i.e., setting the angle of beam propagation inside the crystal with regard to the different axes of the crystal. This method has several serious drawbacks: Since the method relies on given material properties of dispersion and birefringence, it is not always possible to find conditions in which phase matching is possible. Moreover, when the beams do not propagate along primary axes of the crystal, the effect of walk-off is observed [16]. In addition, this technique does not allow working with the more efficient diagonal components of the nonlinear susceptibility tensor, for example d_{33}, which is accessed only when all beams are polarized along the Z-axis.

In QPM [17], the basic idea is to overcome the phase mismatch by modulating the sign of the nonlinear coefficient. In ferroelectric crystals, this can be done by inverting the ferroelectric domain orientation. In the specific case of a periodic modulation in the sign of the nonlinear coupling coefficient, the nonlinear coefficient is

$$d(z) = d_{ij}\mathrm{Sign}(\cos(2\pi z/\Lambda)), \tag{4}$$