Formation of spatial optical solitons in periodic refractive index gratings formed by arrays of coupled optical waveguides was first studied theoretically by Christodoulides and Joseph. A standard theoretical approach to study the nonlinear localization of light in gratings is based on the decomposition of the total electric field in a sum of weakly coupled fundamental modes excited in each waveguide of the array; a similar approach is known in solid-state physics as the tight-binding approximation. Then, the wave dynamics can be described by an effective discrete nonlinear Schrödinger (NLS) equation, that has stationary, spatially localized solutions in the form of discrete optical solitons. Discrete solitons have been extensively explored in a number of theoretical papers (see, e.g., Refs. 2,3,4), and also generated experimentally.5,6 On the other hand, several recent studies7,8,9 indicate that the dynamics of nonlinear localized modes in periodic structures cannot always be adequately described within the discrete (tight-binding) approximation, and the full study of the continuous models with periodic potentials is more accurate.

Recently, Fleischer et al.10 reported the first experimental observation of spatial optical solitons in an array of optically-induced waveguides. They created optical gratings by interfering pairs of plane waves in a photorefractive crystal, and employed screening nonlinearity to observe self-trapping of a probe beam in the form of staggered and unstaggered localized modes. Being inspired by these observations, in this Letter we study experimentally novel self-trapping effects in optically-induced gratings. We create a well-controllable index grating by plane-wave interference in a photorefractive crystal, and then demonstrate the excitation of odd and even nonlinear localized states and their bound states.

Following Efremidis et al.,11 we consider a photorefractive Strontium Barium Niobate (SBN:60) crystal as a nonlinear medium. The SBN sample is assumed to be externally biased with a DC field along its extraordinary x-axis (crystalline c-axis). Optically-induced refractive index gratings are created in the crystal via photorefractive effect, by periodic intensity patterns resulting from the interference of two or more ordinary-polarized plane waves (wide beams of high intensity, polarized along the ordinary y-axis). Then we study evolution of the extraordinary polarized probe beam propagating through this periodic structure. Since the relevant electro-optic coefficients of the SBN crystal are substantially different for orthogonal polarizations, the grating created by ordinary polarized beams can be treated as being essentially one-dimensional and constant along propagation z-axis. This one-dimensional grating, created by the interference of plane waves with wavelength \( \lambda \) has the intensity pattern \( I_g = I_0 \cos^2[Kx] \), where \( K = n_0 k_0 \sin \theta \), \( \theta \) is the angle between a plane wave and the z-axis, \( k_0 = 2\pi/\lambda \), and \( n_0 \) is the refractive index along the ordinary axis.

Provided that the intensity of the probe beam, \(|E|^2\), is weaker than that of the grating, \( I_0 \), one can assume that the back-action of the the probe beam on the grating is negligible. Then the evolution of a probe beam in the grating is governed by the following equation:

\[
2ik_1 \frac{\partial E}{\partial z} + \frac{\partial^2 E}{\partial x^2} - k_0^2 n_e^4 r_{33} E_0 E = 0,
\]

where \( n_e \) is the refractive index along the extraordinary axis, \( k_1 = k_0 n_e \), and \( E_0 \) is the space-charge field, \( E_0 E = E_0/(1 + I) \), expressed through the total intensity, \( I = |E|^2 + I_g \), normalized with respect to the dark irradiance of the crystal, \( I_g \). For our choice of the polarity of the biasing DC field, \( \gamma_{nl} = k_0^2 n_e^4 r_{33} E_0 > 0 \), and the nonlinearity exhibited by the probe beam is self-focusing.

When \(|E|^2 \ll I_0\), the probe beam experiences effectively linear grating. This grating is shallow when \( I_0 < 1 \), and deep when \( I_0 \gg 1 \). In this case, Eq. (1) can be presented as the linear Schrödinger equation with a periodic potential, \( V_{nl}^{\text{lin}} \approx \gamma_{nl}/[1 + I_0 \cos^2(Kx)] \), with its stationary modes found in the form \( E(z, x) = E_0(x) \exp[i(\beta/k_1)z] \). The energy spectrum, \( \beta \), of the waves guided by the grating, as a function of \( I_0 \), displays a band-gap structure (see Fig. 1). The spectral bands correspond to the regime when the beam spreads across the entire lattice;
FIG. 1: Band structure of the energy spectrum, $\beta$, in the linear grating potential $V_{lin}^{\beta} = [1 + I_0 \cos^2(Kx)]^{-1}$ (for $\gamma_{nl} = 1$): numbered - Bloch bands, hashed - band gaps. Inset: effective potential $V_{nl}^{\beta}$ shown for two values of the grating intensity ($I_0$).

these extended states are Bloch waves of the periodic structure. In the gaps separating the bands, no periodic guided modes exist. Even when the effective linear grating becomes very deep, the Bloch-wave bands remain wide, which means that the coupling between the individual waveguides in the grating remains very strong. As a result, the tight-binding approximation and the corresponding discrete NLS model, valid for a weak coupling, may be not valid for optical gratings induced in nonlinear saturable media.

When the probe-beam intensity grows, the effective grating becomes nonlinear, as the beam experiences self-focusing. In this case, the probe beam can be trapped in the form of spatially localized modes - bright spatial solitons. For the focusing nonlinearity, these localized modes are found in the semi-infinite gap (below band 1 in Fig. 1), and they resemble conventional bright solitons modulated by the lattice. These modes are analogous to unstaggered discrete solitons of the nonlinear lattices only in the tight-binding regime which has a limited applicability in our case. However, this analogy can still be employed to understand the structure of the localized states, even though the saturable nature of nonlinearity does not allow us to apply the discrete model directly.

Recently, the model similar to Eq. (1) has been analyzed, beyond the tight-binding approach, in the context of coherent matter waves in optical lattices.[1] It was shown that it supports a number of nonlinear localized states, some of which are analogous to the solitons of the discrete NLS equation. Moreover, the localized modes were found to exist in the form of multi-soliton bound states, and one of the simplest bound states is a two-soliton state that corresponds to the so-called “twisted mode” of discrete lattices.[4] Below, we demonstrate experimentally the existence of different types of nonlinear localized states in an optically-induced grating in the regime of the self-focusing nonlinearity.

The experimental setup is shown in Fig. 2. The light of a Nd:YVO$_4$ laser at 532nm is split into two parts. The transmitted (extra-ordinary polarized) beam is focused by a 6-cm (or 5-cm) focal-length lens on the input face of a 15mm long SBN:40 crystal. The second, ordinary-polarized beam is used to form the optical lattice. It passes through a Mach-Zehnder interferometer aligned such that its two output beams intersect at a small angle, thus producing interference fringes inside the crystal. The difference in the optical paths of the interferometer could be locked by use of a piezo-controlled mirror, in order to stabilize the interference pattern. It also enabled for precise positioning of the interference maxima in respect to the location of the probe beam, which propagates parallel to the induced waveguides. The input and output faces of the crystal could be imaged by a micro-
At low intensities of the probe beam (|\text{Intensity}|), we observed both types of the localized modes. When the optical lattice is formed, a pair of out-of-phase “odd” states is created [(d)]. If the beam is centered on a maximum of the optical lattice, a pair of “even” states is observed with a central waveguide not being excited at all [(e)].

In conclusion, we have demonstrated experimentally the generation of spatial optical solitons in optically-induced gratings created by interfering plane waves in a photorefractive crystal. Since the light-induced optical lattices provide much greater control of the grating parameters than fabricated waveguide arrays, we believe that these results open many new possibilities for the study of various nonlinear effects in optically induced gratings, including gap solitons.

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