We study tunable refraction of light in one-dimensional periodic lattices induced optically in a photorefractive crystal. We observe experimentally both positive and negative refraction of beams which selectively excite the first or second spectral bands of the periodic lattice, and demonstrate tunability of the output beam position by dynamically adjusting the lattice depth. At higher laser intensities, the beam broadening due to diffraction can be suppressed through nonlinear self-focusing while preserving the general steering properties.

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Recent interest in the effect of negative refraction is associated with the experimental demonstration of left-handed composite metamaterials which bend light in the opposite direction to that observed in isotropic media. This negative refraction occurs due to the effectively negative refractive index for simultaneously negative dielectric permeability and magnetic permittivity of the medium. However, negative refraction of waves is a fundamental physical phenomenon that may occur in different systems as a result of anisotropy or periodicity, and it was recently demonstrated in two-dimensional photonic crystals.

As a matter of fact, it has been known for many years that negative refraction in periodic structures is possible due to the specific properties of the extended periodic eigenmodes or Bloch waves, and it can be observed even in weakly modulated one-dimensional periodic lattices. Indeed, when light bends at the interface between homogeneous and periodic media, the refraction angle depends on the effective diffraction coefficients of the particular Bloch waves of the structure. Since diffraction of the Bloch waves depends strongly on the refractive index contrast, the refraction angle can be controlled by dynamically varying the lattice depth. Such tunability of the lattice depth and negative refraction can be achieved in several physical systems, including holographic gratings induced optically in photorefractive crystals and liquid-crystal waveguides with patterned electrodes.

In this Letter, we study theoretically and demonstrate experimentally the control over light refraction in optically-induced photonic lattices. For the first time to our knowledge, we realize dynamic tunability of the beam refraction associated with different Bloch waves by using a tilted lattice of a variable depth. We demonstrate that while beams corresponding to the first band of the lattice bandgap spectrum are positively refracted following the direction of the lattice, the beams associated with the top of the second band experience enhanced negative refraction in the direction opposite to the lattice tilt. Furthermore, we combine such tunability with spatial localization of the beams through nonlinear self-focusing in the normal diffraction regime.

We consider an optically-induced lattice in a biased photorefractive crystal where the propagation of extraordinarily polarized beams with amplitude \( E(x,z) \) is described by the equation

\[
\frac{\partial E}{\partial z} + D \frac{\partial^2 E}{\partial x^2} + \mathcal{F}(x-\alpha z, |E|^2)E = 0, \tag{1}
\]

where \( x \) and \( z \) are the transverse and propagation coordinates normalized to the characteristic values \( z_0 \) and \( z_0 \), respectively, \( D = D_0 \gamma/(4\pi n_0^2 z_0^2) \) is the beam diffraction coefficient, \( \alpha \) is the normalized angle of the lattice tilt [see Fig. 1(a)], \( n_0 \) is the average refractive index of the medium, \( \lambda \) is the wavelength in vacuum, \( \mathcal{F}(x, |E|^2) = -\gamma \left[ I_b + I_g \cos^2(\pi x/d) + |E|^2 \right]^{-1} \), \( I_b \) is the constant dark irradiance, \( I_g \) is the peak intensity of the interference pattern of period \( d \), and \( \gamma \) is a nonlinear coefficient linear proportional to the applied DC field. To match our experimental conditions, we use the following parameters: \( \lambda = 0.532 \mu m \), \( n_0 = 2.4 \), \( z_0 = 1 \mu m \), \( z_0 = 1 \mu m \), \( d = 19.2 \), \( I_b = 1 \), \( I_g = 1 \), and the crystal length \( L = 15 \mu m \). Then, the refractive index contrast in the lattice is \( \Delta n = \gamma \lambda/(4\pi z_0) \).

Propagation of linear waves in a straight lattice (\( \alpha = 0 \)) is defined through the spectrum of Bloch waves \( E(x,z) = \psi(x) \exp(iKx/d + iz\beta) \), where \( \psi(x) \) is periodic, \( K \) is the Bloch wave number, and \( \beta \) is the propagation
constant. Dispersion curves $\beta(K)$ form bands, as shown in Figs. I(b,c). In a tilted lattice, the Bloch-wave dispersion can be written as $\beta(K) = \beta[K - \alpha/(2D)] - K\alpha + \alpha^2/(4D)$, which indicates that the dispersion curves are translated and tilted simultaneously with $\alpha$.

When an input beam excites Bloch waves from a particular spectral band, its normalized propagation angle inside the lattice can be found as $\theta = -d\beta/dK$. Waves corresponding to the middle ($K = 0$) or edge ($K = \pi$) of the Brillouin zone always propagate straight if the lattice is not tilted ($\alpha = 0$), since $\theta = 0$ at all band edges [see Figs. I(b,c)]. However, in a tilted lattice the same waves refract at an angle $\theta = -\beta[(K - \alpha/(2D))/\partial K + \alpha \simeq \alpha(D - D_{\text{eff}})/\partial O(\alpha^2)$, where $D_{\text{eff}} = -(1/2)d\beta/dK^2$ is the effective diffraction coefficient of Bloch waves. Thus, the beam refraction induced by the lattice tilt is proportional to the difference of the diffraction coefficients in a bulk crystal and in the lattice at the corresponding $K$.

Results of our calculations presented in Fig. I(d) show that for the top of the first band $0 < D_{\text{eff}} < D$, and therefore the beam is refracted in the direction of the lattice tilt [Figs. I(e,f), top]. At the bottom of the first band, $D_{\text{eff}} < 0$, and the beam is refracted even stronger in the same direction. In a sharp contrast, for the top of the second band $D_{\text{eff}} > D$ and the beam experiences negative refraction [Fig. I(e), bottom] in shallow lattices with $\Delta n < \Delta n_{\text{cr}}$, whereas $D_{\text{eff}} < D$ and positive refraction should occur in deeper lattices with $\Delta n > \Delta n_{\text{cr}}$. Most remarkably, in the critical case when $\Delta n \simeq \Delta n_{\text{cr}}$ and $D_{\text{eff}} \simeq D$, the band-2 beam always goes straight [Fig. I(f), bottom] even when the lattice is tilted (at relatively small angles). Linear diffraction leads to beam broadening which can be suppressed in nonlinear media due to the effect of self-focusing. In the examples shown in Figs. I(e,f), we have chosen the wave intensity to achieve the formation of lattice solitons which do not diffract and have constant width. These mobile solitons spanning several lattice periods exhibit the same refraction as linear beams.

In experiment, we induce a periodic lattice in a $15 \times 5 \times 5$ mm SBN:60 photorefractive crystal externally biased and homogeneously illuminated with white light. An optical lattice with the period of $19.2 \mu m$ is created by interfering two ordinarily-polarized broad beams from a frequency-doubled Nd:YVO$_4$ laser at 532 nm. By varying the bias voltage, we change the contrast of the refractive index modulation of the lattice, thus altering the bandgap structure and correspondingly modifying the diffraction properties of the Bloch waves.

Different Bloch waves of the induced periodic structure are excited by several extraordinarily polarized beams. The wave at the top of the first band is excited by a single Gaussian beam of a full width at half maximum (FWHM) of $30 \mu m$, propagating along the induced lattice. To selectively excite Bloch waves at the two edges of the Bragg-reflection gap, we employ a two-beam excitation technique, where a pair of beams, each propagating under the Bragg angle (in opposite directions), is focused at the front face of the crystal to a FWHM of $65 \mu m$. By tilting the lattice without changing the initial direction of the probe beams [Fig. I(a)], we study the steering of the propagating beams. This steering strongly depends on the lattice tilt, as the latter changes the diffraction coefficient of the Bloch waves by scanning along the dispersion curves [Fig. I(b,c)]. In Fig. I(a) we show the change of the beam position at the output face of the crystal as a function of the lattice tilt. The
Refraction is positive for waves in the first band and negative for those in the second band. Consequently, beams associated with these two bands are seen to be shifted in opposite directions. For the two waves at the edges of the Bragg reflection gap, the output shift approaches that of a beam propagating at the Bragg angle (corresponding shift of 76 $\mu$m) as the lattice tilt is increased. This effect can be considered as an angular amplification of beam deflection since the output propagation angle is substantially larger than the initial lattice tilt. In our particular case, we measure a six fold increase of the tilt angle with a positive or negative gain for the waves of the top and bottom of the spectral gap, respectively. On the other hand, the deflection of waves from the top of the first band is much smaller and less sensitive to the lattice tilt. The corresponding output beam profiles for a lattice tilt of 3 mrad are depicted in Fig. 3(b). It is clearly seen that these profiles are well represented by the structure of the corresponding Bloch waves superimposed on a bell-shaped envelope. These findings are in full agreement with our theoretical predictions.

In order to demonstrate tunability of the beam refraction and steering, we measured the change of the beam position at the crystal output face as a function of bias voltage. In Fig. 3(a) we show the output beam shift for the three different Bloch modes vs. the applied voltage. The lattice is tilted to the right at an angle of 2 mrad, measured in air, corresponding to 15% of the Bragg angle. At low voltages (shallow lattice) waves corresponding to the bottom of the first band and the top of the second band experience positive and negative refraction, respectively. However, increasing the bias voltage results in reduced beam mobility and hence a monotonical decrease of the output shift for both beams. The beam deflection can be almost entirely suppressed for a deep lattice, corresponding to voltages higher than 2.5 kV. For voltages lower than 1000 V, the lattice is too shallow to support beams of the particular spectral width. In contrast to this strongly voltage dependent steering of beams belonging to the edges of the Bragg reflection gap, the beam associated with the top of the first band is seen to be deflected less than the lattice itself, and this deflection does not change significantly with the voltage.

An important requirement for practical realization of controllable beam steering is that beams stay localized as they propagate through the sample. For a focusing nonlinearity, such localization can be realized for beams at the top of the bands, where diffraction is positive. In this case the propagation constant moves inside the gap at increased laser intensity and leads to formation of lattice solitons. An important question, however, is whether the effect of localization preserves the steering properties of Bloch waves. In Fig. 3(b) we show two intensity profiles of a beam associated with the top of the second band, taken at low (90 nW) and high power (800 nW). At higher laser power the beam is self focused from an output FWHM of 81 $\mu$m in the linear regime to 46 $\mu$m in the nonlinear regime. It is seen that the effect of self-focusing preserves the negative refraction properties, with only a small decrease of the deflection angle (10 $\mu$m at the output). We would like to point out that the degree of self-focusing depends on the lattice tilt, since this tilt determines the effective beam diffraction.

In conclusion, we have studied theoretically and demonstrated experimentally tunable refraction of light in optically-induced one-dimensional photonic lattices. We have observed negative refraction associated with the top of the second band of the lattice bandgap spectrum, and demonstrated tunability of the output beam position by a dynamically reconfigurable lattice depth. We have studied the light propagation at higher laser intensities for self-focusing nonlinearity and observed that the basic steering properties and negative refraction are preserved in the self-trapping regime.

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