Self-trapping of polychromatic light in nonlinear photonic lattices

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We study dynamical reshaping of polychromatic beams due to collective nonlinear self-action of multiple-frequency components in periodic photonic lattices and predict the formation of polychromatic discrete solitons facilitated by localization of light in spectral gaps. We show that the self-trapping efficiency and structure of emerging polychromatic gap solitons depends on the spectrum of input beams due to the lattice-enhanced dispersion, including the effect of crossover from localization to diffraction in media with defocusing nonlinearity.

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The fundamental physics of periodic photonic structures is governed by the wave scattering from periodic modulations of the refractive index and subsequent wave interference. Such a resonant process is sensitive to a variation of the beam frequency and propagation angle. Accordingly, refraction and diffraction of optical beams may depend strongly on the optical wavelength, allowing for construction of superprisms that realize a spatial separation of the frequency components.

In this Letter we address an important question of how the periodicity-enhanced sensitivity of diffraction upon wavelength influences nonlinear self-action of polychromatic light. We show that interaction between multiple-frequency components of an optical beam can lead to a collective self-trapping effect and polychromatic solitons, where spatial diffraction is suppressed simultaneously in a broad spectral region. These solitons can exist in periodic structures with noninstantaneous nonlinear response, such as optically-induced lattices or waveguide arrays in photorefractive materials. We demonstrate that the spectrum of polychromatic solitons possesses a number of distinctive features, related to the structure of the photonic bandgap spectrum. This suggests the possibility to perform nonlinear probing and characterization of the bandgap spectrum in the frequency domain, extending the recently demonstrated approach for nonlinear Bloch-wave spectroscopy with monochromatic light.

We study the dynamics of polychromatic light in planar nonlinear photonic structures with a modulation of the refractive index along the transverse spatial dimension, such as optically-induced lattices or periodic waveguide arrays. Then, the evolution of polychromatic beams in media with slow nonlinearity can be described by a set of normalized nonlinear equations,

\[
\frac{i}{\lambda_n} \frac{\partial A_n}{\partial z} + \frac{\lambda_n z_0}{4 \pi n_0 x_0^2} \frac{\partial^2 A_n}{\partial x^2} + \frac{2 \pi z_0}{\lambda_n} [\nu(x) + \gamma I] A_n = 0 , \tag{1}
\]

where \(A_n\) are the envelopes of the different frequency components of vacuum wavelengths \(\lambda_n\), \(x\) and \(z\) are the transverse and longitudinal coordinates normalized to \(x_0 = 10 \mu m\) and \(z_0 = 1\) mm, respectively, \(I = \sum_{n=1}^{N} |A_n|^2\) is the total intensity, \(N\) is the number of components, \(n_0\) is the average refractive index, \(\nu(x)\) is the refractive index modulation in the transverse spatial dimension, and \(\gamma\) is the nonlinear coefficient. We consider the case of a Kerr-type medium response, where the induced change of the refractive index is proportional to the light intensity and neglect higher-order nonlinear effects such as saturation, in order to clearly identify the fundamental phenomena independent of particular nonlinearity. We note that Eq. (1) with \(\lambda_n = \lambda\) describe one-color multigap solitons.

Linear dynamics of optical beams propagating in a periodic photonic lattice is defined through the properties of extended eigenmodes called Bloch waves. We consider an example of lattice with \(\cos^2\) refractive index modulation [see Fig. (a)] with the period \(d = 10 \mu m\), and calculate dependencies between the longitudinal (\(\beta\), along \(z\)) and transverse (\(k\), along \(x\)) wave-numbers for Bloch waves, see Figs. (b-d). The top spectral gap is semi-infinite (extends to large \(\beta\)), and it appears due to the effect of the total internal reflection. The effective diffraction of Bloch waves becomes anomalous at the upper edges of Bragg-reflection gaps, where \(D_{\text{eff}} = -\partial^2 \beta/\partial k^2 < 0\).

It is known that the presence of Bragg-reflection gaps and associated anomalous diffraction regions allows for the formation of monochromatic spatial gap solitons even in media with self-defocusing nonlinearity. Results in Figs. (b-d) show that the spatial bandgap spectrum depends on the optical wavelength and, in particular, we find that the anomalous diffraction regime is strongly frequency dependent as \(D_{\text{eff}} \sim \lambda^3\) at large wavelengths, whereas the bulk diffraction coefficient is proportional to \(\lambda\). Accordingly, the Bragg-reflection gap becomes much narrower at larger wavelengths, limiting the maximum degree of spatial localization that is inversely proportional to the gap width.

The variation of the gap width can have a dramatic
Fig. 1. (a) Refractive index contrast in a lattice; (b) Dependence of the bandgap spectrum on the wavelength, and (c,d) corresponding spatial Bloch-wave dispersion for two different wavelengths, 665nm and 443nm, respectively. Transverse Bloch wavevector component $k$ is normalized to $K = 2\pi/d$. Grey shading marks spectral gaps where waves become exponentially localized: semi-infinite gap at the top (large $\beta$) and Bragg-reflection (BR) gaps at smaller $\beta$.

The effect on self-action of an input Gaussian beam focused at a single site of a defocusing nonlinear lattice\(^6\), where a sharp crossover from self-trapping to defocusing occurs as the gap becomes narrower. We note that, most remarkably, these distinct phenomena can be observed in the same photonic structure but for different wavelength components. In our numerical simulations, we put $\gamma = -10^{-4}$ and choose the lattice parameters such that the critical wavelength corresponding to the crossover is around 591nm. We confirm that the monochromatic beam with $\lambda = 443\text{nm}$ experiences strong self-trapping, whereas the largest fraction of input beam power becomes delocalized at a shorter wavelength $\lambda = 665\text{nm}$.

We then address a key question of how an interplay between these opposite effects changes the nonlinear propagation of polychromatic beams.

We model the self-action of polychromatic light beams by simulating the propagation of nine components with the wavelengths ranging between 443nm and 665nm. The input corresponds to a narrow Gaussian beam that has the width of one lattice site, i.e. in our case 5\,$\mu$m. Figure 2 shows our numerical results for the propagation of polychromatic light over 70mm. The spectrum of the light at the input is ‘white’, i.e. the light beams of different wavelength all have the same input profile and intensity. In the linear regime (small input intensity), all components of the beam strongly diffract, and the beam broadens significantly at the output, as shown in Fig. 2(a). As the input power is increased, we find that the spatial spreading can be compensated in a broad spectral region by self-defocusing nonlinearity. We observe a spatially localized total intensity profile at the output, indicating the formation of a polychromatic gap soliton [Fig. 2(b)].

We note that the spatial localization of the soliton components strongly depends on the wavelength [Figs. 2(d)], so that the long wavelength component has a much larger spatial extent than the short wavelength component. Hence, the soliton has a blue center and red tails, and this effect is more pronounced than for solitons with the same spectra in bulk media. Additionally, the power
observe self-trapping of the polychromatic light beam, and a small percentage of the red light is trapped by the nonlinear index change caused by the blue parts of the spectrum. In fact, the self-trapping efficiency for the red part of the spectrum is almost identical to the case of a white spectrum shown in Fig. 2(c). Fundamentally different behavior is observed for a polychromatic beam with red-shifted spectrum [Figs. 2(c,d)]. In this case, the beam strongly diffracts and self-trapping does not occur even when the total input intensity is increased several times compared to the case of white spectrum. This happens due to the tendency of red components to experience enhanced diffraction as the effect of defocusing nonlinearity is increased at higher intensities. We note that, according to Fig. 2(c), the blue part of the spectrum is also diffracting.

In conclusion, we have studied the propagation of polychromatic light and the formation of polychromatic solitons in periodic photonic lattices, and demonstrated that light self-action can be used to reshape multiple frequency components of propagating beams in media with noninstantaneous nonlinear response, such as photorefractive materials or liquid crystals. We have demonstrated that self-trapping efficiency and structure of emerging polychromatic gap solitons depends strongly on the spectrum of input beams due to the lattice-enhanced dispersion, and identified the effect of crossover between localization and diffraction in defocusing media.

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