Polychromatic interface solitons in nonlinear photonic lattices

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We demonstrate that interfaces between two nonlinear periodic photonic lattices offer unique possibilities for controlling nonlinear interaction between different spectral components of polychromatic light, and a change in the light spectrum can have a dramatic effect on the propagation along the interface. We predict the existence of polychromatic surface solitons which differ fundamentally from their counterparts in infinite lattices.

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Nonlinear optics has focused on the study of self-action of monochromatic light for many decades. This was due to the fact that high-power light necessary to observe strong nonlinear effects could only be obtained from laser sources, which usually show only a few rather narrow spectral lines. However, since nonlinear photonic fibers have been used to successfully generate supercontinuum radiation, polychromatic light is attracting more and more attention in the nonlinear optics community. After an early paper on nonlinear focusing of white light and incoherent spatial solitons [1], several papers studied the topic of spatially localized modes for polychromatic light in nonlinear media [2,3]. As a general result, we mention that it has always been observed that the blue components of a polychromatic light beam were much better localized than the red components, because the diffraction is weaker for light of shorter wavelength.

In this Letter, we study the light localization near the interface between two nonlinear semi-infinite periodic photonic lattices and the generation of polychromatic interface solitons. In particular, we show that nonlinear interfaces can be tailored to obtain the opposite result: self-focusing of the red parts of the spectrum with the blue parts which only weakly or even not at all localized. Furthermore, we show that at interfaces the nonlinear interaction between spectral components can have dramatic effects on the propagation of light offering a new approach to control the spectrum of polychromatic light.

In many recent studies, the properties of light propagating through periodic photonic lattices have been explored. The bandgap structure of the lattice spectrum plays the decisive role for many intriguing effects observed. Also, the interfaces between a photonic lattice and homogeneous media have been known to be of particular interest for a long time, because they support linear modes localized at the surface, the so-called optical Tamm states [4]. Recently, it was predicted theoretically and demonstrated experimentally that nonlinear self-trapping of light near the edge of a waveguide array which can lead to the formation of discrete surface solitons [5,6], surface gap solitons [7], and multi-gap surface solitons [8]. This concept can also be extended to interfaces between two different photonic lattices. Obviously, for any localization to be possible, there has to be an overlap of the bandgaps of the lattices.

We consider the interface between two periodic photonic lattices shown in Fig. 1(a). Both lattices have the same period but having different unit cells. In the region $x < 0$ the lattice consists of narrow waveguides, whereas for $x > 0$ we choose the waveguides to be wider and deeper. Figure 1(b) shows the diffraction coefficient (i.e. the curvature of the spectral bands) at the bottom of the first band of the narrow-waveguide and at the bottom of the second band of the wide-waveguide lattice for different wavelengths. We observe that the blue spectral components could be localized much easier than the red ones if they were propagating within one of the lattices.

We study the propagation of polychromatic light beams described by the system of coupled equations

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

where $A_n$ are the envelopes of different wavelength components of vacuum wavelength $\lambda_n$. $\nu(x)$ stands for the periodic modulation of the refractive index in the transverse spatial dimension, $I = \sum_n |A_n|^2$ is the total light intensity, and $\gamma$ measures the nonlinearity strength. In Eqs. 1, the transverse ($x$) and longitudinal ($z$) coordinates are normalized to $x_0 = 10 \mu m$ and $z_0 = 1 \ mm$, respectively, and the nonlinearity is defined by $\gamma = 10^{-3}$.

The bandgap structure of both lattices as a function of the light frequency (scaled to $\omega_0 = 2\pi c/532nm$) is shown

[FIG. 1: (a) Schematic of an interface separating two photonic lattices. (b) Diffraction coefficients for the bottom of the first band of the narrow- (solid line) and the second band of the wide-waveguide lattice (dashed line).]
in Figs. 2(b,c) while (c) shows their overlaps. We chose the lattices in such a way that the overlap between the first gap in the region $x < 0$ and the second gap in the region $x \geq 0$ vanishes above a certain cut-off frequency $\omega_c \approx 2\pi c/475\text{nm} \approx \sqrt{1.25}\omega_0$.

First, we analyze the existence of polychromatic localized modes at the interface, i.e. polychromatic surface solitons. We choose the frequency range close to the cut-off frequency $\omega_c$, and find numerically different types of localized modes. Figure 3 shows an example where the polychromatic interface soliton is composed of five components with different wavelengths $\lambda = 506, 519, 532, 546$ and 560nm (equidistantly spaced in frequency space). All five components carry the same power. In the soliton, the blue components have a larger spatial extent than the red ones. This is in a sharp contrast to other types of polychromatic solitons in infinite systems.

Single components shown in Fig. 3 are indeed located within the first spectral gap of the narrow-waveguide lattice and the second gap of the wide-waveguide lattice. We study numerically the propagation of such multicomponent soliton in the presence of an initial perturbation and could not observe any signs of instabilities. This is in agreement with results obtained for monochromatic surface solitons [7].

However, polychromatic surface solitons are of practical relevance only if they can be generated under experimentally realistic conditions. Therefore, we simulate numerically a situation where polychromatic light with a Gaussian intensity profile is injected into the narrow waveguide closest to the interface. The polychromatic light is modeled by nine components with different wavelengths $\lambda = 475, 488, 502, 517, 532, 548, 566, 585,$ and 604nm. Our results clearly show that it is indeed possible to generate a polychromatic surface soliton in this way. Figure 4(a) shows the evolution of the total intensity with propagation and Fig. 4(b) shows the spectrum of the light beam at the input and output (considering only the waveguides closest to the interface and the space between them). We chose the light to have a flat spectrum at the input. Fig. 4(b) shows that the propagation along the interface considerably alters the beam spectrum. Most of the intensity of the red part of the spectrum is trapped into the interface soliton, while most of the blue part diffracts away from the interface. This is due to the fact that we chose the polychromatic light beam to lie in a frequency range close to the cut-off frequency $\omega_c$, above which the overlap between the first gap of the narrow- and the second gap of the wide-waveguide lattice disappears.

However, we have seen in Figure 2(c) that there is not only an overlap between the first gap of the narrow- and the second gap of the wide-waveguide lattice. The semi-infinite gap of the narrow overlaps with the first and sec-
second gap of the wide waveguide lattice in the frequency region under consideration. Surface solitons should exist in these band-gap overlaps as well. To understand, why the soliton is forming not in these overlaps, but in the overlap between the spectral gaps, one has to keep in mind that in an infinitely extended medium (i.e. in the absence of any interface) solitons can form in the semi-infinite gap only in the case of a self-focusing nonlinearity. Here, however, we have a self-defocusing nonlinearity. Let us now consider a surface soliton that resides in a spectral gap of one and the semi-infinite gap of the other lattice. In the case of defocusing nonlinearity, increasing the soliton intensity will make localization in the semi-infinite gap more difficult, because diffraction is enhanced by nonlinearity. Increasing the intensity further, the nonlinearity-enhanced diffraction in the semi-infinite gap is too strong for any surface state to exist. Therefore, the light beam excites preferentially a soliton in the overlap between the spectral gaps of the two lattices.

For the blue components this overlap is too small and they diffract. The situation changes though, when we look at the propagation of a monochromatic light beam at the blue end of the spectrum. In the absence of the red part that did excite a soliton in our polychromatic simulation, the blue light is free to go into the overlap between the semi-infinite gap of the narrow and the second gap of the wide waveguide lattice. (Localized solutions do exist in this overlap despite the nonlinearity enhanced diffraction in the semi-infinite gap.) This is seen in Fig. 4(b) which shows the propagation of a monochromatic light beam of wavelengths $\lambda = 475\text{nm}$. Except for the spectrum, all parameters are the same as in Fig. 4(a).

In Fig. 4(a) we observe that a noticeable fraction of the power remains at the interface. This is quantified in Fig. 4(b), and also compared to the case of $\lambda = 532\text{nm}$, showing the evolution of the power localized at the interface as a function of propagation distance. After 10 cm of propagation roughly 20% of the initial power is still remains at the interface. This is a striking result, when comparing it to the results of the polychromatic soliton generation, where basically all the power of the 475 nm component has diffracted away from the interface after 10 cm of propagation, as can be seen in Fig. 4(b). Thus we have a situation in which the presence of the other (localized) components prevents the localization of the 475 nm beam. We note that the opposite effect (enhanced localization due to the interaction with other components) can also be observed in our system when moving to the other end of the overlap between the band-gaps.

The different behavior of the $\lambda = 475\text{nm}$ component in the poly- and the monochromatic case highlights the intriguing nonlinear interaction between the spectral components of polychromatic light propagating along a nonlinear interface. The complex nature of the interaction leaves much space for engineering interfaces that can transform the spectrum of polychromatic light in a specific way.

In conclusion, we have predicted the existence of polychromatic interface solitons localized at the interface separating two different semi-infinite periodic photonic lattices, and demonstrated that such multi-component gap solitons can differ considerably from their counterparts in infinite photonic lattice. In particular, our study of the localization of polychromatic light near the interface has demonstrated that the red parts of the spectrum can be localized better than the blue parts, so that the interface can be employed for controlling nonlinear interaction between spectral components of polychromatic light.

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