Invited Paper

Optical lattices as nonlinear photonic crystals

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ABSTRACT

We review our experimental development in the field of optical lattices, emphasizing their unique properties for control of linear and nonlinear propagation of light. We draw some important links between optical lattices and photonic crystals, pointing towards practical applications in the fields of optical communications and computing, beam shaping, and bio-sensing.

Keywords: Optical lattices, nonlinear self-action, optical solitons, supercontinuum generation

1. INTRODUCTION

Nonlinear propagation of light in periodic structures has become an attractive topic of research in recent years,[1] holding strong promises for novel photonic applications. The underlying physical effects are analogous to those occurring in a number of different systems, including biological molecular structures, solid-state systems, and Bose-Einstein condensate on optical lattices. A special class of periodic structures are the co-called photonic crystals, materials with optical bandgaps, which offer the possibility to control the propagation of light in a way similar to the way semiconductors are used for manipulation of the flow of electrons. Photonic crystals represent a broad class of structures with periodicity of the refractive index on the wavelength scale in one, two, or three dimensions. They were first suggested in the pioneering works of Eli Yablonovitch[2] and Sajeev John,[3] and nowadays this terminology is applied to many different materials (see Fig. 1), some of which commonly used in almost any optical laboratory. Examples of one-dimensional photonic crystals include dielectric mirrors, Bragg gratings, and arrays of optical waveguides.[4] The class of two-dimensional photonic crystals is commonly represented by photonic crystal fibers[5] and planar photonic crystals.[6] In three dimensions photonic crystals cover structures such as opal, wood-pile, or inverse opal geometries.[7] The common between all the different structures is that they allow for manipulation of the flow of light in the direction of periodicity. Therefore, photonic crystals offer the possibility to achieve ultimate control over the linear and nonlinear properties of light propagation, as well as enchanced control over light emission and amplification. Herewith we concentrate primarily on the abilities of periodic structures to control the linear and nonlinear propagation of light.

Several approaches for control of light propagation by engineered periodic structures have been predicted and demonstrated experimentally in recent years. These include manipulation of linear light propagation (refraction, diffraction, and dispersion) as well as various nonlinear effect (harmonic generation, stimulated scattering, and nonlinear self-action). Important examples for control of refraction and diffraction of light constitute the effects of negative refraction[8] and self-collimation,[9] respectively. Furthermore, designing of the structural dispersion allows one to manipulate the group velocity of light, resulting in slow light propagation,[10] or enhancement of the spectral response with the fascinating example of the superprism effect.[11] The nonlinear response of the material offers opportunities for dynamic tunability of the structures sensitive to the light intensity.[12] The interplay between nonlinearity and periodicity represents a unique way to efficiently manipulate light by light for optical switching and signal processing applications. Furthermore, light control can be scaled down to micron-scale structures suitable for integration of multiple functionality on a photonic chip.

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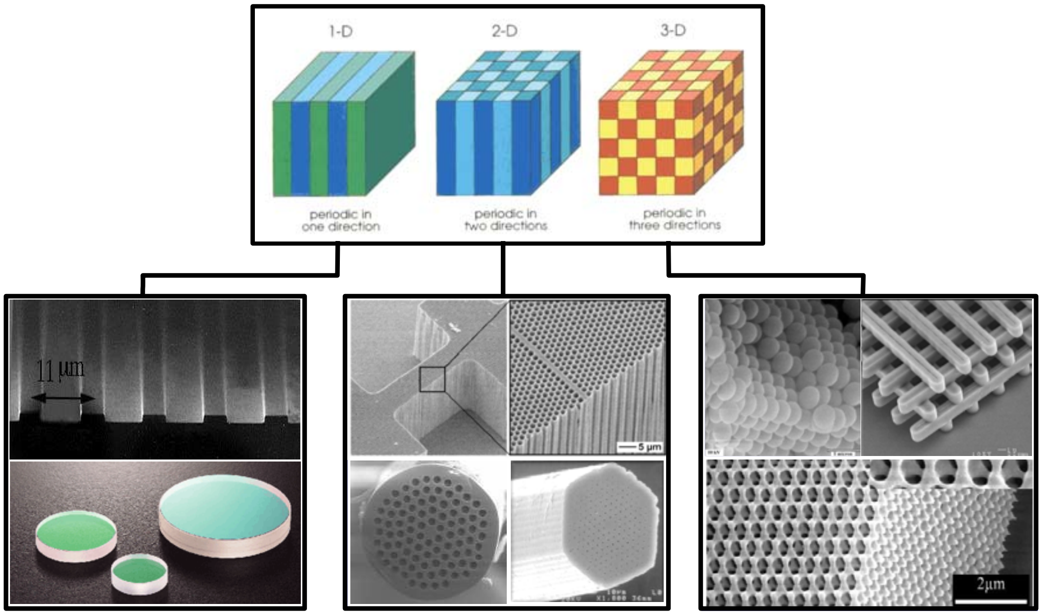

Figure 1. Examples of one-, two-, and three-dimensional photonic crystals.

The goal of our studies is two-fold: (i) to describe the fundamentals of nonlinear wave physics in periodic media and (ii) to exploit these effects for practical applications. Currently, the major research on photonic structures is concentrated on the demonstration of fundamental physical phenomena. However, novel photonic applications are showing on the horizon, promising a significant impact on various technologies in optical communications and computing, beam steering and shaping, bio-sensing and medical diagnostics.

To achieve our goals we need to employ periodic structures of different geometries, easy to fabricate, and with strong nonlinearities at moderate laser powers. Currently there exist a number of different approaches for fabrication of photonic crystals, including focused ion beam milling, e-beam lithography combined with reactive ion etching, two-photon and UV polymerization. All these techniques, however, are resource demanding and cost ineffective, imposing great constrains on fundamental research, where flexible and quick modification of the structural parameters is required. A simpler fabrication and characterisation of the periodic photonic structures can be achieved when the scale of periodicity is larger than the wavelength of light. Covered by the general term *optical lattices* such large period photonic structures include optical waveguide arrays,[13] photonic crystal fibers,[5] and optically-induced lattices.[14] The scale of periodicity in such structures is of the order of a few micrometers, therefore their fabrication is facilitated by standard lithographic techniques, fiber drawing, or multiple beam interference. The challenge is to achieve strong nonlinear response of the material at moderate laser powers. The nonlinear response can be enhanced through extended propagation length (as in the case of fibers), stronger light confinement (as in nanowires and photonic crystals), or through slow and resonant nonlinearities (as in the case of optically-induced lattices). In our current studies we chose materials with slow nonlinear response, but with the access to nonlinear effects at micro-Watt laser powers. The periodic photonic structures with strong nonlinear response and various geometries allow us to study the basics of nonlinear physics in periodic structures. The obtained knowledge can be then applied to fabricated photonic structures, and photonic crystals in particular, thus bringing the advantages of miniaturization and integration on a photonic chip. We believe that the process of basic knowledge accumulation and its further application is the successful path towards future photonic technologies.

In this paper we review some recent advances and fundamental concepts of nonlinear light propagation in periodic photonic structures, emphasising their abilities to control the spatial dynamics of light propagation. The paper is organised as follows: In Section 2 we present the concept of optically-induced lattices and discuss how their tunability can be used to engineer the linear light propagation such as refraction and diffraction.

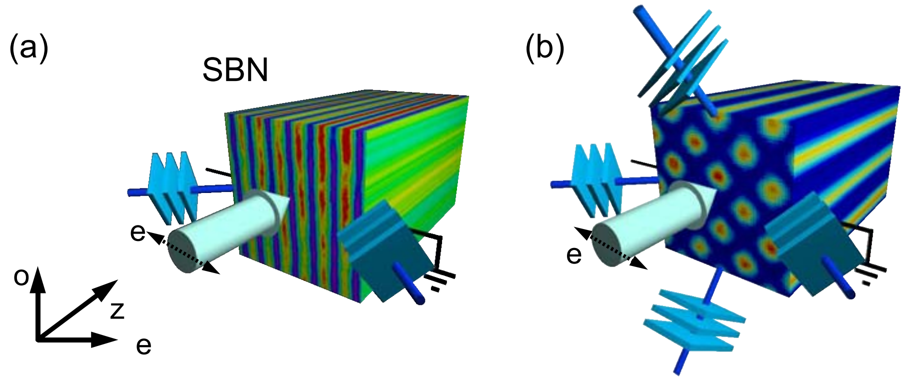

Figure 2. Optical induction of (a) one- and (b) two-dimensional photonic lattice in a biased photorefractive SBN crystal.

In Section 3 we review the results of nonlinear localisation of light in periodic structures and present some novel ideas for nonlinear control of the wave transport in periodic structures. Section 4 is focused on novel physical phenomena, when light propagating in such periodic structures interacts with interfaces, and Section 5 presents some fundamental ideas for simultaneous spatial and spectral nonlinear control of polychromatic light propagation in periodic photonic structures.

2. LIGHT PROPAGATION IN OPTICAL LATTICES

The propagation of light in periodic optical lattices is determined by three major effects: (i) the coupling between neighboring sites of the lattice (inter-site coupling), (ii) Bragg scattering arising from the periodicity of the lattice, and (iii) the specific lattice geometry, being one- (1D), two- (2D), or three-dimensional (3D). The geometry is of particular importance in 2D and 3D, where the lattice symmetry (e.g. square, hexagonal) significantly affects both the inter-site coupling and wave scattering in different directions. Being able to engineer all those characteristics, one can fully control the propagation of light. Additionally, dynamic tunability of the lattice depth and periodicity in real time, will provide an ideal system for fundamental experiments.

2.1. Optically-induced lattices

A great opportunity for controlling the lattice parameters was offered by the idea of optically-induced lattices in a biased photorefractive crystal proposed by Efremidis and coworkers.[14] With this theoretical proposal the optical lattice is induced by the interference of two or more broad laser beams propagating inside the photorefractive crystal. The authors took advantage of the strong electro-optic anisotropy of the crystal, such that the ordinarily polarised lattice-forming beams are not affected by the applied electric field. The strong but anisotropic electro-optic effect of the crystal leads to index changes predominantly for the extraordinarily polarised light. Thus, the periodic light pattern resulting from the multiple beam interference will induce a periodic optical potential for any extraordinarily polarised probe beams. At the same time, probe beams will experience strong nonlinear self-action at moderate (μW) laser powers. The propagation of light in such system can be described (in isotropic approximation) by the nonlinear Schrödinger equation for the slowly varying amplitude of the electric field[14–16]

$$i\frac{\partial E}{\partial z} + D\left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2}\right) - \frac{\gamma V_0}{I_b + I_p(x,y) + |E|^2}E = 0, \tag{1}$$

where (x, y) and z are the transverse and propagation coordinates normalized to the characteristic values $x_s = y_s = 1\,\mu$m and $z_s = 1\,$mm, respectively, $D = z_s\lambda/(4\pi n_0 x_s^2)$ is the diffraction coefficient, λ is the wavelength in vacuum, n_0 is the average refractive index of the medium, and V_0 is the bias voltage applied across the crystal. The term $\gamma V_0(I_b + I_p(x,y) + |E|^2)^{-1}$ characterises the total refractive index modulation induced by the optical lattice and the probe beam, linearly proportional to the applied electric field. Here $I_b = 1$ is the normalised constant dark irradiance, and the lattice intensity I_p depends on the specific lattice geometry controlled by the number and position of the lattice forming beams. For example, $I_p(x, y) = I_g|\exp(ikx) + \exp(-ikx)|^2$, for 1D

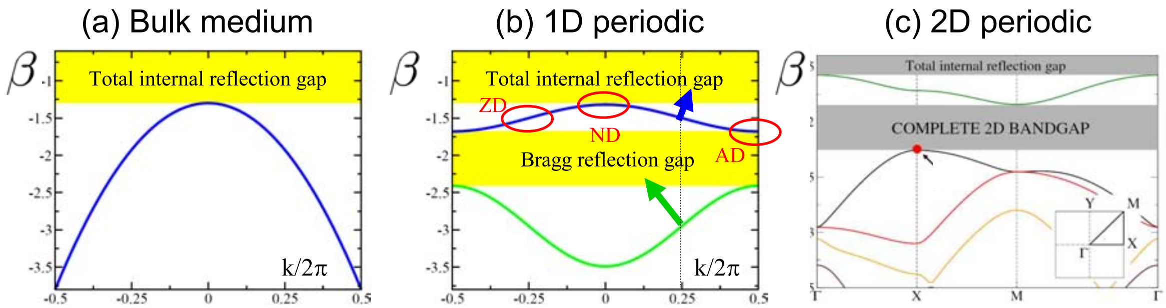

Figure 3. Dispersion of linear waves in a bulk medium, 1D optical lattice, and 2D optical lattice of square symmetry.

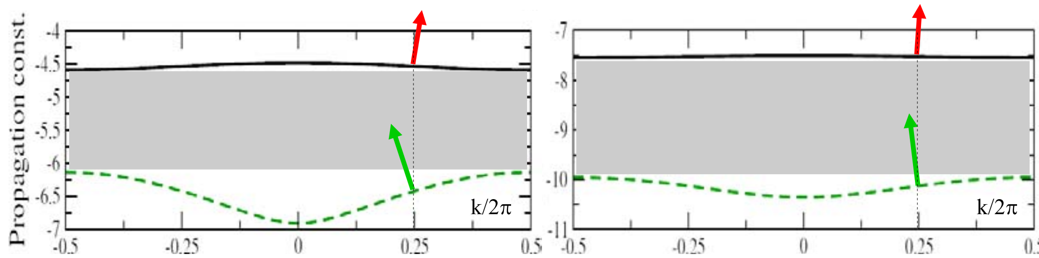

Figure 4. Tuning of the bandgap structure of a 1D lattice by increasing index modulation. Left and right: bandgap structure for optically induced lattices with smaller and higher applied bias fields, respectively.

lattice produced by two-beam interference [Fig. 2(a)]; $I_p(x,y) = I_g[\cos(\pi(x+y)/d) + \cos(\pi(x-y)/d)]^2$ for a 2D lattice of square geometry created by four coherent beams [Fig. 2(b)]; or $I_p(x,y) = I_g|\exp(ikx) + \exp(-ikx/2 - iky\sqrt{3}/2) + \exp(-ikx/2 + iky\sqrt{3}/2)|^2$ in the case of a hexagonal lattice generated by three-wave beam interference.

The advantage of using optically induced lattices as a test-bed physical system comes from the fact that the inter-site coupling can be easily controlled via the applied bias voltage V_0 (positive ot negative) or lattice-forming beam intensity, while the Bragg scattering can be controlled via the period of the lattice, which is inversely proportional to the angle between the interfering beams. A disadvantage of the system is the relatively low index modulation, typically of the order of few times 10^{-4}. This disadvantage results in the need of a rather large lattice period, and relatively short propagation distances (typical crystal is 1-2 cm long). The possibility for dynamic reconfiguration of the lattice, however, makes the optically induced lattices an attractive tool for studies of nonlinear phenomena in periodic photonic structures of various geometries. Indeed, this technique was applied by several groups and the experimental demonstration of various fundamental effects came quickly.[15–18]

2.2. Bandgap structure

Even though the technique of optical induction results in weak index modulation, this can be sufficient for the appearance of a distinct bandgap structure for propagating linear waves. When the applied bias voltage is zero, the photorefractive crystal is homogeneous and the dispersion relation for the propagation of waves is parabolic as shown in Fig. 3(a). Once a voltage is applied across the crystal the periodic light pattern induces an index modulation. Due to this modulation, waves propagating under small angles in the structure will experience Bragg scattering, which results in the appearance of forbidden gaps of the transmission spectrum (forbidden directions of propagation) [Fig. 3(b)]. The modification of the dispersion relation dramatically changes the beam propagation. The direction of propagation is determined by the normal to the dispersion curves [see the arrows in Fig. 3(b)], while diffraction is determined by the curvature at the corresponding point. Thus waves associated with the top of the first band and propagating along the lattice will experience normal diffraction [marked as ND in Fig. 3(b)], while waves corresponding to the bottom of the first band (convex curvature) will experience anomalous diffraction [marked as AD in Fig. 3(b)]. The curvature of the dispersion curves changes in between those two zones from concave to convex, therefore there will be a point where the curvature is zero. Waves belonging to this zone [marked as ZD in Fig. 3(b)] will, therefore, experience no diffraction.

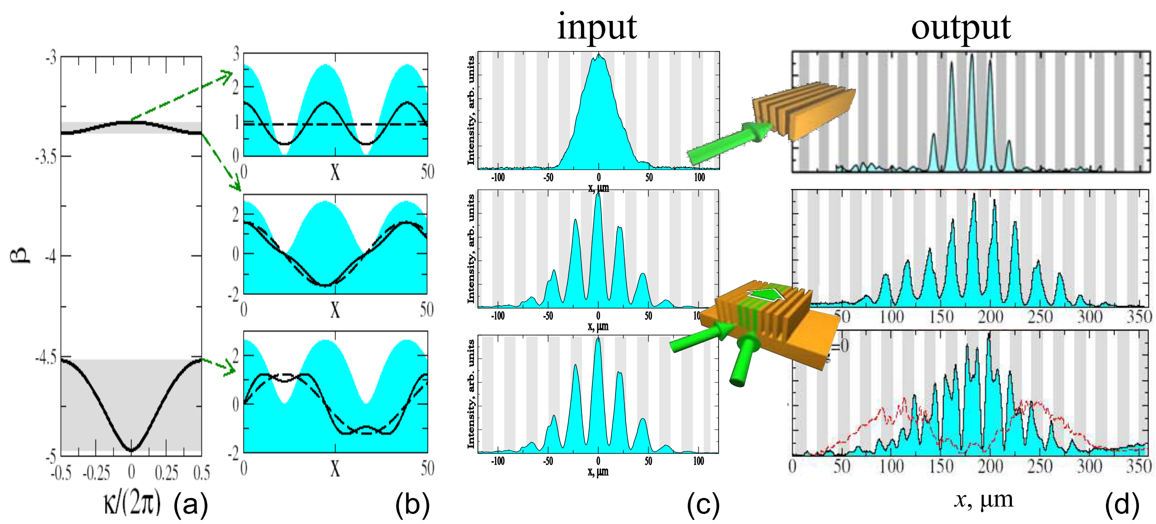

Figure 5. Bloch waves and their excitation: (a) typical bandgap diagram for 1D optical lattice. (b) Profiles of the Bloch waves (solid line) corresponding to the edges of the first and second bands, superimposed on the leading-order Fourier component (dashed line) and induced refractive index change (shading). (c,d) Experimental excitation of Bloch waves: input and output of the lattice, respectively. Insets show the excitation geometry.

It is important to note that the size of the forbidden gaps is proportional to the induced index modulation. An increase of the index modulation leads to flattening of the bands and therefore a wider Bragg reflection gap. This effect is accompanied by a change of the dispersion curves curvature and thus affects the propagation of waves inside the structure. Therefore, if one increases the index modulation by increasing the applied bias field one can dynamically control the direction of propagation of waves inside the structure. As illustrated in Fig. 3(b) and Fig. 4, the increase of the applied voltages makes the waves with a normalised transverse momentum of 0.25 to propagate under smaller and smaller angles inside the structure. Such dynamic tuning of wave propagation is not an isolated phenomenon for optically-induced lattices, but can be applied to other electro-optic periodic structures, or structures infiltrated with liquid crystals.[19]

The optically induced bandgap structure is also well defined in the case of higher dimensionality. As shown in Fig. 3(c) an optically-induced 2D lattice of square geometry with a period of $23\,\mu$m can possess a complete 2D bandgap between the first and the second band. This fact underlines the importance of the optically-induced lattices as an *analogue of 1D and 2D photonic crystals*. Therefore, the optically induced lattices represent an accessible test-bed for studies of generic bandgap phenomena in photonic periodic structures.

2.3. Bloch waves and their excitation

In order to explore the ability for control and steering of beams in an optical lattice, it is important to understand the character and the profiles of the propagating linear waves. Finite beams propagating inside the lattice can be naturally represented as a superposition of eigenfunctions of the induced periodic potential. Such eigenfunctions, known as Bloch waves, are naturally periodic and follow the periodicity of the underling lattice potential. The Bloch wave profiles corresponding to the top and bottom of the first band and the top of the second band of the 1D lattice bandgap spectrum [Fig. 5(a)] are given in Fig. 5(b, solid line), together with the underlying periodic index modulation Fig. 5(b, shading). These Bloch waves have the periodicity of the lattice itself, but can also have a nontrivial phase structure. The Bloch wave from the top of the first band is periodic, but always positive. On the other hand the Bloch waves from the bottom of the first band and the top of the second band change sign at each lattice period. Furthermore, the maxima of the Bloch wave intensity associated with the bottom of the first band are centered on the maxima of the refractive index modulation, while the intensity maxima of the Bloch waves corresponding to the top of the second band are centered in between the lattice maxima.

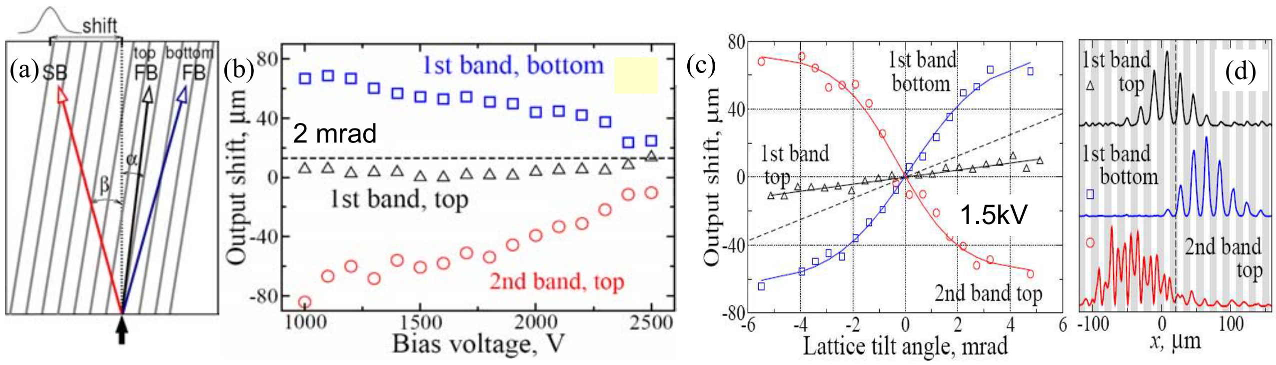

Figure 6. Tunable refraction in a tilted lattice: (a) Scheme of beam propagation. (b) Tuning of beam refraction for the different Bloch modes by varying the applied bias field. The lattice tilt is 2 mrad. (c) Tunable refraction by varying the lattice tilt at a constant bias field 3 kV/cm. (d) Corresponding output intensity profiles for a lattice tilt of 3 mrad.

Each Bloch wave has a well defined propagation direction and diffraction coefficient, following the dispersion curves of the bandgap diagram. In order to explore their specific properties, it is important to know how to selectively excite each Bloch wave. Experimentally, this means that most of the light entering the lattice should be efficiently coupled to the desired Bloch wave. For best excitation one needs to exactly match the field profile of the corresponding Bloch wave. Exact matching of the Bloch wave profile, however, is not always possible. A good approximation is given by the leading-order Fourier component of the Bloch wave profile, plotted in Fig. 5(b) with a dashed line. The leading-order Fourier component for the Bloch wave associated with the top of the first band is a constant beam intensity, while for the Bloch waves from the edges of the Bragg reflection gap the leading order Fourier component is cosine or sine functions. Having this in mind we demonstrated experimentally efficient excitation of the Bloch waves by a broad Gaussian beam for the Bloch wave of the top of the first band and by two-beam interference for the Bloch waves from the bottom of the first band and top of the second band, respectively.[20] The only difference in the excitation between the latter two is the position of the interference pattern with respect to the lattice [see Fig. 5(c)], being centered at or in between the lattice sites. The position of the interference maxima is easily controlled by the relative phase between the two input beams (see the bottom inset in Fig. 5). The experimental profiles of the excited Bloch waves at the crystal output are shown in Fig. 5(d) and clearly demonstrate that our technique leads to efficient excitation of the corresponding Bloch waves. This is particularly expressed for the excitation of the Bloch wave from the top of the second band which have a characteristic double peak structure, successfully reproduced in our experiments.

2.4. Tunable refraction

The efficient excitation of Bloch waves can be used in experimental schemes for steering and switching of beams in periodic structures. For example, coupling of light into a particular Bloch wave can dramatically change the direction of beam propagation and thus the transport of energy inside the structure can be controlled. To demonstrate this idea we performed experiments on tunable beam refraction and beam steering in optically induced lattices.[21] In a straight lattice all Bloch waves from the top and bottom of each band propagate exactly along the lattice (zero transverse wavevector component). The different Bloch waves, however, can be separated if the lattice is tilted at a small angle as shown in Fig. 6(a). Such a lattice tilt translates into a tilt of the bangap structure, causing Bloch waves from the first band to bend (or refract) along the tilt of the lattice, while Bloch waves from the second band bend in the opposite direction [Fig. 6(a)]. The change in the direction of propagation leads to an output beam shift if the initial light is coupled to a specific Bloch wave.

As already discussed, the direction of propagation of each Bloch wave will depend on the depth of the induced refractive index modulation and therefore the output shift can be also tuned by changing the bias voltage applied to the crystal. Experimentally, we measured this shift as a function of the applied voltage across our 5 mm thick crystal. Our experimental results are depicted in Fig. 6(b). It is clear from the figure that with increasing index modulation (bias voltage ~ 2.5 kV), all the Bloch waves approach the tilt of the lattice given by the dashed line in

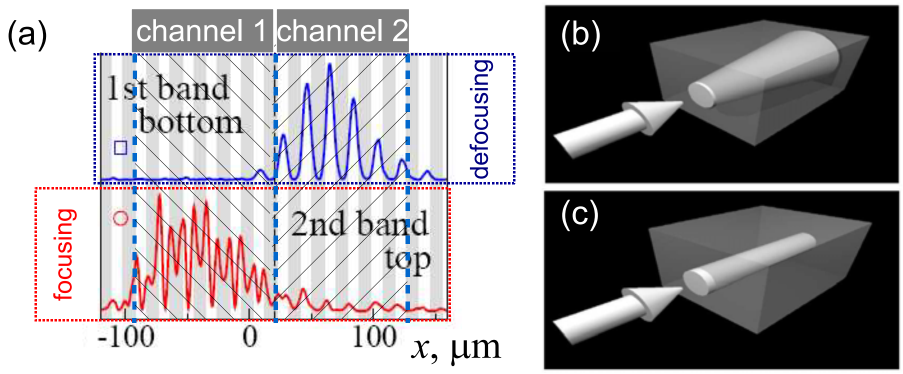

Figure 7. (a) Proposed scheme for optical switching between two channels (channel 1 and channel 2) by selective excitation of Bloch waves from the bottom of the first and top of the second band. The cross talk between both channels is affected by the natural beam diffraction (b), which can be arrested by beam localisation (c) in a self-focusing or self-defocusing nonlinear medium as marked in (a).

the figure. At lower voltages ($1-2$ kV), however, we observe that Bloch waves from the top of the first band are shifted less than the lattice, while those from the bottom of the first band and top of the second band are shifted substantially more. We measured a six-fold increase of the lattice shift (at 1 kV) with positive and negative gain for Bloch waves associated with the bottom of the first band and top of the second band, respectively. These experimental observations demonstrate the first example of tunable refraction in periodic structures, pointing towards potential applications in beam steering technologies.

Furthermore, we measured the dependence of the beam shift at the output as a function of the lattice tilt [Fig. 6(c)]. Our results showed that for a small lattice tilt, the dependence is linear, while it saturates to a value equal to the Bragg angle inside the lattice for Bloch waves from the bottom of the first band and top of the second band. The corresponding output beam profiles of the three different Bloch waves are shown in Fig. 6(d). They show that in each case the input light is coupled directly to a particular Bloch wave, with no mixed excitation, and that the beams experience a strong transverse shift.

The spatial separation of different Bloch waves at the crystal output appears promising for beam switching applications. Having in mind that the excitation of Bloch waves from the bottom of the first band and top of the second band can be changed by simple phase shifting of one of the input beams, switching between two separate channels [channel 1 and channel 2 in Fig. 7(a)] can be performed at a very high speed. Nowadays, commercial "off-the-shelf" phase modulators can work at frequencies of several GHz, and therefore optical switching of beams by selective excitation of Bloch waves appears compatible to modern ultra-fast all optical technologies. In Fig. 7(a) we show a schematic of such optical switching, where the input light can be directed towards channels (1) or (2) depending on the initial relative phase of the input beams [Fig. 5(bottom inset)]. The contrast of the switching, however, is not 100% as the two channels have a non-zero cross-talk due to the overlap of the beam profiles in the region of $x = 0$. This cross talk appears naturally as a result of beam diffraction inside the structure [Fig. 7(b)]. A possible solution to arrest the diffraction broadening is to utilize nonlinear self-localisation of the beam (or formation of spatial solitons) as shown in Fig. 7(c). Being able to balance the beam diffraction is an important task, therefore, in our studies we pay special attention to the characterisation of the effects of beam self-localisation in periodic structures.

3. NONLINEAR LOCALISATION AND WAVE TRANSPORT

In order to confine optical beams inside the periodic structure it is necessary to balance the beam diffraction through nonlinear self-action. However, as we already know the diffraction of beams can be significantly modified by the effects of periodicity. Beams associated with the top of each band have normal diffraction [Fig. 3(b)] which can be balanced by a self-focusing type nonlinearity [Fig. 7(a, top)]. Beams from the bottom of each band, on the other hand, exhibit anomalous diffraction [Fig. 3(b)], which can be balanced by a self-defocusing type nonlinearity [Fig. 7(a, bottom)].

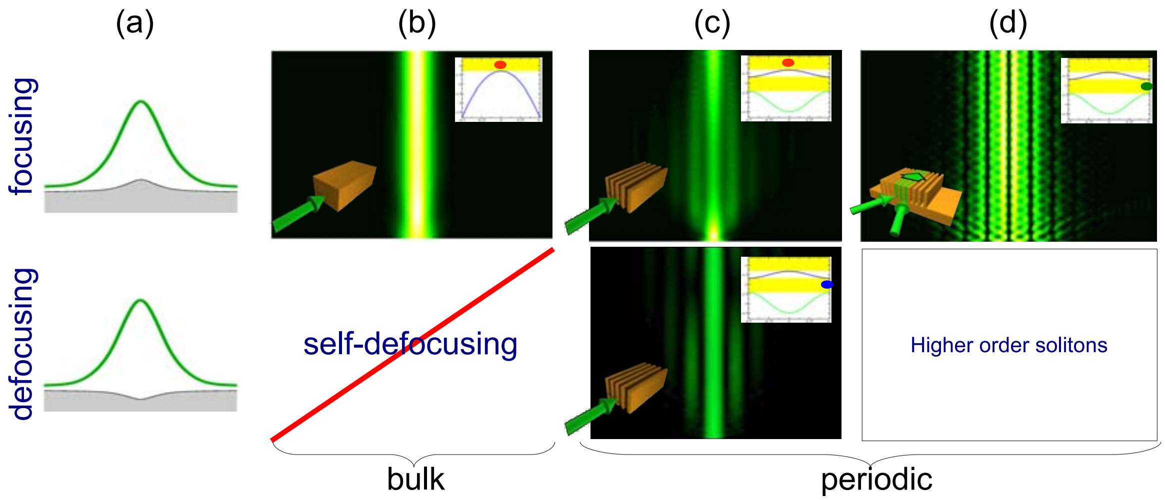

Figure 8. Formation of spatial solitons: (a) self-focusing and self-defocusing nonlinearity will induce a positive or negative defect in the material, respectively. (b) In a bulk material solitons can form only for self-focusing nonlinearity. In a periodic medium solitons can form from the first (c) and second bands (d) for both focusing and defocusing nonlinearity.

3.1. Solitons in periodic structures

In a bulk nonlinear medium, the propagation of light of high intensity will result in a local refractive index change of the material [Fig. 7(a)]. For focusing nonlinearity, this index change is equivalent to an induced optical waveguide which can trap and guide the beam in the structure [Fig. 7(b, top)], resulting in the formation of spatial solitons.[22] In the case of defocusing nonlinearity, the induced index change is negative and will result in anti-guiding of the light, or beam self-defocusing. Therefore, no localised ("bright") solitons can exist in the case of bulk defocusing material. This picture, however, changes fundamentally in periodic structures. In the case of focusing nonlinearity solitons exist near the top of each band, where diffraction is normal. This can result in the formation of discrete spatial solitons from the top of the first band.[23] Discrete solitons can be excited by a narrow input beam launched into a single lattice site [Fig. 7(c, top)]. They were first observed in AlGaAs waveguide arrays[24] and later reproduced in optically induced lattices,[16,17] and liquid crystal waveguide arrays.[25] In the case of higher order bands, spatial solitons have been predicted to exist in the Bragg reflection gap.[26,27] Their excitation is less trivial, and both side-on excitation[28] and head-on excitation with periodically modulated input beam[29,30] have been demonstrated [Fig. 7(d, top)]. The latter appears beneficial when the transverse soliton velocity needs to be controlled, including the special case of excitation of immobile gap solitons.

In the case of defocusing nonlinearity 1D solitons exist near the bottom of each band and their propagation constant moves down into the Bragg reflection gap with increasing beam intensity. Solitons in periodic systems with defocusing nonlinearity were predicted already in 1993.[31] They possess a staggered phase structure and the propagation constant lies inside the first Bragg reflection gap [Fig. 7(c, bottom)]. Therefore such solitons have properties similar to both discrete and gap solitons in self-focusing nonlinear materials. Herewith we will refer to them as *staggered solitons*. Staggered solitons were first demonstrated experimentally by excitation with an inclined input beam.[17,32] With this method only a fraction of the input light is coupled into the staggered soliton mode. Later, generation of staggered solitons was demonstrated in defocusing lithium niobate waveguide arrays by excitation with a TEM_{10} laser mode.[33] Such excitation leads to coupling to the unstable "even" soliton mode, which then transforms to the stable "odd"-symmetry mode. The similarity of the staggered solitons with the discrete solitons, however, points to a simpler excitation method of high efficiency. As we recently demonstrated[34] efficient excitation of staggered solitons can be achieved with a narrow input beam coupled to a single lattice site [see Fig. 7(c, bottom)], provided the refractive index contrast of the structure is high enough. In this case the beam propagation inside the lattice is very similar to the propagation in lattices with focusing nonlinearity, with the only difference being the staggered phase structure of the output beam. Therefore, one can conclude

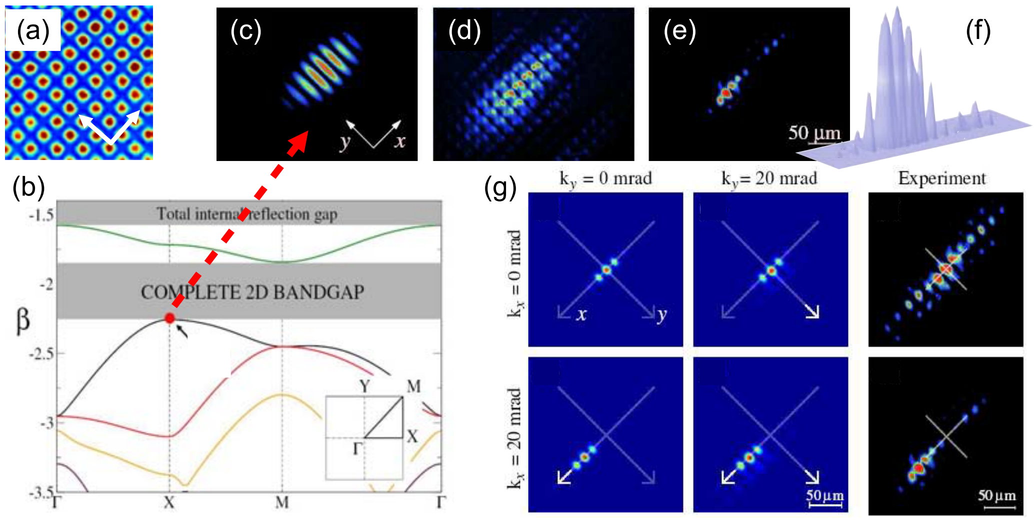

Figure 9. Reduced symmetry gap solitons: In a two-dimensional square lattice (a) gap solitons can exist near the top of the second band (X-symmetry point) (b). (c-f) Experimental excitation of reduced symmetry gap solitons: (c) input beam profile; (d) linear diffraction at the output; (e) soliton formation; (f) 3D representation. (g) Anisotropic soliton mobility when initial momentum is applied to the input beams. Left - numerical simulations; right - experimental results.

that if the optical lattice can be treated as a discrete system, there is a full analogy between the localisation of light for focusing and defocusing nonlinearity.

3.2. Two-dimensional solitons and their mobility

The localisation of optical beams is even more interesting and nontrivial in the case of higher dimensions. In a 2D lattice, for example, waves can experience anisotropic diffraction,[35] which strongly affects the formation of solitons. For a square lattice with a period of 23 μm [Fig. 9(a)] optically induced in a photorefractive SBN crystal, the typical bandgap structure folded along a contour through the high-symmetry points of the lattice is shown in Fig. 9(b). For self-focusing nonlinearity, solitons are associated with the top of each band, where diffraction is normal. Due to the crossing of higher order bands, there are only two complete gaps in our 2D lattice: the total internal reflection gap and one Bragg reflection gap. This is in sharp contrast to the 1D case, where multiple Bragg reflection gaps always exist. Therefore, the soliton family in a 2D lattice is restricted to those two gaps. Discrete solitons are associated with the Γ point of the first band.[14] They have been observed exclusively in the context of optically-induced lattices by several groups.[15,18,36] Staggered solitons have also been observed in the case of defocusing nonlinearity[15] and exist near the M-symmetry point of the first band.

Gap solitons in self-focusing nonlinear media can exist near the X-symmetry point at the top of the second band[37,38] and have highly anisotropic structure and properties. These solitons are localised in one direction due to Bragg reflection and in the other due to total internal reflection. To study such solitons experimentally[39] we created a 2D square lattice and used a modulated extraordinarily polarised input beam [Fig. 9(c)] to match the profile of the Bloch wave associated with the X-symmetry point of the second band. At low laser power the beam diffracts and evolves into the corresponding Bloch wave [Fig. 9(d)]. Once the input laser power is increased, the output beam experiences a quasi-collapse to a reduced symmetry gap soliton as shown in Fig. 9(e,f). The important characteristic of this type of solitons is that they have highly anisotropic mobility properties. The solitons are mobile along their modulated x direction and highly immobile along the y direction. This mobility is illustrated when initial momentum is applied to the soliton. Our numerical simulations and experimental results are summarised in Fig. 9(g). An initial momentum along the y direction does not lead to any shift of the soliton, but only to a small modulation of its profile. A momentum along x, on the other hand, leads to a shift of two lattice sites at the output. Our experimental observations well reproduced the numerical simulaitions [Fig. 9(g, right)]. The observed mobility properties of the reduced symmetry gap solitons relate to unique nonlinear transport of beams across the lattice, where the direction of beam propagation is determined by the

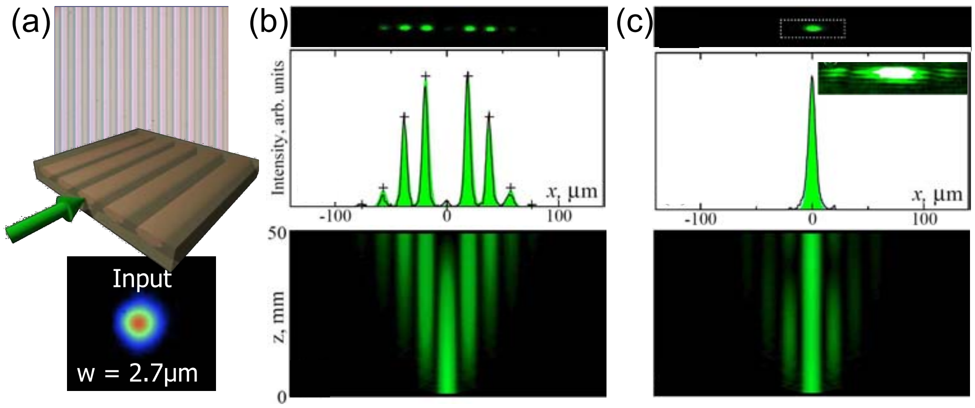

Figure 10. (a) Fabricated lithium niobate waveguide array, scheme of excitation, and intensity profile of the input beam. (b) Discrete diffraction at low laser power (10 nW): (top) 2D intensity profile, (middle) transverse intensity distribution and comparison with discrete model (crosses); (bottom) numerically calculated propagation inside the sample. (c) Formation of a staggered soliton at 1 mW laser power, soliton intensity profile and interferogram revealing the staggered phase structure. (bottom) Numerically calculated nonlinear propagation.

localised state itself, and not by externally fabricated defects in the structure. The ability to robustly move along one particular direction of the lattice makes the reduced symmetry solitons good candidates for flexible soliton networks in 2D periodic structures. This offers new opportunities compared to the soliton networks suggested earlier for optical signal routing and switching.[40] Furthermore, the reduced symmetry gap solitons can be regarded as an analogue of a nonlinearity induced waveguide in periodic structures (for mobile solitons),[39] or as an optically induced high-Q cavity.[41] We believe that these ideas can be successfully applied in other types of periodic structures such as photonic crystals and microstructured optical fibers.

3.3. Solitons in fabricated waveguide arrays

Even though the optically-induced lattices offer great flexibility for dynamic modification of the lattice parameters, experiments are complex and require extensive stability of the experimental setup in order to avoid fluctuation of the interference pattern of the lattice forming beams and averaging of the lattice potential. A typical experimental setup covers roughly half an optical table, hence the direct applicability of the obtained results is limited. Therefore, it is important to translate the gained knowledge of nonlinear lattices into some more compact fabricated structures, offering closer connection to practical applications and devices.

To explore the propagation of light in fabricated periodic photonic structures we utilized an array of optical waveguides fabricated by titanium indiffusion in a mono-crystal x-cut lithium niobate wafer [see Fig. 10(a, top)]. The array is 5 cm long and consists of 100 closely spaced waveguides with a period of 19 or 10 μm. These fabricated structures offer great reduction of the experimental setup and simplification of the experiments. Furthermore, lithium niobate is known to exhibit strong photovoltaic nonlinearity of defocusing type[42] at micro-Watt power levels for visible wavelengths. To test the linear propagation of light and demonstrate nonlinear localisation in such arrays,[34] we coupled light into a single channel of the array as shown in Fig. 10(a) and monitored the intensity profile at the output with increasing laser power. The input beam was circular with a size of 2.7 μm. At low laser powers (10 nW) the beam experiences discrete diffraction, where most of its energy is coupled away from the central waveguide [Fig. 10(b)]. This behaviour is well reproduced by calculations using both a discrete model for weakly coupled lattice cites [crosses in Fig. 10(b, middle)], and a more realistic continuous model corresponding to our array (bottom). When the input laser power is increased light is coupled back into the central guide of the array, and at powers of about 1 mW all light is concentrated in the central guide of the array [Fig. 10(c)]. An interferometric measurement of the output beam profile reveals that light in the central and the neighboring channels is out of phase, which is a direct indication that the observed localised state has a staggered phase structure and resembles a staggered soliton.[31]

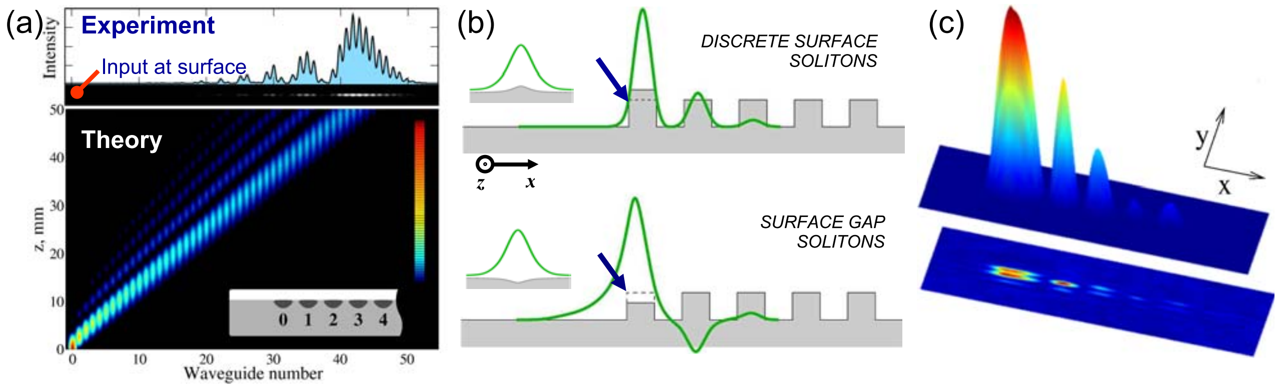

Figure 11. Surface waves: (a) Linear repulsion from the surface. (b) Theoretically predicted nonlinear surface waves for focusing (top) and defocusing (bottom) nonlinearities. (c) Experimentally observed surface gap soliton in defocusing lithium niobate waveguide array.

The power dependent transition between discrete diffraction at low power where almost no light is transmitted inside the central channel, and the single channel localisation proves to be beneficial for applications of laser mode locking.[43] In such application the spatial dynamics of light is translated to temporal dynamics and short pulse formation in the laser cavity. Furthermore, the waveguide technology is well compatible with fibers and applications of Kerr-lens mode-locking of fiber lasers leading to high contrast pulse generation seems feasible. The staggered phase structure of the localised state in the case of defocusing nonlinearity also appears to be an advantage comparing to localisation in structures with self-focusing nonlinear response.[43] We expect that the staggered profile can lead to improved contrast of the pulse generation. It is also important to note that the transition from diffraction to nonlinear localisation has a well defined threshold,[44] in contrast to the localisation in homogeneous media. Such a threshold behaviour can be also applied to an optical diode device, replicating the transmission characteristics of usual electronic diodes.

4. NONLINEAR SURFACE WAVES

Additional functionality for control of light propagation in photonic lattices can be achieved when the optical beam interacts with a defect or an interface ("surface") of the structure. For example, an optical beam injected at the edge waveguide of the array will be reflected from the interface formed between the periodic and homogeneous parts of the structure [Fig. 11(a)]. This effective "repulsion" from the surface leads to modified discrete diffraction of the beam[45] and practically no light remains in the input edge waveguide. At high input powers, however, the surface can support various types of nonlinear surface waves.[45] In the case of focusing nonlinear response of the material, such nonlinear surface waves exist in the form of discrete surface solitons.[45] They have a propagation constant inside the total internal reflection gap of the periodic structure since the high power light induces a positive index defect at the edge waveguide of the array [Fig. 11(b, top)]. Such solitons were recently observed experimentally in AlGaAs waveguide arrays.[46] In the case of defocusing nonlinearity, surface solitons can also exist.[45] Their propagation constant resides inside the Bragg reflection gap and therefore they can be termed as surface gap solitons.[47] Due to the defocusing nonlinearity, the high intensity of the light results in a negative index defect at the edge waveguide [see Fig. 11(b, bottom)]. This defect leads to a less localised nonlinear surface wave which extends deeper inside the bulk medium. This implies that the surface gap solitons can be potential candidates for application of surface sensing and testing. Furthermore, unlike their discrete counterparts, the surface gap solitons have a well pronounced staggered phase structure, resulting in zero intensity in between the waveguides.

In our experiments[48] we demonstrated the formation of surface gap solitons by injecting a narrow beam at the edge waveguide of a lithium niobate waveguide array. At low laser power (100 nW) the light is reflected by the surface [Fig. 11(a, top)], while as the power is increased the beam is attracted to the surface and at a power of 0.5 mW a surface gap soliton is formed in the array [Fig. 11(c, top)]. By use of interferometric measurements

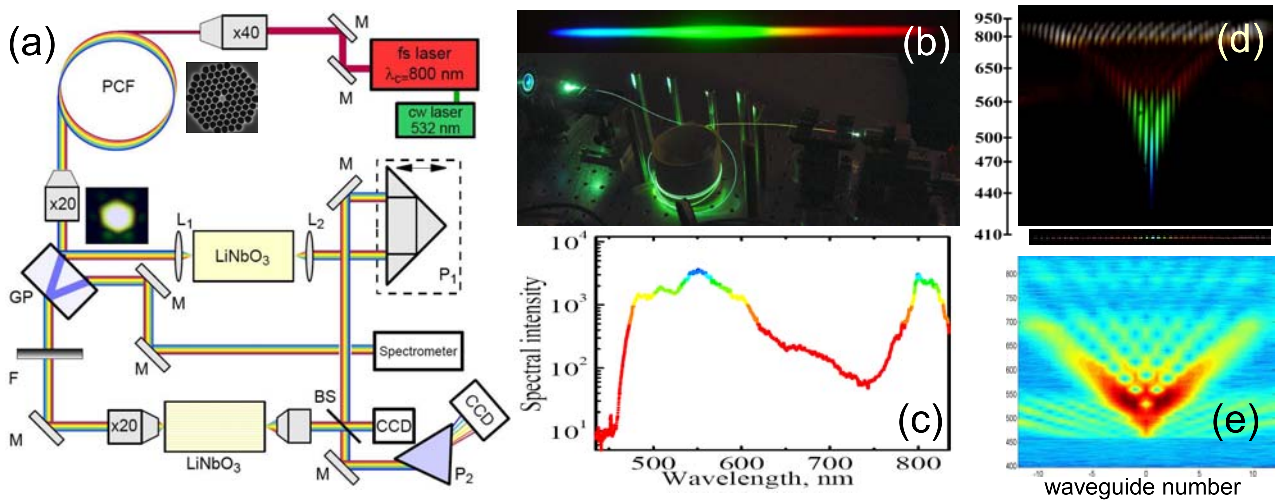

Figure 12. Polychromatic light in nonlinear periodic structures: (a) Experimental setup. (b) Photograph of the supercontinuum generation and its spectrum (c). (d,e) Spectrally resolved discrete diffraction in a waveguide array of a period 19 μm measured by (d) single shot CCD camera and (e) by a spectrometer integrating over each waveguide of the array.

we also confirmed the staggered phase structure of the gap soliton. As seen in Fig. 11(c, bottom) the interference fringes in each neighboring guide are shifted by half a period.

Similar formation of nonlinear surface waves have been demonstrated by other groups in iron doped lithium niobate waveguide arrays,[49] and for quadratic type nonlinearity.[50] The latter system deserves special attention as the nonlinear response is dependent on the coupling between the fundamental beam and the generated second harmonic, and thus the nonlinear response can be tuned from focusing to defocusing by temperature control, adjusting the phase mismatch of the harmonic generation process.

5. POLYCHROMATIC EFFECTS

So far all of the discussed effects were obtained with coherent light of narrow spectral bandwidth. However, an important question arises, *can one use periodic structures to control light of ultra-broad spectral bandwidth?* Polychromatic light is common in our everyday life, with light sources as the Sun, incandescent light bulbs, amplified spontaneous emission sources, supercontinuum generation, or even ultra-short laser pulses with a bandwidth of more than 100 nm. The answer to the above question is not clear as periodic structures are naturally highly dispersive, the condition for Bragg reflection being strongly wavelength dependent. Thus each spectral component propagates and diffracts differently in the lattice. A typical example of the strong dispersion of different spectral components in periodic structures is the superprism effect.[11,51]

A solution to counteract the strong dispersion of periodic structures can be achieved by employing nonlinear self-action effects. Recent theoretical predictions[52,53] show that optical nonlinearity can be successfully used to control the dispersion and spatial propagation of polychromatic light. To demonstrate experimentally such simultaneous spatio-spectral control we employed supercontinuum generation[5] from 150 fs pulses in a highly nonlinear photonic crystal fiber [see Fig. 12(a)]. After the fiber, the supercontinuum beam was attenuated and coupled to a single channel of our fabricated lithium niobate waveguide array. The output of the array was monitored onto a CCD camera, where a dispersive prism can be inserted in front of the camera in order to simultaneously resolve all spectral components. Additionally, a small part split off from the supercontinuum beam was used for interferometric measurements of the output beam profile, taking advantage of the high spatial coherence of the supercontinuum radiation. This reference beam was dispersed in the same way as the object beam by passing it through a second lithium niobate sample of identical length. The length of the reference arm of the interferometer was adjusted by a tunable delay line in order to match the timing of the pulses on the camera. The spectrum in each channel could also be independently measured by a fiber spectrometer, which integrates over the whole mode of the waveguide channel. An example of the generated supercontinuum inside the fiber is shown in Fig. 12(b) and its spectrum spanned a full octave covering the range 450-900 nm [Fig. 12(c)].

At low supercontinuum power, the different spectral components freely diffract in the array, where the diffraction is stronger for the long wavelength components. A single shot image on the CCD camera, resolving the discrete diffraction of all spectral components is shown in Fig. 12(d). An enhanced resolution of the discrete diffraction is obtained with the spectrometer and a picture of the output spectrum versus the waveguide number is given in Fig. 12(e). At high laser power the spectral components start to interact inside the array and the supercontinuum beam localises in the central channel of the array. The longest wavelength trapped in the central channel depends on the total supercontinuum power, so by its adjustment one can achieve dynamic tunability of the supercontinuum spectrum transmitted through the array. At high powers all spectral components are localised in the central channel, leading to the formation of a polychromatic supercontinuum gap soliton. In this a way, by utilizing the interplay between spectral dispersion and nonlinear localisation in periodic photonic structures, one can achieve tunable control of the spatial and spectral properties of the supercontinuum radiation. Additional control can be achieved through interaction of the supercontinuum light with surfaces and defects.[54]

6. CONCLUSIONS

In this review we demonstrated several fundamental effects of the control of light propagation in nonlinear periodic structures. Among the various effects it is important to emphasise the ability to control beam diffraction and refraction by tuning of the structural parameters of the photonic lattice. We have also demonstrated how the nonlinear self-action of beams can be used to balance their diffraction through the formation of nonlinear localised states, or solitons. These solitons can have different properties and characteristics, depending of the type of nonlinearity and their association with specific Bloch waves of the periodic structure. Furthermore, we have demonstrated how surfaces at the edges of periodic structures can affect the nonlinear localisation through the formation of nonlinear surface waves. We also discussed the implication of the spectral bandwidth of the light on the observed effects and demonstrated experimentally that periodic structures can simultaneously control the spatial and the spectral characteristics of supercontinuum radiation.

In this review we also pointed towards possible applications of the observed effects. However, it is important to state that a wider range of applications is still to follow. We have shown that most effects are scalable and can be applied to structures with different periodicity. We were able to demonstrate results in different periodic structures – from optically-induced lattices to waveguide arrays in lithium niobate crystals. The application of the presented concepts to smaller structures and their integration in photonic devices on a chip is an exciting direction to follow. We hope that with the current development of modern technologies and fabrication of photonic crystals a bright future of nonlinear periodic structures for light control on micro and nano scales is soon to come.

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