Discretizing light behaviour in linear and nonlinear waveguide lattices

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Light propagating in linear and nonlinear waveguide lattices exhibits behaviour characteristic of that encountered in discrete systems. The diffraction properties of these systems can be engineered, which opens up new possibilities for controlling the flow of light that would have been otherwise impossible in the bulk: these effects can be exploited to achieve diffraction-free propagation and minimize the power requirements for nonlinear processes. In two-dimensional networks of waveguides, self-localized states—or discrete solitons—can travel along 'wire-like' paths and can be routed to any destination port. Such possibilities may be useful for photonic switching architectures.

The ability to mould the flow of light in photonic periodic structures is a fundamental issue of scientific and practical importance. Optical waves propagating in such an environment experience a spatially periodic refractive index distribution and therefore behave in a way that is analogous to electrons travelling through a semiconductor crystal. A vital aspect associated with wave motion in photonic lattices is that, on many occasions, light can exhibit behaviour that is characteristic of that encountered in discrete systems. Such a case arises when the Floquet–Bloch modes of an optical field can be approximated by a finite, discrete set of bound states or modes. As a result, the underlying field evolution effectively becomes 'discretized'. Arrays or lattices of evanescently coupled waveguides are prime examples of structures in which discrete optical dynamics can be observed and investigated. These arrays consist of equally spaced identical waveguide elements or sites (Fig. 1a, b) and, therefore, possess all the essential characteristics of a photonic crystal structure (Brillouin zones, allowed and forbidden bands and so on). In this physical setting, light 'hops' from site to site through optical tunnelling or coupling, and, in doing so, it profoundly alters its diffraction characteristics. The discrete diffraction properties of one-dimensional (1D) waveguide chains were first theoretically addressed in 1965[1] and experimentally observed in gallium arsenide arrays a few years later[2]. At the time, however, it was by no means clear how one could either take advantage of or suppress this peculiar discrete diffraction process, and, as a result, the field remained dormant for several years.

In 1988, the idea that light could trap itself in nonlinear optical waveguide arrays or lattices was suggested[3]. This self-localization can take place provided that the on-site nonlinearity exactly balances the discrete diffraction arising from linear coupling effects among adjacent waveguides. As a consequence, the optical field is confined within only a few waveguide sites, and it forms what is better known as a discrete soliton (a nonlinear particle-like wavepacket, the shape of which remains invariant during propagation). The same discrete evolution equation that governs optical nonlinear waveguide lattices is also believed to describe quantum excitations in α-helical proteins—an idea first suggested in the early 70s[4,5]. This link between optics and bioenergetics hints at the exciting possibility that biological processes can be mimicked entirely by light.

The prospect of observing discrete solitons (DSs) in nonlinear optical waveguide arrays sparked a flurry of important theoretical studies in the 90s; all of them revealed fundamental differences between these discrete systems and their continuum counterparts[6–9]. This effort culminated in the first successful experimental observation[10] of optical DSs in AlGaAs waveguide arrays (Fig. 1a). Recent advances in microfabrication technology that allowed the fabrication of precision-made defect-free waveguide lattices made this possible. These initial experiments were followed by a series of breakthroughs, including the first observation of anomalous diffraction and diffraction management[11,12], Bloch oscillations and Floquet–Bloch solitons[13–15], DSs in nonlinear quadratic[16] arrays and photorefractive[17,18] arrays, to mention a few.

In this article, we review the current state of this emerging and exciting field. We emphasize that waveguide arrays can serve as archetypal structures in which the potential of linear and nonlinear discrete interactions can be assessed for future optical technologies. These types of interaction are universal: they are expected to occur in a variety of periodic structures such as photonic crystals[19–21] and photonic crystal fibres[22]. DSs, the natural modes of any nonlinear lattice, can also be thoroughly investigated in waveguide arrays as a prelude to analysis in more complex nonlinear optical crystal systems. Furthermore, progress in this area is expected to shed light on other areas of science[23–26], where similar discrete-like dynamics are encountered, such as, Bose–Einstein condensates trapped in optical periodic potentials[25,26].

Linear diffraction properties of waveguide arrays

Optics deals with electromagnetic waves that are continuous functions of space and time. There are situations, however, where the evolution of an optical field can be represented as a discrete problem. As previously mentioned, one such simple and important case is that of light in a coupled 1D waveguide array[1–3]. In a waveguide array, a large number (infinite in principle) of single-mode channel waveguides are laid next to each other in such way that their individual modes overlap. As a result, every waveguide is coupled to its nearest neighbours, and, consequently, light propagation in such waveguide arrays is drastically affected. In this case, the optical mode electric field amplitude, E_n, at array site n

evolves according to the following linear discrete differential equation: $i(dE_n/dz)+\kappa(E_{n-1}+E_{n+1})=0$. In this equation, the first term describes the modal field evolution along the z direction (parallel to the waveguides), and the second one accounts for the evanescent field coupling, κ, of site n to its neighbouring waveguides.

To further understand the peculiarities of light propagation in linear waveguide arrays, let us first consider the simple case where only one waveguide is excited at the input. Under these conditions, the light intensity redistributes itself within the array as shown in Fig. 1c. Note that most of the light is concentrated in two distinct outer lobes. This is in contrast to the diffraction process that occurs in a bulk system, where most of the power is concentrated around the centre. This indicates that such discrete diffraction is profoundly different and has no analogue in continuous systems.

Discrete diffraction, however, has much more to offer. Unlike a bulk system, where the magnitude of diffraction is fixed at a given wavelength, in arrays, discrete diffraction can be engineered. To appreciate this, consider the dispersion relation of the governing discrete evolution equation, which is given by $k_z=2\kappa\cos(k_xD)$ (ref. 3), where k_z is the propagation eigen value (or longitudinal **k**-vector) and k_xD represents the so-called Bloch momentum (where D is the spacing between waveguide sites)[3]. The Bloch momentum vector is determined by the angle at which the beam is launched into the array[11,12]. It is important to emphasize that in coupled arrays the dispersion curve is sinusoidal and not parabolic as it is in continuous media. Because the diffraction process is proportional to the curvature (or the second derivative) of the dispersion relation, one can conclude that diffraction is normal for $0<k_xD<\pi/2$ (normal diffraction), it reverses its sign for Bloch momenta $\pi/2<k_xD<\pi$ (anomalous diffraction) and it becomes zero at $k_xD=\pi/2$ (refs 11,12) as further explained in Fig. 2. These peculiarities led to a renewed interest in the linear properties of discrete optical structures. In particular, diffraction can be managed or engineered by concatenating sections with different signs of diffraction[11]. Finally, the concept of discrete diffraction can be extended to higher-order Floquet–Bloch bands, as will be described in a later section of this review.

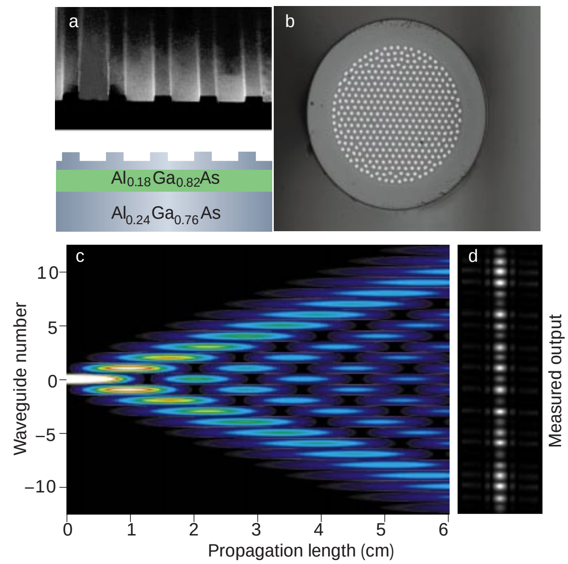

Figure 1 Waveguide arrays and their diffraction behaviour. Discrete optical dynamics can be observed in arrays of equally spaced identical waveguide elements, for example, (**a**) in aluminium gallium arsenide (AlGaAs) arrays (University of Glasgow, UK) and (**b**) in silica glass (Institute for Physical High Technology Jena, Germany). **c**, A numerical simulation of a narrow input beam that excites a single site of a periodically poled lithium niobate waveguide array with a spacing between waveguides (D) of 15 μm and a wavelength of 1.56 μm. In this view (from above), under discrete diffraction, most of the light is distributed in two distinct outer lobes. **d**, Experimental measurement of the intensity distribution at the output facet of a lithium niobate waveguide array at 1.56 μm (ref. 16).

Photonic Bloch oscillations

As a direct consequence of the discrete translational symmetry, the underlying physical mechanism leading to discrete diffraction and refraction in homogeneous arrays is the band structure of the dispersion relation. Thus, the question naturally arises of how the field dynamics change if the waveguide lattice becomes inhomogeneous, for example, through introduction of a linear variation in the effective refractive index across the array. This brings forth a fundamental issue in discrete systems first addressed by Bloch and Zener 70 years ago[27,28]. They raised the question of how do electrons behave in a crystal lattice when a DC field (linear potential) is applied, and they predicted the occurrence of periodic oscillations, later termed Bloch oscillations. These oscillations are caused by field-induced acceleration of electrons travelling in this tilted periodic potential. When the particle Bloch momentum reaches the Brillouin zone boundary, it is Bragg reflected and subsequently decelerated by the DC field until it comes to rest, completing one period of oscillation. Thus Bloch oscillations are the result of discreteness and lead to linear localization of excitation rather than unlimited spreading. The existence of these oscillations remained controversial for a long time and was finally confirmed when Bloch oscillations of electrons in semiconductor superlattices were experimentally observed[29]. Inspired by these results, similar phenomena were searched for in other disciplines that involve periodic systems, for example, cold atoms and Bose–Einstein condensates in optical lattices and photons in periodic optical systems such as waveguide arrays.

An important advantage optical systems offer is the ability to directly visualize effects such as Bloch oscillations. In waveguide arrays, optical Bloch oscillations are possible so long as the refractive index distribution varies linearly with site n[30]. In this case, the discrete field amplitudes E_n obey $i(dE_n/dz)+\alpha nE_n+\kappa(E_{n-1}+E_{n+1})=0$, where the array discrete evolution equation has been modified to account for the linear index tilt αn, with α being the strength of the 'linear potential'. This model exhibits localized solutions of identical shape. These are the so-called Wannier–Stark states, which have equally spaced eigen values (the Wannier–Stark ladder). Thus, any input distribution excites a certain set of Wannier–Stark states, and the superposition of these confined states leads to a periodic recurrence of the input field after a propagation distance $z=2\pi m/\alpha$, where m is an integer. This wavepacket recurrence phenomenon was experimentally verified in an AlGaAs array consisting of waveguides of varying width[13] and in a thermo-optic polymer array of identical waveguides[14] as explained in Fig. 3.

Discrete solitons

Optical DSs are, in general, self-trapped entities of a finite extent that exist in coupled periodic nonlinear lattices[3]. They are self-localized wavepackets whose energy resides primarily in distinct waveguide array sites (hence discrete) and exist through a balance of discrete diffraction/coupling effects and material nonlinearity. Unlike their continuous counterparts, DSs represent collective excitations of the nonlinear chain (array), and, as a result, they exhibit a host of interesting characteristics that are absent in the bulk[31].

Depending on the nature of the underlying nonlinear process, different families of discrete solitons are possible. To date, arrays made from materials with intensity-dependent Kerr[10], quadratic[16] or photorefractive nonlinearities[18] have been shown to support such discrete localized states. For a given material, the nonlinear mechanism can be either self-focusing or defocusing[6]. In the self-

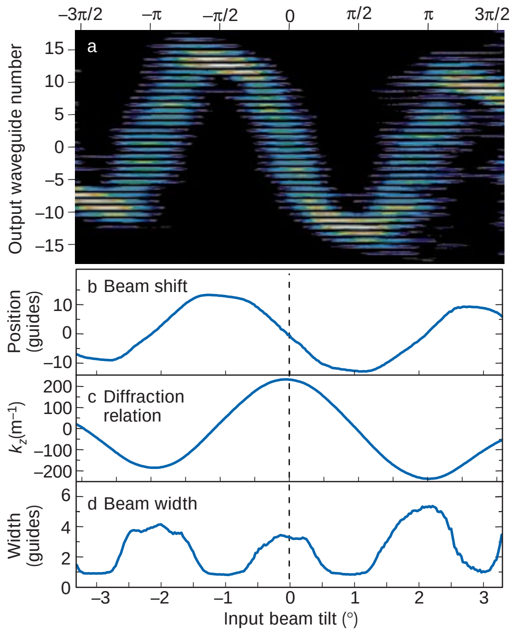

Figure 2 Phase difference between adjacent waveguides (k_xD). **a**, Displacement of a Gaussian beam launched in a 6 cm long polymer array at 0.633 μm (ref. 12). The beam displacement as measured experimentally at the output facet of the array is shown as a function of the initial beam tilt or phase difference between adjacent waveguides (k_xD). This displacement or shift is proportional to the transverse 'velocity' with which a beam travels across the array lattice. Because the group velocity happens to be the first derivative of the sinusoidal dispersion relation $k_z=2\kappa\cos(k_xD)$ (see **b**), the beam exhibits zero displacement at the base of the band ($k_xD=0$) and at the edge of the Brillouin zone ($k_xD=\pm\pi$). By contrast, the beam shift is at its maximum at $k_xD=\pm\pi/2$ (middle of Brillouin zone), as illustrated in **b**. From these data, the sinusoidal dispersion relation (see **c**) for k_z can be determined through integration. The diffraction experienced by a beam in the array is proportional to the second derivative of the dispersion relation d^2k_z/dk_x^2 and is therefore normal around the base of the band ($k_xD=0$) and anomalous close to the edge of the Brillouin zone ($k_xD=\pm\pi$) (ref. 58). For a Bloch momentum $k_xD=\pi/2$, diffraction is completely arrested, thus a wavepacket can propagate in the linear array with virtually no diffraction. **d**, The measured beamwidth (proportional to the array diffraction) at the output of the array as a function of the input beam tilt or phase difference k_xD is shown. It is easily seen that beam spreading is minimal at $k_xD=\pm\pi/2$ and attains a maximum at $k_xD=0,\pm\pi$.

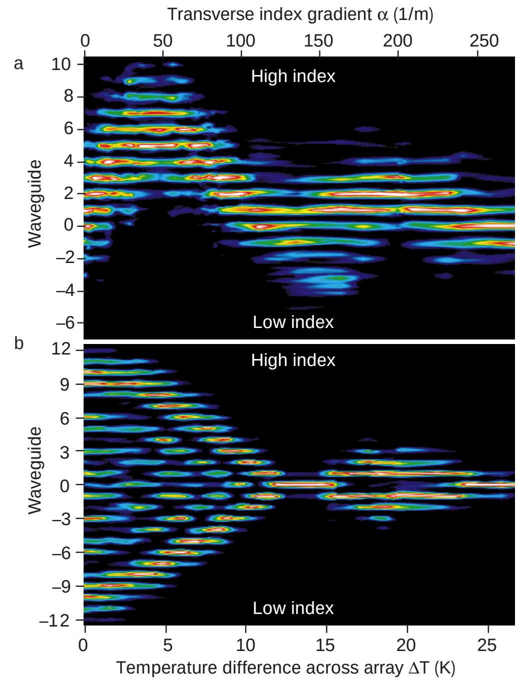

Figure 3 Experimental results depicting optical Bloch oscillations in a 4.5 cm long thermo-optically tuned polymer array at a wavelength of 0.633 μm (ref. 14). **a**, The intensity distribution at the output facet of the array versus the index gradient α or the temperature difference ΔT when the array is initially excited with a Gaussian beam. By increasing the temperature difference ΔT the oscillating transverse motion of the output beam can be measured. The decrease in the maximum elongation between α=70 to 210 m^{-1} is due to the stronger localization of Wannier–Stark states. At α=140,280…m^{-1}, full Bloch oscillations occur and the initial Gaussian distribution is recovered. **b**, Similar results were observed when only one waveguide was initially excited. When ΔT=0, the familiar discrete diffraction pattern (Fig. 1c, d) is recovered, whereas for integer multiples of the Bloch period α=140,280,…m^{-1}, the beam narrows. Similar effects were observed in AlGaAs arrays at low intensities by monitoring the output intensity for different sample lengths[13].

focusing case, the refractive index increases locally with intensity, whereas in the defocusing cases it decreases.

Before we discuss the various DS families, it may be beneficial to understand the physics behind DS formation. To comprehend this nonlinear self-trapping effect, it is important to reiterate some of the most significant aspects of linear wave propagation in array lattices. In the linear regime, the optical field travelling in a waveguide array is subjected to a periodic potential, and, as a result, the dispersion relation (between the propagation eigen value and the transverse **k**-vector) is organized as a succession of allowed bands and bandgaps, as shown in Fig. 4a, within the Brillouin zone[15]. Waves are only able to 'travel' if their eigen values fall within an allowed band (Floquet–Bloch modes), whereas wavefunctions with propagation constants lying in the bandgaps decay exponentially in the transverse direction.

Under nonlinear conditions (such as in Kerr-like media), however, the optical field perturbs, through nonlinearity, the refractive index, thus, inducing a defect within an otherwise perfect waveguide lattice. Consequently, the eigen value of this nonlinear defect-like state moves into a bandgap, and, therefore, its wave function decays rapidly away from the perturbed region. Hence, the field becomes self-localized and a DS forms. Note that as the power of this optical field increases, the deeper its propagation eigen value moves into the gap, resulting in a more confined and transversely immobile DS. If the waveguide sites are sufficiently separated, then the Floquet–Bloch functions belonging to the first allowed band of the array could be described through coupled-mode theory or tight-binding approximation[32]. In this formalism, the local bound states or waveguide modes discretely interact with each other through evanescent coupling. In this case, for Kerr nonlinear arrays, the electric field amplitudes, E_n, of the modal fields involved obey the so-called discrete nonlinear Schrödinger equation[3]: $i(dE_n/dz)+\kappa(E_{n+1}+E_{n-1})+|E_n|^2E_n=0$. This is a generalization of the discrete evolution equation, and the last term describes the on-site nonlinearity. Like other discrete nonlinear lattice equations, such as the Fermi–Pasta–Ulam problem, the Toda equation or the Ablowitz–Ladik equation[33], this equation has DS solutions (see ref. 6 for more details). In general, DS solutions with zero transverse velocity can be subdivided into two basic categories: (i) those with zero Bloch momentum $k_xD=0$ (at the base of the band) and (ii) those at the edge of the band within the Brillouin zone where the Bloch momentum is $k_xD=\pi$. For example, at the base of the first band of Fig. 4a, the curvature of the dispersion curve is such that discrete diffraction is normal. As a result, in-phase bright DSs exist in

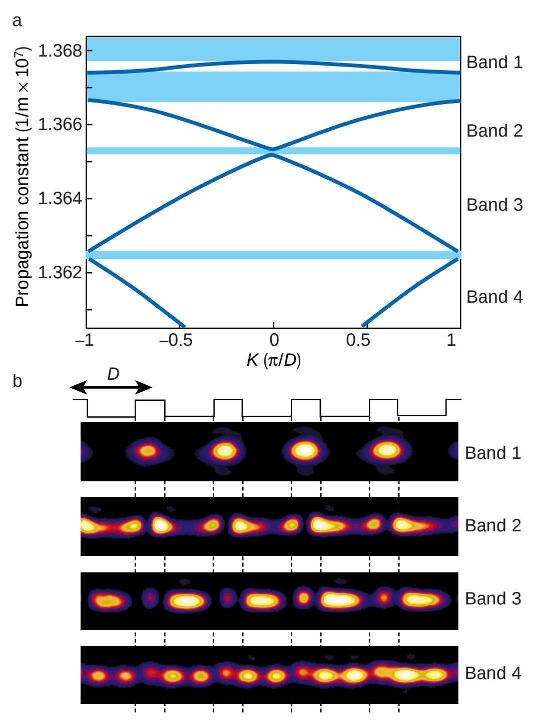

Figure 4 Array band structure and the associated Floquet–Bloch modes. **a**, Reduced bandgap diagram of a typical waveguide array (folded into the first Brillouin zone), where the Floquet–Bloch mode propagation constant or eigen value is plotted as a function of the Bloch momentum wavevector (*K*). The shaded regions represent the gaps, and the blue curves the bands. The first four allowed bands are shown. **b**, Highly magnified images of the excited Floquet–Bloch modes corresponding to the first four bands obtained experimentally in ref. 15 at a wavelength of 1.55 μm and using an AlGaAs array with D=11 μm.

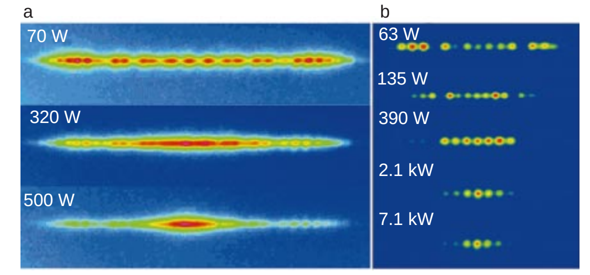

Figure 5 Experimental observation of discrete solitons. **a**, Intensity images at the output of a Kerr AlGaAs array with a waveguide spacing of D=8 μm and operated at 1.53 μm observed at various power levels. At low powers (70 W), the beam discretely diffracts, whereas at 500 W, a discrete soliton forms[10]. **b**, Intensity images from a periodically poled lithium niobate (PPLN) array with D=15 μm and used at 1.56 μm (ref. 16). At a power level of 7.1 kW, a discrete soliton forms.

arrays with self-focusing nonlinearities. By contrast, in defocusing systems, dark in-phase DSs exist instead. At the edge of the band where the discrete diffraction is anomalous (negative curvature), the situation is reversed. In this case, dark solitons exist in self-focusing arrays and bright solitons in defocusing ones[9,34,35]. This time, however, the modal fields happen to be π out of phase or staggered.

Figure 5a shows the first experimental observation of an in-phase bright discrete soliton in a self-focusing AlGaAs waveguide array[10]. At low optical powers, the optical field discretely diffracts in the array, as previously discussed. At higher powers, however, the optical field self-localizes, which provides a clear indication of discrete soliton formation. In addition, dark staggered solitons ($k_x D$=π) have been recently observed in the same waveguide array by launching the beam at an appropriate angle into the system[35]. Similarly, transport dynamics of DSs, as well as effects arising from the so-called Pierls–Nabbaro potential, have also been experimentally investigated[36]. Very recently, Floquet–Bloch solitons have been successfully observed in waveguide arrays[15]. These solitons 'reside' in the higher-band gaps of Fig. 4a and therefore involve Floquet–Bloch modes from higher bands. Figure 4b shows the Floquet–Bloch structure of these higher-order soliton modes. Within the past few months, DSs have also been observed in biased photorefractive crystals[17]. In this system, both in-phase bright and staggered bright DSs have been observed by using the versatility of photorefractive nonlinearities. Other interesting DS families, such as vector[37], diffraction-managed[38] and gap solitons in diatomic lattices[39], are predicted to exist in waveguide arrays. Furthermore, interaction forces among discrete solitons[40] have been experimentally observed in AlGaAs arrays under various input conditions[41]; discrete vector solitons were also observed[42].

During the past several years, a great deal of attention has been paid to the behaviour of spatial solitons in quadratic nonlinear media[31]. Unlike their Kerr counterparts, quadratic spatial solitons are symbiotically or dichromatically localized objects, because their fundamental and harmonic waves are mutually locked and do not exchange energy. Moreover, in these systems the wave vector mismatch between both constituents introduces an additional degree of freedom with regard to soliton formation. Discrete quadratic solitons were predicted[43] in the late 90s, and since then they have been the focus of ongoing research[6]. Yet, it is only recently that the technology of Ti-indiffused (doped) periodically poled lithium niobate (PPLN) waveguides has matured to the point that quadratic waveguide arrays can be fabricated. The first experimental results confirming the existence of discrete quadratic solitons[16] are shown in Fig. 5b.

Discrete solitons in higher dimensions and other settings

So far we have focused on DSs in a 1D environment. Nevertheless, these entities can exist in higher dimensions (2D and 3D) so long as a nonlinear lattice system is present to host them. Indeed, there are many exciting DS features that can only occur in higher dimensions. These include vortex lattice solitons[44], bright discrete solitons carrying angular momenta and slow light DSs in 3D photonic crystal networks[45,46], just to mention a few. Even though creating such lattices in multiple dimensions has always been technologically challenging, recent developments are now promising to alleviate the fabrication difficulties that have so far inhibited progress in this field.

DSs were predicted[47] and subsequently experimentally observed[18] for the first time in biased photorefractive crystals such as Strontium–Barium–Niobate:75 (SBN). A key element that led to the success of this particular experiment was the large electro-optic anisotropy of SBN:75, which allowed virtually linear propagation in one polarization and highly nonlinear propagation in the other. By exploiting this, a 2D waveguide lattice can be optically induced by interfering plane wave pairs polarized along the linear axis. By contrast, a beam polarized along the other axis will experience strong nonlinearity as well as the optically induced periodic potential, thus forming a 2D discrete optical soliton. Moreover, owing to the high nonlinearity of photorefractive crystals, new families of 2D DSs can be observed at milliwatt power levels. This technique offers considerable flexibility in that the same photorefractive waveguide lattice can be either self-focusing or defocusing depending on the crystal bias polarity. Last but not least, a rich variety of optically induced 2D lattices is possible in these systems, such as rectangular,

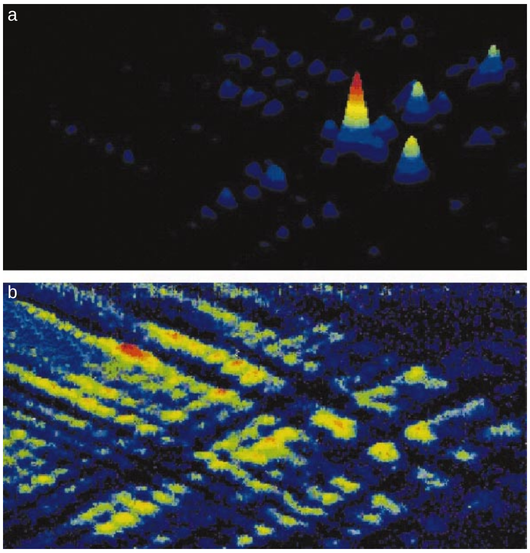

Figure 6 Experimental results in 2D photorefractive lattices. **a**, Observation of a two-dimensional discrete soliton in a biased highly nonlinear SBN:75 photorefractive crystal at a sufficiently high optical intensity. The power levels involved are in the milliwatt range. **b**, Discrete diffraction of an optical beam in a 2D waveguide lattice when the optical intensity is low[18]. In both cases, the waveguide spacing (*D*) was 11 μm and the wavelength was 0.488 μm.

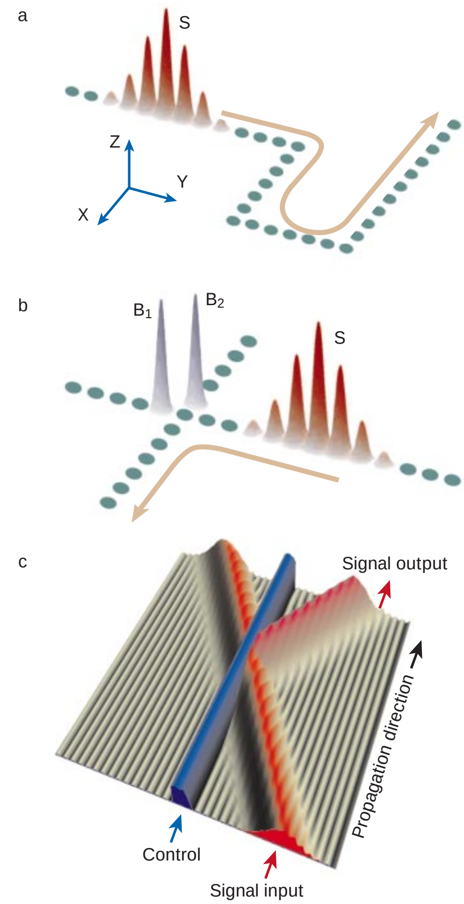

Figure 7 Possible applications of discrete solitons. **a**, A nonlinear array network involving consecutive bends. Light in this array propagates along the *z*-axis and is confined in the transverse *x*–*y* plane. The waveguide cross-sections are shown in green. A discrete soliton, S, shown in red, is set in motion in this system by appropriately tilting the beam. Computer simulations indicate that DSs can successfully negotiate a sequence of bends, producing very little radiation/reflection loss[54]. The DS follows the pre-assigned path and remains essentially invariant during propagation. These losses can be effectively minimized by engineering the corner of the bend. **b**, An X-switching junction that uses two different DS families, the so-called 'signals' and 'blockers', denoted by S and B, respectively. Signals are moderately confined DSs, whereas blockers (depicted in blue) are strongly confined, occupying effectively one site. Unlike signals, which are highly mobile, blockers tend to retain their position after a collision event. In the junction shown, the blockers B_1 and B_2 interact 'incoherently' (different colours or polarizations) with S. The signal soliton S is routed towards the lower branch, because of the presence of the two blockers at the entries of the respective pathways. Had one of the two blockers not been present at the junction, the signal DS would have totally disintegrated into transmitted and reflected waves. Thus in essence, the junction operates as an AND gate[53]. Animations illustrating these processes can be found at the website indicated in ref. 59. **c**, All-optical routeing of on input signal beam to a specific output position using a parametric interaction in a quadratic nonlinear waveguide array. A tilted ($k_x D=\pi/2$) signal input beam crosses the array, producing virtually no diffraction. A control beam at about the second harmonic wavelength is used to generate, and all-optically deflect, an idler beam.

hexagonal and 'diatomic' lattices. Figure 6a demonstrates DS formation for a sufficiently high optical intensity, whereas Fig. 6b shows 2D discrete diffraction of an optical beam under linear conditions.

In addition, 2D DSs are possible in microstructured or photonic crystal fibres (PCFs), where a 2D waveguide lattice can be permanently embedded within the bulk. Very recently, nonlinear light localization has been experimentally observed in 2D optical fibre arrays[48]. This is a promising technology because nonlinear interactions can take advantage of the long propagation lengths offered by silica fibres, thus reducing power requirements. The formation of self-localized states in active fibre laser arrays is also a topic of current interest[49,50].

In principle, DSs exist in a 3D environment[45,46]. One such possibility may be in coupled-resonator optical waveguides (CROWs)[51], where waveguiding is accomplished through light hopping among successive high-*Q* microcavities that effectively act like defects when embedded in a photonic crystal[52]. In this system, it is predicted that DSs can propagate without distortion along chains of coupled nonlinear microcavities. However, unlike their spatial cousins in waveguide arrays, DSs in this type of environment are by nature spatiotemporal entities[45]. These states are possible as a result of the balance between discrete lattice dispersion and material nonlinearity. These self-localized entities can exhibit very low group velocities, depending on the coupling strength among successive microcavities and in some cases may remain immobile like frozen bubbles of light[45,46]. In addition, this class of solitons can be effectively routed along any pre-assigned path in a 3D environment.

Soliton navigation and switching in waveguide array networks

One of the most important functions of a photonic network is to route information from a particular point of origin A to its final destination port Z. In such optical systems it is often highly desirable for routeing to be accomplished completely optically so as to avoid unnecessary opto-electronic conversion. If, for example, data are re-directed by a space-switching matrix or a crossbar, it is crucial that this process occurs with minimum diffraction-induced crosstalk losses among nodes. DSs can offer a promising solution to this problem. By exploiting the nonlinearity of the array, discrete diffraction effects can be effectively counteracted, therefore eliminating undesirable crosstalk among sites (which serve as the network nodes). The success of such schemes, of course, relies on the availability of fast-responding highly nonlinear materials. Even though waveguide arrays have thus far been realized in material systems that lack the required figures of merit (regarding their nonlinear properties), research into new materials promises to overcome these problems. In that case, one can envisage all-optical switching networks that play a vital role in tomorrow's communication systems.

Quite recently, it has been theoretically demonstrated that DSs in 2D nonlinear waveguide array networks can provide a rich environment for all-optical data processing applications[53]. More specifically, this family of solitons can realize intelligent functional operations such as routeing, blocking, logic functions and time-gating. These DSs can be routed anywhere in the network along pre-assigned array pathways that act like 'soliton wires' as explained in the proposed architectures of Fig. 7. Even more importantly, DSs can be routed at array intersections using vector–incoherent interactions with other DSs[53–55]. In essence, these intersections behave as DS switching junctions. Such systems can also be used to realize logic operations (see Fig. 7b).

The distinct features of discreteness can also be exploited for other important applications in optical signal processing. Above, we have shown how nonlinearity and, in particular, DSs offer such possibilities. However, the engineering of linear wave diffraction is by itself highly promising in terms of controlling light in discrete configurations without the need for the power levels required in soliton-based schemes. In specifically designed configurations, discrete diffraction can be tailored so that signal beams suffer from virtually no diffraction-induced losses even at low power levels.

The dependence of the Bloch oscillation amplitude on the transverse index gradient is just one example of how waveguide arrays can be used to steer a single input beam to several output positions[56]. An experimental realization of this concept demonstrated that a temperature change of only 5 K was sufficient to address six separate output channels.

The quadratic parametric interaction in waveguide arrays is another example of how light signals can be all-optically manipulated while complying with the low-power signal demands of modern telecommunication systems[57]. In the switching configuration, which is shown in Fig. 7c, the input signal beam travels at an angle where diffraction is zero ($k_x D = \pi/2$). In this case, the control beam does not diffract because the stronger confinement in the waveguide renders the coupling zero. This allows two diffractionless beams to cross at an arbitrary position in the waveguide array. Parametric interaction provides phase-insensitive all-optical switching by generating a third diffractionless output beam. By implementing this scheme in the highly mature PPLN waveguide technology, routeing applications of 100 Gbit/s signals should be feasible.

The field of optical dynamics in linear and nonlinear discrete waveguide lattices is at an exciting stage of development. Even though some of the basic concepts regarding discrete optical arrays have been around for a while, much remains to be understood and discovered. It is only very recently that fabrication techniques have matured to the point that experiments can be successfully conducted in these systems. This flurry of activity will allow us to assess the potential of these discrete structures for use in tomorrow's optical communication systems and switching networks. And, as is always the case in science, the best is yet to come. □

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