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Optical spatial solitons at the interface between two dissimilar periodic media: theory and experiment

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Abstract: Discrete spatial solitons traveling along the interface between two dissimilar one-dimensional arrays of waveguides were observed for the first time. Two interface solitons were found theoretically, each one with a peak in a different boundary channel. One evolves into a soliton from a linear mode at an array separation larger than a critical separation where-as the second soliton always exhibits a power threshold. These solitons exhibited different power thresholds which depended on the characteristics of the two lattices. For excitation of single channels near and at the boundary, the evolution behavior with propagation distance indicates that the solitons peaked near and at the interface experience an attractive potential on one side of the boundary, and a repulsive one on the opposite side. The power dependence of the solitons at variable distance from the boundary was found to be quite different on opposite sides of the interface and showed evidence for soliton switching between channels with increasing input power.

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References and links

1. P. St. J. Russell, “Photonic Crystal Fibers,” Science 299, 358-362 (2003).
2. D. N. Christodoulides, F. Lederer, and Y. Silberberg, “Discretizing light behavior in linear and nonlinear waveguide lattices,” Nature 424, 817-823 (2003).
3. J. D. Joannopoulos, P. R. Villeneuve, and S. H. Fan, “Photonic crystals: putting a new twist on light,” Nature 386, 143-149 (1997).
4. W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," Nature 424, 824-830 (2003).
5. A. D. Boardman, P. Egan, F. Lederer, U. Langbein, and D. Mihalache, Nonlinear Surface Electromagnetic Phenomena, H. E. Ponath and G. I. Stegeman, ed. (North-Holland, Amsterdam, 1991), Vol. 29, p.73.
6. F. Lederer, L. Leine, R. Muschall, T. Peschel, C. Schmidt-Hattenberger, T. Trutschel, A. D. Boardman, and C. Wächtler, “Strongly nonlinear effects with weak nonlinearities in smart waveguides,” Opt. Commun. 99, 95-100 (1993).
7. K. G. Makris, S. Suntsov, D. N. Christodoulides, G. I. Stegeman, and A. Hache, "Discrete surface solitons,” Opt. Lett. 30, 2466-68 (2005).
8. S. Suntsov, K. G. Makris, D. N. Christodoulides, G. I. Stegeman, A. Hache, R. Morandotti, H. Yang, G. Salamo, and M. Sorel, “Observation of Discrete Surface Solitons,” Phys. Rev. Lett. 96, 063901 (2006).
1. Introduction

Discreteness and periodicity on the wavelength and sub-wavelength scales of electromagnetic waves have recently led to the emergence of new research areas and novel phenomena, amongst them photonic crystal fibers, photonic crystals, and weakly coupled waveguide arrays [1-3]. A number of applications have already been suggested, indicating that optical processing circuits can be implemented using different periodic structures on the same substrate. This has led to basic questions as to how the breaking of translational symmetry can affect optical wave propagation at the boundaries of two dissimilar periodic...
structures. In optics, the disruption of translational symmetry leads to the existence of various types of guided waves such as surface plasmons characterized by fields that also decay into the bounding media [4]. Yet, in the absence of some intrinsic material resonance arising from electron plasma, excitons, optical phonons etc., linear surface waves cannot be guided at the interface between two continuous dielectric media. In the 1980s, it was shown that optical nonlinearities can allow guiding along a boundary provided that the nonlinearly induced index change cancels out the initial index difference across the interface [5]. Due to difficulties in identifying pairs of bulk media with a linear index difference small enough that it can be exceeded by a nonlinear optically induced index change, experimental verification was lacking. In 1993 Lederer and co-workers proposed using two multilayers of AlGaAs and AlAs films engineered to produce an interface with a small effective refractive index difference [6]. Recently surface solitons were predicted (2005) and observed (2006) to exist at the boundary between 1D continuous and discrete, periodic, self-focusing media in which the intrinsic material resonances were replaced by the geometric resonances inherent to waveguide lattices [7-11]. This was quickly followed by the observation of surface gap solitons in 1D defocusing quadratic and photorefractive media [10,12-15], and in both self-focusing and defocusing media at boundaries between continuous and 2D discrete media [16,17].

This has raised the fundamental question whether nonlinear interface waves could also exist along the boundaries of two dissimilar periodic media such as those encountered in photonic crystals or waveguide arrays. To date, only a single experiment has been reported on electromagnetic surface states at the boundary between dissimilar periodic media, where a linear mode was observed [18]. Theory has recently shown that a rich variety of solitons should also exist at the interfaces in such hetero-structures under conditions dictated by the parameters of the system and the nonlinearity [19-23]. Here we report the first prediction and observation of the complex properties and power-dependent dynamics of 1D discrete spatial solitons propagating along and near the boundary between two 1D dissimilar, periodic, self-focusing media [24,25]. We found fascinating features both theoretically and experimentally not predicted before by theory. Very recently the observation of interface discrete solitons at the 2D interface between square and hexagonal lattices has also been reported [26].

2. Sample structures and their characterization

The geometry we consider is shown in Figs. 1(a)-(c) [25]. The two 1D arrays with identical inter-channel spacing of 10μm (and therefore with identically sized Brillouin zones) but with different potential wells, are separated by a distance \( d = 3.4\mu m \) or \( 5.2\mu m \).

The modulation of refractive index is achieved by creating high index ridges with different widths in the two regions. Standard MBE deposition and etching fabrication techniques were used in constructing the 1.35cm long samples in the Al\(_{x}\)Ga\(_{1-x}\)As system. Isolated single channels were also fabricated on the same chip and their transmission properties at 1550nm.
were used to evaluate experimentally the linear propagation losses ($\alpha = (0.15 \pm 0.01)\text{cm}^{-1}$ [25]. Using excitation at a wavelength around 1550nm with photon energies just below the half of the band gap of the semiconductor material helps to dramatically reduce two-photon absorption at high power levels. Nonlinear transmission experiments showed that two-photon absorption was indeed negligible but three-photon absorption (3PA, $\Delta \alpha = \alpha_I I^2$ with $\alpha_I = 0.04\text{cm}^3/\text{GWcm}$ where $I$ is the optical intensity) was present [27]. 3PA produces significant absorption at peak powers $\geq 1\text{kW/channel}$ and becomes the limiting factor for the power [25].

The samples depicted in Fig. 1 are characterized by many physical parameters. In addition to nonlinear effects, the evolution of light injected into a single channel within an array involves many linear parameters including the coupling coefficients between adjacent channels in the left and right lattices, $C_l$ and $C_r$, the inter-array coupling constants between the two interface channels, $C_{l\rightarrow r}$ and $C_{r\rightarrow l}$ and the initial mismatch $\Delta k_z$ between the individual propagation wavevectors $k_z$ of isolated channels of the two arrays. Here: $C_l = 440\text{m}^{-1}$, $C_r = 360\text{m}^{-1}$, calculated from the channel dimensions and separation, and measured experimentally from the discrete diffraction patterns for single channel excitation in the arrays. Also $310\text{m}^{-1}$ and $540\text{m}^{-1}$ were found for $C_{l\rightarrow r}$, and $940\text{m}^{-1}$ and $1420\text{m}^{-1}$ for $C_{r\rightarrow l}$ for the inter-array separations $d = 5.2\mu\text{m}$ and $3.4\mu\text{m}$, respectively. Finally, $\Delta k_z = k_{z,l} - k_{z,r} = 2600\text{m}^{-1}$.

Noteworthy is the large difference between the coupling constants $C_{l\rightarrow r}$ and $C_{r\rightarrow l}$. This difference has a large impact on the discrete diffraction for boundary channel excitation and the evolution into surface solitons at high powers. Shown in Figs. 2(a)–(d) are the experimental linear diffraction patterns for single boundary channels excitation which were in excellent agreement with continuous wave (cw) Beam Propagation Method (BPM) simulations based on the actual sample geometry. The asymmetry in the coupling between arrays is clear. Furthermore, the samples are $>5$ discrete diffraction lengths long.

3. Floquet-Bloch analysis

These particular geometries have been analyzed in terms of the Floquet-Bloch modes of the composite structure, including a nonlinear term which represents the self-focusing Kerr nonlinearity of the AlGaAs system [19]. The governing equation is

$$i \frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial x^2} + V(x)u + \gamma |u|^2 u = 0,$$

where $V(x)$ is the refractive index distribution of the hetero-structure as shown in Fig 1(b). The periodic solution for the field distribution along x is written as $u(x, z) = \phi(x) \exp[i k_z z]$ where $k_z$ is the propagation wavevector for a particular Floquet-Bloch mode. The dispersion
diagrams associated with the linear (γ = 0) Floquet-Bloch modes of the individual arrays are shown in Fig. 3 in which $k_{z,\ell}$ and $k_{z,r}$ are plotted for the first Brillouin zone for the left side ($\ell$) and right side ($r$) arrays versus the transverse wavevector $x_k$.

![Fig. 3. The dispersion in $k_z$ versus $k_x$ for the Floquet-Bloch bands associated with the right (red) and left (blue) side arrays. The red dot identifies (not to scale) the quasi-linear mode peaked in the right array and the rising red and blue arrows (not to scale) identify the interface solitons whose propagation wavevector increases with increasing power.](image)

When the self-focusing nonlinearity (γ > 0) is introduced, new nonlinear solutions which correspond to interface spatial solitons appear. They are of two kinds and are shown schematically by the blue (peaked in the left side boundary channel) and red (peaked in the right side boundary channel) vertical arrows. For n=1, as the separation between the boundary channels $d$ is increased from zero, a quasi-linear mode (weak power-dependence) with fields in phase, and peaked in the boundary channel of the right side array, appears above the linear bands (at $k_x = 0$, center of the Brillouin zone) up to $d = 2.6\mu m$ [18]. This mode becomes strongly power-dependent at $d = 2.6\mu m$ and turns into a discrete spatial soliton with rapidly increasing localization with increasing $d$. The second type consists of two discrete soliton families that have no low power starting point, and are well-confined discrete solitons. Their fields which are peaked on individual channels on either side of the boundary are in phase with one another in both arrays. The variation in threshold power with $d$ is shown in Fig. 4, and the boundary (n=±1) channel field distributions are shown schematically in Fig. 5. As the array separation increases, these interface solitons degenerate asymptotically into those associated with array - uniform semi-infinite medium boundaries, as measured previously [9].

![Fig. 4. The calculated threshold power for interface solitons peaked in the left side (a) and right side (b) arrays versus array separation.](image)
The differences between the surface soliton threshold powers for the two arrays and the field distributions identified with the excitation of the two interface \((n=\pm 1)\) waveguides provide insight into the soliton physics here. Because a soliton guided by both arrays must have a common \(k_z\) for field components on both sides of the boundary, only one of these solutions can be a soliton of the composite structure, i.e. the one with fields guided by channels on both sides of the boundary as indicated in Fig. 5(a).

Fig. 5. The field structure for the interface solitons peaked in the left side (a) and right side (b) boundary channels of the arrays.

Since \(k^\text{sol}_z = k_{z,\ell} + \Delta k^\text{NL}_z = k_{z,r} + \Delta k^\text{NL}_z\), where \(\Delta k^\text{NL}_z\) and \(\Delta k^\text{NL}_z\) are the nonlinear contributions to the soliton propagation wavevector, then a negative \(\Delta k_z = k_{z,\ell} - k_{z,r} = -2600 m^{-1}\) implies \(\Delta k^\text{NL}_z > \Delta k^\text{NL}_z\). Since the difference in the peak powers in the boundary channels is approximately proportional to \(\Delta k^\text{NL}_z - \Delta k^\text{NL}_z\), thus the only soliton guided in both arrays will have a peak in or near the boundary channel of the left array. This condition also explains why the power for the left array soliton should be considerably larger than that for the soliton associated with the left array - slab waveguide interface which requires a smaller \(\Delta k^\text{NL}_z\) since the initial linear \(\Delta k_z\) is smaller [8,9]. For the self-focusing nonlinearity in our samples, there is a minimum \(\Delta k^\text{NL}_z\) required to close the gap between the two linear dispersion curves, see Fig. 3. It varies with ridge width and is given approximately by \(\Delta k^\text{NL}_z(m^{-1}) \equiv -\frac{2}{m^2}(m^{-1})\). Since the composite structure soliton requires \(\Delta k^\text{NL}_z > 0\) in both media, this equation also predicts the right order of magnitude for the required power. Using the same arguments as above, any soliton peaked in the right side array cannot be guided in the channels of the left side array with a common soliton wavevector. This soliton is effectively associated with a right array - semi-infinite continuous medium boundary and experiences a higher effective refractive index in the left array region than for a semi-infinite medium without the ridges, thus lowering the threshold power relative to that case.

In general, as discussed previously for an array-continuum boundary, the larger the eigenvalue \(k^\text{sol}_z\), the higher the soliton power. This dependence is shown in Fig. 6 for the four boundary channel cases of interest here, along with the field distributions at threshold. As the soliton power increases, the field distributions become progressively more confined to the boundary channels. According to Vakhitov-Kolokolov criterion [28], these solitons are stable only in the regions where the condition \(\partial P^\text{sol} / \partial k^\text{sol}_z > 0\) is satisfied.

There are a number of noteworthy features to the \(P^\text{sol}_z - k^\text{sol}_z\) soliton curves. The required powers for surface solitons peaked in the left side array are much higher than those for the right side array. Hence even at threshold the interface soliton fields are strongly localized to the left boundary channel. For the right array the field distributions are much broader. An
interesting case occurs for $d = 3.4\mu m$ (Fig. 6(b)) for which the field is only marginally higher in the $n=1$ channel than that in the $n=2$ channel. This could imply some difficulty in exciting solitons in one or both of these two channels individually.

Similar to the waveguide array - slab waveguide case [9], there is a family of stable soliton states with power thresholds peaked on channels progressively further into each array. The variation of their power thresholds with array separation for channel numbers $n=1\text{-}3$ shown in Fig. 4(b) is fascinating. Because the $n=1$ surface soliton evolves from a quasi-linear mode, the curves actually cross, despite the fact that all these solutions are stable. Furthermore, in previous calculations for the waveguide array - continuous medium case, this family of surface solitons has exhibited decreasing threshold powers with increasing $n$ and this behavior has been confirmed experimentally [9]. For the right array with $d = 3.4\mu m$ the analogous results are shown in Fig. 7.

Fig. 6. The dependence of the cw soliton power $P_{sol}$ on the normalized eigenvector $k_z^{sol}$ for the solitons peaked in the left ($n=-1$) and right ($n=+1$) boundary channels for $d=3.4\mu m$ [(a) and (b) respectively] and $d=5.2\mu m$ [(c) and (d) respectively]. The field distributions at threshold are shown as insets.

Fig. 7. The $P_{sol}-k_z^{sol}$ curves (a) and field distributions at threshold (b)-(d) for interface solitons peaked in the $n=1$, 2 and 3 channels of the right side array for $d=3.4\mu m$. In each case there is a well-defined minimum threshold power.
Indeed the $p^{\text{sol}} - k_z^{\text{sol}}$ curves appear anomalous since the $n=1$ soliton does not exhibit the highest threshold power and the curves for $n=2$ and $n=3$ are almost perfectly overlapped away from their thresholds. For $d = 5.2 \mu m$ the behavior appeared more normal indicating that it is the proximity of the left array that was responsible for this anomalous behavior. And indeed, as discussed below, the experiments did show evidence for these anomalies.

4. Experiments

The input beam, shaped by cylindrical lenses and other optics to coincide closely with the modal shape of the lowest order mode of a single (isolated) channel, was focused onto single waveguides at and near the boundary of the arrays. Pulses of 1ps duration at 1550nm were used to obtain the high peak powers necessary to excite spatial solitons and the output facet of the hetero-structure was imaged onto a line detector array camera for subsequent analysis. Details are given in reference 25.

4.1. Left-side channels (lower effective index array)

The $>2kW$ cw power level (Fig. 4(a)) required from theory for observing at $d = 3.4 \mu m$ the soliton peaked in the left boundary channel implies a pulsed power exceeding 3kW, i.e. 1.5-2 times larger than for the cw case [21]. This was not possible experimentally because of facet damage as well as the very large 3PA which would occur. Nevertheless, self-trapping was observed in the left array near the boundary. Examples of the evolution with increasing power of the output intensity patterns are shown in Fig. 8 for $n=-1$ and $n=-3$ single channel excitation. Note that the graphed results are re-normalized by the software as follows: at every input power level the channel with the largest output signal was found and that signal was given the same maximum graphic intensity for each of the input power values. Hence the color graphs indicated the relative power distribution for a given input power level and do not reflect the increasing power along the horizontal axis. At low powers, the discrete diffraction patterns for single channel excitation were observed, in good agreement with the corresponding simulations of discrete diffraction. Collapse of the optical power towards the excitation channel occurred as the incident power was increased. We define the threshold power for a single channel soliton as the minimum input power at which the peak output intensity in the excitation channel exceeds twice that of its adjacent channels [25]. This criterion was chosen because subsequent further increase in input power normally results in only small subsequent changes in the output pattern [25]. The measured single channel threshold powers lie above the powers associated with minima of the $p^{\text{sol}} - k_z^{\text{sol}}$ curves, even when the effects of pulses are taken into account.

![Fig. 8. The evolution of the output intensity pattern from the arrays with increasing input power for $d=3.4 \mu m$ with the excitation of the $n=-1$ (a) and $n=-3$ (b) channels. (c) shows a cw simulation of the propagation in the arrays for excitation of the $n=-1$ channel for input power 1100W.](image-url)
The measured single channel soliton threshold powers for \( d = 3.4 \mu m \) separation between the arrays are shown in Fig 9, along with the values reported previously for the array - 1D continuous medium (slab waveguide) interface. The values are comparable to within the experimental uncertainty. Note also in Fig. 8(a) the large amount of power that appears in the right array, especially in the \( n=+1 \) channel, but also in the discrete diffraction into that right side array. Therefore these solitons appear to be only quasi-stable, leaking energy continuously across the gap into the right array, as well as diffracting into the left array.

Nonlinear cw simulations were performed to investigate in some detail the nature of these solutions. (cw simulations were performed because simulations for pulsed excitation of cw stable spatial solitons always lead to quasi-stable pulsed solitons since power is continuously lost due to the low power tails of the pulses.) The cw simulations utilized a Beam Propagation Split Step Fourier Algorithm and did not include linear or nonlinear loss. For example, the field evolution simulation in Fig. 8(c) at the cw input power corresponding approximately to the “measured” pulsed threshold for the soliton in the \( n=-1 \) channel clearly shows that the observed localization is actually a transient condition due to the strong coupling across the gap to the \( n=+1 \) channel. In fact, for propagation distances larger than our samples allowed, localization actually occurs in the \( n=+1 \) channel where the surface soliton has a far lower threshold power as calculated above (Figs. 4 and 6). The stable interface soliton with fields in both boundary channels and primary localization in \( n=-1 \) appears numerically only beyond the power levels predicted in Fig. 4(a), which experimentally would lead to large 3PA.

For single channels excited deeper into the left array, the discrete diffraction pattern collapses smoothly into the single channel excited solitons with increasing input power. An example for \( n=-3 \) is shown in Fig. 8(b). As indicated in Fig. 9, the threshold power levels are consistent with those measured previously for surface solitons near the array - slab waveguide boundary. Both the experiment and the simulations show only weak coupling to the right array.

The situation is more interesting for \( d = 5.2 \mu m \). The predicted \( n=1 \) hetero-structure soliton has a cw threshold of 1.6kW (Figs. 4(a) and 6(c)) and its confinement corresponds to a single channel soliton. The evolution at the output facet of the observed intensity pattern versus input power is reproduced in Fig. 10(a) for \( n=-1 \) excitation. There is clear localization in the \( n=-1 \) channel at 2.4kW pulsed peak power, in good agreement with the theory for the composite soliton discussed above. This power also coincides with the threshold for 3PA.
becoming a significant loss (>10%). Larger powers require that three-photon absorption be explicitly taken into account in the analysis. Finally, the output intensity pattern in Fig. 10(b) indicates strong localization in the \( n=-1 \) boundary channel with a much weaker field in \( n=+1 \), and remnants of the discrete diffraction pattern from the low power pulse wings in both arrays. Hence this is a clear evidence for the excitation of a true interface soliton guided in both arrays. For channels deeper into the left array (\( n \) increasing), the situation becomes more complex. For \( n=-2 \) and \( n=-3 \) (Fig. 10(c)) excitation, no clear soliton thresholds were observed with power switching back and forth between the \( n=-2 \) and \( n=-3 \) channels. This is consistent with the approximately equal thresholds found for these channels in Fig. 4(a). The measured thresholds for solitons found deeper into the left array were well-defined.

![Fig. 10](image.png)

Fig. 10. (a) The measured evolution with increasing input power of the intensity pattern obtained at the output of the arrays for \( d=5.2 \mu m \) and \( n=-1 \) excitation. (b) The intensity distribution observed at the output facet for the interface soliton just above its threshold power. (c) The measured evolution with increasing input power of the intensity pattern obtained at the output of the arrays for \( d=5.2 \mu m \) and \( n=-3 \) excitation.

4.2. Right-side channels (higher effective index array)

The single channel soliton observed for \( d = 3.4 \mu m \) when the \( n=1 \) channel is excited has its peak in this boundary channel and is stable, as confirmed numerically. The intensity patterns recorded are shown in Fig. 11(a). The clean collapse of the discrete diffraction pattern is strongly reminiscent of that reported previously for an array – slab waveguide boundary [9]. The observed threshold power shown in Fig. 11(a) agrees very well with theory, when corrected for the pulsed input. Note that there is no intensity peak in the \( n=-1 \) channel indicating minimal excitation of a guided mode in that channel. From the previous arguments based on the juxtaposition of the two linear bands, this soliton is associated with the interface between the right array and an effective slab waveguide on the left. Furthermore, as indicated in Fig. 9, the threshold power measured here is lower than that for the interface with just a 1D slab waveguide, indicating that the presence of the left array raises the effective index of that region towards that of the right array, thus reducing the threshold power. That is, the smaller the effective indices difference between the two array regions, the lower the soliton threshold power. The fact that this threshold rises with increasing \( n \) indicates that the single channel soliton potential near the interface is attractive, in contrast to the repulsive potential seen for the left array, and previously for the boundary between an array and a continuous medium [25]. To the best of our knowledge such behavior is observed for the first time. All of these observations were confirmed by the cw simulations.
Fig. 11. (a)-(d) The measured evolution with increasing input power of the intensity patterns obtained at the output of the arrays for \( d = 3.4 \mu m \) and the excitation of the \( n = 1, 2, 3 \) and 4 channels, respectively.

As we already mentioned above for the 1D waveguide array - slab waveguide interface, there is a family of spatial solitons with decreasing power thresholds for channels progressively deeper into the array. For the composite structure, this was the case for the left array. From Fig. 9, it is clear that the behavior for the first few channels of the right array is different. As discussed earlier, this is a consequence of the fact that the \( n = 1 \) soliton evolves from a quasi-linear mode peaked on channel \( n = 1 \) when a threshold separation between the arrays is exceeded. Figure 9 shows a single channel soliton threshold that rises as \( n \) increases from 1 to 3, and then falls with further increase in \( n \). The evolution of the output intensity patterns with increasing input power into single channel solitons for these cases with \( d = 3.4 \mu m \) is reproduced in Fig. 11. At high input powers, it is expected that the output will always eventually localize into a single channel soliton centered on the excitation channel because the intensity induced change in refractive index traps the light in the incidence channel right at the input facet. As the input power is increased, the behavior of light in the right array for \( n = 2-3 \), as reflected by the intensity distributions at the output, is quite different from that deeper in the array. In these cases light first collapses into the boundary channel \( n = 1 \) for power levels typical of the \( n = 1 \) soliton and, with further increase in power, eventually ends up in the excitation channel.

Numerically it was verified that this \( n = 1 \) soliton is stable as a breather over a limited range of input powers, see Fig. 12. For \( n = 2 \) excitation, stable trapping occurs first in the \( n = 1 \) channel, and then at higher power in the \( n = 2 \) channel as shown in Fig. 11(b). For excitation of the \( n = 3 \) channel, plateaus also exist in \( n = 1 \) and \( n = 2 \) channels for powers above the threshold of the corresponding single channel solitons, i.e. first in the \( n = 1 \) channel and then at slightly higher power in the \( n = 2 \) channel (Fig. 11(c)). Simulations indicate that both correspond to breather solitons, see Fig. 12. The collapse into a \( n = 4 \) single channel soliton with increasing input power is quite abrupt, similar to the \( n = 1 \) case, see Fig. 11(d). For \( n \geq 5 \), the behavior is typical of that observed for \( n = 4 \).
Experiments were also performed for an intra-array spacing of $d = 5.2\mu m$. Quantitatively (Figs. 9 and 13) the results track very closely those for the array - slab waveguide boundary, with the exception of only $n=1$ soliton which has a lower threshold power than that for a boundary with a semi-infinite slab waveguide. This anomalously low threshold power is increased relative to the $d = 3.4\mu m$ case because the evanescent fields decaying from the right array now samples less of the left array due to the larger separation of the arrays. This $n=1$ soliton exhibits a weaker attractive potential, i.e. its power threshold lies above the one for $d = 3.4\mu m$, but still depressed relative to array - slab waveguide case.

5. Discussion and summary

Discrete spatial solitons excited at and near the interface between two dissimilar one-dimensional arrays of waveguides exhibit a rich variety of behavior. The channel center-to-center separation was identical for the two arrays and the effective indices of the individual weakly coupled channels were different. It was found theoretically that two cw families of stable solitons exist, each family peaked at or near the boundary of a different array. One family, with peaks in the boundary channels of the lower effective index array, corresponded to interface solitons with guiding in boundary channels of both arrays. Its threshold powers were high, decreasing with increasing inter-array separation. The second stable family had peaks at and near the boundary of the higher effective index array with fields decaying into the low index array without guiding in any of those channels. Quasi-linear surface modes occurred in this family for small separations between the arrays and evolved into surface solitons with power thresholds at larger separations.

Single channels on both sides of the boundary were excited and the intensity patterns at the output facet were measured as a function of input power. Because of the high power thresholds for family one, an interface soliton was only observed for $d = 5.2\mu m$. In addition a family of leaky surface solitons was found which decayed with propagation distance into both
arrays. These leaky solitons were the remnants of the surface solitons bound to the lower index array boundary when the bounding medium is a slab waveguide, i.e. no array. Their threshold power decreased as the soliton peak moved further into the array. This behavior, observed previously for the boundary between a 1D array and a 1D slab waveguide, is indicative of a repulsive soliton potential due to the boundary.

The existence of linear modes peaked at the boundary in the high effective array led to anomalously low power thresholds for the solitons near and at the boundary of that array. This resulted in the lowest threshold power for the boundary channel soliton ($n=1$). With increasing $n$, the soliton threshold power increased, reached a peak in a channel which depended on the array separation and then decreased asymptotically to the value associated with an infinite array. This is indicative of an attractive soliton potential for this boundary region. The actual evolution of the intensity distributions at the output facet of the sample with increasing input power showed that this attractive potential had a large impact on the collapse into single channel solitons. Since the boundary channel soliton had the lowest threshold power, the collapse of discrete diffraction pattern with power for $n=1$ channel excitation was monotonic. However, for $n=2$ channel excitation, first a stable breather soliton was formed in the $n=1$ channel and only at higher powers did it switch abruptly into a stable $n=2$ soliton. For $n=3$, three stages of solitons appeared with increasing input power, first a $n=1$ soliton, then a $n=2$ soliton and then finally a $n=3$ soliton, with the first two appearing only over a narrow range of input powers. For $n=4$, the discrete diffraction pattern collapse was monotonic into the $n=4$ soliton over a relatively narrow range of power. These behaviors were confirmed numerically for cw solitons.

In summary, the boundary between two dissimilar arrays with self-focusing nonlinearities exhibited a rich variety of interesting soliton features which were predicted theoretically and observed experimentally. We expect that analogous interesting behavior would occur for discrete surface (gap) solitons for self-defocusing media.

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