Light localization at surfaces of modulated photonic lattices

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Abstract - *We predict that truncated but otherwise perfect modulated photonic lattices can support a novel type of generic surface states, which are fundamentally different from the previously studied Tamm or Shockley type surface waves, and present the first experimental observation of such defect-free surface waves in laser-written waveguide arrays.*

Interfaces separating different physical media can support a special class of transversally localized waves known as surface waves. Linear surface waves have been studied extensively in many branches of physics [1]. Electro-magnetic waves localized at the boundaries of periodic photonic structures, such as optical waveguide arrays or photonic crystals, have been extensively analyzed theoretically and experimentally [2]. The appearance of localized surface waves in photonic structures is commonly explained as the manifestation of either Tamm or Shockley type localization mechanisms [3]. In particular, it was found that surface waves can exists at the edge of an array of optical waveguides when the effective refractive index of the boundary waveguide is modified [4], whereas surface localization was shown to be impossible when all waveguides are exactly identical, as sketched in Fig. 1(a). In the latter case, the beam launched into array delocalizes due to diffraction [Fig. 1(b)], and it is also strongly reflected from the boundary as illustrated in Fig. 1(c).

We predict, for the first time to our knowledge and contrary to the accepted notion, that *novel type of generic defect-free surface waves* can exist at the boundary of a periodic array of identical optical waveguides, which axes are periodically curved along the propagation direction as schematically shown in Fig. 1(d). We note that the periodic bending of waveguide axes was shown to result in the modification of diffraction [5, 6], which strength nontrivially depends on the bending amplitude and optical wavelength. An interesting feature is that the diffraction can be completely suppressed for particular values of the bending amplitude, and this effect is known as dynamic localization or beam self-collimation. Under such very special conditions, the beam remains localized at its input location, either inside the array [Fig. 1(e)] or at its boundary [Fig. 1(f)]. However, our most nontrivial finding is that *surface localization is possible for an extended range of structural parameters even when diffraction is non-vanishing*.

We perform direct numerical calculations of the full mode spectrum, and present the dependence of the mode wavenumbers on the bending amplitude in Fig. 2(a). One can see

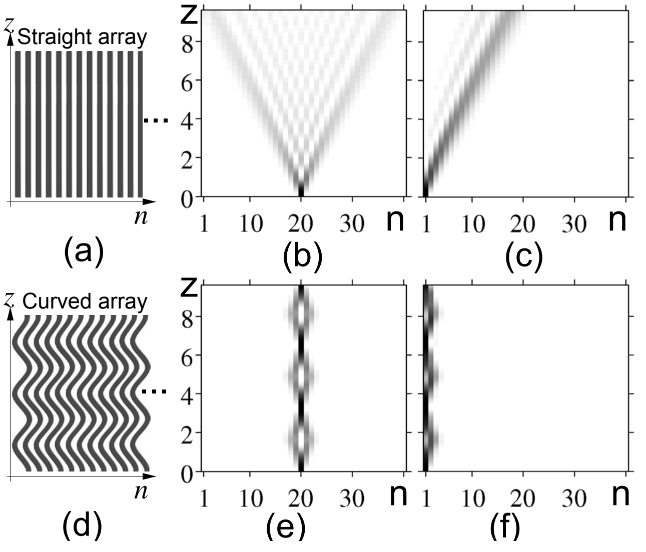

Figure 1: Beam propagation in (a-c) straight and (d-f) periodically curved waveguide arrays. (a),(d) Sketches of waveguide arrays. (b) Beam diffraction in the middle of straight waveguide array. (c) Beam reflection from the boundary and subsequent diffraction in a straight waveguide array. (e),(f) Dynamic localization inside and at the boundary of curved waveguide array, for a specific value of the bending amplitude corresponding to the regime of diffraction cancelation.

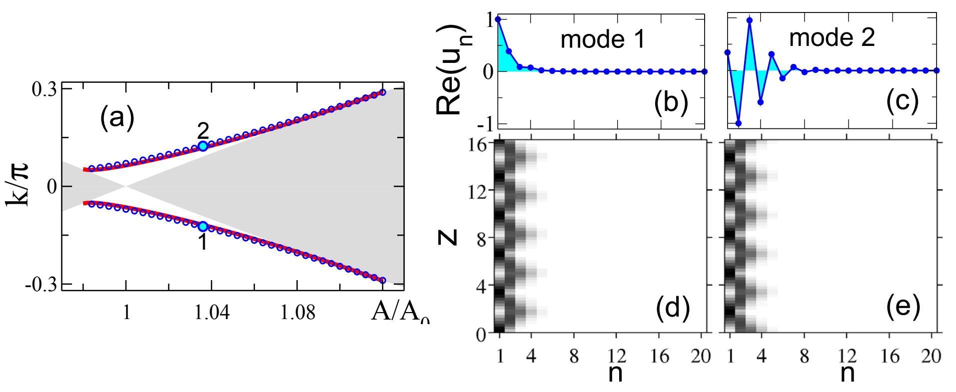

Figure 2: (a) Dispersion of defect-free surface modes vs. the bending amplitude. Circles and solid lines show modes Bloch wave numbers k calculated numerically and using asymptotic analytical expansion, respectively. Shading marks transmission band of the lattice. (b-c) Numerically calculated modes profiles at $z = 0$ and (d-e) their dynamical reshaping are shown for the points marked 1 and 2 in (a), respectively.

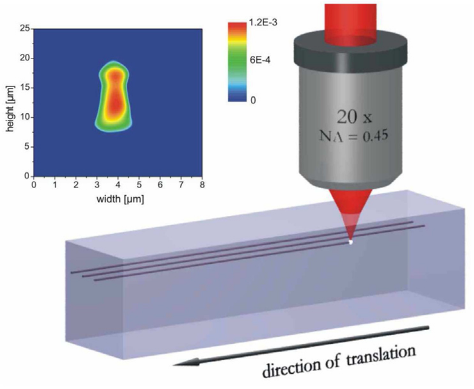

Figure 3: Schematic of the direct femtosecond laser-writing method of waveguides in a glass sample.

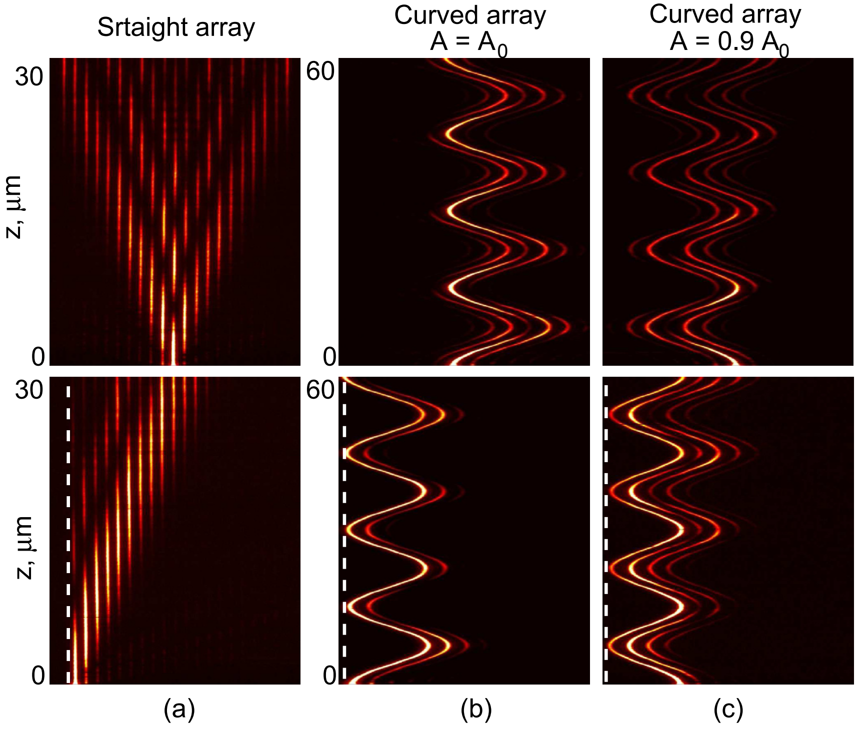

Figure 4: Observed experimentally fluorescent images of light propagation in femtosecond laser-written waveguide arrays. Top row: input beam position is away from the surface. Bottom row: beam is coupled at the edge waveguide [the surface position is marked with dashed lines]. (a) Diffraction in a straight waveguide array (top), combined with strong reflection from the boundary (bottom). (b) Diffraction cancelation in curved waveguide array, enabling beam self-collimation at arbitrary positions. (c) Reduced, but non-vanishing, diffraction in curved array (top), and mode localization at the surface in the same structure (bottom). Waveguides bending amplitude is $A_0 = 28.5\ \mu$m.

that for modulation amplitudes around the self-collimation value there indeed appears a pair of surface modes, which existence is defined by the condition that the wavenumbers are outside the lattice transmission band indicated with grey shading. One mode has unstaggered input profile [Fig. 2(b)], while the other one exhibits staggered structure [Fig. 2(c)]. We have observed numerically stable propagation of these surface modes over distances of several thousands of bending periods, examples of their propagation dynamics are shown in Figs. 2(d) and (e).

To study these effects experimentally, we fabricated waveguide arrays in fused silica using the femtosecond laser writing technique, which was performed using a Mira/RegA (Coherent) system [7], see a schematic of the writing setup in Fig. 3. Our arrays consisted of 21 waveguides, with separation of 14 μm, the sample length of 70 mm, and the wavelength was $\lambda = 633$ nm. Most importantly, we were able to *monitor directly the beam evolution inside the glass sample*, by observing the fluorescence form excited oxygen centers. In straight waveguide array, we observe beam diffraction and repulsion from the surface [Fig. 4(a)], in agreement with theoretical prediction [Fig. 1(b,c)]. In curved waveguide arrays, when the modulation amplitude corresponds to the self-collimation condition, the beam remains localized at arbitrary locations [Fig. 4(a), c.f. Fig. 1(e,f)]. Most remarkably, when the modulation amplitude is tuned away from the self-collimation condition, the surface mode remains localized [Fig. 4(c), bottom], despite the significant beam diffraction away from the boundary [Fig. 4(c), top]. This illustrates the fundamental difference between the dynamical localization in infinite waveguide arrays [6] and formation of the defect-free surface modes. While dynamical localization is a purely resonant effect which takes place just for a specific value of the modulation amplitude $A = A_0$ [see Fig. 4(b)], the defect-free modes form families which always exist in a finite region of the modulation amplitudes.

Since the normalized modulation amplitude is proportional to the optical wavelength, our results suggest *new possibilities for the manipulation of polychromatic surface waves* in photonic lattices [8]. We note that the defect-free surface states introduced here for modulated photonic lattices may also appear in other physical systems. In particular, by introducing special periodic shift of lattice potential it may be possible to observe peculiar surface localization in Bose-Einstein condensates. On the other hand, our results indicate the possibility for novel mechanism of surface localization of charged particles in complex time-varying driving electric fields.

References

[1] S. G. Davidson and M. Steslicka, *Basic theory of surface states* (Oxford Science Publications, New York, 1996).

[2] P. Yeh, A. Yariv, and A. Y. Cho, Appl. Phys. Lett. **32**, 104 (1978).

[3] N. Malkova and C. Z. Ning, Phys. Rev. B **76**, 045305 (2007).

[4] S. Suntsov *et al.*, Phys. Rev. Lett. **96**, 063901 (2006).

[5] H. S. Eisenberg *et al.*, Phys. Rev. Lett. **85**, 1863 (2000).

[6] S. Longhi *et al.*, Phys. Rev. Lett. **96**, 243901 (2006).

[7] A. Szameit *et al.*, Opt. Express **15**, 1579 (2007).

[8] A. A. Sukhorukov, D. N. Neshev, and Yu. S. Kivshar, Opt. Express **15**, 13058 (2007).