Single interfaces and coupled-waveguide arrays: off-axis nonparaxial analyses

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Summary

We report on our most recent results concerning arbitrary-angle spatial soliton refraction at the interface between dissimilar dielectrics, each of which comprises both $\chi^{(3)}$ and $\chi^{(5)}$ susceptibilities. Attention is also paid to the oblique injection of spatial solitons into optical structures with a periodically-patterned refractive index.

From Schrödinger to Helmholtz

In their most general form, wave-interface problems are inherently angular in nature. For instance, the interaction between light waves and material boundaries essentially defines the entire field of optics. The ground-breaking works of Aceves *et al.* [1] considered scalar bright spatial solitons impinging on the planar boundary between two dissimilar Kerr-type materials. While these classic nonlinear-Schrödinger models paved the way toward understanding how self-collimated light beams behave at material discontinuities, adoption of the paraxial approximation means that, in the laboratory frame, angles of incidence, reflection and refraction (relative to the interface) must be near-negligibly small. This intrinsic angular restriction may be circumvented by deploying a mathematical and computational framework that is based on the solution of nonlinear Helmholtz equations [2].

Here, we present our latest research detailing bright soliton refraction in materials whose nonlinear polarization has contributions from both $\chi^{(3)}$ and $\chi^{(5)}$ susceptibilities [3]. Our model is based on an inhomogeneous Helmholtz equation with a cubic-quintic nonlinearity, and analysis is facilitated by knowledge of the exact solutions of the corresponding homogeneous problem [4]. We also report on our latest findings regarding oblique propagation of spatial solitons in coupled-waveguide arrays.

Off-axis nonparaxiality: *single interfaces*

The Goos-Hänchen (GH) shift [1,5] is an effect whereby a beam reflecting from an interface experiences a displacement in its outgoing trajectory relative to the path predicted by geometrical optics (see Fig. 1). Such shifts are most pronounced close to the critical angle, and they can be greatly enhanced (often then termed *giant*) in

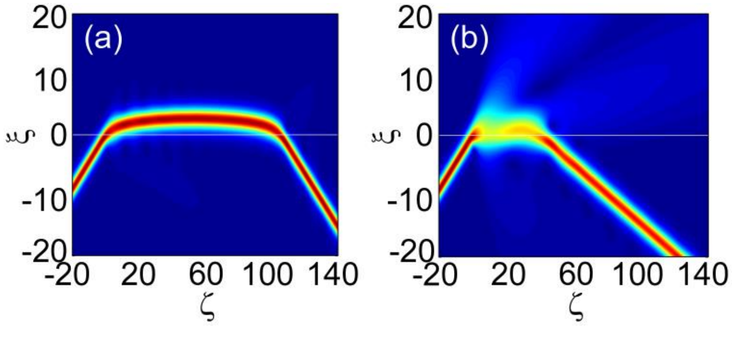

Fig. 1. (a) Simulations of typical GH shifts in the propagation plane (with normalized spatial coordinates ξ and ζ). These shifts are characterized by external refraction, and involve (a) linear and (b) nonlinear interfaces. The soliton interaction with the linear interface is relatively 'clean', while much more radiation is generated in the nonlinear scenario.

systems where the host media are nonlinear. Recently, we quantified the GH-shift characteristics of Helmholtz bright solitons at interfaces involving the Kerr nonlinearity [6], and particular attention was paid to regimes involving external linear refraction. Here, we will give an overview of similar considerations in material regimes where the $\chi^{(5)}$ susceptibility can no longer be neglected. Detailed numerical calculations, guided by our new Snell's law for $\chi^{(3)}$–$\chi^{(5)}$ systems, have uncovered novel qualitative behaviours at highly nonlinear interfaces and we have predicted shifts that are orders-of-magnitude greater than those found in our earlier studies.

Off-axis nonparaxiality: *waveguide arrays*

Recent research efforts have been concentrating on the way in which spatial solitons propagating in a continuum (i.e., a uniform nonlinear medium) can couple into a periodic structure with a periodically-patterned refractive-index profile. Archetypal examples of such structures include coupled-waveguide arrays and photonic crystals. These two geometries are linked through rotational symmetry; the mode of operation depends on the relative orientation of the incident light beam with respect to the patterning. In general, oblique incidence involves elements of both configurations (see Fig. 2).

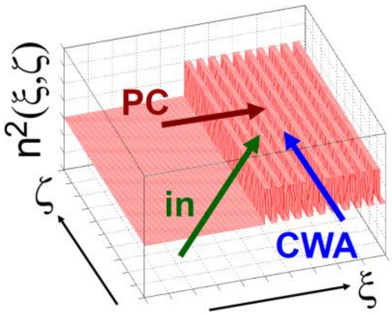

Fig. 2. Schematic diagram showing the implicit connection between photonic crystal (PC) and coupled-waveguide array (CWA) geometries. An incident soliton beam (denoted by 'in') generally experiences facets of both periodic configurations.

The power of the Helmholtz nonparaxial approach is such that we can now describe, for the first time, arbitrary incidence angles in the laboratory frame. To date, essentially all analyses consider regimes where launching angles (in either head-on or side-coupling geometries) are near-negligibly small. Here, we focus primarily on the side-coupling of beams into the array. Simulations predict a wide range of new effects in regimes involving arbitrary-angle coupling (e.g., the lattice periodicity experienced by the beam depends upon the local propagation angle).

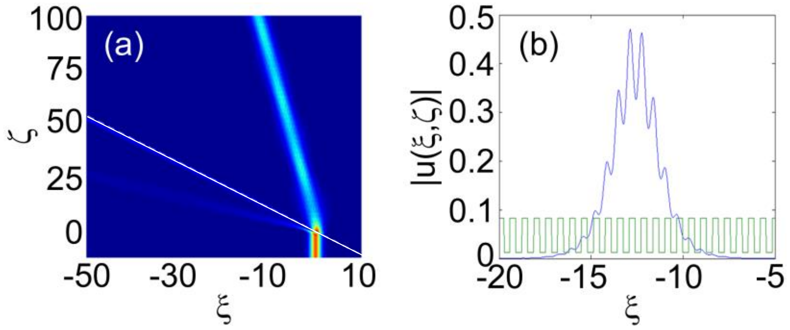

Fig. 3. Simulation showing side-coupling of an oblique spatial soliton beam (incidence angle of 10° in the laboratory frame) into a coupled waveguide array (c.f. Fig. 2). (a) Numerical solution for the envelope $|u(\xi,\zeta)|$. (b) The field inside the array is periodic and its amplitude is modulated by a sech-type envelope.

References

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