Photorefractive Spatial Solitons

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Abstract. Non-diffracting wave packages or solitons have been the subject of intense study over the last three decades. In particular optical spatial solitons, for which diffraction is exactly balanced by self-focusing in a nonlinear medium, have strongly stimulated the research in the field of solitons in the 90’s, especially in photorefractive crystals. Such optical spatial solitons exhibit particle-like behavior in their interactions and stability properties, conserving energy and momentum, and the fascinating results obtained in this field have major consequences in many non-optical systems that can support solitons. This article explains the basic mechanisms that lead to soliton formation, in particular in photorefractive crystals, and gives a short overview of new directions like composite solitons, incoherent solitons formed with spatially incoherent light, and incoherent modulation instability.

1 Introduction

When the scottish scientist John S. Russel reported about what he called a ‘rounded smooth and well defined heap of water’ or ‘the great primary wave of translation’ in 1834, wave propagation was believed to be a solely linear phenomenon showing broadening or dispersion during propagation. Therefore, it may be understandable that at that time the scientific community had serious problems in believing in what Russel noted eleven years later to be a solitary elevation [1], and it took more than fifty years until the two theoreticians Korteweg and de Vries explained this observation in 1895 [2]. The two dutchmen found out that such a solitary wave must have an unusually large amplitude when compared to the depth of the water, and that in this case the water waves behave and propagate in a completely unusual manner, i.e., they behave as nonlinear waves, or more exact, as waves that propagate in a nonlinear medium. For more then half a century these results gained only little attention, although nonlinear waves where observed in many different wave supporting systems like electron gas in plasmas or phonons in solids. However, it was in 1965 when Zabusky and Kruskal realized that if two of such solitary waves intersect or collide with each other, they may completely maintain their amplitude and shape [3]. Because this behavior is closely related to the collision of particles, they named these nonlinear waves ‘solitons’. Following this discovery, a large amount of theoretical and experimental work was done in this new field of nonlinear wave propagation or soliton physics [4,5,6].
A large amount of today’s knowledge on solitons and their behavior upon collision has been obtained by using optical systems, either optical beams (in the spatial domain) [7,8,9,10] or optical pulses (in the temporal domain) [11,12,13,14] that propagate in a nonlinear optical medium. Such materials possess significant optical nonlinearities, which means that the materials’ properties are modified by the light itself. The formation of spatial solitons can be understood as a result of an exact balance between the tendency to broaden because of diffraction and the nonlinear self-focusing. Similarly, temporal solitons form when the natural chromatic dispersion is exactly compensated by the nonlinear self-phase modulation. An intuitive picture for understanding soliton formation is a focused optical beam that gets self-trapped in its own written waveguide. When a narrow light beam travels through a linear medium without affecting the materials’ properties, it undergoes natural diffraction and broadens during propagation. The narrower the beam is at the beginning, the larger is its spatial divergence. One of the simplest realization of a nonlinear optical medium is a Kerr-type material where the refractive depends on the light intensity. If the light-induced refractive index change is positive, i.e., the refractive index is increased in the region of higher intensity, a narrow beam is self-focused by the induced nonlinear lens. It is obvious that there must exist a certain strength of the lens where the spatial diffraction of a narrow optical beam is exactly balanced by the self-lensing effect: a bright optical soliton has formed that propagates without diffraction. Dark solitons, by the same definition, are dark stripes or notches on an otherwise homogeneous intensity background, which do not change their profile during propagation, too [10]. In this case, a self-defocusing nonlinearity acting upon the illuminated parts balances the diffraction of the dark notch. A schematic view of this picture of diffraction of bright and dark beams that is balanced by nonlinear focusing and defocusing, respectively, is given in Fig. 1.

This article is devoted to optical spatial solitons in photorefractive crystals [15,16]. In this class of materials large nonlinear index changes can be obtained at a very small light power level that is in or even below the microwatt regime. Depending on the experimentally controllable parameters, both nearly Kerr-type and saturable nonlinearities can be obtained. In the next section, some basic properties of these two types of nonlinearities will be discussed as well as some fundamentals of photorefractive materials. Section three is devoted to the interaction of solitons, where two possible scenarios, namely coherent and incoherent interactions, are discussed separately. The last section deals with soliton formation and its precursor, modulation instability, using partially spatially incoherent light.