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Bright and dark spatial solitons in metallic nanowire arrays

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Abstract

We investigate the formation and propagation of bright and dark three-dimensional unstaggered spatial solitons with cylindrical symmetry in a nonlinear nanowire metamaterial. The metamaterial is formed by metallic nanowires embedded in a Kerr-type dielectric host and is modeled using an effective medium approach. Unlike conventional Kerr media, the metamaterial supports bright solitons when the host is a self-defocusing material and dark solitons when the host is a self-focusing material. Our numerical calculations show that the confinement of the spatial-solitons results from the interplay of the host nonlinear response strength and the hyperbolic dispersion of the photonic states in the nanowire array. Subwavelength solitary beams may be observed for sufficiently strong nonlinearities.

Keywords: Metamaterials; Spatial solitons; Bright solitons; Dark solitons; Effective medium theory; Nanowire array

1. Introduction

In the recent years there has been a growing interest in reducing the characteristic size of photonic devices, as the race for small operating devices, compared to the operation wavelength, is always in demand. In this context, metallic nanowire arrays provide many opportunities for the manipulation of electromagnetic radiation on a subwavelength scale [1–4]. It was predicted that subwavelength stable spatial solitons can be formed in a metallic nanowire array embedded in a nonlinear Kerr-type dielectric [5–7]. Other families of plasmonic lattice solitons were investigated in Refs. [8,9]. The theoretical framework of these studies is based on coupled mode theory, which provides a somewhat limited physical understanding of the formation mechanism of the solitons in the metamaterial. More recently, Ref. [10] put forward an effective medium model for the nonlinear nanowire metamaterial. This approach regards the structure as a continuous medium characterized by a few effective parameters [10]. Based on such a theory, it was demonstrated in Ref. [7] that two-dimensional (2-D) unstaggered (i.e. modes that vary slowly in the scale of the period of the metamaterial) bright spatial solitons can only be formed if the host medium is a self-defocusing material. Here, we will show that this analysis can be further extended to characterize the propagation of three-dimensional (3-D) spatial solitons with cylindrical symmetry and dark solitons. Dark temporal and dark spatial solitons consist of dip-like shapes in the amplitude of a constant wave background [11–15]. The phase of spatial dark solitons has odd symmetry, and depending on

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the dip amplitude in the constant wave background, they can be classified as either "black" dark spatial solitons, when the dip drops to zero and the phase is flat, or "gray" if the dip does not go to zero and the phase is not flat [12,13]. Bright and dark temporal solitons in metamaterial structures were reported in [16–18].

The organization of the article is as follows. In Section 2, we review the effective medium model of the nonlinear wire metamaterial and the conditions for the formation of solitary waves. In Section 3 we present numerical calculations for two distinct families of bright spatial solitons with cylindrical symmetry, highlighting the impact that structural parameters and losses have on wave propagation. A similar study is reported in Section 4, but for dark spatial solitons. In Section 5 the conclusions are drawn. This work assumes a time variation of the type $e^{-i\omega t}$, with ω the oscillation frequency.

2. Effective medium model and trapped states

The uniaxial wire medium is formed by a set of infinitely long parallel metallic wires, typically arranged in a square lattice with period a. The wires have radius r_w and complex permittivity ε_m. Here, we consider that the host medium is a nonlinear Kerr-type dielectric material such that the electric permittivity, for a fixed frequency, can be expressed as $\varepsilon = \varepsilon_h^0(1+\delta\varepsilon)$, where $\delta\varepsilon = \alpha \mathbf{e}^* \cdot \mathbf{e}$ is a nonlinear function of the microscopic electric field and $\alpha = 3\chi^{(3)}/\varepsilon_{h,r}^0$ is proportional to the third order electric susceptibility $\chi^{(3)}$ of the host medium. The metamaterial geometry is sketched in Fig. 1.

In the homogenization model developed in Ref. [10], the dynamics of the electromagnetic field is described by an eight component state vector $(\mathbf{E}, \mathbf{H}, \varphi_w, I)$ that satisfies a nonlinear first-order partial-differential system of equations. Here, $\mathbf{E}$ and $\mathbf{H}$ represent the macroscopic electromagnetic field (after spatial averaging of the microscopic fields $\mathbf{e}$ and $\mathbf{h}$), I is the current that flows along the nanowires (interpolated in a such a manner that it is defined over all the space) [19] and φ_w is a quasistatic potential defined as the average potential drop measured from the center of the wire to the boundary of the unit cell [19].

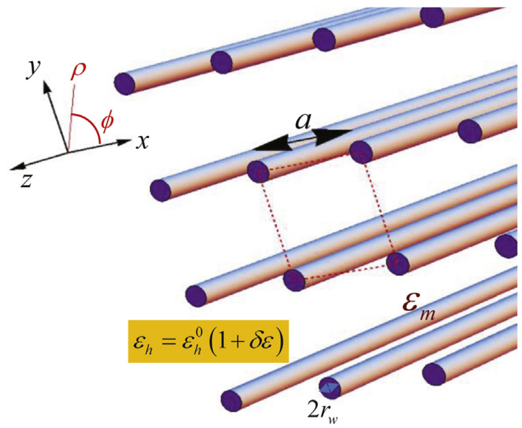

Fig. 1. Geometry of the periodic array of metallic nanowires embedded in a nonlinear Kerr-type host material.

From Ref. [7,10] it is known that in the absence of external optical sources and for paraxial (quasi-transverse) optical beams propagating along the z-direction, $(\mathbf{E}, \varphi_w)$ satisfy the following second-order nonlinear partial-differential system:

$$\nabla \times \nabla \times \mathbf{E} - k_h^2 n_{ef,h}^2 \mathbf{E} = \frac{\beta_p^2}{\zeta_w}\left(\frac{\partial \varphi_w}{\partial z} - E_z\right)\hat{z}, \tag{1}$$

$$\frac{\partial^2 \varphi_w}{\partial z^2} + k_h^2 \zeta_w n_{ef,h}^2 \varphi_w = \frac{\partial E_z}{\partial z}, \tag{2}$$

where $k_h^2 = \omega^2 \varepsilon_h^0 \mu_0$, $\zeta_w = 1 - (Z_w / i\omega L)$, $Z_w = -(1/i\omega\pi r_w^2(\varepsilon_m - \varepsilon_h^0))$ is the per unit length (p.u.l.) self-impedance of the nanowires [19], $L = (\mu_0/2\pi)\log(a^2/4r_w(a-r_w))$ is the p.u.l. inductance of the wires [19] and $\beta_p = a^{-1}\sqrt{\mu_0/L}$ is the geometrical component of the plasma wave-number of the effective medium [19]. The parameter $n_{ef,h}^2$ is the effective (squared) normalized refractive index of the host medium defined by:

$$n_{ef,h}^2 \approx 1 + \alpha \mathbf{E}_t^* \cdot \mathbf{E}_t \tag{3}$$

where $\mathbf{E}_t = E_x\hat{\mathbf{x}} + E_y\hat{\mathbf{y}}$ is the transverse component of the electric field. Even though we are interested in paraxial beams, it is not possible to neglect E_z because in wire media the permittivity along the z direction can be extremely large, and thus the normalized z-component of the electric displacement D_z/ε_0 typically has a magnitude comparable to $\mathbf{E}_t$. It is useful to note that for waves such that the variation along z is of the form $e^{ik_z}z$, Eq. (1) can be written as

$$\nabla \times \nabla \times \mathbf{E} - \omega^2 \mu_0 \bar{\bar{\varepsilon}}_{eff}(\omega, k_z) \cdot \mathbf{E} = 0 \tag{4}$$

where we introduced a nonlocal dielectric function $\bar{\bar{\varepsilon}}_{eff}(\omega, k_z)$ that satisfies:

$$\frac{1}{\varepsilon_h^0}\bar{\bar{\varepsilon}}_{eff}(\omega, k_z) = n_{ef,h}^2 \bar{\bar{I}} - \frac{1}{\zeta_w}\frac{\beta_p^2}{(k_h^2 - k_z^2/n_w^2)}\hat{\mathbf{z}}\hat{\mathbf{z}}. \tag{5}$$

The parameter $n_w^2 \approx \zeta_w n_{ef,h}^2$ is the slow-wave factor [10,19], such that an increase in n_w^2 reduces the effects of spatial dispersion. Note that $\bar{\bar{\varepsilon}}_{eff}(\omega, k_z)$ is a nonlinear