Excitation of Bright and Dark Gap Solitons in a Negative Index Material

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Abstract

We predict the existence of bright and dark gap solitons in a slab of negative index material as a result of the interplay between the linear dispersive properties and the effect of a cubic nonlinearity.

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The presence of a cubic (Kerr) nonlinearity in structures characterized by a periodic variation of the linear refractive index leads to the formation of localized electromagnetic modes in spectral regions that otherwise would just allow evanescent modes. These localized modes are generally referred to as gap solitons (GS) [1].
The aim of this work is to show that the presence of bright and dark GS is supported in a single slab of negative index material (NIM). NIMs most impressive property is their ability to refract light in the opposite way with respect to what an ordinary material does [2]. Let us begin by describing the effective electric susceptibility and magnetic permeability of a NIM with a lossy Drude model:

$$\varepsilon(\tilde{\omega}) = 1 - \frac{1}{\tilde{\omega}(\tilde{\omega} + i\tilde{\gamma}_e)} \quad , \quad \mu(\tilde{\omega}) = 1 - \frac{(\omega_{pm}/\omega_{pe})^2}{\tilde{\omega}(\tilde{\omega} + i\tilde{\gamma}_m)} \quad , \tag{1}$$

where $\tilde{\omega} = \omega/\omega_{pe}$ is the normalized frequency, ω_{pe} and ω_{pm} are the respective electric and magnetic plasma frequencies, $\tilde{\gamma}_e = \gamma_e/\omega_{pe}$ and $\tilde{\gamma}_m = \gamma_m/\omega_{pe}$ are the respective electric and magnetic loss terms normalized with respect to the electric plasma frequency. Let us now suppose the FP possesses a Kerr nonlinearity. The Helmholtz equation that governs the nonlinear dynamic at normal incidence is given by:

$$\frac{d^2E}{dz^2} + \frac{\omega^2}{c^2}\varepsilon\mu E = -\frac{\omega^2}{c^2}\mu\chi^{(3)}|E|^2 E \quad , \tag{2}$$

where ε and μ are the effective electric susceptibility and magnetic permeability given by Eq.(1), $\chi^{(3)}$ is the coefficient of the cubic nonlinearity. The boundary conditions that apply to Eq.(2) are those valid in the case of normal incidence in a magnetic material. Eq.(2) has been numerical integrated using an explicit method in conjunction with a shooting procedure. In Fig1 we show the linear transmission property of a Fabry-Perot (FP) etalon made by a NIM. The details of the structure are described in the caption of the figure. In this case a dark gap soliton is excited by tuning the incident field in the band gap near the low frequency band edge (see Fig.2(a)), while a bright gap soliton is excited by tuning the incident field in the band gap near the high frequency band edge (see Fig.2(b)). The excitation of dark solitons is somewhat surprising because their appearance in the gap has to our knowledge never been predicted. In conclusion, using a numerical approach, we have predicted the existence of a new class of bright and dark gap solitons that are supported by NIMs. Our results suggest that NIMs could find further applications in all-optical switching devices, all-optical buffering, for example.

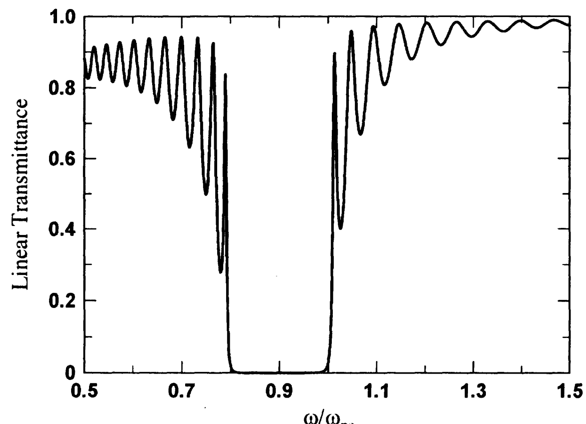

Fig.1: Linear transmittance vs. normalized frequency (ω/ω_{pe}) for a Fabry-Perot etalon of length $L=5\lambda_{pe}$ where $\lambda_{pe}=2\pi c/\omega_{pe}$. The NIM is characterized by the following parameters: $\omega_{pm}/\omega_{pe}=0.8$ and $\tilde{\gamma}_e \approx \tilde{\gamma}_m \approx 4.5*10^{-4}$.

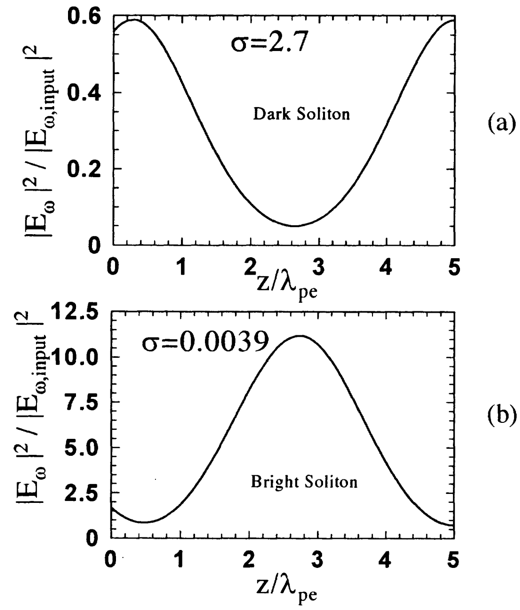

Fig.2: Field localization in the cavity for different values of the control parameter $\sigma=\chi^{(3)}|E_{input}|^2$ and different tuning conditions. The tuning conditions are respectively: (a) $\omega_0=0.81\omega_{pe}$. and (b) $\omega_0=\omega_{pe}$.

References

[1] Chen and D.L. Mills, *Phys. Rev. Lett.* **58,** 160 (1987).
[2] J. Pendry, *Opt. and Photon. News,* **15** , No9, 33 (2004), and references therein