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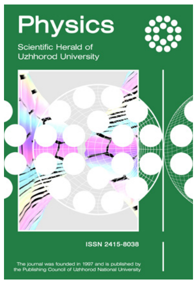

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Nonlinear Surface Polaritons near the Interface between a Magneto-Optical Substance and a Nonlinear Metamaterial with a Permittivity Close to Zero

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Abstract

Relevance. Considerable attention of researchers is drawn to nonlinear surface optical waves, as they are promising for application in optical information processing systems, ultra-sensitive sensors, and modern telecommunications components.

Purpose. To obtain an exact solution of the Maxwell equation system for TM-polarised nonlinear surface polaritons propagating along the interface between an optically linear magnetic medium and an optically nonlinear medium with saturated nonlinearity.

Methods. Analysis of the properties of nonlinear surface polaritons (NSP) and mathematical modelling of the dependence of the permittivity of a nonlinear medium on the intensity are used.

Results. TM-polarised nanoparticles propagating along the interface of a magneto-optical medium and a nonlinear optical metamaterial with a permittivity close to zero (ENZ-metamaterial) are studied. For NSP in such a structure, an exact solution of the Maxwell equation system is obtained, considering the saturation effect of optical nonlinearity. On this basis, the dependences of constant propagation on the total energy flux of NSP and energy fluxes in contact media in the structure were investigated: magneto-optical ENZ-metamaterial with negative permittivity/nonlinear self-focusing ENZ-metamaterial.

Conclusions. The NSP energy flow is positive in a nonlinear medium and negative in a linear one. As the saturation level decreases, the NSP energy fluxes in the contacting media increase modulo, if the value of the NSP propagation constant (NSPPC) is fixed. The lowest NSPPC value for guiding nonlinearity is obtained when the total energy flow of the NSP becomes zero. As the saturation level decreases, the NSP propagation variable (NSPPV) increases. At a fixed NSPPC, with a decrease in the magnetic permeability, the energy fluxes of NSP in the contacting media increase. When the magnetic permeability decreases to zero and the NSP energy flux is positive, the NSPPV change range narrows

Keywords: guiding nonlinearity, propagation constant, permittivity of a nonlinear medium, magneto-optical metamaterial, magnet, saturation

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Introduction

Nonlinear surface optical waves attract considerable attention of researchers due to the possibility of their application in modern telecommunications components, optical information processing systems and ultra-sensitive sensors.

The properties of such waves are determined by the dielectric and magnetic properties of the contacting media at the corresponding frequency. Studies of TM-polarised nonlinear surface polaritons (NSP) propagating along a single interface, as well as nonlinear waves in multilayer structures, which were conducted earlier [1-3], were limited by the values of parameters of natural materials at optical frequencies, e.g., the magnetic permeability of the medium was considered equal to one.

Metamaterials are artificially created composite media, and the proper formation of their nanostructure allows obtaining any desired values of material parameters [4-6]. This creates wide possibilities for controlling the properties of electromagnetic waves [7]. For example, surface polaritons can propagate along the surface of an ENZ-metamaterial with an extremely high phase velocity [8]; in metal-ferromagnetic structures, the wave vector of a surface polariton can be controlled using a weak external magnetic field [9]; metamaterials with both near-zero permittivity and magnetic permeability (epsilon-and-mu-near-zero (EMNZ)), which are also called zero-index materials (ZIM), allow adjusting the phase delay surface polaritons [10] and implement waveguides with exotic properties [11]. The use of materials in which the transition between phase-changed materials occurs under external influence [12-14] is of particular interest for creating switching components of integrated optical devices.

The resulting ENZ-metamaterial for the optical range [15] has a multilayer Ag/SiN structure. The real and imaginary parts of its permittivity are simultaneously close to zero in a wide spectral range. The ENZ-metamaterial for near-infrared radiation was manufactured as a multilayer Ag/Ge structure [16]. Magneto-optical metamaterials were created as AU-core-Co-shell structured arrays of metal microparticles [17], periodic arrays of Au/Ni bimetallic plasmon ring resonators [18], and Ni nanowire arrays embedded in an anodised aluminium oxide base [19]. Energy losses can be considerable in such metallic nanostructures, which encourages the development of fully dielectric magneto-optical metamaterials. The first fully dielectric NIZ-metamaterial for infrared frequencies has a structure comprising stackable silicon rods separated by layers of silicon oxide [20]. The first NIZ-metamaterial suitable for placement on an electronic chip for optical frequencies was manufactured as an array of silicon columns based on an insulator-silicon base [21]. Therefore, a monolithic CMOS NIZ-metamaterial comprising a square array of air holes in an insulator silicon wafer, which is more suitable for standard planar technological processes, was created [22].

Nonlinear ENZ-metamaterials are produced mainly as structures consisting of layers of metal and nonlinear matter located between them, or as a nonlinear medium doped with metal particles [23-25]. The effect of local field amplification in such structures [26] can lead to an increase in their nonlinearity [27]. For example, the nonlinear refractive index of a nonlinear multilayer ENZ-structure Ag/TO_2 is six orders of magnitude greater than the nonlinear refractive index of the voluminous TO_2 [23]. High local field values in such metamaterials can lead to saturation of their nonlinear permittivity. The effects caused by saturation of the nonlinear permittivity of metamaterials can be studied for NSP based on the exact solution of the Maxwell equation system for a nonlinear medium [1].

In this paper, the authors present an exact solution of the Maxwell equation system for TM-polarised NPCs propagating along the interface between an optically linear magnetic medium and an optically nonlinear medium with nonlinear saturation. Using the obtained solution, the authors investigated the dependence of the stable propagation of NSP on the total energy flux of NSP and energy fluxes in contacting media for the structure: magnetic ENZ-metamaterial/nonlinear self-focusing ENZ-metamaterial. The results for the case of saturating nonlinearity are compared with the case of guiding nonlinearity.

The purpose of this study was to obtain an exact solution of the Maxwell equation system for TM-polarised NPCs propagating along the interface between an optically linear magnetic medium and an optically nonlinear medium with saturated nonlinearity.

Materials and Methods

The authors considered a TM-polarised electromagnetic wave propagating along the interface (plane z=0) of an optically nonlinear medium with permittivity saturation (region z>0) and an optically linear magnetic medium (region z<0). The magnetic permeability of a nonlinear medium is equal to one, and the permittivity is denoted as ε. The magnetic permeability and permittivity of a linear medium are denoted by μ_1 and ε_1, respectively. Both environments are non-dissipative. The problem is considered homogeneous towards *y*. The electric and magnetic fields of the NSP are written as (1-2):

$$\vec{E}(\vec{r},t)=\frac{1}{2}\left(\vec{E}(z)\exp i(kx-\omega t)+c.c.\right), \vec{E}(z)=(E_x,0,E_z) \quad (1)$$

$$\vec{H}(\vec{r},t)=\frac{1}{2}\left(\vec{H}(z)\exp i(kx-\omega t)+c.c.\right), \vec{H}(z)=(0,H,0) \quad (2)$$

The dependence of the permittivity of a nonlinear medium on the intensity is modelled according to the following formula (3):

$$\varepsilon=\varepsilon_{xx}=\varepsilon_{zz}=\varepsilon_0+\varepsilon_2\left(\left|\vec{E}\right|^2\right)=\varepsilon_0+\frac{a(|E_x|^2+|E_z|^2)}{1+b(|E_x|^2+|E_z|^2)} \quad (3)$$

where ε_0 and are the linear and nonlinear parts of the permittivity.

The authors believe that ε_0, *a*, *b*, ε_1, μ_1 are valid. Value *b* is considered integral. Signs ε_0, *a*, ε_1, μ_1 are arbitrary. The permittivity (3) is a guide for weak fields and tends to the saturation level $\varepsilon_s=\varepsilon_0+a/b$ at high intensities.

The problem is to determine the relationship between the steady-state propagation and the energy flux of the NSP based on the exact solution of the Maxwell equation system for the NSP in the structure under study.

NSP at the interface between magneto-optical matter and nonlinear metamaterial

Components of the NSP field. The components of the NSP field correspond to the following system of equations (4a-4c):

$$\frac{dH}{d\zeta} = i\varepsilon E_x \tag{4a}$$

$$nH = -\varepsilon E_z \tag{4b}$$

$$\frac{dE_x}{d\zeta} - inE_z = i\mu H \tag{4c}$$

where $n \equiv k/q$ is the dimensionless steel distribution $\zeta \equiv zq$ is the dimensionless coordinate; $q = \omega/c$. Magnetic field H is considered valid and integral.

For a linear medium, the solution of system (4a-4c) gives components of the NSP field that decrease exponentially as one distances from the interface. For example, the magnetic field distribution of the NSP has the following form (5):

$$H(\zeta) = \widetilde{H}\exp(k_1\zeta) \tag{5}$$

where (6):

$$k_1 \equiv +(n^2 - \varepsilon_1\mu_1)^{1/2} \tag{6}$$

$\tilde{H}$ there is a value of the magnetic field at the interface z=0.

For a nonlinear medium, the solution of system (4a-4c) is based on the general solution obtained by Leung [28] for an arbitrary function $\varepsilon_2(|E|^2)$, which allows expressing the components of the NSP field in terms of ε and determine the dimensionless coordinate ζ as an integral by ε within the range of $\tilde{\varepsilon}$ K ε, where is the permittivity on the surface of a nonlinear medium. Later, this general solution was developed [1] for the permeability expressed by Equation (3). Using the solution [1] and boundary conditions for the tangential components of the field, the constant propagation of NSP can be expressed in terms $\tilde{\varepsilon}$ (7):

$$n^2 = \frac{\varepsilon_1\tilde{\varepsilon}^2((\mu_1\tilde{\varepsilon} - \varepsilon_1)I(\tilde{\varepsilon} - \varepsilon_0) - \mu_1 J(\tilde{\varepsilon} - \varepsilon_0))}{\tilde{\varepsilon}(\tilde{\varepsilon}^2 - \varepsilon_1^2)I(\tilde{\varepsilon} - \varepsilon_0) - (\tilde{\varepsilon}^2 + \varepsilon_1^2)J(\tilde{\varepsilon} - \varepsilon_0)} \tag{7}$$

where $I(\varepsilon-\varepsilon_0)$ and $J(\varepsilon-\varepsilon_0)$ are determined by equations (9) and (10) from [1].

NSP energy flow *Q* per unit length towards *y* consists of the flow of energy in a linear medium *QL* and energy flow in a nonlinear medium *QN*. Both flows can be obtained by using the expression for constant propagation (7) in equations (21) and (22) from [1].

Results and Discussion

Relationship between energy flow and steady-state NSP propagation

Next, the authors consider the relationship between the steady spread of NSP *n* and the energy flow of the NSP *q* (per unit length towards *y*NSP energy fluxes in linear and nonlinear media for NSP propagating along the interface of an optically linear magnetic ENZ-metamaterial with negative permittivity and an optically nonlinear self-focusing ENZ-metamaterial.

Calculations are performed for the following parameter values: $\lambda = \frac{2\pi c}{\omega} = 1.06\mu m$, linear permittivity of the medium ε_1=-0.2; linear part of the permeability of a nonlinear substance ε_0=-0.04, Kerr coefficient $a=1.76\times10^{-17}\ m^2/V^2$ (typical value for a nonlinear optical material multiplied by a gain factor of 400, as in Argyropoulos et al. [27]).

The relationship between the steady-state NSP propagation and the total NSP energy flow per unit length towards y is presented in Figures 1-3.

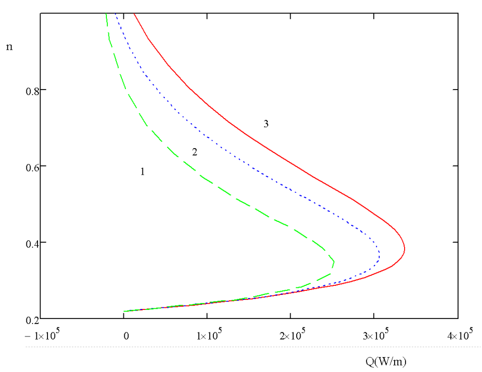

Figure 1. Constant distribution dependence *n* from the total energy flow of the NSP *Q* for magnetic permeability μ_1=0.8 at the following saturation levels: 1) ε_s=0.26; 2) ε_s=0.34; 3) $\varepsilon_s=+\infty$

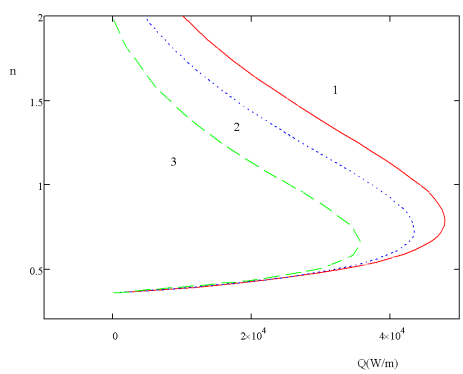

Figure 2. Constant distribution dependence *n* from the total energy flow of the NSP *Q* for magnetic permeability μ_1=10 at the following saturation levels: 1) ε_s=0.26; 2) ε_s=0.34; 3) $\varepsilon_s=+\infty$

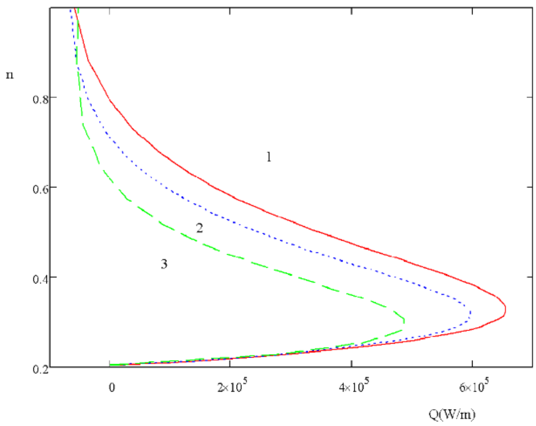

Figure 3.Constant distribution dependence *n* from the total energy flow of the NSP *Q* for magnetic permeability μ_1=0.01 at the following saturation levels: 1) ε_s=0.26; 2) ε_s=0.34; 3) $\varepsilon_s = +\infty$

Dependency graphs $n=n(Q)$ are S-shaped. For high nonlinearity, the total energy flux of the NSP is negative. The results shown in Figure 1 correspond to the value of the magnetic permeability of a linear medium μ_1=0.8; these graphs are remarkably similar to the graphs for the non-magnetic case given in paper by A.D. Groza [29] (Fig. 3). The fractions of the energy flux in a nonlinear medium and in a linear medium are presented in Figures 4-6.

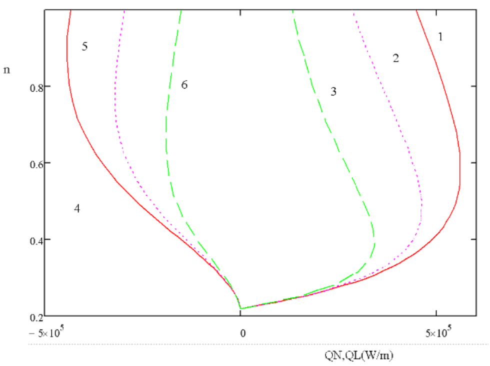

Figure 4. Fraction of the NSP energy flow in a nonlinear medium *QN* (1,2,3) and in a linear environment *QL* (4,5,6) for magnetic permeability μ_1=0.8 at the following saturation levels: 1) ε_s=0.26; 2) ε_s=0.34; 3) $\varepsilon_s = +\infty$

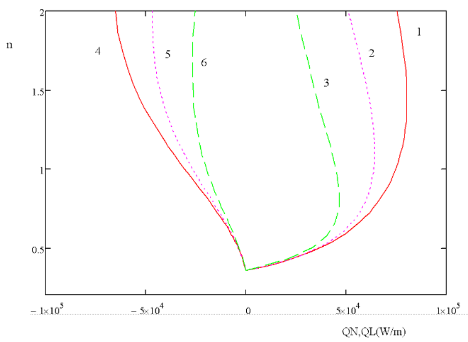

Figure 5. Fraction of the NSP energy flow in a nonlinear medium *QN* (1,2,3) and in a linear environment *QL* (4,5,6) for magnetic permeability μ_1=10 at the following saturation levels: 1) ε_s=0.26; 2) ε_s=0.34; 3) $\varepsilon_s = +\infty$

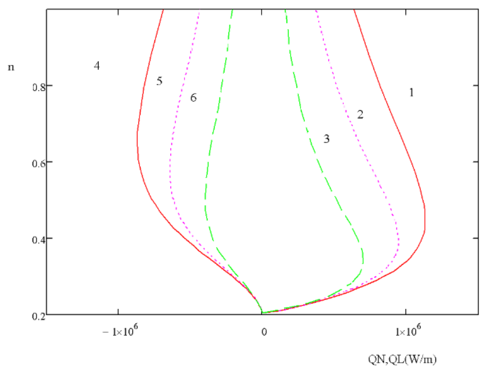

Figure 6. Fraction of the NSP energy flow in a nonlinear medium *QN* (1,2,3) and in a linear medium *QL* (4,5,6) for magnetic permeability μ_1=0.01 at the following saturation levels: 1) ε_s=0.26; 2) ε_s=0.34; 3) $\varepsilon_s = +\infty$

The energy flow is always negative in a linear medium and always positive in a nonlinear medium. The modules of these energy fluxes are of the same order of magnitude. Figure 2 and Figure 5 demonstrate the magnetic permeability of a linear medium and the graphs are shifted to lower values of the NSP energy flow.

In Figure 3 and Figure 6, the magnetic permeability has a value close to zero , in this case, the graphs are shifted to higher values of NSP energy fluxes.

In all cases, for the selected value of the steady-state propagation of the NSP, the value of the share of the NSP energy flux in the contacting media increases modulo when the saturation level decreases.

Charts $n=n(Q)$ intersect the axis n if the total energy flow of the NSP is zero. The value of the steady-state propagation, which corresponds to the zero value of the total energy flux of the NSP, is the smallest for the control nonlinearity and increases with decreasing saturation level.

Conclusions

The paper presents an exact solution of the Maxwell equation system for TM-polarised nonlinear surface polaritons propagating along the interface of an optically linear magnetic medium and an optically nonlinear medium with nonlinear saturation. The solution allows calculating the NSP parameters for any signs and values of material parameters of contacting media. Its application to the analysis of NSP properties in the ENZ structure of a magnetic metamaterial with negative permittivity/nonlinear self-focusing ENZ metamaterial allows drawing the following conclusions:

1. The energy flow of NSP is positive in a nonlinear medium and negative in a linear medium. For low levels of nonlinearity, the NSP energy flow in a nonlinear medium dominates. For high levels of nonlinearity, the relative part of the NSP energy flow decreases in a nonlinear medium, the total NSP energy flow tends to zero, and then becomes negative.

2. For a fixed value of the steady-state propagation of NSP, the NSP energy fluxes in contacting media increase modulo when the saturation level decreases. The value of the NSP propagation constant, for which the total NSP energy flux becomes zero, is the smallest for the control nonlinearity and increases with decreasing saturation level.

3. According to the selected value of the steady-state propagation, the energy fluxes of NSP in contacting media increase when the magnetic permeability decreases. The range of changes in steady-state propagation for a positive NSP energy flux narrows when the magnetic permeability tends to zero.

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Нелінійні поверхневі поляритони біля межі поділу магніто-оптичної речовини та нелінійного метаматеріалу з близькою до нуля діелектричною проникністю

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Анотація

Актуальність. Значна увага дослідників привертається до нелінійних поверхневих оптичних хвиль, оскільки вони мають хороші перспективи у застосуванні в системах оптичної обробки інформації, надчутливих сенсорах і сучасних телекомунікаційних компонентах

Мета. Отримати точне рішення системи рівнянь Максвелла для ТМ-поляризованих нелінійних поверхневих поляритонів, що поширюються вздовж межі розділу між оптично лінійним магнітним середовищем і оптично нелінійним середовищем з насиченою нелінійністю.

Методи. Використано аналіз властивостей нелінійних поверхневих поляритонів (НПП) та математичне моделювання залежності діелектричної проникності нелінійного середовища від інтенсивності.

Результати. Досліджено ТМ-поляризовані НПП, що поширюються уздовж межі поділу магніто-оптичного середовища та нелінійно-оптичного метаматеріалу з близькою до нуля діелектричною проникністю (ENZ-метаматеріал). Для НПП в такій структурі отримане точне рішення системи рівнянь Максвелла з урахуванням ефекту насичення оптичної нелінійності. На цій основі досліджено залежності постійного поширення від сумарного потоку енергії НПП та потоків енергії в контактних середовищах у структурі: магнітооптичний ENZ-метаматеріал з негативною діелектричною проникністю / нелінійний самофокусуючий ENZ-метаматеріал.

Висновки. Потік енергії НПП є позитивним в нелінійному середовищі та негативним у лінійному. При зменшенні рівня насиченості потоки енергії НПП у контактуючих середовищах зростають за модулями, якщо значення сталої розповсюдження НПП (СРНПП) фіксоване. Найменше значення СРНПП для керівської нелінійності отримуємо, коли загальний енергетичний потік НПП стає нулевим. Із зменшенням рівня насичення ПРНПП збільшується. При фіксованій СРНПП при зменшенні магнітної проникності потоки енергії НПП у середовищах, що контактують, зростають. Коли магнітна проникність зменшується до нуля і потік енергії НПП позитивний, діапазон зміни СРНПП звужується

Ключові слова: керівська нелінійність, стала розповсюдження, діелектрична проникність нелінійного середовища, магніто-оптичний метаматеріал, магнетик, насичення