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Optical bistability in reflection from multilayer metal-dielectric structure with Kerr nonlinearity

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Abstract. Both static and dynamic characteristics of light reflected from a specially designed multilayer metal-dielectric structure with Kerr nonlinearity have been studied in this work. Various regimes of nonlinear reflection from the structure have been demonstrated, including bistable switching between low and high reflection states, which occurs at low intensity of the incident light due to a significant enhancement in the optical field in the nonlinear layer under conditions of total internal reflection. This nonlinear structure has been proposed to use as an optically controlled intracavity laser modulator.

Keywords: multilayer metal-dielectric structure, optical bistability, laser modulator.

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1. Introduction

Optical bistability, characterized by two different stable states at the same input intensity, is of great interest for applications in optical information processing [1]. It can be observed in nonlinear systems with a feedback such as nonlinear Fabry–Perot interferometers and multilayer metal-dielectric (MMD) structures. Bistable switching is shown to exist in Bragg reflector with metal layer on the top, which is based on the optical Tamm states [2, 3]. For the implementation of low threshold optical bistability, a specially designed MMD structure [4] is of interest. This MMD structure supports both hybrid plasmonic TM and waveguide resonant TE modes and is characterized by a significant optical field enhancement in the latter dielectric layer. In the case, when the latter layer of MMD structure has Kerr-type nonlinearity, the field enhancement can lead to a large nonlinear resonance shift even at relatively small change of the incident light intensity.

In this work, the authors investigate effects of nonlinear resonance shift, when monochromatic light is reflected from the nonlinear MMD structure at different fixed angles of incidence. The nonlinear resonance shift takes place for both hybrid plasmonic TM and waveguide TE modes. The following analysis refers to the TE modes, for which these nonlinear shift effects are more pronounced.

2. Materials and methods

We consider the resonant MMD structure with the parameters described in [4] except that the latter layer has Kerr-type nonlinearity (Fig. 1). To make model of this structure, we derived the system of equations that describes the reflection coefficient R and enhancement factor Q, which are dependent on the intensity I_0 of the incident light. Solutions for both stationary and dynamic cases were obtained.

The reflection coefficient for MMD resonant structure can be approximated by the following expression:

$$R = 1 - \exp\left[-\frac{(\theta - \theta_{\min})^2}{\sigma^2}\right], \tag{1}$$

where θ is the angle of incidence of a plane electromagnetic wave onto the structure, σ – width of the resonant minimum.

The angular position of the resonant minimum $\theta_{\min}$ depends on the change of the refractive index Δn of the dielectric layer (Fig. 2):

$$\theta_{\min} = \theta_0 + \alpha \cdot \Delta n, \tag{2}$$

where θ_0 is the angle of the minimum at $\Delta n = 0$, α – angular sensitivity of the structure:

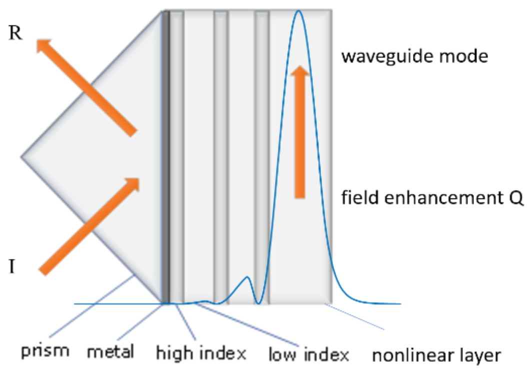

Fig. 1. The scheme of MMD structure: the electromagnetic field (blue line) has its maximum in the latter nonlinear layer. Arrows indicate directions of light propagation.

$$\alpha = \frac{\partial\theta_{\min}}{\partial n}. \qquad (3)$$

If the latter layer has a nonlinear response to the field intensity I, then

$$\Delta n = n_2 \cdot I, \qquad (4)$$

where n_2 is the nonlinear index, and I – intensity in the nonlinear layer.

The intensity $I = |E|^2$ in the nonlinear layer is approximately defined by the reflection coefficient R and can be represented by the following formula:

$$I = \beta \cdot I_0 \exp\left[-\frac{(\Delta\theta - \theta_{res})^2}{\sigma^2}\right]. \qquad (5)$$

The enhancement factor in nonlinear layer $Q = I/I_0$ is represented by the ratio of internal field intensity $|E|^2$ and incident field $|E_0|^2$. This factor is denoted as:

$$Q = \beta \cdot \exp\left[-\frac{(\Delta\theta - \alpha \cdot \Delta n)^2}{\sigma^2}\right], \qquad (6)$$

where β is the maximum value of Q and $\Delta\theta = \theta - \theta_0$.

Summarizing, we obtain the system of equations for the stationary solution:

$$R = 1 - \frac{Q(\Delta n)}{\beta},$$
$$I_0 = \frac{\Delta n}{n_2} Q(\Delta n), \qquad (7)$$

from which one can find the dependence of the reflection coefficient R on the incident field intensity I_0 for a fixed angle of incidence θ. The parameters α, β, θ_0, σ are defined by MMD structure properties.

To describe the dynamical behaviour of $Q(t)$ and $n(t)$ for the nonlinear MMD structure, we derived the following system of equations:

$$\frac{d}{dt}Q(t) = \frac{1}{\tau_1}\left[\beta \cdot \exp\left[-\frac{(\Delta\theta - \alpha\cdot\Delta n)^2}{\sigma^2}\right] - Q(t)\right]$$
$$\frac{d}{dt}\Delta n(t) = -\frac{\Delta n(t)}{\tau_{21}} + \frac{1}{\tau_{22}}\left[n_2 I_0 Q(t) - \Delta n(t)\right]. \qquad (8)$$

The life time of the field in the MMD structure can be estimated as $\tau_1 = \beta \cdot d/c$, where d is the thickness of the structure, c – speed of light. The nonlinear index relaxation time τ_{21} and rise time τ_{22} depend on the properties of material with NLO response. For example, τ_{21} and the rise time τ_{22} should be about 10 ps for Kerr effect.

The enhanced light field is localized in the dielectric layer with low loss, therefore this nonlinear MMD structure can be used as a fast and high contrast laser modulator. Other useful properties of the structure for applications in lasers are as follows: the structure operates within a wide spectral range; it has a fast response time and narrow angular width of the resonance.

The nonlinear elements and plasmonic structures have been already used in a laser cavity [5, 7]. Here, we modify the laser rate equations [8, 9] by substitution the expression for saturable absorber with the system of equations (8) for the reflection coefficient of the described nonlinear MMD structure. The rate equations for the photon density ϕ inside the resonator and the population inversion density in the gain medium n_g are given by

$$\frac{d}{dt}\phi(t) =$$
$$= \frac{c\phi(t)}{l_c}\left[\left(\sigma_g n_g(t) l_g\right) + \ln\left(1 - \frac{Q(\Delta n(t))}{\beta}\right)\right] - \frac{\phi(t)}{\tau_c} + \frac{\xi n_g(t)}{\tau_g},$$
$$\frac{d}{dt}n_g(t) = \frac{n_g(t)}{\tau_g} - \gamma_g \sigma_g c\,\phi(t) n_g(t) + \frac{N_{tot} - n_g(t)}{N_{tot}} W_p,$$
$$\frac{d}{dt}I(t) = \frac{1}{\tau_1\left[\phi(t) a_p Q(\Delta n(t)) - I(t)\right]},$$
$$\frac{d}{dt}\Delta n(t) = -\frac{\Delta n(t)}{\tau_{21}} + \frac{n_2 I(t) - \Delta n(t)}{\tau_{22}}. \qquad (9)$$

We use the same notation as in the paper [5]: ϕ is the photon density, c – speed of light, l_c – optical cavity length, σ_g – crystal gain emission cross-section, l_g – gain crystal thickness, γ_g – thermal population reduction factor for the gain crystal, τ_c – photon lifetime, τ_g – gain crystal relaxation time, N_{tot} – concentration of active media ions. The absorber based on the nonlinear MMD structure is characterized by the following parameters: I is the light intensity in the nonlinear layer of MMD structure, Δn – refractive index change of the nonlinear layer.

3. Results and discussion

The considered MMD consists of three pairs of high (Nb_2O_5) and low (SiO_2) refractive index and metal (Ag) layers deposited on a silica prism. The values of thickness inherent to high and low dielectric layers were 90 and 140 nm, respectively. The metal layer was close to 40 nm and terminal low index layer was 300 nm. Fig. 2 shows the reflectance R *vs* the incident angle θ. The starting point 1 (Fig. 2) can be shifted by the angle $\Delta\theta$ from the position of resonance θ_{min}. The shifted by nonlinearity reflectance curve leads to move the reflectance to the point 2 (Fig. 2). Typical values α, β, σ for this MMD structure at the wavelength 632 nm are: $\alpha = 20°/\text{RIU}$, $\beta = 1000$, $\sigma = 0.02°$.

Fig. 3 shows the dependences of the reflectance coefficient R on the parameter $\chi = I_0 n_2 \beta$ for various initial points $\Delta\theta$. The dimensionless parameter I_0 characterizes the linear relationship between the nonlinear reflection index n_2, maximum value of field enhancement factor β and the intensity of incident light I_0. Since I_0 and β are positive values, negative χ corresponds to the negative nonlinear index n_2. The curve 4 represents the bistable behavior of reflectance. Note that the reflection bistability of the nonlinear MMD structure is similar to that of the simple planar waveguide [10]. For the limiting case $\Delta\theta = \sqrt{2}\sigma$, the uncertainty of the reflection coefficient takes place at a certain critical intensity. This can lead to dynamic nonlinear processes such as self-oscillations. In this case, a stable soliton-like space-time inhomogeneity can takes place. And due to the large value of the gain field β, these effects can be realized experimentally.

The result of numerical modelling the dynamical behavior of reflectance (Eq. (8)) is shown in Fig. 4.

For $d = 1$ μm, we obtain $\tau_1 = 3.3$ ps. We assume that the medium relaxation time τ_{21} and rise time τ_{22} should be close to 10 ps. We use the following parameters for modelling: $\alpha = 0.5°/\text{RIU}$, $\sigma = 10^{-4}$, $\beta = 1000$ [4], $n_2 = 10^{-5}$. For the initial detuning angle $\Delta\theta = 2\sigma$, the enchancement factor Q has its maximum, which corresponds to the minimum in the reflection coefficient (Fig. 3). Thus, the nonlinear MMD structure can modulate the incident light intensity with a high efficiency. The parameter $\chi = 0.01$.

Titanium dioxide (TiO_2) has large nonlinear refractive index, n_2 is about 10^{-6} mm^2/MW (30 times that of silica). Therefore, titanium dioxide promises to be an attractive candidate for nonlinear optical devices due to its large refractive index and large Kerr nonlinearity [11]. Maximizing the intensity is necessary for practical using the nonlinear optical effects [12]. This value of n_2 is enough to achieve the desired value of $\chi = 10^{-3}$. It allows to obtain the bistability regime at the intensity level usual for microlasers, namely, close to 1 MW/mm^2.

There are materials with significantly larger nonlinear refractive index. Bi_2Se_3, a kind of topological insulator, has a giant nonlinear refractive index of

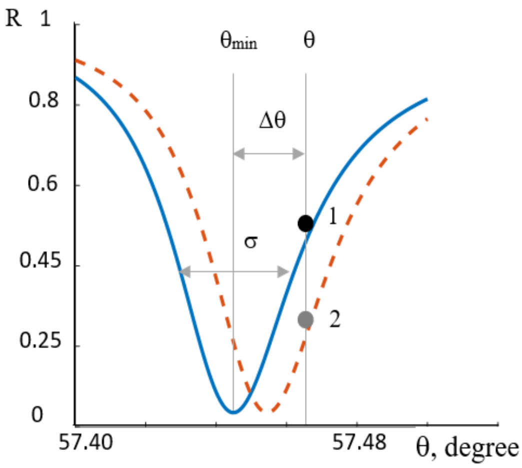

Fig. 2. The enhanced light field in the latter layer causes a change in the refractive index, which leads to the shift of the reflection curve *R*.

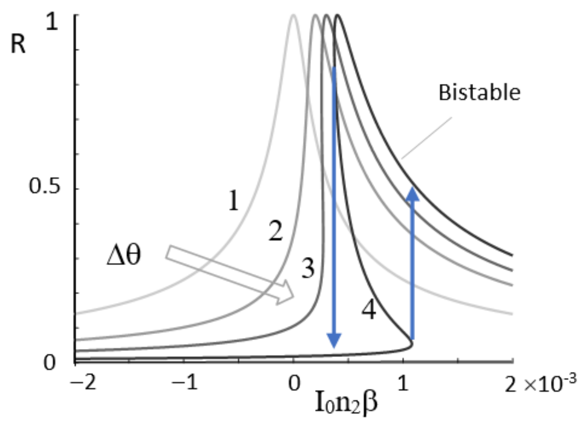

Fig. 3. The nonlinear reflection coefficient has different shapes depending on the displacement of the angle of incidence $\Delta\theta$: $\Delta\theta = 0$ (*1*), $\Delta\theta = \sigma$ (*2*), $\Delta\theta = \sqrt{2}\sigma$ (*3*) and $\Delta\theta = 2\sigma$ (*4*).

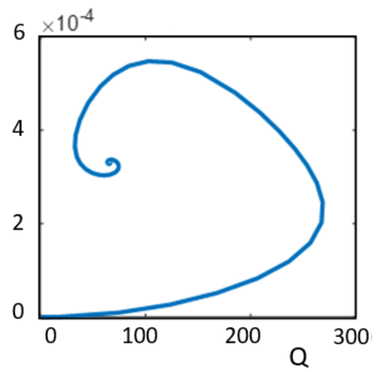

Fig. 4. Dynamic response of the enhancement factor Q corresponding to the refractive index change Δn in the nonlinear layer.

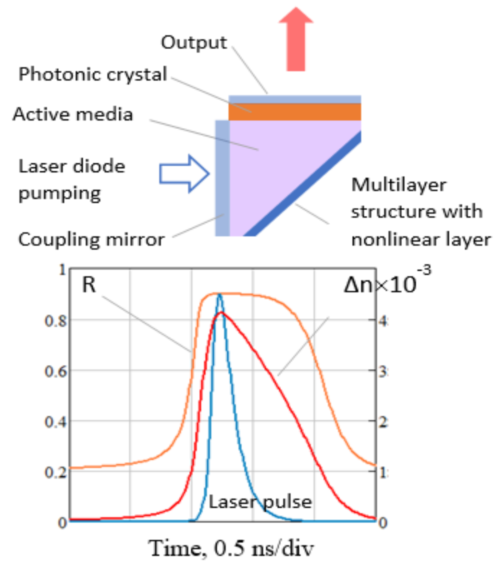

Fig. 5. Scheme of Q-switched laser with nonlinear MMD structure as saturable absorber (top) shows the possibility of sub-nanosecond laser pulse generation (bottom).

10^{-14} m^2/W, almost six orders of magnitude larger than that of bulk dielectrics [13]. Also, the GaAs, Si, quantum dots in ZnS, ZnO have $n_2 \sim 10^{-17}$ m^2/W. The highest value of n_2 is obtained for graphene [14] $6 \cdot 10^{-12}$ m^2/W. The duration time is usually less than 200 fs, except materials with quantum dots (10 ns) [13].

The enhanced light field is localized in the dielectric layer with low losses, therefore this nonlinear MMD can be used as a fast and high contrast laser shutter. Other useful properties of the structure for applications in lasers are as follows: the structure operates within a wide spectral range; it has a fast response time and narrow angular width of the resonance.

The scheme of a diode-pumped solid-state laser with the nonlinear MMD structure as a saturable modulator is shown in Fig. 5 (top).

The results of typical parameters for solid-state diode-pumped YAG:Nd^{3+} laser modelling (pulse, reflection coefficient and refractive index change) are shown in Fig. 5 (bottom). It should be noted that a characteristic feature of the MMD structure is the narrowness of the angular width corresponding to the reflection resonance. Therefore, using the angular filter like 3D photonic crystal [15] for transversal mode selection may be necessary.

4. Conclusions

We have proposed a nonlinear MMD structure supporting both hybrid plasmonic TM and waveguide resonant TE modes and studied various regimes of nonlinear reflection from the structure including bistable switching between low and high reflection states. We have demonstrated the possibility to use the nonlinear MMD structure as an optically controlled intracavity laser modulator. Due to the large value of the internal electromagnetic field enhancement, these effects can be realized experimentally using the promising nonlinear optical nanomaterials with high nonlinear refractive index (Bi_2Se_3 – 10^{-14} m^2/W, GaAs, Si, quantum dots in ZnS, ZnO – ~10^{-17} m^2/W, graphene – 10^{-12} m^2/W, *etc.*). It is possible to use the nonlinear MMD as an optically controlled fast intracavity laser modulator.

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Оптична бістабільність при відбиванні від багатошарової метал-діелектричної структури з нелінійністю Керра

С.Г. Ільченко, Р.А. Лимаренко, В.Б. Тараненко

Анотація. Досліджено як статичні, так і динамічні характеристики світла, відбитого від спеціально розробленої багатошарової метал-діелектричної структури з нелінійністю Керра. Продемонстровано різні режими нелінійного відбивання від структури, включаючи бістабільне перемикання між низьким і високим станами відбивання, яке відбувається при низькій інтенсивності падаючого світла завдяки значному підсиленню оптичного поля в нелінійному шарі в умовах повного внутрішнього відбивання. Запропоновано використовувати цю нелінійну структуру як оптично керований внутрішньорезонаторний лазерний модулятор.

Ключові слова: багатошарова метал-діелектрична структура, оптична бістабільність, лазерний модулятор.