Frequency bistability in nonlinear thin-film interferometer

E.V.Glasunova, V.A.Yurevich

Mogilev State University, 1, Cosmonautes St., 212022 Mogilev Belarus

ABSTRACT

The bistability in a thin-film cavity system including a layer with the quasi-resonant polarization is considered. Bistability in reflection frequency dependence and arising phase drift can be applicable for creation of chirping mirrors for laser pulses transformation.

Key words: Optical bistability, resonant subsurface layer, thin-film cavity.

1. INTRODUCTION

At present, planar thin-film systems receive a wide application in systems of data transmission and processing system due to their size and large possibilities in light control. A behaviour of these systems is highly influenced by nonlinearity of interaction of layers with a light field. Even in a case of a single interface layer possessing a feedback mechanism, non-trivial phenomena such as bistability or self-sustained pulsations were predicted, for example, in [1-3], formation of cross-section static and moving spatial structures is also possible.

The important property of these systems is their phase sensitivity, i.e. dependence of dynamic characteristics of the system on phase relations of the light field in a feedback circuit. This type of connection can be be realized in multilayered optical structures. In this work the simplest variant of multilayered structure such as the planar system consisting of two films (dielectric and semiconductor) is considered. It has been shown [4] that in transmission of this system in case of strongly different relaxation and nonlinear characteristics of both layers the dynamic instability of the outside incident radiation can be registered. We study a stationary mode of light reflection by system of two material layers forming a cavity. One of the layers is sufficiently thick film (up to several wavelengths), being essentially a substrate formed by the linear optical medium, on which the active layer is deposited. This second layer is especially thin semiconductor usually applied in optics or laser physics. This active layer was considered as a surface film of resonant atoms. Thickness of the film is much less than wavelength of incident light. Nonlinear reflecting properties of a similar layer are considered, for example, in [5]. The cavity and a film form an optical system, whose reflection and transmission which critical to a frequency of external radiation. The film parameters used below in evaluations were corresponded to the range of real characteristics of the layers made of such materials.

2. NONLINEAR REFLECTION OF INTERFEROMETER

In this connection, it is interesting to study self-modulation of the coherent light field in the optical structure, formed by the film resonator and a surface layer with resonant polarizability. It is clear, that in such structure representing a nonlinear interferometer, combination of components with a different criticalities to external radiation should cause the special dependence of nonlinear reflection of film system on intensity of outside incident light. The study of properties of film interferometer reaction on the resonant light field, whose results are presented below, based on the representations developed in [4-6].

It is assumed that nonlinear reflection occurs on the edge $x = L$ of a plain-parallel layer of a non-active optical dielectric (Fig.1). Initiated by an external plane light wave with an amplitude $E_i = E'_0 = Const$ and frequency ω, the field of counter propagating waves with amplitudes E_0, E_r within the layer is expressed in complex quasi-stationary representation as

$$E(x) = E_0 e^{i[k_i x + \varphi_+(x)]} + E_r e^{i[-k_r x + \varphi_-(x)]},$$

where $\varphi_\pm(x)$ are variable phase components, k_i and k_r are wave vector modules.

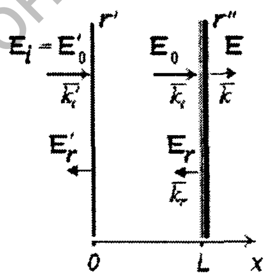


Figure 1. Schematic diagram of a cavity with a nonlinear film.

For the dielectric layer boundary edge $x = 0$ usual the Fresnel reflection with amplitude reflection coefficient r' typical. Light wave falling normally on the active film is characterized by the amplitude $E_0 = (1 - r')E'_0$. In accordance with [6], the intensity of light I within the film is determined through E_0 in the following way:

$$(1-r''^2)I_0 \;=\; I\left[\left(1+\frac{\kappa}{1+\Delta^2+I}\right)^2+\kappa^2\left(\frac{\Delta-\beta I}{1+\Delta^2+I}\right)^2\right] \;, \qquad (1)$$

where

$I_0 = \dfrac{\mu^2}{\hbar^2} T_1 T_2 \, E_0^2$ is f normalized intensity of a field in the resonator (both intensities I_0 and I are normalized by magnitude of saturating radiation power),

$\Delta = (\omega - \omega_0)T_2$ is the normalized defect of the frequency ω relatively to the frequency of transition ω_0,

μ is a dipole moment of the basic transition in energy structure of active atoms in the film,

T_1 and T_2 are times of a longitudinal and transverse relaxation of the transition,

κ is a nonsaturated index of resonant absorption in a film,

r'' is a Fresnel reflection coefficient in the film,

β is the factor of a resonant nonlinear refraction describing the dependence of refraction index on an energy state of the film medium. It should be noted that the presence of a factor proportional to β in formula (1) is an essential point in this model which is based on representations of generalized two-level scheme. A bleachable thin-film element must possess a special phase sensitivity. The Stark shift of basic frequency and the dipole-dipole interaction effect are neglected.

Reflection from the active layer are complex. It is easy to show [5] that

$$E_r \;=\; r''E_o - \kappa\left(\frac{1}{1+\Delta^2+I} + i\,\frac{\Delta-\beta I}{1+\Delta^2+I}\right)\cdot E_s \;\; . \;\; I = E_s^* E_s \;\; .$$

The effective energy reflection coefficient of the active layer can be formally expressed through intensity values I_0, I:

$$r = \left[\left(1+\frac{\kappa}{1+\Delta^2+I}\right)\frac{I}{(1+r'')I_0}-1\right]^2+\left[\frac{\kappa(\Delta-\beta I)}{(1+r'')(1+\Delta^2+I)}\frac{I}{I_0}\right]^2 . \qquad (2)$$

A complex character of the coupling of an external field E_0 with equilibrium values E_r and E_s means, that when reflecting from the layer with resonant polarizability the light wave should get nonlinear phase shift $\Delta\varphi = \varphi_+(x = L) - \varphi_-(x = L)$, which can be evaluated using on representations accepted above as

$$\Delta\varphi = \mathrm{arctg}\left\{\left(\kappa\,\frac{\Delta-\beta I}{1+\Delta^2+I}\,\frac{I}{I_0}\right)\Big/\left[1+r'' - \left(1+\frac{\kappa}{1+\Delta^2+I}\right)\frac{I}{I_0}\right]\right\} \; . \qquad (3)$$

Values of transmission or reflection of the cavity depend on the phase matching of counter propagating waves. An optimum reflection value (maximum) is reached under the following condition if for a phase correlation the requirement is executed: $2k_c L + \Delta\varphi = 2s\pi$, $s = 0, 1, 2, \ldots$, where $k_c = k_i = k_r = \dfrac{\omega}{c}\eta$ is the module of the wave vector of a light wave in the cavity (η – refraction index of a dielectric layer).

Arising due of resonant polarizability shift of a phase of the reflected wave on the second layer edge can disturb the initial interference matching of the counter waves $2k_c L = 2s\pi$, and in this case, cavity reflection dependent on external radiation power. The variable energy reflection factor of system formed by the cavity and the thin active film with allowance for the interference of counter propagating waves in a stationary mode can be formally determine from a known relation (see, for example, [7]):

$$R = \frac{r'^2 + r + 2r'\sqrt{r}\cos\left(2k_c L + \Delta\varphi\right)}{1 + r'^2\, r + 2r'\sqrt{r}\cos\left(2k_c L + \Delta\varphi\right)} \quad . \tag{4}$$

The model presented by expressions (1)–(4) describes a nonlinear reflection of the thin-film cavity. Using a solution to this system, it is possible to valuate the dependence of cavity reflection or transmission at the corresponding frequency in the stationary regime on probing intensity or dispersion of the cavity with allowance for the absorption saturation and self-modulation drift of the light frequency in the nonlinear film.

3. CALCULATIONS OF NONLINEAR AND DISPERSIVE DEPENDENCES OF REFLECTION

Numerous estimations of nonlinear characteristics of reflection using formulas (1) - (4) are conveniently performed by varying I as a linearly increasing (non-negative) parameter and calculating values of I'_0, r, $\Delta\varphi$ and R as functions of I. This allows dependence $R(I'_0)$ to be constructed.

The reflection of nonlinear interferometer is critical to frequency and the probing intensity. Figure 2 shows plots of the effective reflection coefficient versus the normalized intensity $I'_0 = E'^2_0$ for various values of frequency defect Δ and material factors κ and β. Being based on results of this estimation, the following conclusions are possible. The reflection from the cavity containing the thin layer with the surface polarizability is essentially nonlinear (Fig.2, *a*, *b*). The curves describing nonlinear dependences of that kind, are characterized by an extremum because at a certain value of I'_0 the reflection coefficient R is minimum (in this case, a magnitude of cavity transmission I/I'_0 is characterized, accordingly, by a maximum (Fig. 2, *d*)). This feature is caused by a saturation of absorption in active film and self-modulation shift of frequency as two intercoupling reasons initiating nonlinear change of cavity reflection. At further increase in input power of probing radiation R is saturated. The saturated value of R_S is defined by final nonzero frequency detuning. Magnitudes of this detuning and corresponding reflection R_S depend on values of parameters β and Δ.

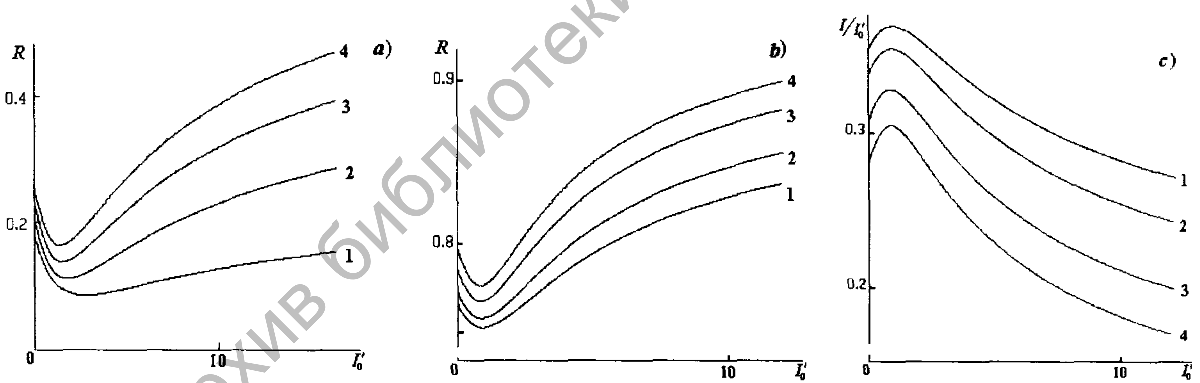
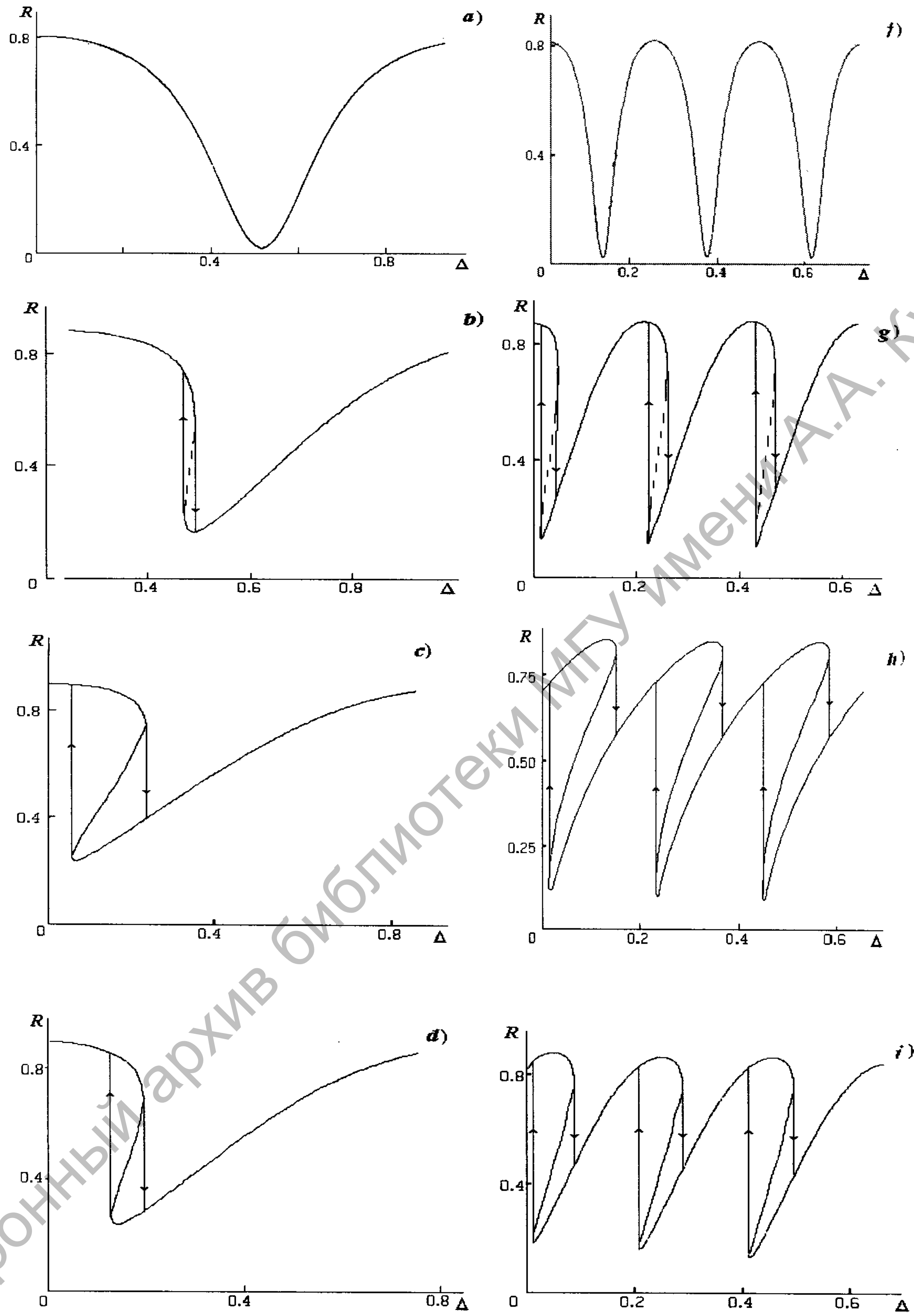


Figure 2. Plots of the effective reflection index R versus normalized probing intensity I_0 for various values of the nonlinear absorption index κ:
a – κ = 0.2 (1), 0.3 (2), 0.4 (3), 0.5 (4) and Δ = 0.3, β = 5.0, ***b*** – κ = 0.25 (1), 0.3 (2), 0.4 (3), 0.5 (4) and Δ = 1.0, β = 2.5, and also ***c*** – nonlinear transmission dependences for κ = 0.25 (1), 0.3 (2), 0.4 (3), 0.5 (4) and Δ = 0.3, β = 2.5, L = 0.05 *cm*.

The nonlinear phase shift obtained by the light wave reflected from the cavity with a nonlinear subsurface layer is a rather significant effect. The nonlinear drift caused by laser pulse action on the resonator in a dynamic mode can result in peak transformation of a laser field.

It is necessary to note one more important property of the nonlinear reflection, which is characteristic for this cavity system.


a)
R
0.8
0.4
0
0.4
0.8
Δ
f)
R
0.8
0.4
0
0.2
0.4
0.6
Δ
b)
R
0.8
0.4
0
0.4
0.6
0.8
Δ
g)
R
0.8
0.4
0
0.2
0.4
0.6
Δ
c)
R
0.8
0.4
0
0.4
0.8
Δ
h)
R
0.75
0.50
0.25
0
0.2
0.4
0.6
Δ
d)
R
0.8
0.4
0
0.4
0.8
Δ
i)
R
0.8
0.4
0
0.2
0.4
0.6
Δ

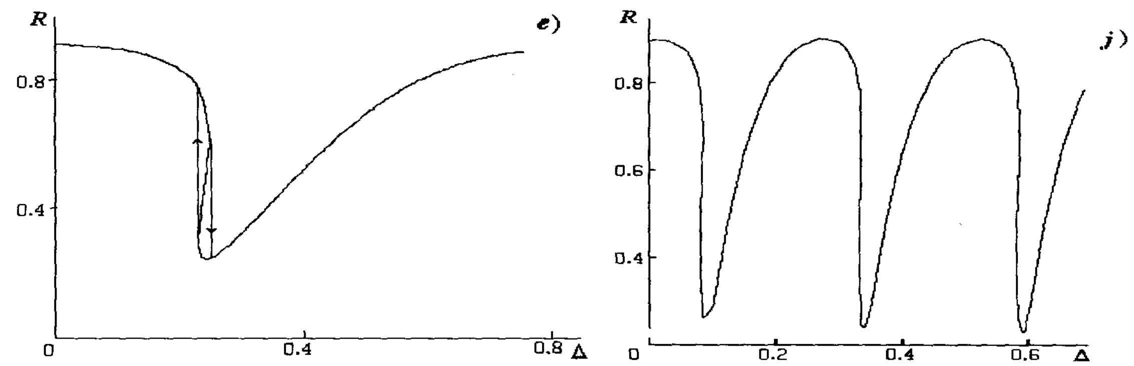


Figure 3. Plots of the effective reflection index R versus the normalized defect of frequency for various values of the probing intensity: I_0' = 0.5 (*a,f*), 4.0 (*b,g*), 12.0 (*c,h*), 15 (*d,i*), 25 (*e,j*), L = 0.0125 *cm* (*a-e*), 0.05 *cm* (*f-j*), β = 2.5 and κ = 0.3.

Formula (1) represents the equation of 5-th degree for I of and 4-th degree for defect Δ. For the fixed I'_0 and variable values I expression (1) can be resolved as the equation for values of normalized defect Δ by the Ferrari method. Then, both Δ and R, just as at an estimation of the nonlinear reflection characteristic under consideration above, calculate as functions of the increasing parameter I for dispersive dependence $R(\Delta)$ construction. In Fig. 3 results of calculation of frequency dependence of reflection R on the basis of expressions (1) - (4) are perfomed. To a rather small value of probing intensity I'_0 there corresponds an usual dispersive dependence in the form of one resonance (Fig.3, *a*) or in the form of a series of resonances (Fig.3, *f*) for greater cavity length. The nonlinear phase detuning and optimization of its efficiency with an increase of intensity leads to an inclination of reflection resonances (Fig.3, *b-e* and *g-i*). As a result, these curves can exhibit special regions where the function R (Δ) is not single-valued. In other words, the reflection under a certain level of absorption saturation reveals bistability, whereby one value of the frequency corresponds to two possible values of the reflection coefficient.

In this range of a frequency scale dispersive dependences should show an anomalous behavior indicative of the optical hysteresis. The switching from one R (Δ) branch to another can take place when the frequency defect is changed from the values corresponding to the turning points of the hysteresis curves. In a real device, this anomalous behavior is manifests itself by a sharp (jumplike) decrease in reflection of the light field along increasing frequency. A decrease of frequency in the vicinity of the jump does not lead to as sharp changes in the reflection: a jump down in the R (Δ) curves is possible at a lower frequency. A distance between the turning points (i.e., the width of the hysteresis loop) can be controlled by changing of the probing intensity, accordingly to a level of saturation. The appearance of hysteresis depends to a considerable extent on the level of radiation phase modulation (nonlinear shift) in the active layer. It is necessary to note, however, that because of absorption saturation, an inclination of resonances and corresponding hysteresis loop on a frequency scale has an optimum. With growth I'_0, i.e. at rather strong saturation, the width of hysteresis loop decreases (Fig.3, e, j), the bistability should disappear. Resonances of the reflection on the same curves have a little difference from each other (see, for example, Fig. 3, h or Fig. 3, i). This difference depends on a value of relation of cavity eigen-mode frequencies ω_c to the transition frequency ω_0.

4. CONCLUSIONS

Above obtained expressions (1) – (4) characterize a method of calculation of nonlinear reflection of the thin-film cavity. Basing on data of Figure 2, a position of the extremum R on the scale I'_0 and the saturated value of R_s depend on parameters of resonant absorption and nonlinear refraction, and also from detuning of frequencies of the field and the resonance. That is why an analysis of really recorded dependences $R(I'_0)$ for nonlinear interferometer can be used for comparative estimation or determination of parameters of these films. In it there is an indisputable important feature of evaluation above for the development of a technique of diagnostics of nonlinear properties of submicronic films.

The main result of this study presents in the proof of the possibility of hysteresis in dispersive dependence of reflection of a cavity with a thin resonant film with the nonlinear refraction under the condition of a high density of active centers. Nonlinear drift of frequency and hysteresis of the cavity reflection caused by the light under the condition of saturation of absorption, are promising for creation on the basis of the thin-film structures similar to the considered ones so-called chirping reflectors used in laser schemes for reduction of duration of impulses.

ACKNOWLEDGMENTS

The authors would like to thank Prof. A.V.Tomov for useful discussion. This work was supported by Belarussian Republican Fund for Fundamental Research (Project No Ph06M-231).

REFERENCES

1. Ya. Ben-Aryeh, C.M.Bowden and J.C.Englund, "Intrinsic optical bistability in collection of spatially distributed two-level atoms", *Optics Comms* **61,** 147, 1987.
2. A.M.Basharov, "Thin film of two-level atoms – simple model of bistability and self-sustained pulsations", *JETP* **94,** 12, 1988.
3. I.V.Babushkin, Ya.A.Logvin and N.A.Loiko, "Interrelation of space and temporal instabilities in system of two nonlinear thin films", *JETP* **117,** 149, 2000.
4. E.V.Glasunova, A.V.Khomchenko and V.A.Yurevich, "Self-induced instability of radiation in thin-film planar structure", *Proceedings of SPIE* **6259,** 62590Y-1, 2006.
5. E.V.Glasunova and V.A.Yurevich, "Nonlinear reflection of light by thin–film resonant structure", *Proceedings of F.Skaryna State Univ.* (Gomel), *N*6, 53, 2006.
6. V.A.Yurevich, "Bistability of transmission of thin layer of matter with quasi-resonant components of polarizability", *Zh. Prikl. Spektr.* **66,** 661, 1999.
7. The Directory on Lasers. Ed. by A.M.Prokhorov. – M: Sov.Radio, 1984.