Optica Applicata, Vol. XXIV, No. 4, 1994

Bistable operation of lasers with saturable absorber

P. Szczepański

Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, ul. Koszykowa 75, 00–666 Warszawa, Poland.
Institute of Electronic Materials Technology, ul. Wólczyńska 133, 01–919 Warszawa, Poland.

An approximated method of analysis of the nonlinear operation of the laser containing a saturable absorber beyond mean field approximation is presented for one-photon and two-photon absorber. The influence of the system parameters on hysteresis loop is investigated. The results are compared to the exact solutions and they are found to be in good qualitative agreement.

1. Introduction

Optical bistability has received much attention from the theoretical physicists during the last decade. Bistable optical devices may play an important role in the fields of optical computing as well as optical processing.

In this paper, we present an approximate analysis of the two-mirror laser with one- and two-photon saturable absorber. In our analysis, we take into account longitudinal field dependence, which lets us distinguish between possible configurations of a device with constant total length for the gain and the absorbing regions. Our approach is based on an energy theorem and threshold field approximation developed earlier for various structures of interest [1]–[9].

In the next section, an approximate expression relating the small signal gain to the output power and the system parameters is presented. It takes into account nonlinear gain in the active medium as well as loss saturation in the absorber region. Section 3 presents laser characteristics revealing difference between behaviour of the laser with one-photon and two-photon absorber.

2. Theory

We begin our analysis with the basic equation of the two-mirror laser with a saturable absorber (Fig. 1). The coupled equations taking into account nonlinear gain saturation as well as nonlinear loss saturation can be written in the following form:

$$\frac{dR}{dz}+(-g+\alpha_l+\alpha_s+i\delta)R = 0, \tag{1}$$

$$-\frac{dS}{dz}+(-g+\alpha_l+\alpha_s+i\delta)R = 0, \tag{2}$$

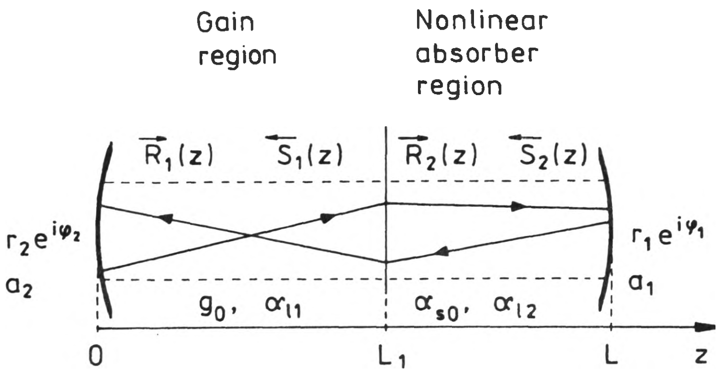


Fig. 1. Laser system considered in this paper

where R and S are the complex amplitudes of the counter-running waves of the laser mode, δ is the frequency parameter, g is the nonlinear gain in the active medium, α_l denotes linear losses, α_s is the saturable loss coefficient.

For homogeneous broadening with spatial hole burning effect neglected the saturated gain g can be related to the small signal gain g_0 for single mode operation and central tuning in the following way:

$$g = \frac{g_0 F_g(z)}{1+\dfrac{(|R_1|^2+|S_1|^2)}{P_{sg}}}, \tag{3}$$

for $z \subset (0, L_1)$ and $g = 0$ in the absorber region, $z \subset (L_1, L)$, where L_1 is the length of the active medium and L is the total length of the laser. The normalized function describing spatial distribution of the small signal gain is denoted by $F_g(z)$ and P_{sg} is the saturation power of the active medium.

Similarly we can express the saturable losses α_s by small signal losses α_{s0}. Thus, for one-photon saturable absorber we have

$$\alpha_s = \frac{\alpha_{s0} F_1(z)}{1+\dfrac{(|R_1|^2+|S_1|^2)}{P_{ls}}} \tag{4}$$

for $z \subset (L_1, L)$, and $\alpha_1 = 0$ in the active medium region, $z \subset (0, L_1)$. P_{sl} is the saturation power of the nonlinear absorber and $F_1(z)$ describes spatial distribution of the small signal loss coefficient α_{s0}. In the case of two-photon absorber we have

$$\alpha_s = \frac{\alpha_{s0} F_1(z)(|R_2|^2+|S_2|^2)}{1+\left[\dfrac{(|R_2|^2+|S_2|^2)}{P_{ls}}\right]^2} \tag{5}$$

for $z \subset (L_1, L)$, and $\alpha_1 = 0$ in the active medium region, $z \subset (0, L_1)$. The boundary conditions for our structure can be written in the following form:

$$|R_2(L)|^2 r_1^2 = |S_2(L)|^2, \quad |S_1(0)|^2 r_2^2 = |R_1(0)|^2, \tag{6}$$
$$(1-r_1^2)|R_2(L)|^2 = P_{Rout}, \quad (1-r_2^2)|S_1(0)|^2 = P_{Sout}, \tag{7}$$
$$R_1(L_1) = R_2(L_1), \quad S_1(L_1) = S_2(L_1) \tag{8}$$

where $r_{1,2}$ are the real amplitude reflectivities of the end mirrors, $P_{Rout} + P_{Sout} = P_{out}$ (if the total power is emitted by the structure), R_1, S_1 and R_2, R_2 are mode amplitudes in the gain and saturable loss regions, respectively. Multiplying Eq. (1) by R^* (complex conjugate of R) and Eq. (2) by S^*, adding these two equations and their conjugates, integrating the resulting equation while taking into account boundary conditions and using threshold field approximation (see, for example, references for more detailed discussion), we obtained for the one-photon absorber

$$2g_0 = \left\{\frac{1}{r_2}\left[\frac{1-r_1^2}{r_1}+\frac{1-r_2^2}{r_2}\right]+2\int_0^{L_1} dz\alpha_{11}[|f_{R1}|^2+|f_{S1}|^2]+\int_{L_1}^{L} dz\alpha_{12}[|f_{R2}|^2+|f_{S2}|^2]\right.$$
$$\left.+2\int_{L_1}^{L} dz\frac{\alpha_{s0}F_1[|f_{R2}|^2+|f_{S2}|^2]}{1+\frac{P_{out}}{P_{sg}}N\beta[|f_{R2}|^2+|f_{S2}|^2]}\right\}\times\left\{2\int_0^{L_1} dz\frac{\alpha_{g0}F_g[|f_{R1}|^2+|f_{S1}|^2]}{1+\frac{P_{out}}{P_{sg}}N[|f_{R1}|^2+|f_{S1}|^2]}\right\} \tag{9}$$

where:

$$f_{R1}(z) = \exp(\gamma_1 z), \quad f_{S1}(z) = \frac{1}{r_1}\exp(-\gamma_1 z),$$
$$f_{R2}(z) = \exp[(\gamma_1-\gamma_2)L_1]\exp(\gamma_2 z), \quad f_{S2}(z) = \frac{1}{r_2}\exp[(\gamma_1-\gamma_2)L_1]\exp(\gamma_2 z) \tag{10}$$

with the propagation constants defined as:

$$\gamma_1 = \frac{1}{L_1}\left\{\frac{1}{2}\ln\left(\frac{1}{r_1 r_2}\right)+(\alpha_{s0}+\alpha_{12})(L-L_1)\right\}, \quad \gamma_2 = -(\alpha_{S0}+\alpha_{12}). \tag{11}$$

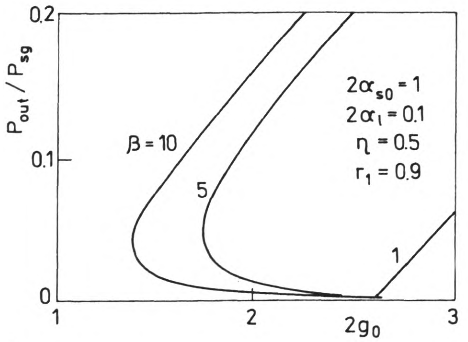
The parameter β describes the ratio of the amplifier to absorber saturation intensity $\beta = P_{sg}/P_{s1}$ and the normalization factor is defined as $N = r_1/\{(1-r_1^2)/r_1 + (1-r_2^2)/r_2\}$. Similarly, for the laser structure with the two-photon non-linear absorber we have

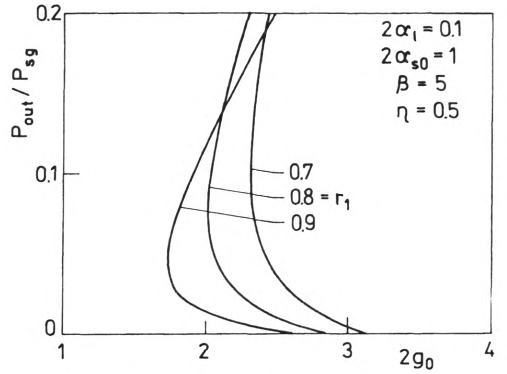
$$2g_0 = \left\{\frac{1}{r_2}\left[\frac{1-r_1^2}{r_1}+\frac{1-r_2^2}{r_2}\right]+2\int_0^{L_1} dz\alpha_{11}[|f_{R1}|^2+|f_{S1}|^2]+\int_{L_1}^{L} dz\alpha_{12}[|f_{R2}|^2+|f_{S2}|^2]\right.$$
$$\left.+2\int_{L_1}^{L} dz\frac{\alpha_{s0}F_1[|f_{R2}|^2+|f_{S2}|^2]^2(P_{out}/P_{sg})N\beta}{1+\left(\frac{P_{out}}{P_{sg}}\right)N\beta[|f_{R2}|^2+|f_{S2}|^2]^2}\right\}\times\left\{2\int_0^{L_1} dz\frac{\alpha_{g0}F_g[|f_{R1}|^2+|f_{S1}|^2]^2}{1+\frac{P_{out}}{P_{sg}}N[|f_{R1}|^2+|f_{S1}|^2]}\right\}. \tag{12}$$

In the next section, we present laser characteristics for the structure with the one-photon and two-photon absorber, using Eqs. (11) and (12), respectively.

3. Laser characteristics

The influence of the system parameters on the bistable operation of the laser with one-photon absorber is illustrated in Figs. 1 and 2. As we can notice in Fig. 1, as the saturation parameter β is increased, the laser output becomes bistable. Simultaneously, both the width and the height of the hysteresis loop increase.





▲

Fig. 2. Normalized output power P_{out}/P_{sg} is plotted as a function of the normalized small signal gain $2g_0$ with the saturation parameter β, as a parameter for one-photon absorber. The linear normalized losses are $2\alpha_1 = 0.1$, the ratio of the active medium length to the total length of the structure is $\eta = 0.5$, the output mirror reflectivity coefficient is $r_2 = 0.9$ and the normalized small signal loss coefficient is $2\alpha_{s0} = 1$

Fig. 3. Normalized output power P_{out}/P_{sg} is plotted as a function of the normalized small signal gain $2g_0$ with the output mirror reflectivity r_2, as a parameter for one-photon absorber. The linear normalized losses are $2\alpha_1 = 0.1$, the ratio of the active medium length to the total length of the structure is $\eta = 0.5$, the saturation parameter $\beta = 5$ and the normalized small signal loss coefficient is $2\alpha_{s0} = 1$

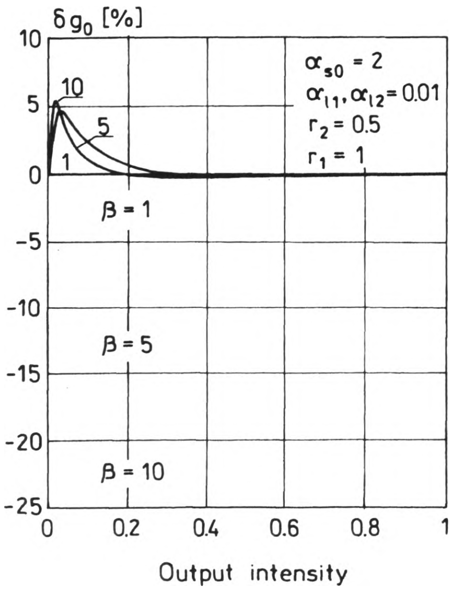
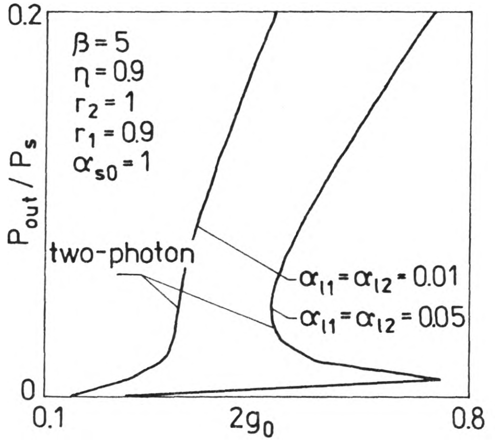
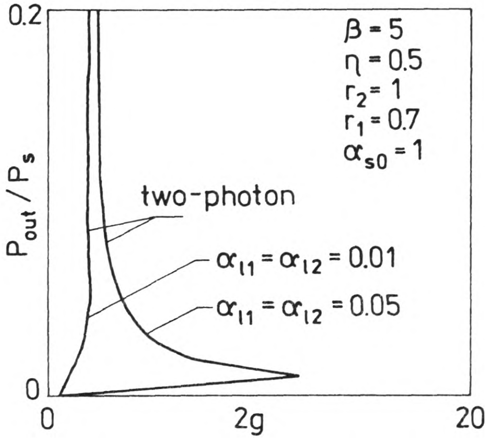


Fig. 4. Difference δ between the normalized small signal gain obtained in threshold field approximation and the normalized small signal gain obtained numerically (exact solution) as a function of the output intensity. The normalized small signal loss coefficient is $2\alpha_{s0} = 2$. The linear normalized losses are $2\alpha_1 = 0.01$ and the output mirror reflectivity coefficient is $r_2 = 0.5$

Figure 3 shows the influence of the output mirror reflectivity on the shape of the hysteresis loop. With increasing output mirror reflectivity coefficient the width of the hysteresis loop increases and its height becomes smaller. However, the hysteresis loop is shifted towards lower values of the small signal gain.

Figure 4 shows the error (calculated as a difference between the small signal gains obtained in our approach and obtained numerically), as a function of the normalized output intensity for other system parameters constant. As we can notice, our approach provides results to be in very good agreement with exact solutions. The error is about 5% and it decreases with increasing output intensity.





▲

Fig. 5. Normalized output power P_{out}/P_{sg} is plotted as a function of the normalized small signal gain $2g_0$ with the linear losses, as a parameter for two-photon absorber. The normalized small signal nonlinear loss coefficient $\alpha_{s0} = 1$, the ratio of the active medium length to the total length of the structure is $\eta = 0.9$, the saturation parameter $\beta = 5$ and the output mirror reflectivity coefficient is $r_1 = 0.9$

Fig. 6. Normalized output power P_{out}/P_{Gs} is plotted as a function of the normalized small signal gain $2g_0$ with the linear losses, as a parameter for two-photon absorber. The normalized small signal nonlinear loss coefficient $\alpha_{s0} = 1$, the ratio of the active medium length to the total length of the structure is $\eta = 0.5$, the saturation parameter $\beta = 5$ and the output mirror reflectivity coefficient is $r_1 = 0.7$

In general, in the case of the laser with one-photon absorber the structure switches to the higher stable branch at the point in which the laser operation starts. We observe a different situation for the laser with two-photon absorber, Fig. 5 and Fig. 6. In general, in this case the laser action is stable at the beginning. In this region of the operation with the increasing gain, resulting in the increasing light intensity in the laser cavity, the losses in the region II also increase (the two-photon absorber is in its linear regime of the operation). The hysteresis loop appears for the certain value of the gain in the structure for which the mode intensity in the laser cavity is high enough to saturate two-photon absorber.

References

[1] SZCZEPAŃSKI P., Appl. Phys. 63 (1988), 4854.

[2] SZCZEPAŃSKI P., SIKORSKI D., WOLIŃSKI W., IEEE J. Quantum Electron. **25** (1988), 871.
[3] SZCZEPAŃSKI P., SKŁODOWSKA M., WOLIŃSKI W., J. Lightwave Technol. **9** (1992), 321.
[4] KUJAWSKI A., SZCZEPAŃSKI P., J. Modern Opt. **38** (1991), 1901.
[5] SZCZEPAŃSKI P., KUJAWSKI A., J. Modern Opt. **40** (1993), 1107.