ANALYSIS OF ENERGY LOSSES IN THE ZIGZAG SLAB-LASERS

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Abstract. The article considers energy losses in a Fabry-Perot laser resonator and zigzag laser in form of a flat truncated prism. It refines the values of the harmful losses of the zigzag laser three-mirror optical resonator, in which apart from material losses on absorption and scattering in the matrix of the active media, the losses on the radiation transferring through the non-ideal reflecting mirrors that provide a zigzag course of the beam in the cavity are included. The dependences of the losses coefficient on the design parameters of the three-mirror zigzag laser resonator are also analyzed.

Keywords: zigzag laser, three-mirror resonator, energy losses

ANALIZA STRAT ENERGII W LASERACH PASKOWYCH TYPU ZYGZAK

Streszczenie: Artykuł poświęcony stratom energii w laserze z rezonatorem Fabry-Perota i typu zygzak w formie płaskiego graniastosłupa ściętego. Zawiera on skorygowane wartości strat dla lasera typu zygzak z rezonatorem zawierającym trzy zwierciadła. Oprócz materiałowych strat na absorpcję i rozpraszanie w ośrodku czynnym, uwzględniono również straty spowodowane wyciekiem promieniowania przez nieidealne zwierciadła. Przeanalizowano również zależności współczynnika strat od parametrów projektowych rezonatora lasera zawierającego trzy zwierciadła.

Słowa kluczowe: zygzak laserowe, trzy-lustro rezonatora, straty energii

Introduction

One possible way of solving the problem of laser radiation sources miniaturization is the development of structures, which ensure the effective interaction of active particles and radiation in the cavity. The main purpose of the optical laser cavity is the implementation of positive feedback and as a result induced in the inside cavity radiation repeatedly passes through the active medium [1].

1. Energy losses in a laser with a Fabry-Perot resonator

The most common type of resonator is a system of two mirrors facing each other by reflecting surfaces (Fabry–Perot cavity) (Fig.1).
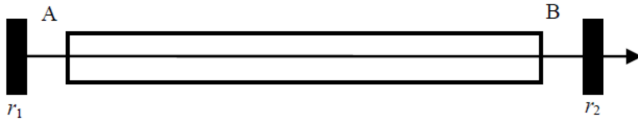

Fig. 1. Optical layout of a Fabry–Perot cavity: r_1 and r_2 - the cavity mirrors reflection coefficients

In the optical Fabry–Perot resonator (Fig.1) we can distinguish the main types of energy losses, determined by scattering on the active medium inhomogeneities and non-resonant absorption by the coefficient ρ and losses on the output radiation from the resonator through a mirror. Mirrors (at least one of them) are made transparent as part of the generated radiation in the active medium must be derived from the resonator. If the mirror reflection coefficients by the intensity are equal to r_1 and r_2, then efficiency losses due to output radiation from the resonator per unit of length are equal to $k_r = \dfrac{1}{2L}\ln\dfrac{1}{\eta\, r_2}$, where L – the length of the beam passing from point A to point B (Fig.1). For a laser with a Fabry - Perot cavity the length of the ray l in the active element is equal to its length L (Fig.1). In order to maintain the lasing condition the gain exceeding the total losses is necessary. The coefficient ρ of material losses and the gain coefficient k are determined by the properties of the active medium. The desire to reduce the size of the laser by reducing the length L will increase the loss factor k_r, which may result in loss of generation. In addition, for small values of L the quantity of energy extracted from the active particles decreases. Consequently, to reduce the size of laser radiation sources it is necessary to find such a resonator structure, in which the length of the radiation passage in the active element l would exceed the length of the resonator L.

2. Three-mirror zigzag laser cavity in form of flat truncated prism

Creation of a compact solid-state lasers is possible in the case of using active elements in the form of flat truncated prism with zigzag course of an optical beam in the three-mirror cavity (zigzag laser) (Fig.2) [2, 3].
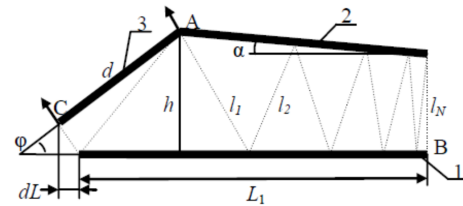

Fig. 2. Optical scheme of the three-mirror laser cavity and the beam course in it (mirrors are indicated by bold lines): 1 and 2 – highly reflecting mirrors, 3 – output mirror

Highly reflecting mirrors *1* and *2* form an angle α, and provide a zigzag course of radiation in the cavity. Output half-transparent mirror *3* forms an angle φ with a mirror *2* [4].

Radiation is propagating perpendicular to the mirror *3*, turns back and is reflected by mirrors *1* and *2* as long as the angle of incidence at one of the mirror does not become zero. At this point, the reflection of radiation and self-propagation of its way to the mirror *3* in the opposite direction take place until the release of radiation through a mirror [4].

All rays parallel to the optical beam propagating in a zig-zag way in the cavity from the point of normal reflection from the mirror *3* to the normal incidence on the mirror *1*, are almost the same length *l*. Expression relating the length of the trajectory *l*, by which the radiation propagates in the active medium in a single pass from point A on the mirror *3* to point B on the mirror *1* with angles α and φ and height *h* is given by [4]:

$$l = h\left\{\frac{1}{\cos\varphi} + \cos(\alpha+\varphi)\sum_{k=1}^{\varphi/\alpha}\{\cos[\varphi-(k-1)\alpha]\cdot\cos(\varphi-k\alpha)\}^{-1}\right\}. \quad (1)$$

The length *l* is the sum of the segments l_1, l_2,..., l_N between mirrors *1* and *2* (Fig.2). Each segment is equal to the height *h* of the active element at $0.1°\le \alpha < 5°$ and $0.1°\le \varphi < 25°$ in the first approximation. Since the number of segments *N* the length of the trajectory *l* can be calculated by a simple relation [5]:

$$l \approx N \cdot h. \quad (2)$$

The effective length of the radiation passage in the active medium can be calculated by formula (2) with a comparatively small relative error δ < 5% in the range of angles $0,1 \le \alpha < 5°$ and $0,1 \le \varphi < 25°$.

A beam of parallel rays propagating in the active element retains its shape and length of radiation single passage in the cavity greatly exceeds the transverse and longitudinal dimensions of the laser for certain values of structural parameters of the construction.

3. Analysis of energy loss in a three-mirror zigzag laser cavity

In the zigzag laser with an active element in the form of flat truncated prism compared to lasers with a Fabry–Perot cavity in addition to harmful losses by the absorption and scattering in the matrix of the active media ρ and useful losses of laser radiation through the output mirror with reflection coefficient r_3, characterized by the quantity $k_r = \dfrac{1}{2l}\ln\dfrac{1}{r_3}$, where l – length of the trajectory along which radiation propagates in the zigzag way in resonator, there are additional losses while radiation reflecting from the mirrors 1 and 2 with reflection coefficients r_1 and r_2 located at a small angle α to each other. In case of equality of coefficients r_1 and r_2 denote them by r. In this case, the total coefficient of harmful losses is given by

$$\rho^* = \frac{2N-1}{2l}\ln\frac{1}{r} + \rho, \qquad (3)$$

where N – number of reflections. Provided that when $0{,}1° \le \alpha < 5°$ and the angle between the output mirror and a mirror with a reflection coefficient r_1 $0{,}1° \le \varphi < 25°$ the length of the trajectory can be calculated by the approximate relation (2). Then the formula (3) becomes:

$$\rho^* = \frac{2N-1}{2Nh}\ln\frac{1}{r} + \rho. \qquad (4)$$

When $N \gg 1$ (4) is simplified to the form:

$$\rho^* = \frac{1}{h}\ln\frac{1}{r} + \rho. \qquad (5)$$

When the values of the angle $0.1° \le \alpha \le 5°$ the mirrors 1 and 2 are parallel to each other in first approximation and form a Fabry–Perot cavity with loss factor on the mirrors determined exactly by the formula (5).

For Nd:glass laser with a coefficient of material losses $\rho = 0{,}01\,\text{cm}^{-1}$ [6] for $h = 1\,\text{cm}$ and $r = 0{,}998$ $\rho^* = 0{,}012\,\text{cm}^{-1}$ and only 20% higher than the coefficient of the material losses ρ.
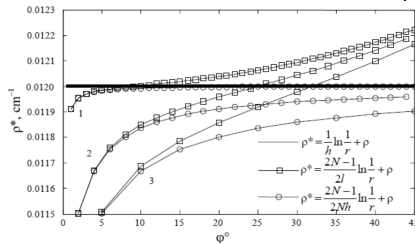
Fig. 3. The dependence of the loss coefficient ρ^* vs angle φ for different values of the angle α for $h = 1cm$ and $r = 0{,}998$: $1 – \alpha = 0{,}2°$; $2 – \alpha = 2°$; $3 – \alpha = 5°$

The values of the coefficient ρ^* can be calculated with a maximum relative error $\delta < 5\%$ (5) and $\delta < 12{,}5\%$ by the formula (5) on the angles $0{,}1° \le \alpha \le 5°$ and $0{,}1° \le \varphi < 45°$, as shown in Fig.3. The value of the loss factor ρ^* increases by 7% with increasing angle φ for constant $h = 1\,\text{cm}$ and $r = 0{,}998$. This is explained by the fact that with increasing angle φ at a constant angle α increases the number of reflections N and, consequently, losses due to radiation transferring through the mirrors 1 and 2 are increasing.

While reducing the reflection coefficient r loss factor ρ^* grows significantly (Fig.4). At low values of r coefficient ρ^* become large (for $r = 0{,}87$ loss factor $\rho^* = 0{,}15\,\text{cm}^{-1}$) and may exceed the value of the gain, such as for the active media on the glass doped with Nd^{3+}, where $\rho = 0{,}01\,\text{cm}^{-1}$, and the gain in the medium reaches $k = 0{,}15\,\text{cm}^{-1}$.

The height of the active element h can be increased for minimizing the loss coefficient ρ^* (Fig. 4). For $h > 10\,\text{cm}$ loss coefficient ρ^* is increasing by only 1% at $r = 0{,}998$.

With decreasing value of h ρ^* will increase. When $r = 0{,}96$ and $h = 0{,}1\,\text{cm}$ $\rho^* = 0{,}4082\,\text{cm}^{-1}$ and as a result is much higher than the value of the gain $k = 0{,}15\,\text{cm}^{-1}$. The increasing in height to minimize losses ρ^* would violate the principle of compactness of the laser.
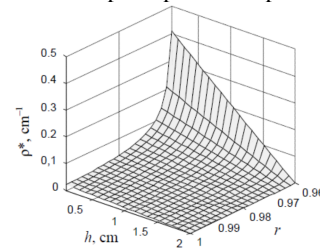
Fig. 4. Dependence of loss factor ρ^* vs the height h and the reflection coefficient r of mirrors 1 and 2

4. Conclusion

Analysis of energy losses in the zigzag laser in the form of a flat truncated prism shows that for decreasing the ratio of harmful losses coefficient in the cavity ρ^* it is necessary to use mirrors, between which the radiation propagates in the zigzag way, with the highest value of the reflection coefficient. However, even with the use of highly reflecting covers the maximum possible reflection coefficient is $r \approx 0{,}998$. The height of the active element can be increased for minimizing the losses coefficient ρ^*, but in this case increasing size of the laser.

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