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Three-mirror Reflector for Frequency Selection in High-gain Lasers

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The influence of different parameters in the reflection coefficient of a three-mirror reflector is calculated. It is demonstrated that such a reflector can be applied for frequency selection in high gain lasers. In an experiment single-mode operation of a flash-lamp pumped Rhodamine 6G-laser was obtained.

A influência de diferentes parâmetros sobre o coeficiente de reflexão de um refletor de três espelhos é calculada. Demonstra-se que tal refletor pode ser aplicado na seleção de freqüência em lasers de alto ganho. Em uma experiência obteve-se a operação de um 6G-laser de Rhodamine com bombeamento através de uma lâmpada-flash.

1. INTRODUCTION

A three-mirror reflector is equivalent to a Fabry-Perot etalon with the front mirror replaced by an interference filter. The reflectivity of the arrangement shows narrow maxima in dependence of its length, which is opposite to the behaviour of a Fabry-Perot etalon. Frequency selection and single-mode operation using a three-mirror reflector has been investigated previously only for low gain lasers, especially for the He/Ne-lasers[1,2,3].

In this paper a computer study is presented yielding parameters for three-mirror reflectors suitable for high gain lasers. An experiment is described applying a reflector of this type for frequency selection in a dye laser yielding single-mode operation in combination with other intracavity pre-selection elements (Fig.4).

The three-mirror reflector can be compared with other interferometric systems for frequency selection[4,5,6,7], e.g. the Fabry-Perot etalon and the Fox-Smith-interferometer. Fabry-Perot etalons have to be tilted with respect to the laser axis. This produces losses due to beam walk-off and limits the length and bandwidth. These restrictions do not exist for the three-mirror reflector. A Fox-Smith interferometer replacing one laser mirror has frequency selective properties similar to a three-mirror reflector. However, the optical components and the mechanical design are quite different. Probably, the mechanical construction and the adjustment of a three-mirror reflector are easier in many cases because all components have a common optical axis.

2. THEORY

In the three-mirror reflector (TMR see Fig.4) the mirrors 2 and 3 are separated by a $\lambda/2$-layer with the transmission coefficient T_0. The mirrors 3 and 4 represent a resonator with the length $L_R=\lambda(k\pi+\beta/2)/2\pi$, where k is an integer, λ is the wavelength, and β the phase shift. The amplitude reflection and the power transmission coefficients of the mirror i are r_i and T_i. Ref.2 gives an expression for the amplitude reflection r_2^* of the three-mirror reflector which may be simplified for the case of an exact $\lambda/2$ layer between mirror 2 and 3 to

$$r_2^* = -|r_2| + \frac{T_0T_2(|r_3|(\exp(-i\beta) - |r_3||r_4|) - T_3|r_4|)}{(\exp(-i\beta) - |r_3||r_4|)(1-T_0|r_2||r_3|) + T_0T_3|r_2||r_4|} \qquad (1)$$

The half-width $\Delta\nu$ of $R_2^* = |r_2^*|^2$ is given by *

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* The half-width is defined with an additional factor 2 in ref.2.

$$\Delta\nu = \beta_0 c/2\pi L_R$$

with

$$\beta_0 = \text{arc cos}\ (-2r_{3/2}|r_4| + r_{3/2}^2|r_4|^2)) \tag{2}$$

and

$$r_{3/2} = -|r_3| + T_0T_3|r_2|/(1 - T_0|r_2||r_3|).$$

The dispersion range of the system is

$$\Delta\nu_D = c/2L_R\ . \tag{3}$$

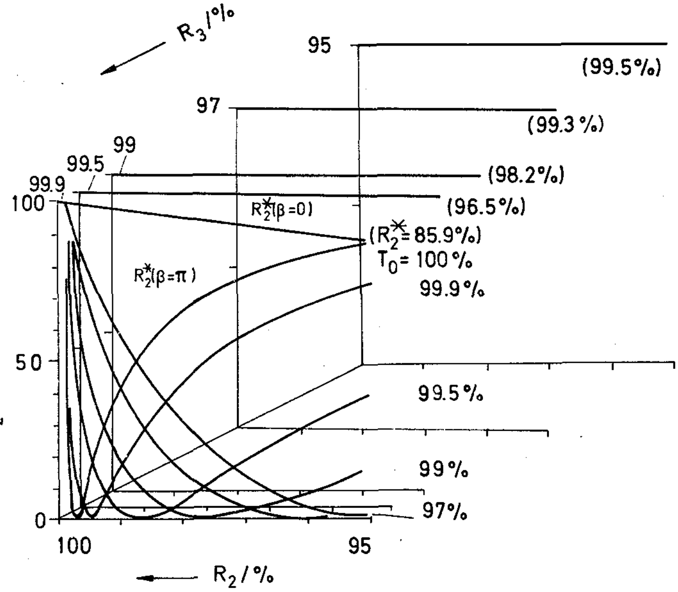
According to Eq.(1) the reflection coefficient $R_2^* = |r_2^*|^2$ can be calculated. For the cases interesting here a maximum for $\beta = 0$ and a minimum for $\beta = \pi$ results (Fig.1).

3. CALCULATIONS

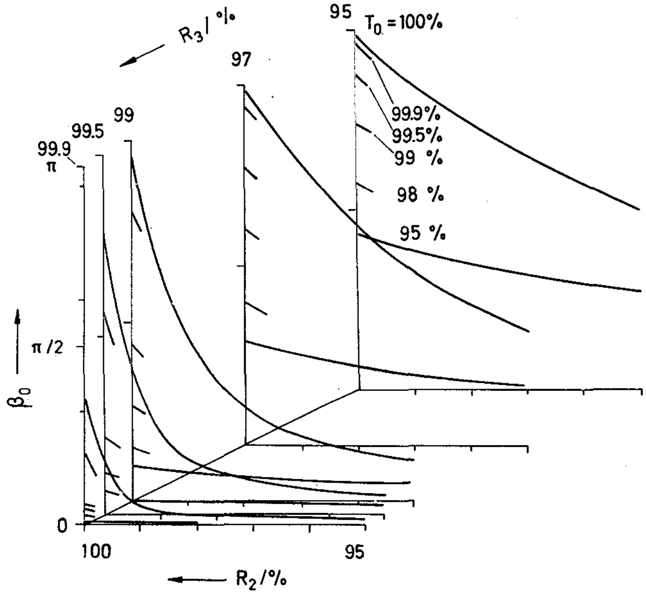
A maximum reflection coefficient $R_2^*(\beta=0)$ near 100%, a small minimum reflection coefficient $R_2^*(\beta=\pi)$, and a narrow band-width $\Delta\nu$ are required for mode selection in high gain lasers. The narrow band-width can be obtained by a small β_0 or a large length L_R of the resonator. The conditions for low gain lasers are less restrictive because a larger minimum reflection coefficient is permissible.

In what follows calculations are discussed which lead to a system suitable for high gain lasers.

In Fig. 1 (a) and (b) the calculated maximum $R_2^*(\beta=0)$ and minimum $R_2^*(\beta=\pi)$ and β_0 are shown in dependence of R_2 and R_3 with T_0 as parameter. The other physical data used for the calculation according to Eq. (1) and (2) are determined by the following conditions: The reflection coefficient R_4 of the mirror 4 should be as high as possible and the absorption coefficients $R_2 = 1 - R_2 - T_2$ and $A_3 = 1 - R_3 - T_3$ of the mirrors 2 and 3 should be very small. Using typical dielectric mirrors of ZnS and $Na_3Al_6F_3$ the following data were used in Fig. 1: $R_4 = 99.8\%$ (13 layers) and $A_2 = A_3 = 0.1\%$.



1a



1b

Fig.1(a) - $R_2^*(\beta=0)$ and $R_2^*(\beta=\pi)$ in dependence of R_2 and R_3 with T_0 as parameter. $R_2^*(\beta=0)$ is nearly independent of T_0 and $R_2^*(\beta=\pi)$ of R_3. The data $A_2 = A_3 = 0.1\%$ and $R_4 = 99.8\%$ were used. 1(b) - Dependence of β_0 on R_2 and R_3 with T_0 as parameter.

Fig.1(a) demonsrrates that the maximum $R_2^*(\beta=0)$ is approximately independent of T_0 and the minimum $R_2^*(\beta=\pi)$ is independent of R_3 for the parameters choosen. $R_2^*(\beta=\pi)$ shows a zero minimum at

$$|r_2| = T_0(1 - A_2)(|r_3| + |r_4|(1 - A_3))/(1 + |r_3||r_4|), \qquad (4)$$

which depends strongly on T_0. In Fig. 1(a) $R_2^*(\beta=0)$ is a nearly linear function of R_2 yielding values of $R_2^*(\beta=0)$ = 99.9% for R_2 = 99.9%. The values of $R_2^*(\beta=0)$ which decreasewith increasing R_3 are given in Fig. 1 (a) in brackets for R_2 = 95%.

In Fig.1(b) β_0 is given using a similar representation as for R_2^* in Fig. 1(a). The dependence of β_0 on R and R_3 is shown for T_0 = 97% and 100%. For intermediate T_0 additional values of β_0 are given for $R_2 \approx$ 100%. For application of a three-mirror reflector only cases with $\beta_0 \lesssim \pi/2$ are of interest because for $\beta_0 \gtrsim \pi/2$ the system has the propertieâ of a Fabry-Perot etalon which has broad reflectivity maxima. The limiting case of $\beta_0 = \pi/2$ is given by

$$R_3 = T_0^2\, R_2(1 - A_3)^2 \qquad (5)$$

It may be concluded from Figs. 1(a) and (b) that three-mirror reflectors with high $R_2^*(\beta=0)$ and low $R_2^*(\beta=\pi)$ and β_0 can be constructed especially in the region R_2 > 99%, R_3 > 99%, and T_0 near 100%. The optimum choice of R_2, R_3, and T_0 depends on the laser type and gain and other experimental conditions. As two examples from Figs. 1(a) and (b) three-mirror reflectors can be constructed with

(1) $R_2 = R_3$ = 99.5% , T_0 = 99.9% yielding

$R_2^*(\beta=0)$ = 99.6% , $R_2^*(\beta=\pi)$ = 0.0%, β_0 = 0.93 or

(2) R_2= 99.7% , R_3 = 98% , T_0 = 97% yielding

$R_2^*(\beta=0)$ = 97.1% , $R_2^*(\beta=\pi)$ = 28.3%, β_0 = 0.05 .

Example (1) shows that values of $R_2^*(\beta=0) \approx 100\%$ and $R_2^*(\beta=\pi) \approx 0\%$ can be achieved only if a large bandwidth parameter β_0 is allowed. According to Refs.(2,3) a value of $R_2^*(\beta=0) \approx$ 100% and a small β_0 is possible if the minimum reflectivity $R_2^*(\beta=\pi)$ is high, e.g. 90%. This type of three-mirror reflector is suitable for frequency selection in low gain lasers. Example (2) shows that for high gain lasers a compromise can be found yielding large $R_2^*(\beta=0)$, small $R_2^*(\beta=\pi)$ and small β_0.

In Figs.2 and 3 the dependence of the properties of the three-mirror reflector on T_2 and T_3 is investigated for example (1) with $R_2 = R_3 = 99.5\%$. The other non-varied data are the same as in Fig.1: $R_4 = 99.8\%$ and $A_3 = 0.1\%$ (Fig.2) or $A_2 = 0.1\%$ (Fig.3).

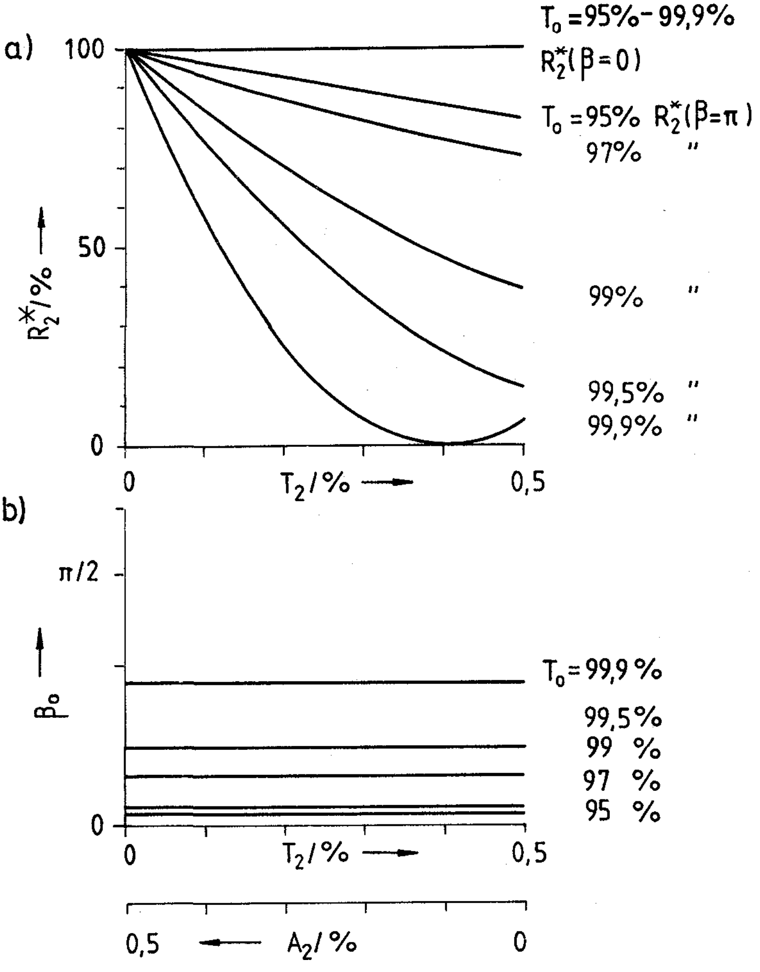


Fig.2(a) - $R_2^*(\beta=0)$ and $R_2^*(\beta=\pi)$ in dependence of T_2 or A_2 with T_0 as parameter. The data $R_2 = R_3 = 99.5\%$, $R_4 = 99.8\%$, and $A_2 = 0.1\%$ were used. 2(b) - Dependence of β_0 on T_2 or A_2 with T_0 as parameter.

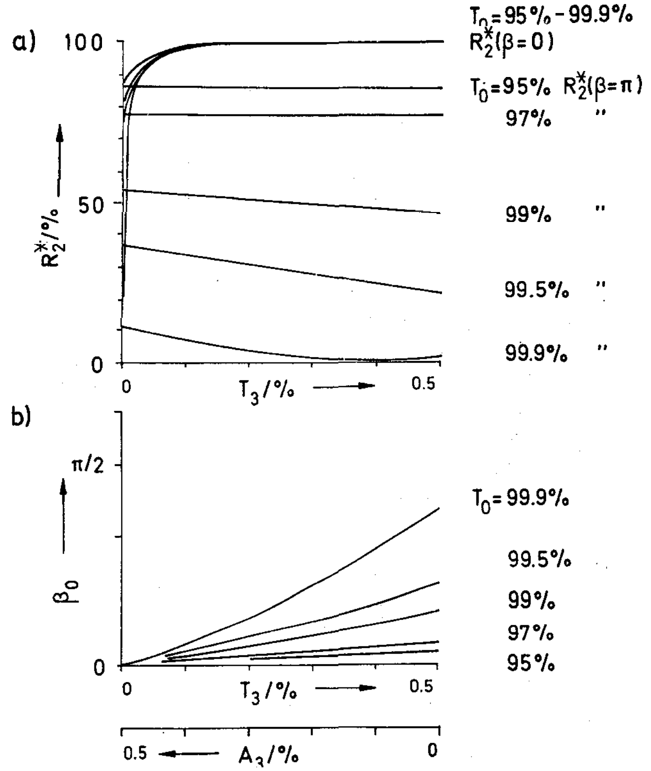


Fig.3(a) - $R_2^*(\beta=0)$ and $R_2^*(\beta=\pi)$ in dependence *of* T_3 or A_3 with T_0 as parameter. The data R_2 = R_3 = 99.5%. [illegible] ≈ 99.8%, and A_2 = 0.1% were used. 3(b) - Dependence *of* β_0 *on* T_3 *or* A_3 with T_0 as parameter.

It may be concluded from Fig. 2 (a) and (b) that the absorption coefficient A_2 should be very small. For the case T_0 = 99.9% a zero minimum of $R_2(\beta=\pi)$ arises at A_2= 0.1%. The same minimum appears for A3 = 0.1% in Fig. 3 (a) and in Fig. 1 (a) which was calculated for A_2 = A_3 = 0.1%. In conclusion the procedure proposed at the beginning of this section seems reasonable: The absorption coefficients of the mirrors 2 and 3 are choosen as small as possible (e.g. 0.1%), and the optimization of the three-mirror reflector is done according to Fig. 1 by a suitable choice of R_2, R_3 , and T_0.

In the computer study also the properties of the three-mirror reflector were investigated varying R_4. A reduction of R_4 results in a decrease of $R_2^*(\beta=0)$ and in a increase of β_0. Thus as mentioned above the optimum choice of the reflection coefficient of mirror 4 is R ≈ 100%.

4. EXPERIMENT

For testing the three-mirror reflector in a high gain laser mode-selection in a dye laser was studied in experiment. A three- mirror reflector TMR (Fig.4) with the following data was available: $R_2 \approx R_3 \approx$ $\approx 99.5\%$, R = 99.8%, $T_0 \approx 99.9\%$, $T_2 = T_3 \approx 0.4\%$. According to Eqs. (1) -(3) or to Fig.1 the maximum and minimum reflection coefficients are calculated to 99.9% and 0.0% and $\beta_0 = 0.93$ (see example (1) in last section). With $L_R = 4.3$ cm the bandwidth is Av ≈ 1.0 GHz, and the dispersion range $\Delta\nu_D = 3.5$ GHz. By a small variation of the parameters three-mirror reflectors with a smaller bandwidth can be obtained. The reflection coefficient depends critically on the separation between the mirrors 2 and 3. Therefore mirrors 2 and 3 have been fabricated on a common substrate, separated by a $\lambda/2$-layer made of LaF_3. The interference filter consisting of mirrors 2 and 3 had a measured power transmission coefficient of 0.2 and a halfwidth of 2 nm as shown in Fig.5. The wavelength for which peak transmission occured varied for different positions of the filter indicating that the $\lambda/2$-layer was wedge-shaped.

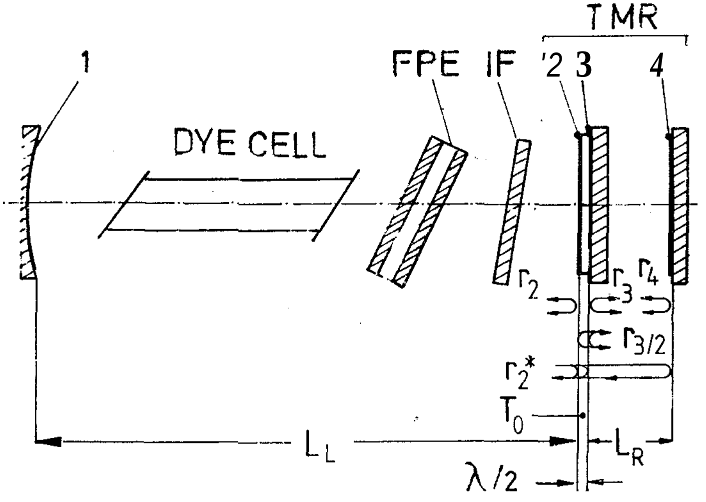


Fig.4 - Dye-laser configuration with three-mirror reflector TMR consisting of mirrors 2, 3, 4, Fabry-Perot etalon FPE, and interference filter IF. r_2, r_3, r_4 are the amplitude reflection coefficiants of the mirrors 2, 3, 4. T_0 is the power transmission coefficient of the $\lambda/2$-layer separating mirrors 2 and 3. $r_{3/2}$ is the amplitude reflection coefficient of the combination of mirrors 2 and 3 which can be considered as an additional interference filter.

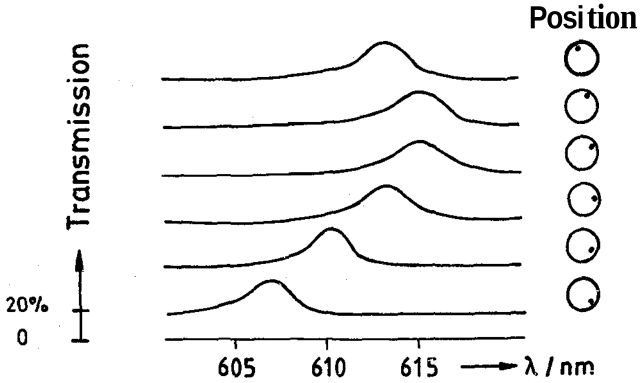


Fig.5 - Transmission coefficient versus wavelength λ of the interference filter consisting of mirrors 2, 3 measured for different positions of the probing beam. The mirror diameter was 3 cm, the position of the probing beam is indicated by a point.

The laser and the mode selective elements are shown in Fig. 4. Rhodamine 6G in a Brewster angled dye cell was pumped by a flashlamp. The laser length was L_L = 52 cm. The mirror 1 has a reflection coefficient of R_1 = 70% and the mirror radii were ρ_1 = 3 m, $\rho_2 = \rho_3 = \rho_4 = \infty$. Narrowing the bandwidth of the laser emission from 12 nm to 0.005 nm (4 GHz) was achieved by an interference filter IF (not to be mixed up with the interference filter built up by mirrors 2 and 3) and a Fabry-Perot etalon FPE using a plane mirror instead of the three-mirror reflector. A schematic: representation of the laser spectrum is given in Fig.6. After insertion of the IF and FPE the laser oscillated in the fundamental transversal mode TEM_{00}. Substituting the three-mirror reflector TMR for the plane mirror yielded single longitudinal mode operation. The action of the THR on the laser spectrum is represented in Fig. 6.

The single mode power amounted to about 1 kW, the energy was -1 mJ. Without frequency selection the laser produced an output energy of 50 mJ. The main power loss was due to the interference filter IF and the Fabry-Perot etalon FPE which have been used for preselection of the frequency. It has not been tried to optimize these components because the aim of the experiment was only to test the performance of the three-mirror reflector. This produced only a power reduction of 25%.

The laser spectrum was analyzed with an external Fabry-Perot interferometer (plate separation 60 mm) . Photographs taken for single-

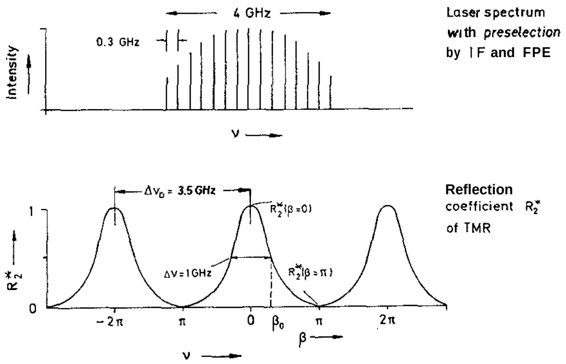


Fig.6 - Laser spectrum with preselection by an interference filter IF and a Fabry-Perot etalon FPE and reflection coefficient R_2^* of the three-mirror reflector TMR.

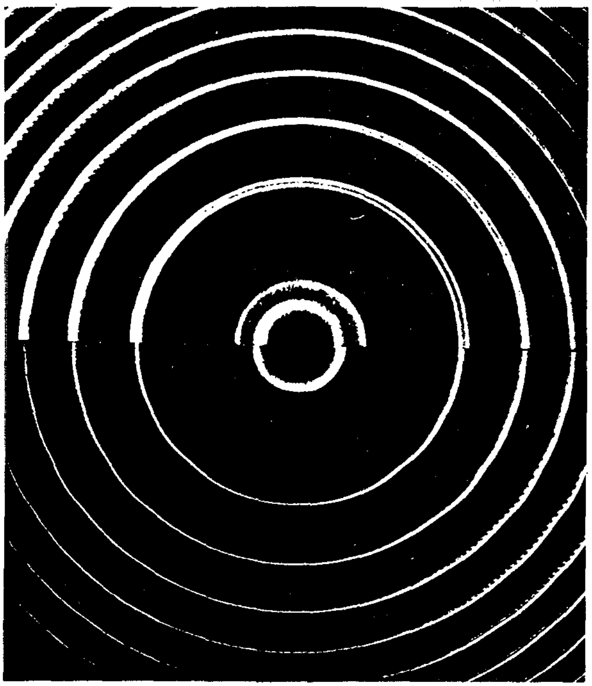


Fig.7 - Two-mode and single-mode output interferogram.

and two mode operation are shown in Fig.7. In order to test the tuning range of the single mode laser both the IF and FPE have to be tilted.

Simultaneously the distance of the mirrors 2 and 3 had to be tuned to be equal to the half of the selected laser wavelength. This was accomplished by using the wedge-shaped λ/2-layer between the mirror layers and displacing the interference filter consisting of mirrors 2 and 3 perpendicular to the laser axis. Because only a slight wedge was available the tuning range was limited from 607 nm to 615 nm.

In conclusion it is demonstrated that a three-mirror reflector can be used for frequency selection in a dye laser which has a much larger gain than the He-Ne-laser investigated previously[3]. Thus, the three-mirror reflector represents an alternative interferometric method for single-mode operation of high gain lasers.

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