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Mode Selection in Ion Lasers

Different methods of longitudinal mode selection in icn lasers and their advantages are discussed. Special attenticn is paid to a technique of an intracavity absorber. Conditions of its Lorentz width and central frequency matching are also derived.

1. Introduction

Some applications of lasers require sources of coherent light of high spectral purity, for example Lamb dip spectroscopy, holography with large depth of field, communication systems, precise interferometry etc. Contrary to this, the medium gain of lasers exhibits gain at several wavelengths and the output consists, therefore, of a number of closely spaced frequencies. Due to the mentioned need for high-power narrow-band width lasers many techniques for reducing the number of laser modes have been developed. We shall discuss briefly some of them, special attention will be devoted to the method of mode selection by means of an intracavity saturable absorber.

2. Review of Mode Selection Methods

There exist two types of modes in an open resonator. The first type with the same spatial energy distribution in the plane transversal to the resonator axis possesses different numbers of half wavelength along the axis of the resonator. They are called longitudinal modes and their frequency spacing $\Delta\nu_L$ is given by

$$\Delta\nu_L = \frac{c}{2L}, \qquad (1)$$

where c is the speed of light, L — resonator length.

The other type consists of transverse modes, i.e., a set of modes of different spatial energy distribution in the transverse direction corresponding to each longitudinal mode. The selection of those is quite simple — usually the oscillation on a prefered mode is allowed by means of a diaphragm. We shall assume henceforth, that there is only the basic transverse mode (TEM_{00}) in the cavity.

Length Reducing

It is obvious from Eq. (1) and Fig. 1 that the larger the mode separation $\Delta\nu_L$ the smaller the length of the cavity. We obtain, thus a single-mode operation

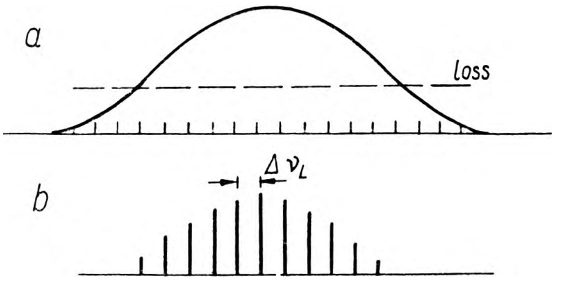

Fig. 1. The course of a laser gain and longitudinal modes: a — gain curve, b — laser output

but at the expense of the output power. This method, although used for He–Ne lasers, is not applicable to ion lasers due to a small gain of output power. (In case of an argon ion laser the gain width is usually 3000 MHz, to obtain a single mode generation the cavity length should be $L \leqslant 5$ cm and the output power in the range of few μW).

Filtering the Output Power

It is possible to let the laser oscillate at a number of longitudinal modes and by passing the output beam through a narrow-band Fabry–Pérot resonator to obtain a single-mode beam. The disadvantageous of this method are, however obvious. Firstly, the power ge-

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nerated in unwanted modes is lost, secondly, it is necessary to prevent coupling between the laser cavity and external Fabry–Pérot resonator, as interference between the reflected and the primary beams could cause instability.

Internal Selective Elements

Due to the disadvantages of the external filtering many systems with internal selective elements have been developed. Let us point out the use of a plane parallel plate and F. P. resonator as internal selective elements. This technique has an advantage of more power being available for one mode. At the same time its successful use requires a very high selectivity of the elements applied.

Interferometric Technique

There are many mode-selective techniques which, according to SMITH [1], are called interferometric. In each case a complex laser resonator is used with more than two mirrors. Such a structure has a very narrow selectivity so that only one longitudinal mode oscillates. Among a few possible interferometric systems one which gives the best results, has originally been described by Fox and Smith and was successfully used in single-mode ion laser experiments. This device is shown in Fig. 3. The three-mirror system can be considered as a mirror of variable reflectivity, the peaks of which are spaced by

$$\Delta\nu_R = \frac{c}{2(d_1+d_2)}. \qquad (2)$$

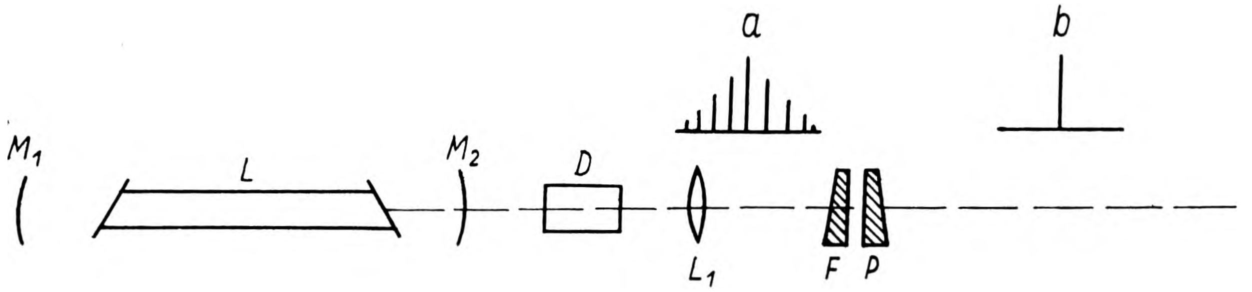


Fig. 2. Filtering of the beam by means of an external element
L – laser, M_1, M_2 – mirrors, D – decoupler, L_1 – matching lens, $F\,P$ – Fabry–Pérot etalon, a – spectrum of the free running laser, b – spectrum of the filtered output

By increasing the reflectivity of the beam splitter one can make the width of the low-loss region as narrow as desired. But the said system has its disadvantage in its sensitivity to mechanical and temperature changes of the length of both cavities.

Absorbing Film

The standing waves in a resonator of different longitudinal modes have nulls at different points along the resonator axis. A thin absorbing film placed in

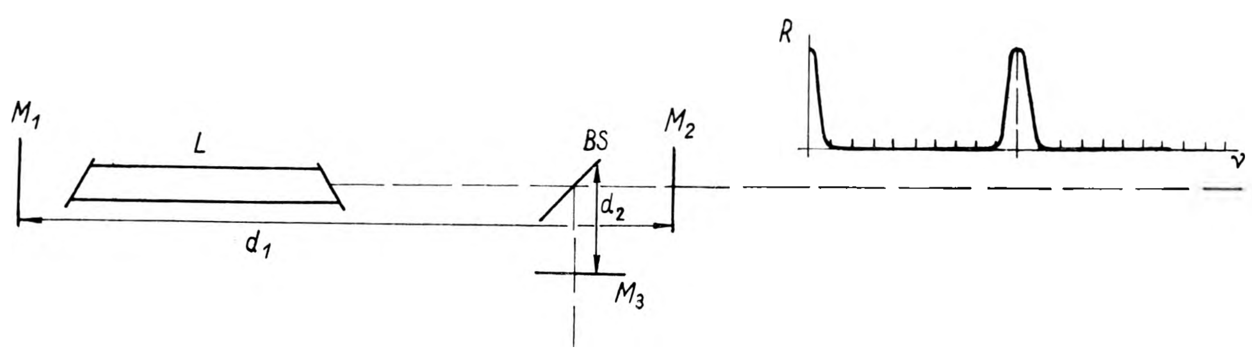
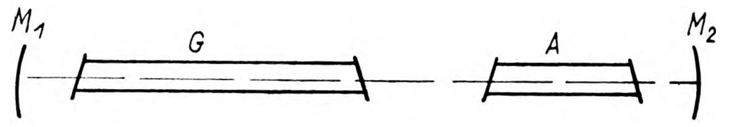


Fig. 3. Scheme of Fox–Smith interferometer
L – laser tube, M_1, M_2, M_3 – mirrors, BS – beam splitter, Rν – dependence of reflectivity of a three-element mirror on the frequency

a laser resonator will therefore absorb energy of those modes which have non-zero fields at that point. A mode with a zero electric field at the point of the film position will experience only small losses, provided that the thickness of the film is small in comparison with the wavelength. The scheme, according to [2], is useful for low-power lasers due to heating of the film in high-power lasers.

Resonant Absorber

The use of a resonant absorber as an intracavity selective element was originally suggested and experimentally proved for He–Ne laser in [3]. The idea is based on the use of a system of the gain element with the wide gain curve and a saturable absorber with the narrow absorption curve, as shown in Fig. 4.



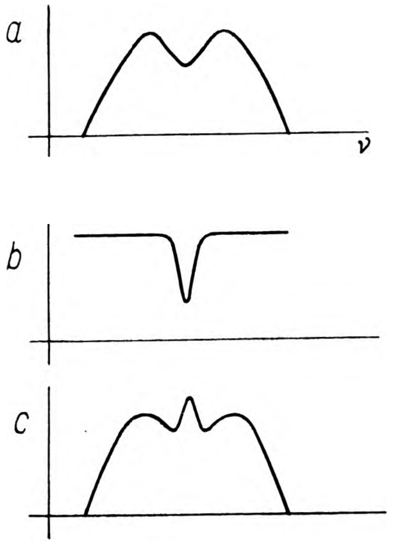


Fig. 4. Scheme of the laser with the intracavity absorber
G – gain tube, A – absorber, M_1, M_2 – mirrors, a – gain curve of the gain tube alone, b – absorption of the absorption tube alone, c – resulting gain curve of the system

The central frequencies of both: the gain and the absorption curve are assumed to be the same. It is possible in such a case to adjust the losses so that the gain will be below the threshold for all – except one – longitudinal modes. Theoretical explantations, based on Lamb's semiclassical theory as well as on a "hole-burning" theory, have been given in several papers. It was shown in paper [4] that the intensity of the field in the resonator is given by the following equation

$$E^2 = 8\gamma_a\gamma_b\left(\frac{\hbar}{2\Pi}\right)^2\left\{\exp\left[-\left(\frac{\Omega-\omega_g}{K_u}\right)^2\right]\times\right.$$

$$\left.\times\left[1-\frac{n_a}{n_g}\exp\left[-\left(\frac{\Delta\omega}{K_u}\right)^2\right]\right]-\frac{1}{n_g}\right\}\times \qquad (3)$$

$$\left\{\left[1+\frac{1}{1+\left(\frac{\Omega-\omega_g}{\gamma_{ab}}\right)^2}\right]-\frac{n_a}{n_g}\left[1+\frac{1}{1+\left(\frac{\Omega-\omega_a}{\gamma_{ab}}\right)^2}\right]\right\}^{-1}$$

which enables to investigate the dependence of the gain on detuning, absorption and gain ratio as well as the dependence of the gain on the linewidth of the gain and absorption curve (Fig. 5) and on the shift of central frequencies (Fig. 6). It was shown in that paper that the linewidth ratio must be greater than 0.5 and the central line shift must be small.

Fig. 5 and 6 indicate that the introduction of the saturable absorber into the cavity is not effective enough to suppress all longitudinal modes except a favourite one. It has to be kept in mind that the results were derived in the third order approximation of the semiclassical theory being actually valid for the threshold region only, while lasers with absorbers are usually operated well above the threshold. It is the author's experience that taking higher terms of approximation makes calculation very cumbersome. In paper [5] the laser with the absorber was investigated on the basis

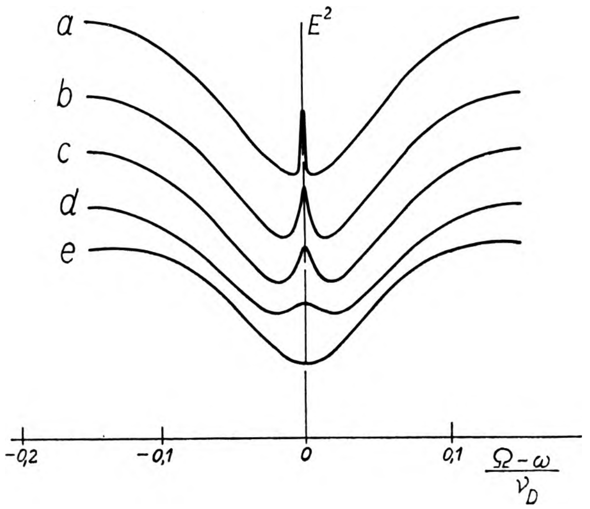


Fig. 5. Gain curves of the gas laser with the intracavity absorber for the varying Lorentz width of the absorber
The values of the parameters: $n_a/n_g = 0.5$, $a_g = 0.05$. The parameter a_n varies as follows: a – 0.001, b – 0.005, c – 0.01, d – 0.025, e – 0.05

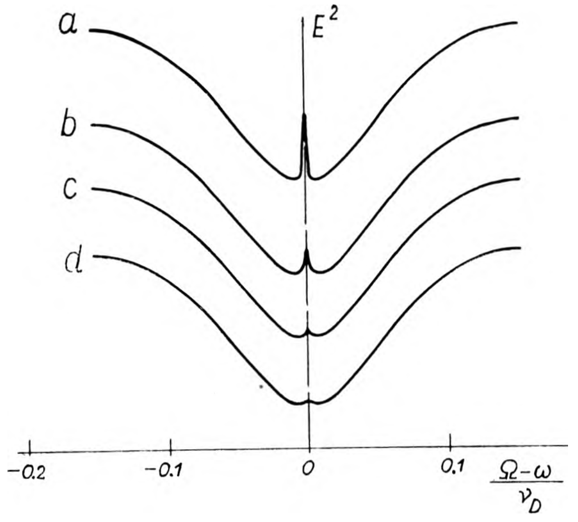


Fig. 6. Gain curves of the gas laser with the intracavity absorber for the varying shift of central frequencies
The values of the parameters for the calculation: a – 0.5, a_a – 0.001, a_g – 0.05. The value of $\Delta\omega$ varies as follows: curve a – 0, b – 0.001, c – 0.002, d – 0.003

of the "hole-burning" theory and the results obtained were in good accord with the experimental ones.

Let us point out that the system with the saturable absorber exhibits to some extent the autostabilization effect, as it tends to oscillate on the peak of the absorption curve, e.g., in a relatively narrow region where the losses are the lowest. However, the laser with the saturable absorber has its disadvantage in a higher level of noise compared with a short length one-mode laser as shown in some theoretical papers [6]. It is author's knowledge that the experiment on noise properties of the laser with the intracavity saturable absorber has not yet been reported.

3. Conclusion

It may be seen from the given review that a number of methods for obtaining one-mode operation of lasers has been developed. The use of a particular one depends on both: the expected power level and stability required in the experiment, as stabilization of many schemes needs a complicated electronics.

At the low power level the most reliable methods seem to be an intracavity etalon as well as an intracavity absorbing film, whereas at the high power level successful operations of the argon laser with Smith–Fox resonator have been reported. The use of the saturable absorber for the low power He–Ne was also reported, while its use for the high power ion lasers has still to be proved.

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