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ASYMMETRIC OUTPUT PROFILE OF Xe LASER

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Abstract

A new set of asymmetric modes was recently revealed in a Xe slab laser with pronounced lens effects originating from gas heating in the discharge. The appearance of these modes is a threshold effect. Their domain of existence in the Xe laser is discussed. It is shown that mode competition can result in output radiation asymmetry. Theoretical results are compared with experimental data.

1. Introduction

Recently it was demonstrated that the RF-excited waveguide Xe slab laser of medium gas pressure displays a number of uncommon properties [1, 2]. A noticeable lens effect arises due to gas heating in the discharge. The lens effect results in strong mode distortion so that the laser modes differ significantly from those of an empty waveguide. The second peculiarity of this laser is the breaking of the radiation symmetry of the output profile. In some cases, the radiation field is appreciably asymmetric relatively to the midplane of the waveguide. Although asymmetry can arise due to the inevitable imperfection of the laser design, the experiments demonstrate that even with special very accurate arrangements it is not always possible to eliminate the asymmetry of the mode pattern.

2. Asymmetric Modes

The presence of a rather strong negative gas lens caused by the discharge of the laser can be considered as a factor in favor of an asymmetric radiation profile. To analyze this situation, the modes are calculated with the help of the following equation [1, 2]:

$$\frac{d^a(x)}{dx^2} + \Big\{ k_0^2 \delta\varepsilon\, [x, a(x)] + q \Big\} a(x) = 0\,, \tag{1}$$

where x is the coordinate across the slab, $a(x)$ is the field amplitude, $1 + \delta\varepsilon\,[x, a(x)]$ is the dielectric permeability of the gas with saturation taken into account (the gain, and consequently the imaginary part of the dielectric permeability of the gas, depends on the field strength), and q is the eigenvalue of the boundary problem with the condition

$$a(l) = a(-l) = 0 \tag{2}$$

(the slab walls are situated at $x = \pm l$). It should be pointed out that Eq. (1) is a nonlinear boundary problem (see [2]).

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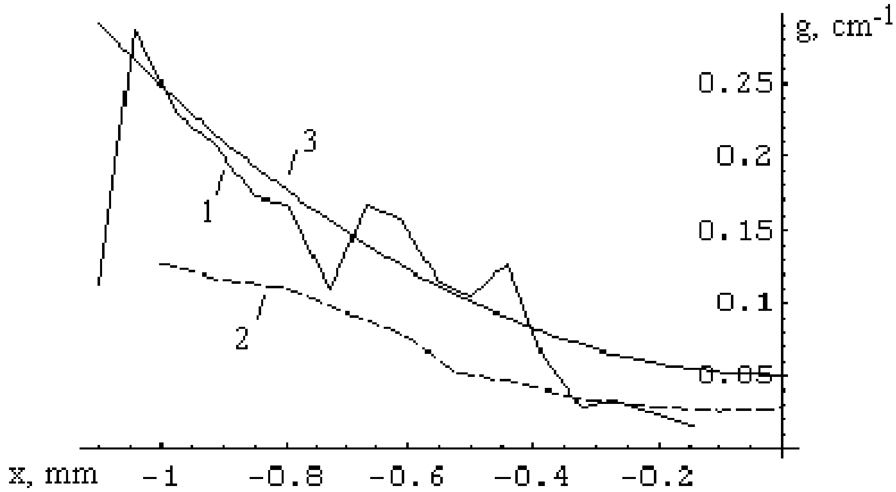

Fig. 1. Gain profile.

The real part of $\delta\varepsilon$ (and hence the refractive index) depends on the transverse coordinate x due to the gas heating. The dependence of the refractive index on temperature was presented in [1, 3] as follows:

$$\delta n = 0.000188\,\frac{273}{T}\,\frac{p\,[\mathrm{Torr}]}{760}\,.$$

The temperature distribution between the electrodes was described by a parabolic function of x [3]. The imaginary part of $\delta\varepsilon$ describes the saturated gain by the radiation. The saturation parameter is assumed to be constant across the slab, so that we write

$$g(x) = \frac{g_0(x)}{\dfrac{1+|a(x)|^2}{I_S}}\,,$$

where I_S is the saturation parameter.

The gain-profile measurements have been performed in [3, 4] and are shown in Fig. 1. The data refers to the "left" part of the slab ($-l < x < 0$). Curve 1 represents the recent measurements [4]. These measurements were performed at the University of Twente (The Netherlands). The dashed curve 2 represents earlier data [3]. The smooth solid curve 3 is a plot of the function

$$g(x) = 0.005 + 0.2\,\frac{x^2}{l^2}\ [\mathrm{cm}^{-1}]\,,$$

which is used in our mode calculations.

It is worth mentioning that the measurements in [4] were taken with better space resolution than those in [3]. The lasing circumstance involves an additional uncertainty due to the saturation influence. However, both results do not differ much in view of the experimental uncertainties.

Figures 2 and 3 demonstrate the calculated transverse profiles of the first two waveguide modes for different gas temperatures in the discharge. The number of nodes of a mode enumerates the mode

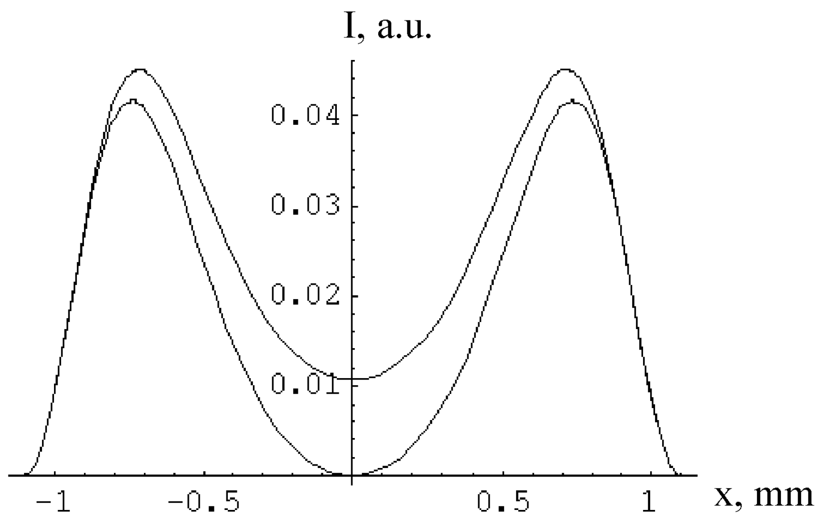

Fig. 2. Intensity contour I of the fundamental waveguide mode (upper plot) and the second one at $\Delta T = 30$ K.

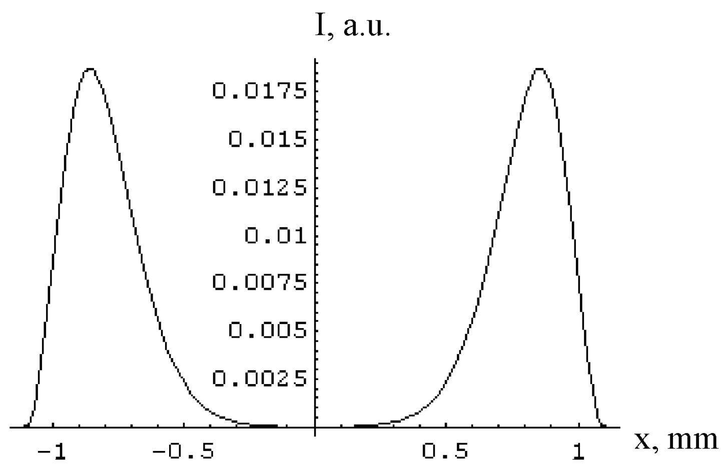

Fig. 3. Intensity profile of the two lowest modes at $\Delta T = 100$ K.

number as usual (the first or fundamental mode has no nodes, the second mode has one node, and so on). Calculations were performed for a slab of 2.2 mm width and 145 mm length filled with a gas mixture of Ar:He:Xe = 60:39.5:0.5 at a total pressure of 110 Torr. Figure 2 presents the intensity profiles of the first two modes for a temperature difference $\Delta T = 30\,\mathrm{K}$ between the electrodes and the center of the waveguide for the wavelength $\lambda = 2.05\,\mu$m.

Curve 1 is the intensity plot of the first (fundamental) mode in arbitrary units versus the transverse coordinate in the slit. Curve 2 represents the second mode (also in arbitrary units).

Figure 3 demonstrates the same data, but now calculated for $\Delta T = 110\,\mathrm{K}$. This time, visually both modes are practically indistinguishable and thus are presented by a single curve. It is evident from Fig. 3 that with increasing temperature the negative gas lens can split the radiation of some modes into two branches that practically do not overlap in the center. In such a situation it seems natural that, at sufficiently high ΔT, two asymmetric modes can arise, each of them propagating in its own part of the slab whereas the gas lens serves as a "barrier" between them.

Two different phenomena are possible here. The first two modes become practically degenerate at sufficiently high ΔT. The frequency difference and field amplitude at the slab center decrease as $\exp(-S)$ when S increases, namely,

$$S \sim k_0 \Delta x \Delta n, \qquad \text{to be more exact} \qquad S \sim k_0 \Delta k \sqrt{|q + k_0^2 \delta\varepsilon|} \quad (q < 0)\,.$$

Here Δn is the refractive-index difference across the slab and Δx is the size of the area inaccessible for radiation in the geometrical-optics approximation.

Mathematically the situation is close to the potential barrier problem in quantum mechanics. It follows from Fig. 3 that the value of S for the fundamental mode can noticeably exceed unity at moderate values of ΔT in an operating Xe slab laser. In such a case, mode distortion can take place under the influence of small perturbations that are inevitably connected with the technical imperfections of a waveguide. Such distortions do not change the overall number of modes.

Another phenomenon is spontaneous symmetry breaking [2]. This nonlinear effect gives rise to a new class of asymmetric modes even in symmetric waveguides. This effect is also connected with pushing the radiation from the center to the slab walls so that the field in the center is practically absent. However, symmetric modes do not vanish. Thus the set of modes increases. Gain saturation is essential for symmetry breaking (it can be shown that in the absence of saturation there is no symmetry breaking in an initially symmetric system).

In fact, the asymmetric performance of the fundamental mode can even show up at a relatively small temperature difference for which the radiation is not so sharply split up into beams. This is demonstrated by Fig. 4 where the asymmetric version of the fundamental mode is presented at $\Delta T = 25\,\mathrm{K}$. All other conditions are the same as above. Of course, mirror symmetric modes with intensity $I(-x)$ also exist.

Next to the fundamental and the second-order mode (one-node) is the third-order (two nodes) mode that also undergoes symmetry breaking under the operating conditions of the laser considered. However, the necessary temperature gradient is higher. It should be pointed out that, strictly speaking, modes of a waveguide (where saturation is taken into account) have, in general, no nodes at all. We found that the saturation has a very small influence on the mode profiles [2] and on the position of the points where the mode field is not exactly equal but close to zero. That is why node number classification can be preserved.

Symmetric (dashed) and asymmetric versions of the third mode are shown in Fig. 5 in the case where the temperature difference is 150 K. The mirror image of the asymmetric mode is omitted in the figure.

3. Threshold of Asymmetric Mode Appearance

The appearance of asymmetric modes seems to be a threshold effect. This conclusion is not the result of rigorous mathematical analysis but is obtained by numerical simulation (numerical experiments). The threshold value of $(k_0 l)^2 \Delta n$ is about 75 for the mode presented in Fig. 4. All parameters are those that were described above except the pressure which is now considered as a variable. Inside the areas between

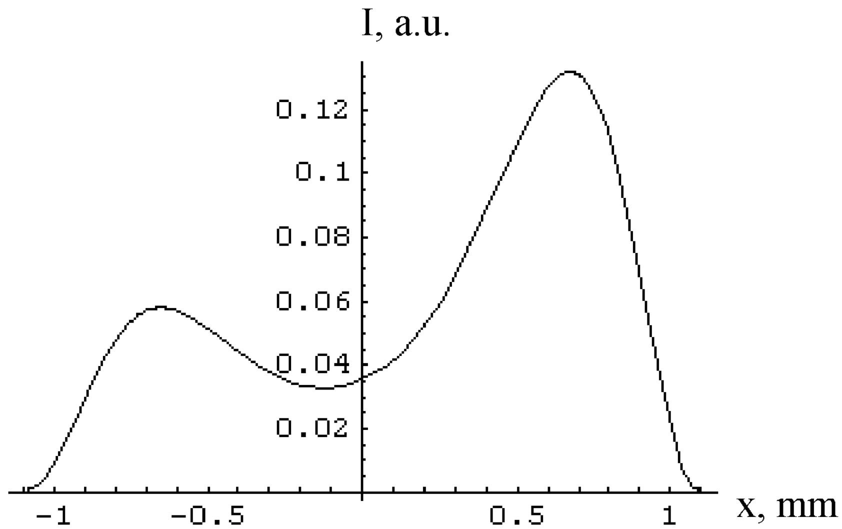

Fig. 4. Asymmetric form of the fundamental mode.

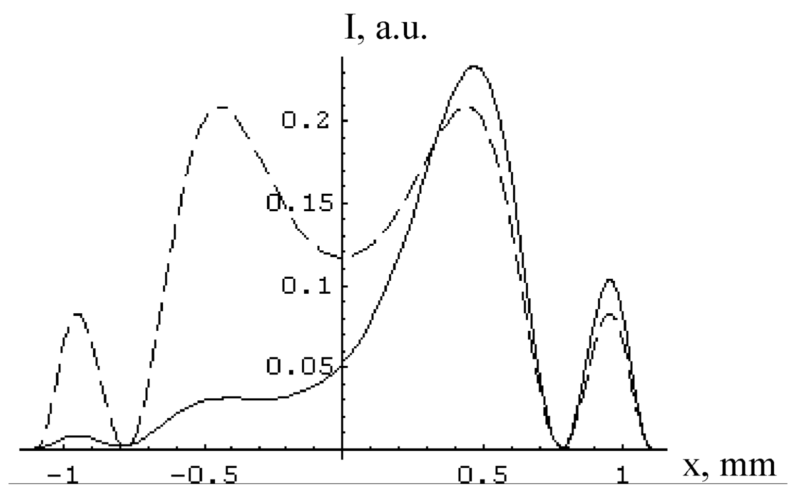

Fig. 5. Symmetric and asymmetric third mode.

the curves and the abscissa axis, numerical simulation could not reveal asymmetric modes of the type shown in Fig. 3. The solid curve refers to $\lambda = 2.65\,\mu$m, whereas the dashed curve refers to $\lambda = 2.05\,\mu$m.

A search for the area where the second asymmetric mode can be found was also carried out. It turns out that $(k_0 l)^2 \Delta n$ is approximately 350 in this case. In Fig. 7 the related results are shown. Indications are the same as in Fig. 6.

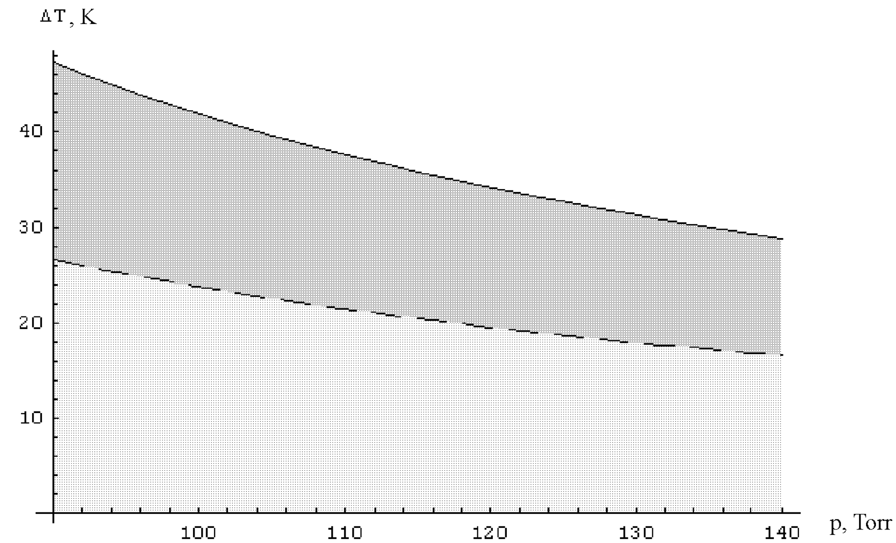

Fig. 6. Domain of asymmetric version of the existence of the fundamental mode.

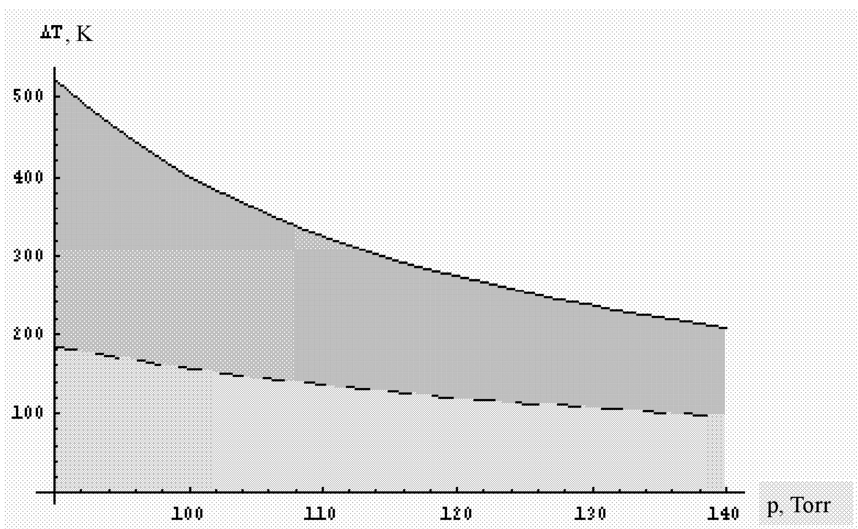

Fig. 7. Domain of asymmetric version of the existence of the third mode.

4. Output Radiation Asymmetry

The observed output radiation of the Xe slab laser is often asymmetric with respect to the central plane of the slab (see, for example, [3]). The asymmetry can be explained if mode competition can suppress one mode in a pair of two different mirror symmetric modes. Such a situation can occur, as was shown by the simplified mode competition model used in [1]. Figure 8 presents asymmetric versions of the fundamental mode (plots 1 and 2) and the symmetric second mode (plot 3). Modes were calculated at $\Delta T = 25\,\mathrm{K}$. According to the mode-competition model used, these three modes cannot be active

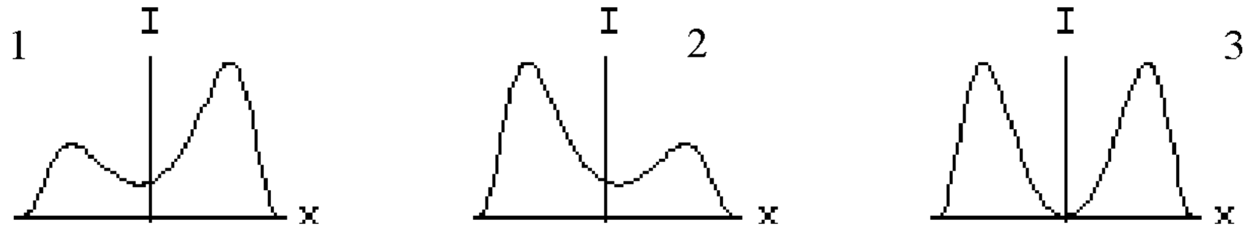

Fig. 8. Competing modes.

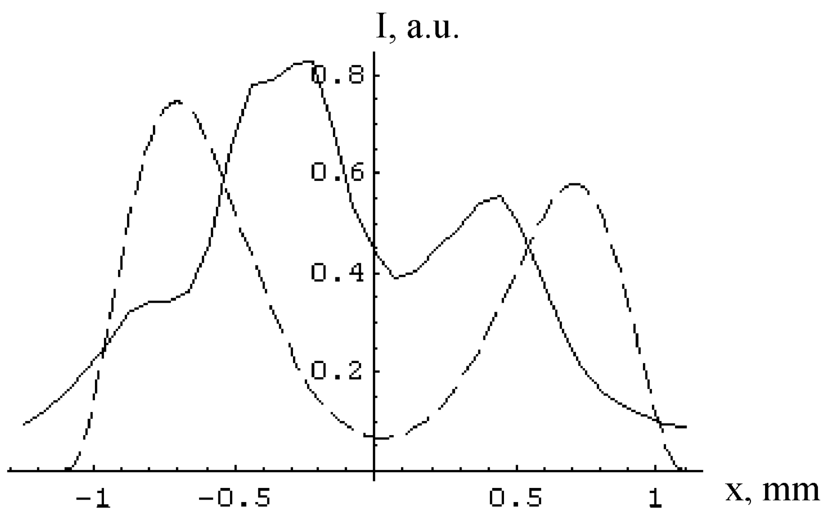

Fig. 9. Calculated profile of the output radiation versus the experimental data.

simultaneously. But one of the asymmetric modes (1 or 2 in Fig. 8) and the second-order (one-node) symmetric mode (plot 3) do not suppress each other. The resulting output field (in arbitrary units) is presented in Fig. 9 (dashed line) where it is compared with an experimentally recorded transverse output-radiation profile. The latter was recorded at a distance of 95 mm from outcoupling mirror. Beam divergence was taken into account by scaling the x coordinate. The low intensity "wings" of the measured profile at this distance are considered to be the result of diffraction and therefore discarded. The mode-competition model presented is too rough to yield good quantitative agreement between numerical and experimental data, but a qualitative agreement can be noted.

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