DETERMINATION OF THE LOSSES IN A RUBY LASER WITH A MISALIGNED RESONATOR

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A technique for the determination of the losses in a ruby laser with a misaligned resonator is presented. It is shown that a probabilistic formula for the power generation correctly describes the relation between the generated power and the angle between the resonator mirrors if the experimentally determined loss figures are inserted into this formula.

The use of a probabilistic technique in studies of the energy parameters of lasers makes it possible in a number of cases to obtain satisfactory agreement between the theoretical and experimental results [1-4]. Since the losses (useful and detrimental losses) must be known for the calculation of energy quantities such as the generated power, efficiency, etc., the extent of agreement between the calculated and measured energy parameters must basically depend upon the reliability of the loss determinations. The fraction of useful losses, which is determined by the transmission of the resonator mirrors, is relatively easy to measure by spectrophotometric methods. The determination of the detrimental losses is much more difficult. The theoretical determination of the detrimental losses with all factors taken into account is a practically insoluble problem. The probabilistic method for the determination of laser parameters [5] does not offer the possibility of calculating the detrimental losses theoretically since they appear in analytical expressions as a parameter governing the energy balance in the laser system. This fact, however, makes this method rather useful for the experimental determination of the detrimental losses. The problem then reduces to one of measuring the energy and time of generation at various loads. At present, this method seems, in essence, to be the only method for an experimental determination of the total detrimental losses in lasers without exploring the actual nature of the losses. In spite of the low accuracy of generator power measurements, the results of the work of [2-4] show that a satisfactory agreement between the detrimental losses determined in solid state lasers can be achieved.

In some cases the generator power must be measured under varying detrimental losses. This problem is encountered, in particular, when the relation between the generator power and the nonparallelism angle of the resonator mirrors is to be determined. In dealing with this relation, basically two problems must be solved: the detrimental losses must be determined for various angles of misalignment and the generator power must be calculated for the loss values established. The theoretical treatment of [6] solved the problem in a similar fashion. A comparison of the results of this paper and the experimentally established relationship between generator power and angle of mirror misalignment indicates considerable discrepancies for solid state lasers, in particular for ruby lasers [7, 8]. It is not possible to make any a priori statements as to the reasons for these discrepancies. They may be caused by incorrect loss determinations or by insufficient accuracy of the formulas used in the probabilistic technique for computing the generator power.

It has been shown in our work that the formulas derived from the probabilistic method described quite well the relation between the generator power and the angle between the resonator mirrors, provided the losses in such a resonator are properly accounted for. The problem is thus reduced to an experimental determination of the losses in a detuned resonator and the subsequent use of the loss values in computations of the generator power.

Fig. 1. Cross section through the laser beam with a misaligned mirror (resonator length 10 cm) for various misalignment angles, a) 0°; b) 30°; c) 90°.

The threshold pumping power as a function of the misalignment angle was investigated for the loss determinations. The measurements were made in a laser with a ruby rod 65 mm long and 12 mm in diameter. A multilayer dielectric coating with a reflection coefficient close to unity was applied to one of the front sides. The reflection coefficient of the second mirror was 0.92; this mirror could be rotated around the vertical by arbitrary angles within the angular interval from 0 to 2°. The angle was measured with an accuracy of 3" by means of a collimator. In a laser with extendable mirrors, the misalignment effect is diminished (particularly at large angles) owing to Fresnel reflections at the ruby face.
The original suggestion was to conduct the investigations with the minimum distance between the resonator mirrors, because this would make it possible to attain the generation threshold in our setup over a sufficiently large angular interval. This possibility had to be discarded because it turned out that from an angle of 3' the threshold pumping power depends slightly upon the misalignment. The assumption that this effect is related to generation in nonaxial directions via the polished lateral faces of the ruby red could be confirmed by an inspection of the cross section of the laser beam at various angles. Figure 1 shows such cross sections. Photographs of the beam cross sections were obtained at two distances from the exit mirror, which made it possible to determine the angle between the nonaxial directions of generation. For a resonator of 10 cm length this angle turned out to be 9'. Since in our treatment of the problem the effect from nonaxial generation had to be excluded, the relations between the threshold pumping power and the misalignment angle were established for various resonator lengths (Fig. 2). The curves of Fig. 2 made it possible to determine the minimum distance between the mirrors at which this effect did not appear. The corresponding distance was 35 cm, at which all the measurements described below were made.

The losses in resonator misalignment were experimentally determined by considering the threshold pumping power for various useful loss figures (mirrors with various reflection coefficients were employed) and for various angles of mirror nonparallelism. Figure 3 shows the curves depicting these relations. Both relations were recorded with the same illuminator and the same resonator base. The conclusion is that identical threshold pumping powers in a misaligned resonator and in a resonator with various mirror reflection coefficients correspond to identical losses. With this conclusion, loss figures for various misalignment angles were obtained from the two relations shown in Fig. 3. These values are shown in the form of a graph (Fig. 4a).

The next stage of our work dealt with the calculation of the power generated, and took into account the loss figures found previously. The calculations were made with a formula of [5]

$$W_{\text{gen}} = \frac{1}{2} \eta B_{13} h v_{21} n \left( 1 - \frac{k}{\kappa} \right) \left( \frac{u_{31}}{u_{\text{thresh}}^3} - \frac{1}{l} \right) \frac{1}{1 + \frac{1}{r_2}}$$

where \(\eta = \frac{P_{22}}{P_{12} + P_{21}}\) (\(P_{ij}\) denotes the transition probability between the corresponding levels), \(B_{13}\) is the Einstein coefficient, \(h v_{21}\) denotes the quantum energy, \(n\) is the number of particles per unit volume of active substance, \(k\) is the overall loss coefficient, \(\kappa\) is the maximum amplification factor, \(u_{31}\) and \(u_{\text{thresh}}\) denote the pumping power and the threshold pumping power, \(r_1, r_2\) denote the reflection coefficients of the resonator mirrors, \(l\) is the length of the ruby rod in the laser. The curves of Fig. 4b indicate a good agreement between calculated and experimentally determined values of \(W_{\text{gen}}\).}

Reference was made above to the considerable discrepancies between the experimental and theoretical values of \(W_{\text{gen}}\) in a misaligned ruby laser. Figure 4b (curve 1) shows for comparison the theoretical angular dependence of \(W_{\text{gen}}\) which we took from Stepanov and Prishivalko [6]. They considered a resonator with plane mirrors, and their calculations agree satisfactorily with the measurements in a gas laser and a neodymium laser. However, comparison of the curves 2 and 1 of Fig. 4b reveals no such agreement. It is natural to assume that this is caused by the considerable inhomogeneity of ruby relative to neodymium glass and, even more so, relative to the medium of a gas laser. In calculations of the losses in a misaligned resonator with an inserted ruby,

$$u_{\text{thresh}}$$

Fig. 2. The relation between the threshold pumping power, \(u_{\text{thresh}}\) and the misalignment angle \(\varphi\) (min) of the resonator mirrors at resonator lengths of 10, 35, 50, 75, and 100 cm (the respective curves are marked 1, 2, 3, 4, and 5).

$$u_{\text{thresh}}$$

Fig. 3. Relation between the threshold pumping power, \(u_{\text{thresh}}\), to the misalignment angle \(\varphi\) (min) of the resonator mirrors and the coefficient of useful losses, \(k_{\text{use}}\) (cm\(^{-1}\)). Resonator length 35 cm.