PHYSICAL REVIEW A VOLUME 46, NUMBER 9 1 NOVEMBER 1992

Intensity correlations of multimode gas lasers

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(Received 9 April 1992)

We investigated the intensity correlation of a multimode Ar-ion laser. By the measurement of mode spectra and correlation times 20–30 simultaneously lasing modes, it was found that the behaviors of mode fluctuations are largely different between modes away from the center of a lasing line and modes near the center. These characteristics can be explained by the fluctuations caused by mode-mode coupling. Using third-order laser theory, we derived numerically the characteristics observed. We discuss the fitting curves of the correlation functions and the limit of the classical treatment.

PACS number(s): 42.50.−p, 42.55.−f, 42.60.−v

I. INTRODUCTION

It is well known that each mode of a multimode gas laser has a large intensity fluctuation, while its total intensity is quite stable. Various behaviors of multimode gas lasers involving stable two-mode oscillation [1], high-frequency modulation [2], and asymmetry of output spectrum [3] have been observed. From the study of intensity correlations of multimode gas lasers, the correlation times of intensity fluctuations were found to be much shorter than that of a single-mode laser, and an increase of an excitation current was observed to reduce the correlation times [4].

Several numerical studies have been made by several authors. On the basis of the third-order laser theory [5], Brunner *et al.* calculated intensity fluctuations and spectral characteristics of multimode lasers in various cases [6–8]. They have obtained the results which explained the several phenomena described above. Recently, McMackin *et al.* have calculated a correlation time of homogeneously broadened multimode lasers using the same theoretical treatment [9]. The usefulness of the theory has also been confirmed by their results.

Our interest is to clarify the origin of the intensity fluctuation by investigating the correlation functions of all modes. In our experiment, it was observed that modes both away from and near the spectral center show different characteristics according to their positions in a leasing linewidth. We studied the mode-mode interactions over all the lines both experimentally and theoretically. By a numerical analysis with the third-order laser theory, taking the Zeeman splitting into account, correlation times evaluated for each mode and output spectra are compared with the experimental results. Although an accurate linewidth of a laser can be derived only by the quantum-mechanical treatment, the correlation times calculated by the semiclassical theory are in good agreement with those from our experiments.

II. EXPERIMENT

The lasing line of an Ar-ion laser consists of 20–30 longitudinal modes. The experimental setup is shown in Fig. 1. We studied an Ar-ion laser NEC model GLS-3300, whose total power extends to 4 W with 1.1-m cavity length. As described later, we chose two laser lines whose wavelengths were 514.5 and 496.5 nm, on account of their linewidths. A spectrum analyzer Tropel model 240-1 with 7.5-GHz free spectral range (FSR) and 37.5-MHz resolution picked up one mode from the multimode laser light. To avoid thermal or mechanical drift of the resonant frequency of the interferometer, an autolocking driver has been developed. The driving voltage for the interferometer is slightly modulated by a 100-Hz square wave. The modulation depth is about 50 mV p.-p., which corresponds to a 10-MHz swing in the frequency of the interferometer. Output light signal is detected by a photodiode, and, together with the modulation signal, is fed to a phase-sensitive detector to keep the tuning at the center frequency of the selected mode. Since the response time of the interferometer is about 1 msec, the measurement of correlation times had to be made after the interferometer became stable during a modulation cycle. So effective measurement was done during every quarter of the modulation period (see Fig. 2).

A multichannel counter array has been developed for the correlation measurement [10], which consists of transistor-transistor logic (TTL) integrated-circuit (IC) shift registers model 74F164, counters model 74LS161, and gate-control electronics. The counter array has 128 channels, and each channel consists of a four-bit counter and a data latch. The date clock can be set higher than 40 MHz, while the maximum photoelectron rate is limited to be 25 MHz by the response time of the counters. In the present measurement, we used only 64 channels to

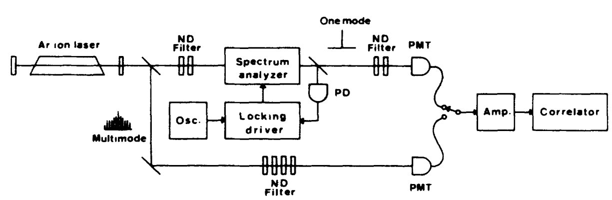

FIG. 1. Experimental arrangement. ND denotes a neutral-density filter and PMT denotes a photomultiplier tube.

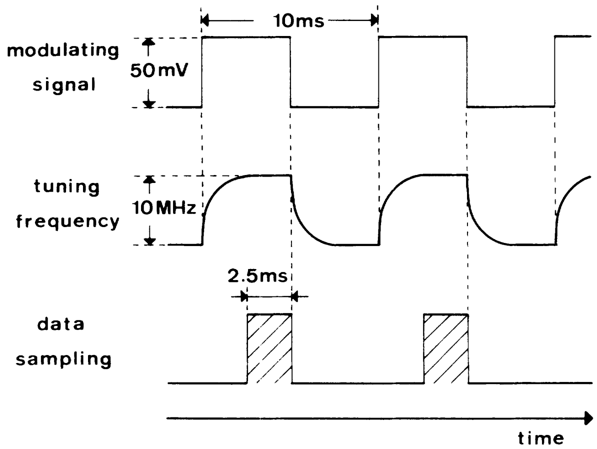

FIG. 2. Autolocking of the tuning frequency of the interferometer to a certain mode by a slight modulation.

keep the period of data transfer, which includes both data accumulation and storage time, within 0.5 msec. Since the gate period of the counters was set to be 800 nsec in the experiment, 190 000 counts/sec at the photomultiplier (PM) tube would certainly cause overflow of the counters. The laser light had to be attenuated with some neutral-density (ND) filters to less than one third of the limit to avoid occasional overflow. The counter array is designed to keep counting even during the periods of a data transfer to a computer.

At first, the accuracy of the system was tested. The locking electronics was checked by observing the laser light of a single-mode oscillation through the interferometer. In this case, the correlation time was too long to be measured, thus it was confirmed that the stability of the locking loop was enough for our study. As shown in Fig. 1, both light intensity of one oscillating mode from the multimode laser and that of all modes were studied. In the all-modes cases, the correlation time was much greater than a msec. Thus it has been confirmed that the intensity fluctuation is not caused by a discharge or mechanical instability, but is due to a basic mechanism of the laser oscillation such as a mode-mode interaction of a multimode laser.

It has been observed that the linewidths of some of the lines in an Ar-ion laser vary widely. In particular, the Zeeman splitting of ionic sublevels caused by a magnetic field plays a principal role in the line broadening. We chose two lines of an Ar-ion laser, 514.5- and 496.5-nm lines. The transition ($^4D_{5/2}$-$^2P_{3/2}$) of the former line has a large Zeeman spreading, which is almost twice as much as the spreading of the latter transition ($^2D_{3/2}$-$^2P_{1/2}$), because both the upper and lower levels have large g factors. The two lines have almost the same natural linewidth (460 MHz) and the Doppler linewidth is determined only by a plasma temperature (3.5 GHz at 2500 K) [11].

Intensity spectra and correlation times of two lines with a weak excitation are shown in Figs. 3 and 4. The spectrum of the 514.5-nm line is wide, with the two peaks 1 GHz away from the center of the line, while the spectrum of the 496.5-nm line is narrow, with a peak at the center. Correlation times obtained are short in the case of the strong modes near the center, increasing values are obtained as the edges of the mode spectrum are approached, and then finally become short again for the weakest modes. In both cases, the mode at the center has

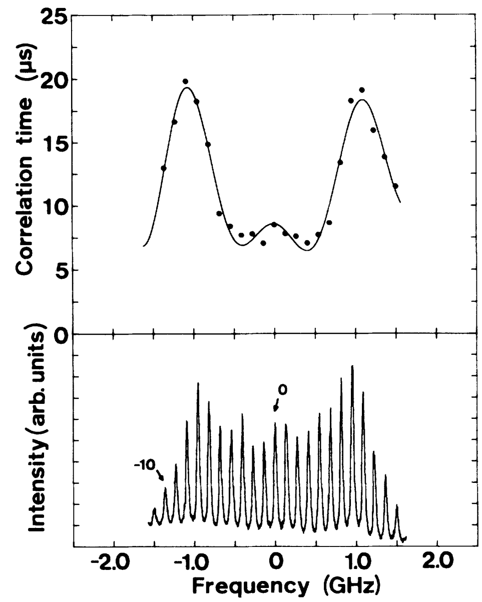

FIG. 3. Spectrum and correlation times of single-mode intensity from multimode laser output of 514.5-nm line at 90 mW. Correlation times are calculated by the parameter of the fitting curve as Eq. (1) with $n=1$. Experimental data are shown in dots, fitted well by a polynomial function.

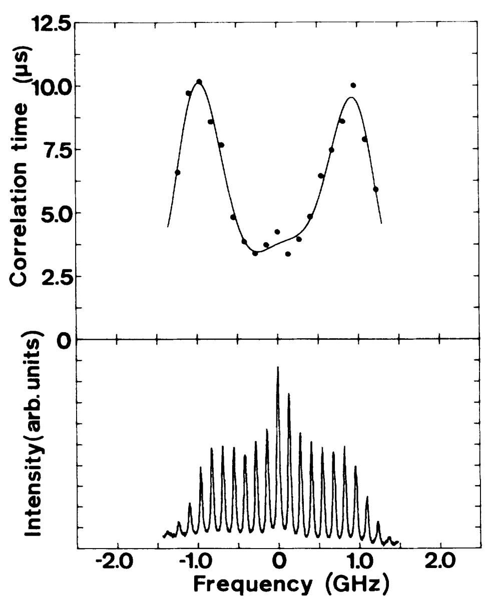

FIG. 4. Spectrum and correlation times of the 496.5-nm line at 90 mW.

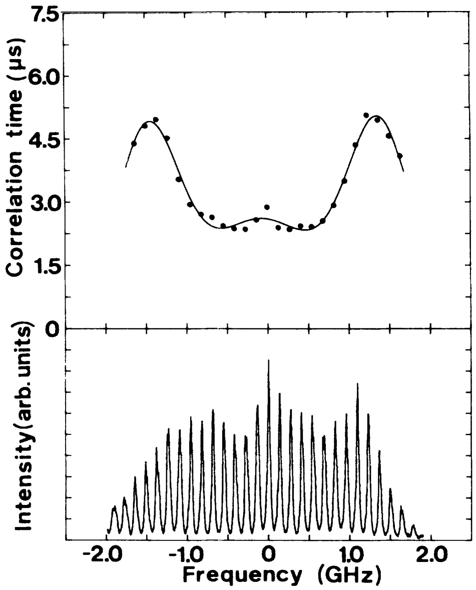

FIG. 5. Spectrum and correlation times of the 514.5-nm line at 520 mW.

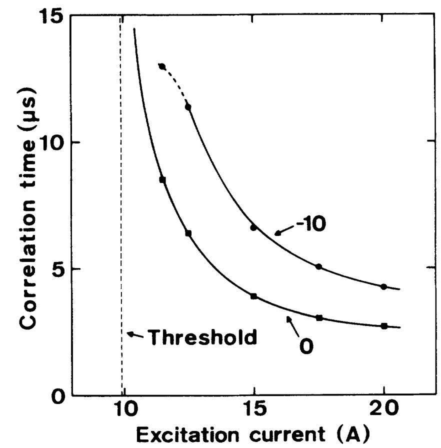

FIG. 7. Excitation dependence of the correlation time of two modes of the 514.5-nm line.

slightly longer correlation time than nearby modes. The same measurements were done with a stronger excitation, and the results are shown in Figs. 5 and 6. In this case, although the correlation times become short, their basic characteristics do not change compared with those in the case of the weak excitation. The excitation dependence of the correlation time was observed for the case of two modes which are marked by mode numbers 0 and -10 in Fig. 3. One can see that the increase of the excitation reduces the correlation time, as shown in Fig. 7.

The intensity correlation functions of the two modes for the same conditions as Fig. 3 are shown in Figs. 8(a) and 8(b), respectively. Now we defined the autocorrelation function of a mode as follows;

$$\overline{I(t)I(t+\tau)}=(I_0^2-I_s^2)\exp[-(\tau/\tau_0)^n]+I_s^2\ , \quad (1)$$

in which τ_0 is a correlation time. I_0 and I_s are the intensities when τ are 0 and ∞, respectively. If the light from a laser has a Lorentzian line profile, n is 1; if the light has a Gaussian line profile, n is 2. In the case of a strong excitation, an exponential function with $n=1$ agrees well with the experimental results. On the other hand, in the case of a weak excitation, some modes are well fitted by the curve with $n=2$. Figure 8(a) shows that the correlation function of the -10 mode can be fitted with $n=1$, while in the case of Fig. 8(b), the central mode can be

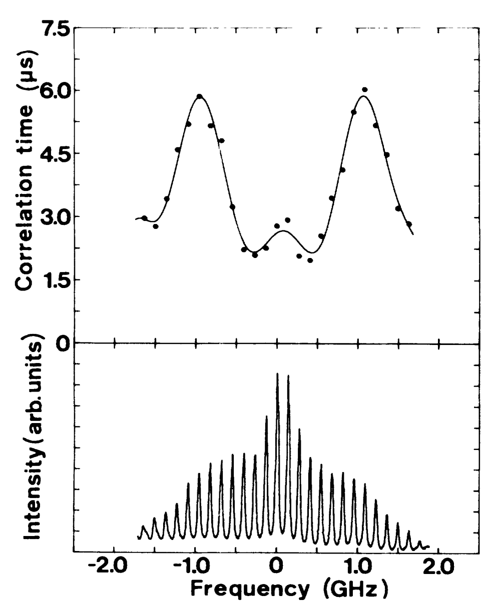

FIG. 6. Spectrum and correlation times of the 496.5-nm line at 390 mW.

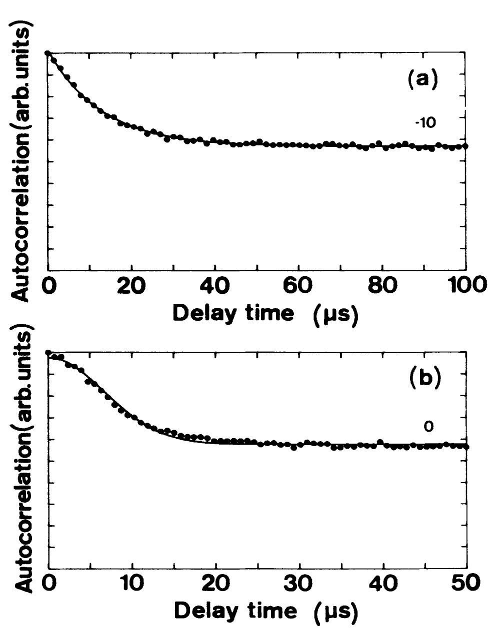

FIG. 8. Measurements of intensity autocorrelation function of the mode numbers -10 (a) and 0 (b) marked in Fig. 3.

fitted with $n=2$. We note that the correlation times from Figs. 3–6 are calculated by a fitting curve using Eq. (1) with $n=1$.

III. THEORY

The lasing behavior of a multimode laser is numerically analyzed according to the third-order laser theory by Sargent, Scully, and Lamb [5]. We follow the treatment by Brunner and Paul [6] with a little improvement. In usual Ar-ion lasers, a strong magnetic field causes large Zeeman splittings, comparable to the Doppler broadening. Each line has a quite different linewidth, because of different g factors in upper and lower transition levels. Here, we chose 514.5- and 496.5-nm lines which consist of transitions with much different g factors. They are estimated at 1.37 and 1.33 for upper and lower levels of the former line, respectively, and are estimated at 0.8 and 0.67 for the latter line. We suppose that the Zeeman splittings affect only the gain profile parameter; i.e., the polarization effect of laser light can be ignored. Therefore, the gain profile given in Ref. [6] is safely employed with a slight modification, and the expression including the influence of Zeeman splittings can be written by the superposition of two Doppler-broadened lines. The peak value of gain is normalized to the gain parameter g/κ, where κ represents the cavity loss. Since the total relaxation rate γ_{ab} is much more influential than that of each level, these rates can be represented by $\gamma_{ab}=\gamma_a=\gamma_b$. Thus the number of effective parameters of the equations is reduced to three; a relative homogeneous line broadening $h\equiv\Delta_{\text{nomo}}/\Delta_{\text{mode}}$, a relative Doppler line broadening $d\equiv\Delta_{\text{Doppler}}/\Delta_{\text{mode}}$, and a relative Zeeman splitting $z\equiv\Delta_{\text{Zeeman}}/\Delta_{\text{mode}}$, which are normalized by the cavity mode spacing. We also suppose that the cavity is filled with a gain medium, and the Doppler broadening is much larger than that due to the level relaxation parameters; a case called the strong Doppler limit. Though excess noise characteristics represented as Langevin forces are not added to the equations, the electric field of each mode calculated according to the same definition of variables, the matrix elements and the parameters as those given in Ref. [6] show chaotic behavior.

The parameters for the Ar-ion laser were chosen as follows: the relative Doppler broadening $d=25$, which corresponds to 3.4 GHz, the relative homogeneous broadening $h=5$, which corresponds to a 680-MHz linewidth, and the relative Zeeman splitting $z=15$–20, which corresponds to (2.0–2.7)-GHz splitting. The parameter h was taken to be larger than the natural width (460 MHz), taking account of the additional broadening due to the Stark effect. The relative gain factor g/κ was varied from 1.2 to 1.35 corresponding to the maximum gain of each line. Calculations were made on up to 53 modes for a line, while the normalized time scale reaches 27 000 by two κ steps. Calculations for different parameters were made simultaneously by several computers.

The electric-field amplitude calculated for the central mode is shown in Fig. 9. In that mode, the electric field shows chaotic fluctuation, while the total field of all modes is seen to be quite stable, with a deviation of less than 2%, 200 steps after the start of an oscillation. Figure 10 shows the calculated mode spectrum and the correlation time of each mode for the case of the wide line corresponding to 514.5 nm, while Fig. 11 shows those for the narrow line corresponding to 496.5 nm. These results were calculated avoiding the start-up period during which the electric fields rise up to stable values. Spectra of these lines agree well with the experimental results by taking account of Zeeman splitting of the line. The former spectrum has two intensity side peaks due to the large Zeeman splitting, while the latter has a single peak at the line center. The longest correlation times are found outside of the intensity peaks in both cases. The magnitude of the correlation time is due to the number of

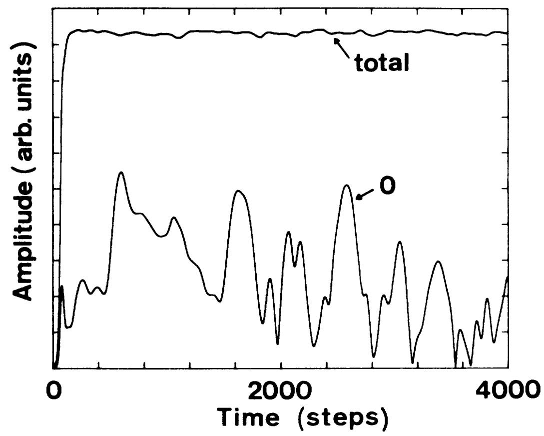

FIG. 9. Development of the total electric field and that of the central mode shown in Fig. 10. The time scale is shown by step that corresponds to the magnitude of the cavity loss κ.

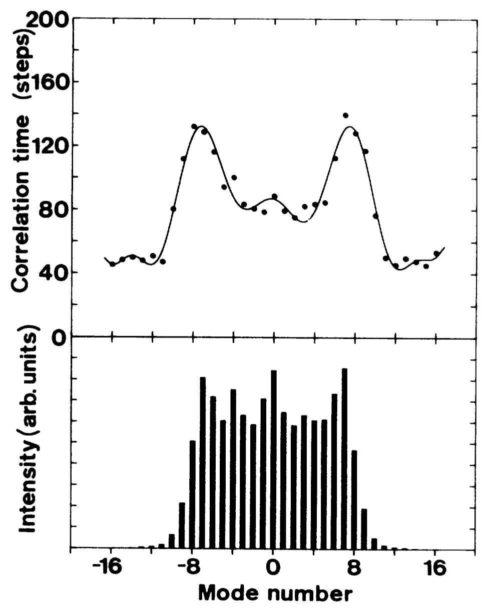

FIG. 10. Calculated spectrum and correlation times of a wide line corresponding to the 514.5-nm line. Calculation parameters are chosen as follows: $h=5$, $d=25$, $z=20$, and $g/\kappa=1.2$. Correlation times are calculated by the parameter of the fitting curve of Eq. (1) with $n=2$.

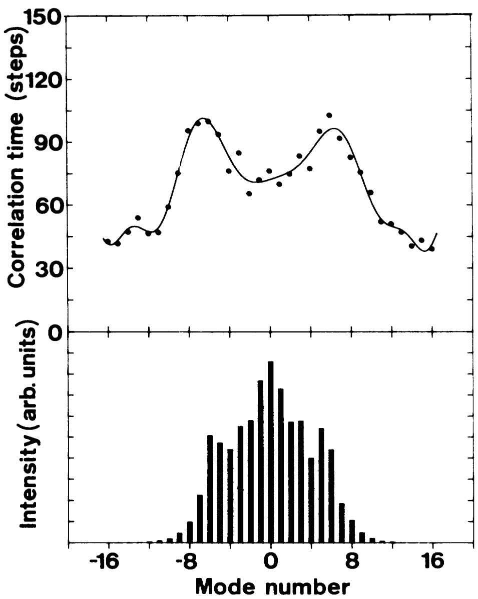

FIG. 11. Calculated spectrum and correlation times of a narrow line corresponding to the 496.5-nm line. Calculation parameters are chosen as follows: $h=5$, $d=25$, $z=15$, and $g/\kappa=1.35$.

modes coupling through a third-order polarization. At both ends of the mode spectrum, the small number of effective combinations of modes causes the long correlation time. On the other hand, the correlation time is found to be short near the intensity peaks. At the line center, we find the small peak of correlation time, in agreement with the experiment. These facts clarify that the magnitude of the correlation time depends mainly on the quenching rate by a mode-mode coupling, and the linewidth of each mode has little effect.

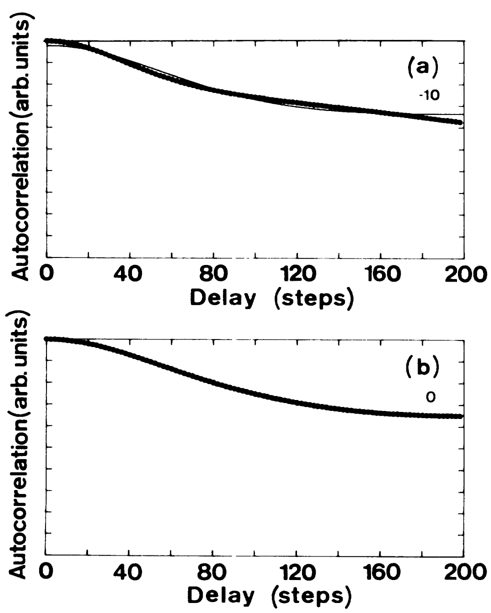

FIG. 12. Calculation of intensity autocorrelation functions of the mode numbers -10 (a) and 0 (b) shown in Fig. 10, with the similar condition of those from the experiment in Fig. 8.

Finally, let us consider the autocorrelation function of the intensity in detail. Calculated correlation functions both for the mode away from the center and for that at the center, with the same condition as Fig. 10, are represented in Figs. 12(a) and 12(b), respectively. Both decay curves fit well to the second-order exponentials corresponding to a Gaussian noise. On the other hand, the curve with the similar condition as in Fig. 12(a) in some cases of the experiment, fit well to the first-order exponentials corresponding to a Lorentzian noise. This can be explained simply from the view point that the semiclassical theory does not afford the estimation of the line profile of each mode. It is worthy of note that the mode dependence of correlation times and spectra such as those shown in Figs. 10 and 11 are thought to be common to various types of multimode lasers with large mode couplings.

IV. CONCLUSIONS

We have discussed mode spectra and correlation times of the individual longitudinal modes in a multimode Ar-ion laser. The characteristics of two laser lines with different widths have been studied in detail both experimentally and theoretically. We have found the existence of peaks in the correlation time away from the center of the oscillating line, and a small peak at the center of the line. They are well explained by the magnitude of a mode-mode coupling; i.e., the number of effective combinations of modes attributing the third-order interaction with a certain mode is large near the line center, while it is small near the side ends of the line.

The results of numerical study with the third-order semiclassical laser theory were also discussed and shown to be in good agreement with the experimental results, including the mode spectra of the light intensity, the correlation times of the intensity fluctuations, and the excitation dependence of the correlation times. The numerical study clearly showed that these are common characteristics to various multimode lasers, irrespective of laser types.

The shape of the correlation function was also studied for several modes. From the numerical study, the correlation functions were always shown to be given by a second-order exponential. On the other hand, some of those in the experiments are fitted well by a first-order exponential. The line profile of each mode cannot be derived by the semiclassical theory.

ACKNOWLEDGMENT

We wish to thank Professor K. Sakurai of University of Tokyo for making a Fabry-Pérot interferometer available to us.

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