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Spectral narrowing and saturation-induced rebroadening in 3.51-μm xenon laser amplifiers

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The spectral width of the amplified spontaneous emission emitted by a xenon 3.51-μm laser amplifier was measured as a function of discharge length using optical heterodyne techniques. Measurements were made for ^{136}Xe at a pressure of 190 mTorr and also for mixtures of ^{136}Xe at a partial pressure of 190 mTorr with helium at partial pressures of 1.3, 2.5, and 4 Torr. Spectral narrowing and, usually, saturation-induced rebroadening were observed for each set of pressures used. The spectral-narrowing data in the regime of unsaturated amplifier gain are in reasonable agreement with existing spectral-narrowing theories which assume a random phase among excited atoms. The observed saturation-induced spectral-rebroadening rates are lower than those predicted by such theories. This behavior indicates that a more complex theoretical treatment of the influence of saturation on a broadband radiation field may be required.

I. INTRODUCTION

The output of a laser amplifier whose only input is the random spontaneous emission occurring within the amplifying medium can have an intensity spectral distribution which is considerably narrower than the spontaneous emission spectral distribution.[1] The spectral width of the amplified spontaneous emission (ASE) is a function of the length of the amplifying medium. The width decreases with increasing amplifier length as long as the amplifying medium remains unsaturated. The effect of saturation is always to reduce the rate of spectral narrowing in a completely homogeneously broadened amplifying medium. In the case of a completely inhomogeneously broadened amplifying medium, saturation-induced spectral rebroadening occurs.[2,3]

The high gain and low saturation intensity of the xenon 3.51-μm $(5p^5 5d[\frac{7}{2}]_3 \rightarrow 5p^5 6p[\frac{5}{2}]_2)$ laser amplifier makes this amplifier particularly well suited for studies of gain narrowing and saturation-induced rebroadening. Values of gain as high as 70 dB/m have been reported[4] in a pure xenon discharge, which closely approximates an inhomogeneously broadened laser amplifier. (The 3.51-μm transition of ^{136}Xe has a natural linewidth[3] of 4 MHz, as compared to a Doppler broadened width[5] of 110 MHz.) The addition of large quantities of helium can increase the amplifier gain to a value[6] as high as 425 dB/m. Addition of helium significantly increases the homogeneous linewidth of the 3.51-μm transition, causing the amplifying medium to become partially homogeneously broadened.[7]

Few studies have appeared in the literature which report measurements of ASE spectral-width dependence on amplifier length.[5,8] Early measurements of width dependence on gain coefficient at fixed length observed only narrowing.[1,2] Studies which have measured spectral narrowing in separate cascaded amplifiers (the last of variable length)[9-11] may not be directly comparable to ASE spectral-narrowing theories which assume an amplifying continuum. Reported here are the first systematic studies of spectral narrowing and saturation-induced rebroadening observed in a variable length amplifier for several ratios of homogeneous to inhomogeneous widths.

II. EXPERIMENT

The ASE spectral density from a xenon multianode laser amplifier was measured as a function of frequency and length by optical heterodyne techniques. A dc-excited cold cathode amplifier was used. The discharge column had an internal diameter of 3.8 mm and a multianode arrangement which allowed ASE spectra for discharge lengths ranging between 40 and 200 cm to be studied. Anodes were spaced in increments of 10 cm for discharged column lengths between 40 and 80 cm, and in increments of 20 cm for lengths between 80 and 200 cm. The smaller spacing between anodes for the shorter discharge lengths was used because of the desire to observe in detail the initially very rapid increase of ASE intensity output with increasing length due to the high gain of the xenon 3.51-μm transition. A nonexcited return path was provided between the two ends of the discharge column to reduce the possibility of cataphoresis effects and pressure differences between the ends of the discharge.

The output of the multianode amplifier was coherently mixed with the output of a single-mode, linearly polarized, tunable He-Xe laser (L1) and focused by a quartz lens on the face of a reverse-biased, high-speed InAs photodiode (see Fig. 1). The laser was tunable over a range of approximately 100 MHz. Because of the high gain and low saturation intensity of the 3.51-μm line, pinholes

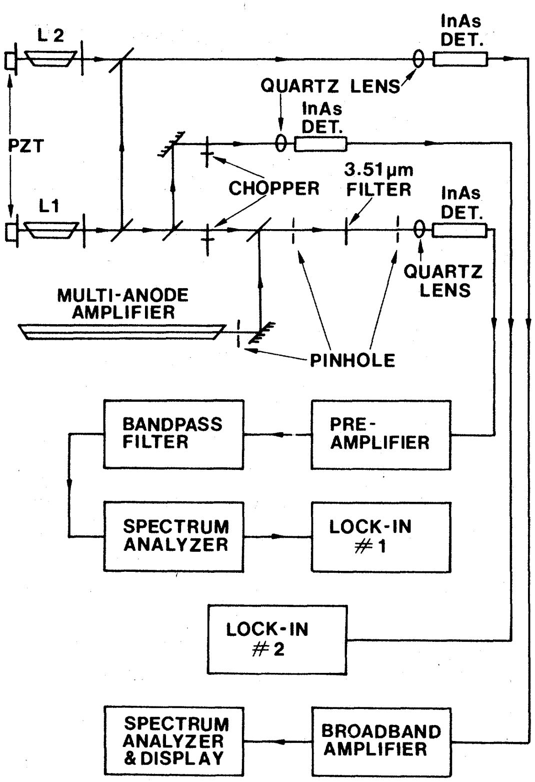

FIG. 1. Experimental setup.

were inserted at several locations in the amplifier beam line to prevent reflections off the surface of intermediate optics from entering the multianode amplifier and possibly distorting the ASE spectral profile. The pinholes also ensured that a single spatial mode in the center of the beam was selected.

The photodiode acts as a square-law detector producing a photocurrent which is proportional to the square of the sum of the electric field amplitudes impinging upon its sensitive area.[12] The photocurrent was amplified by a low-noise preamplifier whose output was applied to a bandpass prefilter with upper and lower cutoff frequencies of 1.2 MHz and 100 kHz, respectively. The filtered signal was applied to the input of an rf spectrum analyzer unit used in a nonscanning mode with a passband center fixed at 1 MHz and a 3-dB bandwidth of 100 kHz. The spectrum analyzer served as a narrow-band tuned filter and detector. It provided a voltage which was proportional to the power (i.e., to the square) of the photocurrent spectral components within its passband. The filtering rejected the dc photocurrent terms due to the time-averaged intensities of the signals from L1 and the multianode amplifier, and passed those photocurrent spectral components resulting from the heterodyning of L1 and the ASE spectral density at frequencies approximately 1 MHz above and below the output frequency of L1. In addition to the heterodyne signal, the spectrum analyzer also passed that portion of the multianode amplifier's homodyne spectrum which fell within the filter's passband. It was followed by a lock-in amplifier (lock-in No. 1) whose reference was provided by a mechanical chopper which modulated the signal from L1 before it was mixed with the laser amplifier's output. The lock-in thus rejected the homodyne signal from the multianode amplifier. The output of lock-in No. 1 was then proportional only to the product of the intensity of L1 and the correspondingly polarized ASE spectral density within 1 MHz of the output frequency of L1.

A fraction of L1's output was picked off from the main beam by a partially reflecting mirror and monitored by a second lock-in amplifier (lock-in No. 2). This provided a measure of the laser's intensity. The ratio of the outputs of lock-in No. 1 and lock-in No. 2 gave the ASE spectral profile as a function of the tunable laser's frequency. (This system has also been used to determine pressure-induced shifts of the 3.51-μm line.[13])

Tuning of L1 was accomplished by means of a piezoelectric transducer (PZT). The resonant cavity tuning was not a linear function of PZT voltage, owing to mode pulling and PZT hysteresis effects. As a result no attempt was made to calibrate the output frequency of L1 as a function of PZT voltage. Instead its frequency was determined with respect to that of a second He-Xe laser (L2) which was frequency stabilized. Portions of the outputs of the two lasers were coherently mixed on the surface of a second high-speed InAs photodiode and the frequency of the resulting beat note was determined by the use of a second rf spectrum analyzer. Frequency stabilization of L2 was accomplished to within 1 MHz by applying a correction voltage to the PZT whenever the laser output frequency tended to drift from the gain peak of an external He-Xe laser amplifier (not shown).

ASE spectral densities were obtained at 5-MHz intervals by tuning L1 across the intensity spectral distribution of the multianode laser amplifier. The peak ASE spectral density and its corresponding frequency were also recorded. Plotting the ratios of the output voltages of the two lock-in amplifiers as a function of frequency provided the ASE spectral profile. An example of such a plot is shown in Fig. 2. The full width at half maximum (FWHM) of the plotted curves was determined by interpolating between points located near the half height. The sensitivity of the ASE spectral profile measurements was limited only by the noise in the output of L1, which was generally less than 4% of its dc output.

ASE spectral widths as a function of multianode amplifier discharge length were obtained for a ^{136}Xe ASE source with a pressure of 190 mTorr and also for a ^{136}Xe partial pressure of 190 mTorr with additions of helium at partial pressures of 1.3, 2.5, and 4 Torr. The isotopic purity of ^{136}Xe was 91%, ensuring that isotopic broadening was not important.

Excellent output stability for the multianode tube was achieved by saturating the tube with xenon, thereby reducing cathode cleanup. This process resulted in an output stability constant to within a few percent over a period of 500 h. Repetition of our filling procedure, when required, yielded output intensities at fixed length constant to within a few percent over the duration of the experimental study.

Since amplifier gain increases when helium is added to the xenon discharge, a different dc excitation current was chosen for each discharge pressure in order to provide an amplifier gain that prevented ASE saturation of the amplifier at the shortest discharge lengths investigated. Greater helium pressure required lesser excitation current. This ensured that both ASE spectral narrowing and the influence of saturation on this narrowing would be observed within the available range of discharge lengths provided by the multianode amplifier.

The line-center gain of the multianode amplifier was obtained for each of the discharge pressures and excitation currents used by measuring the line-center spectral density as a function of discharge length. This data was used to determine the small signal gain coefficient for each pressure and current.

Great care was taken to keep dust and other foreign matter from accumulating on the end windows of the multianode amplifier in order to prevent optical feedback and the resulting possibility of amplifier self-oscillation which would distort the ASE spectral profiles. The measured spectral profiles were free of the spectral asymmetries and temporal spiking which sometimes indicate the onset of amplifier self-oscillation.

The FWHM of the experimentally measured ASE spectral profiles are plotted in Fig. 3 as a function of small signal, line-center gain lengths. (One gain length is defined as that discharge length which provides a gain of e, the natural exponential.) The sets of data points in Fig. 3 are average values of several data sets taken on different dates for each of the partial pressures investigated. In the interest of clarity the experimental uncertainty is indicated only for the pure-xenon data points, which had the largest uncertainty of all the data sets. The error bars for each of these data points are the larger of two values: the standard deviation of the ensemble of measurements for that point

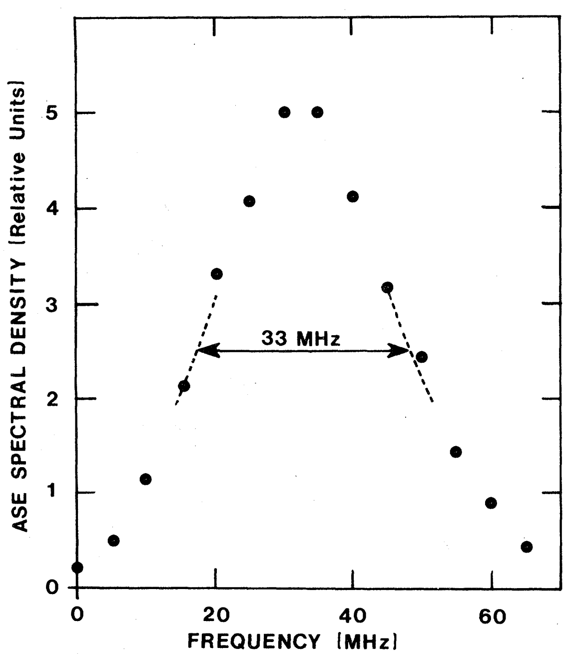

FIG. 2. Measured ASE spectral profile for an amplifier discharge length of 200 cm operated with a discharge current of 2.5 mA and partial pressures of 190 mTorr ^{136}Xe and 1.3 Torr He.

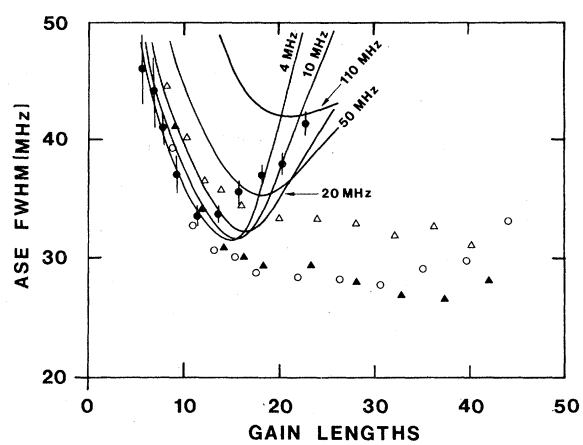

FIG. 3. Solid curves represent theoretical ASE linewidths as a function of amplifier gain lengths for a Doppler width of 110 MHz and various homogeneous linewidths (indicated). Experimental data for ^{136}Xe partial pressure of 190 mTorr, various helium partial pressures, discharge currents, and corresponding small signal line-center gain coefficients are plotted as ●: 0 Torr He, 4 mA, 11 m^{-1}; ○: 1.3 Torr He, 2.5 mA, 20 m^{-1}; ▲: 2.5 Torr He, 1.5 mA, 23 m^{-1}; △: 4 Torr He, 1.5 mA, 19 m^{-1}.

or the accuracy of the FWHM value determined by the plotted ASE spectral profile (±1 MHz).

III. THEORY

The most definitive theoretical treatment to date of the dependence of ASE spectral width on amplifier length has been made by Casperson and Yariv[2] for unidirectional laser amplifiers, and by Casperson[3] for bidirectional laser amplifiers. In both models solutions have been presented for the limiting cases of completely homogeneously and completely inhomogeneously broadened laser amplifying media. In each case the amplifying medium is modeled as a one-dimensional continuum in which the contributions from the excited atoms to the various spectral components of the amplifier gain are assumed to be randomly phased, though power broadening is taken into account.

Recognizing that for strong broadband signals this random-phase approximation must break down, Hopf[14] (in the time domain) and Menegozzi and Lamb[15] (in the frequency domain) have theoretically studied laser amplifiers keeping track of phase information. They find that strong saturation induces cross-spectral modulation and population pulsations which alter the rate of spectral rebroadening. Despite extensive computer modeling these efforts have not provided detailed results. As a first comparison of our experiment with theory we must then work with the random-phase-approximation models.

In general the amplifying medium of a xenon laser amplifier is neither completely homogeneously nor completely inhomogeneously broadened. In order to compare the theoretical models of Casperson and Yariv with our experimental data, their numerical calculations must be extended to the intermediate regimes. Since in the two limiting cases the theoretical results are virtually identical for unidirectional and the physically more realistic bidirectional laser amplifiers, we assume that it is sufficient to make this extension on the basis of the simpler unidirectional theory.

The unidirectional theory describes the evolution of a radiation field along the length of a one-dimensional laser amplifier with the rate equation[2]

$$\frac{dI(y_l,z)}{dz}=G(y_l,z)[I(y_l,z)+\eta]-\alpha I(y_l,z)\,. \tag{3.1}$$

The function $I(y_l,z)$ is the spectral density of the intensity of the radiation field at a particular normalized frequency $y_l=2(\nu_l-\nu_0)/\Delta\nu_H$ found at the position z along the length of the amplifier. Here ν_0 is the atomic resonant frequency, and $\Delta\nu_H$ the FWHM of the homogeneous linewidth. The z dependence of the incremental gain, $G(y_l,z)$, allows for possible saturation along the length of the amplifier. The constant α is a loss coefficient accounting for such processes as scattering and diffraction. (In a high-gain xenon laser amplifier this constant is negligible compared to the incremental gain.) The constant η is the spontaneous emission noise, assumed to have the same frequency and spatial dependence as the incremental gain.

The incremental gain, including saturation effects, is expressed as[2]

$$G(y_l,z)=G_0\int_{-\infty}^{\infty}\exp(-\epsilon^2y^2)[1+(y-y_l)^2]^{-1}\times\left(1+s\int_{-\infty}^{\infty}\frac{I(y_n,z)dy_n}{1+(y-y_n)^2}\right)^{-1}dy\,, \tag{3.2}$$

where for a FWHM value of the Doppler width $\Delta\nu_D$, $\epsilon=(\Delta\nu_H/\Delta\nu_D)(\ln 2)^{1/2}$, G_0 is a pumping constant, and s the saturation parameter. Equation (3.2) describes a Gaussian distribution of Lorentzian lines. The numerator in the integral is proportional to that fraction of the population inversion which has a Doppler-shifted center frequency described by y. The first factor in the denominator provides a coupling factor for how strongly these atoms amplify at the frequency y_l. The last factor in the denominator is a saturation term describing the effect of the spectral density $I(y_n,z)$ on the population inversion at the frequency y. It is this term which leads to power broadening of the homogeneous width.

We have obtained the spectral distribution of the intensity as a function of amplifier length by numerically integrating Eq. (3.2) and then solving Eq. (3.1) by iteration. For the xenon 3.51-μm transition we have taken $\Delta\nu_D=110$ MHz, $\alpha=0$, and $s\eta=10^{-8}$ (Ref. 3). (While the value of $s\eta$ determines the number of gain lengths at which the minimum spectral width occurs, the rates of spectral narrowing and subsequent rebroadening in the vicinity of the minimum are insensitive even to order of magnitude changes in its value.[2,3]) With these parameters Eq. (3.1) was numerically solved with the use of a FORTRAN program for various values of the homogeneous linewidth $\Delta\nu_H$. The values chosen for the homogeneous linewidths were 4 MHz (corresponding to the xenon 3.51-μm natural linewidth at low pressure[3]) and 10, 20, 50, and 110 MHz (corresponding to the expected range of helium-induced collision broadening[7]).

The FWHM of the numerical solutions are presented as continuous curves in Fig. 3 as a function of small signal, line-center gain lengths. The numerical solutions are also shown in Fig. 4 in terms of fractional narrowing versus small signal, line-center gain lengths. The fractional narrowing of the theoretical solutions plotted in Fig. 4 was determined for each homogeneous linewidth by normalizing the computed ASE spectral widths to the FWHM value of the initial spectral distribution of the spontaneous emission. Casperson and Yariv's analytic solution for an unsaturated, completely inhomogeneously broadened, unidirectional laser amplifier[2] is also plotted in Fig. 4.

As Fig. 4 shows, the numerical solutions corresponding to the unsaturated amplifier regimes are all in very close agreement with the analytic solution for an unsaturated, inhomogeneously broadened laser amplifier. This agreement is to be expected, since the numerical solutions were for amplifying media which were not greatly homogeneously broadened. (The values of homogeneous linewidths considered were all significantly less than the width of the gain profile.) The numerical solutions also indicate the occurrence of spectral rebroadening as saturation sets in. The rebroadening rate decreases with increased homogeneous linewidth. This behavior is consistent with the limiting case of a completely homogeneously broadened laser amplifier in which spectral narrowing continues even with heavy saturation.

The numerical solution for the homogeneous linewidth of 4 MHz should closely approximate that of a completely inhomogeneously broadened laser amplifier. The behavior of the ASE spectral narrowing and rebroadening indicated by our computer solution for this width is in very good agreement with the solutions of Casperson and Yariv for completely inhomogeneously broadened amplifiers in both unidirectional[2] and bidirectional models.[3]

IV. COMPARISON OF EXPERIMENT WITH THEORY

It is evident from the data plotted in Fig. 3 that increasing the partial pressure of helium reduces the ASE rebroadening rate. The experimental data in the region prior to saturation are in reasonable agreement with the numerical solutions. The agreement between the pure-xenon narrowing prior to saturation and the numerical solution for the 4-MHz homogeneous width is consistent with the known value for the 3.51-μm low-pressure linewidth. The observed saturation-induced rebroadening, on the other hand, occurs more slowly with increasing gain lengths than is predicted by the numerical solutions. Observe that, after narrowing, the ASE spectral widths for helium partial pressure of 1.3 and 2.5 Torr remain relatively constant over many gain lengths before rebroadening occurs. Rebroadening is not evident in the data taken for a helium partial pressure of 4 Torr.

From Fig. 3 a rough estimate of the xenon 3.51-μm homogeneous linewidth as a function of helium partial pressure can be made by comparing the experimental data corresponding to the unsaturated regime of the multianode amplifier with the numerical solutions for the various homogeneous linewidths. In this regime the ASE spectral widths measured at a given gain length increase monotonically with increasing partial pressures of helium. This is in agreement with collision line broadening theory which predicts a linear increase of homogeneous width with pressure.[16,17]

The experimental data indicate that the broadening of the 3.51-μm homogeneous linewidth due to helium pressure is approximately

$$(5 \pm 3\ \text{MHz})P\,, \qquad (4.1)$$

where P is the helium partial pressure in Torr. This result does not agree with a prior measurement of 3.51-μm collision broadening,[7] in which a collision broadening of $(19 \pm 6)P$ was determined by observing the shape of Lamb dips and fitting to theory.[16] This disagreement is not readily explained.

We can estimate the spontaneous emission spectral widths (prior to narrowing) for the various pressures investigated by assuming a natural linewidth of 4 MHz, using (4.1) to estimate the collision broadening, and then using the sum of these two quantities as $\Delta\nu_H$ in the calculation of Eq. (3.2). The experimental data are normalized to the appropriate spontaneous emission FWHM and are plotted in terms of fractional narrowing versus gain lengths in Fig. 4. As can be seen from this figure, the resulting plots are in very good agree-

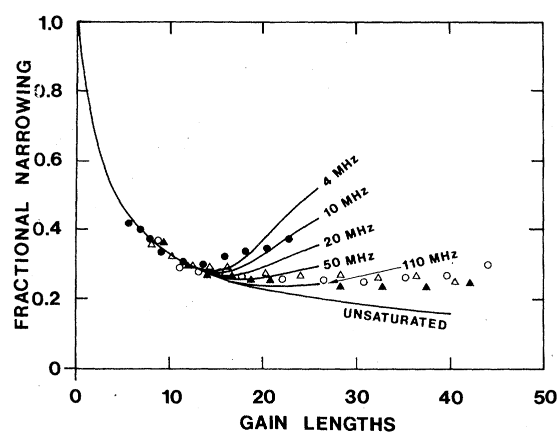

FIG. 4. Theoretical and experimental ASE fractional narrowing as a function of amplifier gain lengths. Plotting conventions are the same as were used in Fig. 3.

ment with the numerical-fractional-narrowing solutions in unsaturated amplifier regimes. The low rate of saturation rebroadening shown by the experimental data for each of the discharge pressures and currents investigated may imply that, upon saturation, population inversions are coupled over frequency ranges which are greater than the power-broadened homogeneous linewidths. Theoretical work which suggests that the random-phase approximation may be invalid for heavily saturated amplifiers is perhaps relevant to these experimental results.

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