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**MEASUREMENT OF THE
STIMULATED THERMAL RAYLEIGH SCATTERING
INSTABILITY***

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26 April 1989

Abstract

Growth of perturbations due to stimulated thermal Rayleigh scattering was observed on a laser beam propagating in a 1 meter cell of CCl₄. Initial sinusoidal irradiance perturbations were seeded onto the laser beam, and their amplification in the cell was recorded by a near field camera. The perturbation growth rate is in agreement with analytical predictions of linearized propagation theory.

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Measurement of the Stimulated Thermal Rayleigh Scattering Instability

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26 April 1989

presented at the CLEO '89 Conference, Baltimore MD

OUTLINE:

We begin this talk with a brief review of the theory of stimulated thermal Rayleigh scattering, to motivate the experiment. Next we show the experiment layout and explain the diagnostic data gathering. Then we show some of the data and compare it to computer simulations of the experiment conditions. A perturbation growth rate is extracted from the data and compared with analytically derived growth rates from linearized instability theory.

Outline

- **The stimulated thermal Rayleigh scattering (STRS) instability**
- **Experiment layout**
- **Comparison of data and theory**
- **Conclusion**

STIMULATED THERMAL RAYLEIGH SCATTERING AMPLIFIES PERTURBATIONS ON A LASER BEAM IN AN ABSORBING FLUID:

Absorption of the laser beam causes heats the fluid and changes its density. This nonlinear self-defocusing process goes by the name "thermal blooming". One of the instabilities in thermal blooming propagation is stimulated thermal Rayleigh scattering, illustrated here. Inhomogeneities or small-transverse-scale perturbations on the laser produce inhomogeneous density fluctuations in the fluid. The laser beam scatters off these density fluctuations(thermal Rayleigh scattering). The scattered waves interfere with the unscattered beam to reinforce the laser inhomogeneities. The laser inhomogeneities and the scatter waves are thereby amplified as the beam propagates to longer range, and also as the fluid is heated for longer time(stimulated scattering). This unstable growth process occurs in free-running propagation--the "open loop" STRS instability. If one attempts to compensate for the growing perturbations by phase-only correction driven by a back-propagated "beacon" wave, then certain modes actually grow faster--the "closed loop" STRS instability. The purpose of our experiment was to observe the open loop STRS instability.

Stimulated thermal Rayleigh scattering (STRS) amplifies perturbations on a laser beam in an absorbing fluid

GROWTH BY STRS FROM AN INITIAL PHASE PERTURBATION AT FRESNEL NUMBER ≈ 0.32 :

This graph shows an analytical prediction of STRS growth. At the start of the path there is a small time-independent sinusoidal phase perturbation on an otherwise uniform laser beam. The Fresnel number of this perturbation, measured at the end of the path, is 0.32. At $t = 0$ the electric field spectrum at path end is the same as the initial perturbation (and the log of the spectrum is 0). Time is measured by the thermal blooming phase shift due to heating by the uniform background beam. At early time the spectrum grows very rapidly, increasing one e-fold in 0.25 waves of blooming. Then the growth continues at the asymptotic rate for low Fresnel numbers. The spectrum has grown a factor of 100 after about 2 waves of blooming. Such rapid growth from small perturbations could be deleterious to the beam quality of a laser propagating in an absorbing fluid such as air.

Growth by STRS from an initial phase perturbation at Fresnel number ≈ 0.32

**BLOOMING-TURBULENCE INTERACTION: STRS AMPLIFIES
HIGH SPATIAL FREQUENCIES AND DAMPS LOW
FREQUENCIES:**

This graph shows an analytical prediction of propagation through an absorbing fluid that has turbulent refractive index inhomogeneities. The free running or open loop STRS instability amplifies the electric field spectrum at path end. The instability is excited by the initial Kolmogorov spectrum of optical turbulence. Perturbations at low spatial frequency are initially damped, then grow. Perturbations at high spatial frequency grow at the asymptotic rate. Initially low levels of optical turbulence are amplified many orders of magnitude.

Clearly it is important to observe the STRS effect under controlled laboratory conditions, to determine whether it does indeed cause this rapid perturbation growth.

Blooming-turbulence interaction: STRS amplifies high spatial frequencies and damps low frequencies

STRS EXPERIMENT LAYOUT:

Our STRS experiment used an Argon ion laser propagated through a stationary 1.2 meter cell of CCl_4 . The laser was spatially filtered to make a near-Gaussian collimated beam. The exact irradiance profile was not recorded on every run, however. A shearing interferometer generated small sinusoidal phase and amplitude fringes with variable orientation and wavelength. The total laser power and the perturbation spacing were measured at the entrance to the cell. The output window of the cell was imaged onto a CCD camera, which was read to a digital frame buffer at 60Hz. A Helium-Neon laser at very low power was propagated backward through the cell as an independent observation of the cell density perturbations. The Argon ion beam power in the cell typically was 1-3 Watts, the beam diameter was 2-5 mm, and the total extinction in the cell was 50-90%. Each day a small quantity of CCl_4 was taken from the cell and its absorption measured by a calorimeter.

An experiment run began with He-Ne observation that the CCl_4 was free from turbulence. Then the perturbation generator was set and the fringes recorded. Then the shutter was opened and the Argon ion beam propagated through the blooming cell. A typical run lasted for about 1 sec, at which time the Argon beam was greatly defocused and the perturbation growth saturated.

STRS experiment layout

COMPARISON OF SELECTED OPEN-LOOP STRS EXPERIMENTS WITH ORACLE COMPUTATIONS: EXPERIMENTAL PARAMETERS:

This table describes the experiment conditions for two runs. The small beam diameter, high absorption and long path caused a very rapid rate of blooming. As a result the STRS growth also was rapid. Thermal diffusion has a significant damping effect in our experiment, but at these Fresnel numbers the STRS growth dominates.

These runs were simulated by the ORACLE propagation code developed at LLNL. ORACLE solves the coupled nonlinear time-dependent partial differential equations of motion of the optical fields and the fluid density. The simulations assumed that the laser irradiance profile was a perfect Gaussian beam at the entrance to the perturbation generator.

Comparison of selected open-loop STRS experiments with ORACLE computations: experimental parameters

Experiment ID:	<u>121888.72c</u>	<u>12989j.488</u>
Blooming rate	87	64 waves/sec
time for 1 wave	12	16 ms
Whole-beam Fresnel number	64	57
Perturbation Fresnel number	0.45	1.0
Diffusion time ($\propto k^2$)	45	246 ms
Diffusion Fresnel number	2.7×10^{-2}	1.6×10^{-2}
at 10 waves		
Absorption optical depths	2.3	0.51
Initial perturbation amplitude	3% (simulation 2%)	
Sample rate	60 Hz	
CCD integration time	33 ms	

COMPARISON OF EXPERIMENTAL AND COMPUTED INTENSITY AT CELL EXIT:

These pictures show the actual CCD images from a run. The noise on the images is dirt on the inside of the cell output window. The amplitude fringes are barely visible in the first image. The grow to nearly 100% modulation in 67 msec. Also, the beam diameter grows, because whole-beam blooming by the near-Gaussian profile makes a defocusing lens in the cell. The noncircular shape of the beam is an artifact of pixel mismatch between the CCD camera and the display device. The perturbation growth saturates after about 100 msec due to thermal diffusion, the drop in irradiance as the whole beam defocuses, and the defocus-induced shearing of optical fringes across density fringes.

The ORACLE simulation of this run is shown alongside. The code image was made with the same computer and display device used for the raw data, to simulate the filtering in this device. The difference in the whole-beam shape is again an artifact of the display device. The qualitative image features are remarkably similar.

Comparison of experimental and computed intensity at cell exit

Experiment
run 1218 88.72c

ORACLE
run XR17

time: 0 ms

33

67

100

FOURIER ANALYSIS OF INTENSITY DATA:

We used the following procedure to extract a growth rate. The near field image was masked to the central 128 by 128 pixels. Each line of camera data was Fourier transformed to get the modulus of the irradiance Fourier transform,

and then the 128 lines were summed. The spatial frequency of the peak of this Fourier amplitude, and the magnitude at that frequency, were plotted as a function of time. The form of the asymptotic STRS growth function was fit to the Fourier amplitude to get an effective STRS growth rate. This was compared to the growth coefficient inferred from the measured absorption, beam power and diameter. The same analysis was done on the ORACLE simulated irradiance.

Fourier analysis of intensity data

- **Analyze only the central 128 (of 256) pixels along each horizontal line**
- **Perform a line-by-line FFT and compute its magnitude**
- **Average over the central 128 horizontal lines**
- **Plot the magnitude and spatial frequency of the perturbation peak**

COMPARISON OF OPEN-LOOP STRS EXPERIMENTS WITH ORACLE COMPUTATIONS: $N_\lambda = 87$ /SEC:

This run had 90% absorption, so the blooming was concentrated near the entrance to the cell. The beam diameter was 2.71 mm and the initial fringe frequency was 2.58/mm.

The graphs show the time history of the Fourier amplitude. The peak Fourier mode chirps to lower spatial frequency at the output cell because of the whole-beam defocusing. The Fourier amplitude grows rapidly, saturates, then decays by the several damping mechanisms noted earlier. The perturbation grew about an order of magnitude. Both the asymptotic analysis and the code simulation are in agreement with the data.

Comparison of open-loop STRS experiments with ORACLE computations: $N_\lambda = 87 \text{ sec}^{-1}$, $N_F = 64$, $N_p = 0.45$, $N_A = 2.3$

coefficients errors 02-08-1989 3120
 $C = 2.62$ const 0.10 c:\qb4.0\5121888.72c
 $B = 30.15$ loss 0.75 $W = .000485$ mm
 $A = 21.44$ gain 0.58 $L = 1225$ mm; abs = 90 %
 $c-c = 0.99$ $P = .77$ watt; FWHM = 2.71 mm

if the following is 1 then; checks OK!

$$\ln(A)/[2 * C - \ln(2 * 3.1415 * \text{sq}(2))] = 1.001$$

time zero adjust = -.9989 / 60 sec.
 camera scaling = 1.31
 frng cycles / mm = 2.58
 chrp c/mm/sec = 1.17

STRS
 hist_fft
 intensity

COMPARISON OF OPEN-LOOP STRS EXPERIMENTS WITH ORACLE COMPUTATIONS: $N_\lambda = 64$ /SEC:

This run had 40% absorption, so the blooming was distributed over the entire cell. The beam diameter was 3.87mm, and the initial fringe frequency was 1.145/mm.

There was less frequency chirp on this run, since the whole-beam thermal lens was closer to the image plane at the output window. The Fourier amplitude time history shows the usual rapid growth, then a decaying episode, followed by more growth. Such oscillations are also seen in the exact analytic theory at some Fresnel numbers. But in this case the oscillation is probably due to the transient shearing of optical fringes past the density fringes. The asymptotic curve fit does not include this effect and does not agree very well. The ORACLE simulation reproduces the early growth very well and gets the oscillation, but the timing is not quite right. This feature of the Fourier amplitude is very sensitive to the exact shape of the beam, which unfortunately was not measured on this run. The perturbation grew about an order of magnitude before whole-beam defocusing forced an end to the run, and growth may not have been saturated yet.

Comparison of open-loop STRS experiments with ORACLE computations: $N_\lambda = 64 \text{ sec}^{-1}$, $N_F = 57$, $N_P = 1.0$, $N_A = 0.51$

coefficients errors 02-08-1989 6240
 C = 2.34 const 0.25 c:\qb4.0\sl2989j.488
 B = 11.17 loss 1.80 W = .000488 mm
 A = 12.85 gain 1.39 L = 1225 mm; abs = 40 %
 c-c = 0.95 P = 2.61 watt; FWHM = 3.87 mm

if the following is 1 then; checks OK!

$$\ln(A)/[2 * C - \ln(2 * 3.1415 * \text{sqr}(2))] = 1.024$$

time zero adjust = -.9989 / 60 sec.
 camerascaling = 1.31
 frng cycles / mm = 1.145
 chrp c/mm/sec = 0.23

STRS
 hist fft
 intensity

STRS EXPERIMENT SUMMARY:

Stimulated thermal Rayleigh scattering does indeed cause growth of high spatial frequency perturbations on a laser beam propagating in an absorbing fluid. The amplification effect is easily observed.

The observed growth rate is in agreement with analytic theory, at least at times before whole-beam blooming and defocusing are significant. The prediction of rapid growth after a few waves of blooming is confirmed.

Detailed computer simulations reproduce the experimental phenomena. The differences are attributable to experimental uncertainties.

STRS experiment summary

- **High spatial frequency STRS is present and easily observed.**
- **At times before whole-beam blooming and diffusion become significant, the observed growth rate is consistent with analytic theory.**
- **Computer simulations reproduce experimental phenomena. Differences are attributable to experimental uncertainties.**