36th AIAA Plasmadynamics and Lasers Conference
6-9 June 2005, Toronto, Ontario Canada

AIAA 2005-5365

Simulation of Time-Dependent Oscillations in a cw HF Chemical Laser Confocal Unstable Resonator

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To simulate the University of Illinois at Urbana-Champaign (UIUC) supersonic, cw HF chemical laser which extracts power with a confocal unstable resonator, the two-dimensional Bell Aerospace Textron Wave-Optics Model was coupled to the ORNECL fluid dynamic, chemical kinetic, rotational non-equilibrium, exact $E_{v,J}$ model. The resulting code, denoted ORNECL-UR, was used to study the time-dependent oscillations which may occur in cw HF chemical lasers that use unstable resonators to extract power. ORNECL-UR accurately predicted outcoupled power as a function of the confocal unstable resonator magnification, size, and mirror spacing. ORNECL-UR accurately predicted the periods of the time-dependent oscillations as a function of the resonator characteristics. The ORNECL-UR unstable resonator calculations for various resonator geometries support the proposed mechanism for the time-dependent oscillations in cw power that may occur in cw HF chemical lasers that use an unstable resonator to extract power. According to the proposed mechanism, the time-dependent oscillations are the result of a competition between chemical pumping and radiative deactivation of upper laser levels of HF. The oscillations occur only if the medium is not strongly coupled to the optical fields diffractively or geometrically. Calculations showed that either of two conditions may reduce or eliminate oscillations in a symmetric confocal unstable resonator.

1. **A resonator Fresnel number less than 3.**
2. **The number of passes required for a wave to exit the Fresnel core of the resonator greater than 4.**

These new computations were made for a supersonic HF chemical laser whereas the previous computations were run for a subsonic device.

Nomenclature

D = effective diameter of the large mirror
D_{FC} = diameter of the Fresnel core
D_S = diameter of the small mirror
λ = optical wavelength
L = mirror spacing of the resonator
M = resonator magnification
N_F = resonator Fresnel number
n_P = number of passes required for a wave to exit the resonator after leaving the Fresnel core
τ = oscillation period
X_C = distance of the optical axis from the nozzle exit plane

I. Introduction

PREVIOUS numerical[1,2] and experimental studies[3,4] of the time-dependent oscillations that may occur in cw HF chemical lasers that use confocal unstable resonators to extract power resulted in a proposed mechanism that is

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responsible for these oscillations. According to the proposed mechanism,[5,6] the time-dependent oscillations are the result of a competition between chemical pumping and radiative deactivation of the upper laser levels of HF. The oscillations occur only if the medium is not strongly coupled to the optical fields diffractively or geometrically. Several new experiments were suggested[5,6] to verify the proposed mechanism. The purpose of this study was to assist in the interpretation of the data from the new experiments[7] through numerical simulation of the laser and resonators used in those experiments.

To simulate the unstable resonator experiments, it was necessary to reactivate a wave-optics model, which had not been used for fifteen years. The restored wave-optics model was coupled to the ORNECL[8] rotational nonequilibrium, chemical kinetic, fluid dynamic, exact $E_{v,J}$ model. The resulting code is denoted ORNECL-UR. ORNECL-UR was verified by reproducing previous calculations. The ORNECL-UR model was used to model the new experiments. Conditions for reduction or elimination of time-dependent power oscillations are derived from the results of the calculations. The time-dependent oscillations may decrease the average total power that may be extracted from high-energy chemical laser unstable resonators. The need to maximize performance of such systems motivates the study of the time-dependent oscillations.

II. Previous Experiments and Calculations

A study[5,6] was performed to determine the mechanism responsible for the time-dependent oscillations that occur on lines whose saturated gain does not fill the unstable resonator. The data[3,4] showed that the occurrence of the 40 ns time-dependent oscillations was Fresnel number dependent and that the period of the oscillation was determined by resonator magnification. The resonator Fresnel number is given by

$$N_F = \frac{D^2}{4\lambda L} \tag{1}$$

The resonator Fresnel number and the resonator magnification determine the diffractive and geometric coupling of the medium to the optical fields. The Fresnel core in an unstable resonator is the region about the optical axis whose radius is such that the Fresnel number is approximately unity. In the Fresnel core, the medium is strongly coupled to the optical fields by diffraction. Diffractive coupling of the medium and the optical fields increases as the Fresnel number decreases. For a fixed resonator size, the number of passes for a wave to exit the unstable resonator after leaving the Fresnel core is determined by the resonator magnification. Geometric coupling of the medium and the optical fields increases as the number of passes for a wave to exit the resonator after leaving the Fresnel core increases. The number of passes required for a wave to exit the resonator after leaving the Fresnel core is given through a geometric optics approximation[9] to the unstable resonator as

$$n_P = \frac{\ln\left[\dfrac{M(D_S)}{2\sqrt{\lambda L}}\right]}{\ln(M)} \tag{2}$$

The diameter of the Fresnel core is obtained by setting $N_F = 1$ in Eq. (1) and solving for D,

$$D_{FC} = 2\sqrt{\lambda L} \tag{3}$$

These effects were studied by performing MNORO3UR calculations[6] for varying resonator magnifications and Fresnel numbers. A strong correlation was found between the period of the time-dependent oscillations, the Fresnel number, and the number of passes for a wave to exit the resonator after leaving the Fresnel core. From this information the mechanism for the time-dependent oscillations was proposed.[5,6]

III. CW HF Chemical Laser Unstable Resonator Model Restoration and Implementation

To aid in the understanding of new experimental cw unstable resonator HF chemical laser data, the numerical model RDRIVER[1] was restored. RDRIVER is a coupling of the Bell Aerospace Textron wave-optics strip resonator model and a simplified rotational non-equilibrium kinetics model. The wave-optics model treats the optical cavity as a strip confocal unstable resonator. The beam is diffractively propagated through the cavity using a solution of the Huygens-Fresnel integral which is obtained by a fast Fourier transform technique. The optics model is coupled to the chemical kinetics model with the thin skin gain approximation in which the active medium is assumed to be a thin sheet in front of the large mirror, Fig. 1. The calculation is an iterative one. The calculation begins by passing a plane wave of the expected intensity through the empty cavity. The resulting intensity distribution is sent to the chemistry. The gains on each spectral line calculated by the kinetics model are then sent to the optics. The stored wave from the previous iteration is propagated through the optical cavity and incremented by the gain distribution from the chemistry. This process is repeated until the difference between successive iterates is less than some prescribed amount. Because each iterate in the solution of the steady state equations corresponds to one round trip of the wave through the cavity, each iterate may be regarded as a time step in the development of the steady state solution.[1,3] Outcoupled power (P_{OUT}) and power loss total ($P_{LOSS\text{-}TOTAL}$) are defined based on the confocal unstable resonator geometry in Fig. 1. The outcoupled power of the confocal unstable resonator is given by

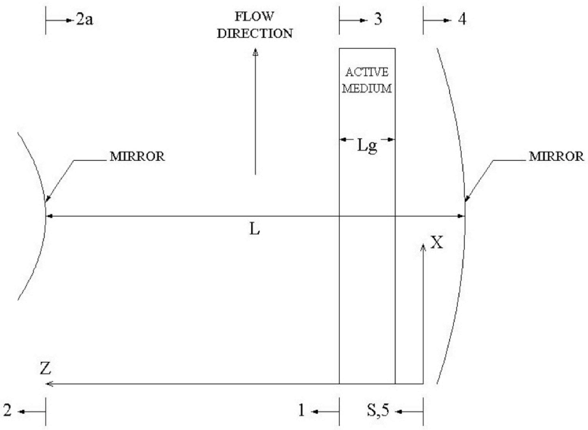

Figure 1. Confocal Unstable Resonator Geometry.

$$P_{OUT} = P_2 - P_{2A} \tag{4}$$

where P_i is the power at point i in Fig. 1. Power loss total is the outcoupled power plus the power lost due to diffraction while the wave traverses the cavity and is given by

$$P_{LOSS-TOTAL} = P_1 - P_3 + P_4 - P_5 \tag{5}$$

where P_i is the power at point i in Fig. 1. Chemistry power (P_{CHEM}) is the power calculated by the kinetics model.

Previous RDRIVER calculations were reproduced for a single line *P*-branch $J = 4$ case.[10] The thirty original iterations for this case were reproduced accurately. RDRIVER calculations were reproduced for a multiple line fifteen *P*-branch $J = 1 - 15$, six *R*-branch $J = 1 - 6$ case.[10] The eighty original iterations[1] for this case were reproduced. Comparison of the dimensionless power vs. iteration number, Fig. 2, with the original calculations in Fig. 6 of Ref. 1, indicates that the optics code is running correctly.

The restored Bell Aerospace Textron wave-optics strip resonator model was coupled[10] to the efficient, rotational non-equilibrium, chemical kinetic, fluid dynamic, exact $E_{v,J}$ model denoted ORNECL.[8] The resulting code is denoted ORNECL-UR for Overtone Rotational Nonequilibrium Exact $E_{v,J}$ Chemical Laser Unstable Resonator. The wave-optics model was modified to permit the use of the exact wavelength for each spectral line and a non-linear resonator cavity height profile. Code was added to modernize the format of the output data. As a result, intensities and gains for each spectral line are recorded for all 912 grid points at a specified iteration. Fluid profiles and chemical concentration profiles are recorded at a specified iteration. Output files have been formatted to be compatible with modern plotting software.

Verification of the ORNECL-UR model motivated the development of a standard method for determining the characteristics of a calculation, such as power, oscillation period, and amplitude modulation. The power versus iteration results of an ORNECL-UR calculation could be described as an average power plus a perturbation. Average total and individual line power is recorded when the average power has reached a constant value. The period of a single oscillation is measured from peak to peak. In certain ORNECL-UR calculations where oscillations are present, the number of iterations between oscillation peaks varies by no more than two integer values rather than remaining constant. To accurately differentiate between the oscillations in different simulations, the period of an oscillation is defined as the average period of the oscillation over the last twenty-five oscillations present in the results. In the cases of a longer period for which twenty-five oscillations are not present, the average is taken over the largest number of oscillations possible. Amplitude modulation is determined by the difference between oscillation peak and trough values for a single oscillation relative to the average. When ORNECL-UR predicts several super-imposed oscillations, the amplitude modulation for a particular oscillation is measured at an oscillation as near as possible to a simultaneous mid-point for the other oscillations. This is possible because more

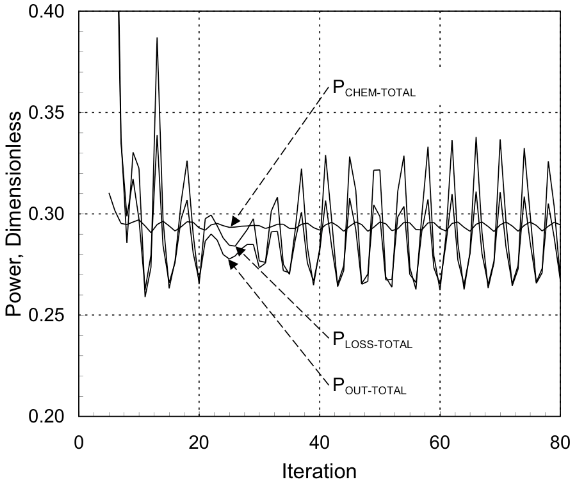

Figure 2. RDRIVER calculated dimensionless power versus iteration number for the M=2, L=50 cm, X_C=0.5 confocal unstable resonator, 15 P branch and 6 R branch case.

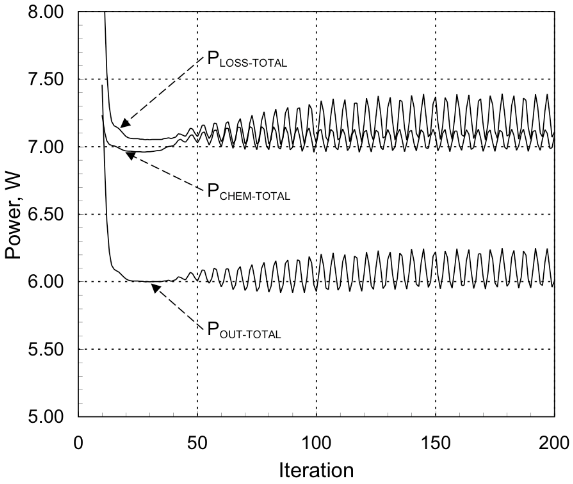

Figure 3. ORNECL-UR calculated total power versus iteration number for an MNORO3UR subsonic CL-II Set-D case, M=2, L=100 cm, X_C=5 mm confocal unstable resonator.

than three simultaneous oscillations with different periods do not appear in the calculations.

The validity of the new model was verified by reproducing the results of an MNORO3UR calculation for the subsonic CL-II laser using the Set-D profiles.[6] The calculation was performed for an M=2, L=100 cm, X_C=5 mm resonator. The calculation was performed for 200 iterations. ORNECL-UR predicted a total outcoupled power ($P_{OUT-TOTAL}$) of 6.09 watts, Fig. 3. The total outcoupled power out had oscillation periods of 31.67 ns and 158.3 ns with amplitude modulations of 4.97% and 0.66% respectively. The MNORO3UR calculation[6] predicted a total outcoupled power of 7.3 watts with an oscillation period of 40 ns and an amplitude modulation of 9%. The ORNECL-UR results exhibited reasonable agreement on total outcoupled power and oscillation period with previous calculations.[6] Since there are differences between the ORNECL-UR and MNORO3UR kinetics models, some differences in the calculations are expected. The reasonable agreement between the total outcoupled power and oscillation period indicates the ORNECL-UR model performs correctly.

IV. Simulation of Resonator Geometries to Check the Proposed Mechanism

Unstable resonator calculations were performed[10] for resonator geometries suggested by previous studies.[5,6] The specified cases were simultaneously studied experimentally.[7] The 100 cm, magnification 2.0 resonator was simulated for large mirror diameters of 8 mm, 10 mm, and 12 mm. The magnification 2.0, 10 mm large mirror diameter case was simulated for resonator lengths of 80 cm and 200 cm. The 100 cm, magnification 1.25, 10 mm large mirror diameter case was simulated. For ease of comparison, case numbers were assigned to the six resonator geometries for which calculations were performed. All cases were simulated using the 8.5% SF_6 dissociation which was determined by matching ORNECL calculations with zero power gain data for the UIUC supersonic laser.[11,12] ORNECL-UR calculations are listed in Table 1.

ORNECL-UR was rebaselined[10] to correctly predict total outcoupled power for the M=2, L=100 cm X_C=5 mm case (Case 2). The rebaselining was achieved by adjusting the percent dissociation of SF_6 in the arcs from 8.5% to 6.3% and by recalculating the fluid profiles. ORNECL-UR Cases 1 – 6 were rerun[10] for the new percent dissociation of SF_6 and the new numerically determined flow profiles and are labeled Cases 7 - 12 respectively. Additional Cases for an M=2, L=100 cm, X_C=3.125 mm resonator and an M=1.25, L=100 cm, X_C=3.125 mm resonator were run and are labeled Cases 13 and 14 respectively. Cases 13 and 14 were run to permit the comparison between M=1.25 resonator calculations that produced oscillations and M=2 resonator calculations that produced oscillations for the same Fresnel number. The ORNECL-UR cases are summarized in Tables 1 and 2.

The base case (Case 8) simulated an M=2, L=100 cm, X_C=5 mm confocal unstable resonator for 400 iterations using 6.3% SF_6 dissociation. The results of Case 8, which are typical for the oscillating cases, are presented in Figs. 4 to 12. ORNECL-UR predicted a P_{OUT-T} of 9.16 watts, Fig 4. The total power had oscillation periods of 46.40 ns and 208.80 ns with amplitude modulations of 0.55% and 0.11% respectively. Figure 5 shows an expanded view of these oscillations. Figure 5 suggests the presence of a longer period oscillation. If Case 8 had been run for 800 iterations as Case 2 was,[10] the 3306 ns oscillation that occurred in Case 2 would be seen. Comparison of the spectra

Case	M	L (cm)	X_C (mm)	SF_6
1	2.00	100	4.000	8.50%
2	2.00	100	5.000	8.50%
3	2.00	100	6.000	8.50%
4	2.00	100	5.000	8.50%
5	2.00	80	5.000	8.50%
6	1.25	200	4.000	8.50%
7	2.00	100	4.000	6.30%
8	2.00	100	5.000	6.30%
9	2.00	100	6.000	6.30%
10	2.00	80	5.000	6.30%
11	2.00	200	5.000	6.30%
12	1.25	100	4.000	6.30%
13	2.00	100	3.125	6.30%
14	1.25	100	3.125	6.30%

Table 1. ORNECL-UR confocal unstable resonator calculations. M is the resonator magnification, L is the resonator mirror spacing, and SF_6 is the percent SF_6 dissociation in the arcs for each case.

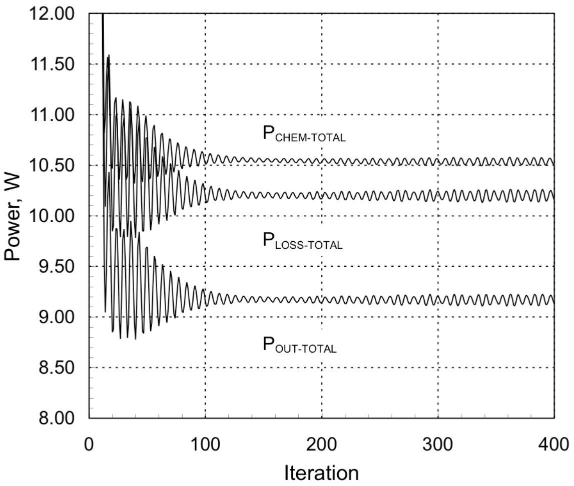

Figure 4. ORNECL-UR Case 8 calculated total powers.

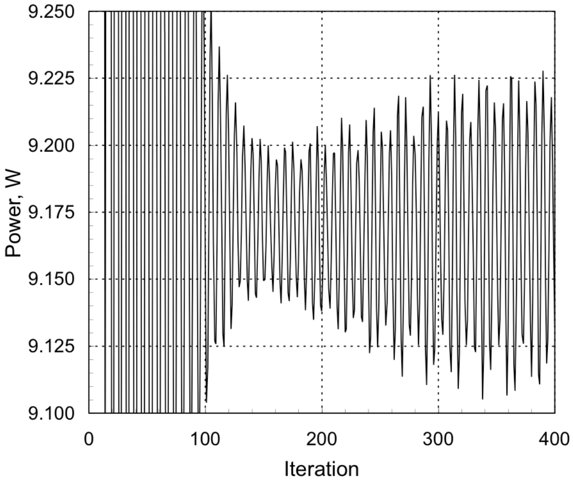

Figure 5. ORNECL-UR Case 8 calculated total outcoupled power (fine scale).

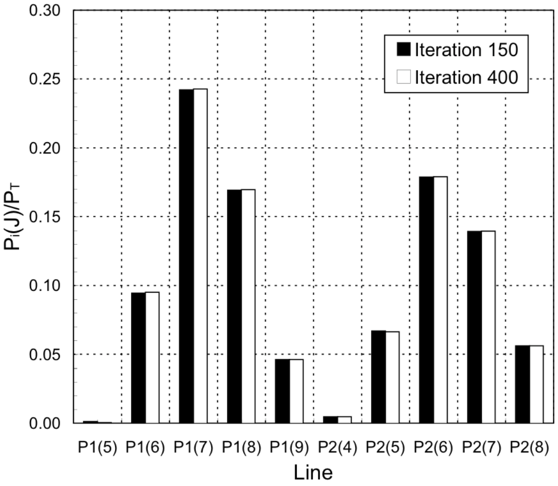

Figure 6. ORNECL-UR Case 8 spectrum.

at iterations 150 and 400, Fig. 6, shows no change. The spectra are typical of an unstable resonator with peak power occurring on $P_1(7)$. The cascade pair $P_2(5)$, $P_1(6)$ exhibit the largest amplitude oscillations at higher iterations, Figs. 7 and 8. The 46.40 ns and 208.8 ns oscillations on $P_2(5)$ have amplitude modulations of 16.97% and 2.97% of $P_2(5)$ line power respectively. The 46.40 ns and 208.8 ns oscillations on $P_1(6)$ have amplitude modulations of 2.24% and 0.13% of $P_1(6)$ line power respectively. The P_2 gains fill less of the resonator than the P_1 lines. Among lines with a significant amount of power, $P_2(5)$ filled the smallest fraction of the resonator and had the largest amplitude modulation, Figs. 9 and 10. It is likely that oscillations on the P_2 lines are driving the oscillations on the P_1 lines. The intensity distributions plotted in Figs. 11 and 12 are typical of an unstable resonator with strong diffraction effects occurring on $P_2(5)$. Long period oscillations have also been observed experimentally.[7]

Based on the proposed mechanism, for a fixed resonator Fresnel number, the period of the time-dependent oscillations should increase as the resonator magnification decreases, which results in more passes for the optical wave to exit the resonator, i.e., the medium is more strongly coupled to the optical fields geometrically. As n_P is increased by decreasing the resonator magnification to M=1.25 for a fixed N_F, the time-dependent oscillations should disappear i.e. the period will tend to infinity. To aid in the verification of the proposed mechanism a pair of cases that oscillate with fixed N_F and M=2 and M=1.25 respectively were chosen. Cases 13 and 14 were chosen to

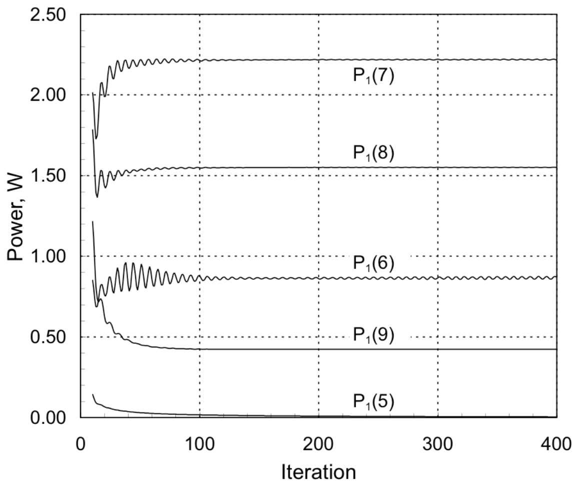

Figure 7. ORNECL-UR Case 8 calculated 1 → 0 individual line power.

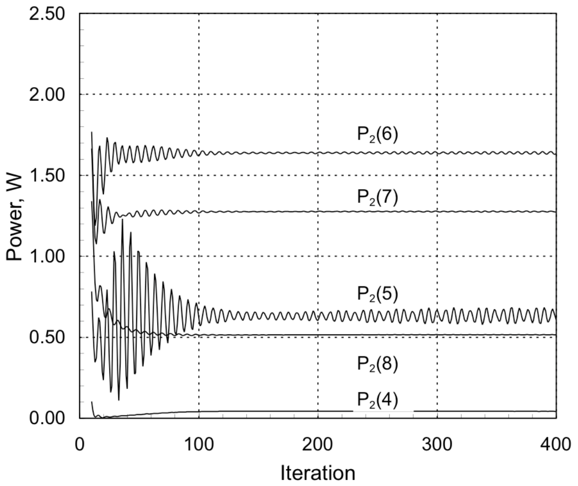

Figure 8. ORNECL-UR Case 8 calculated 2 → 1 individual line power.

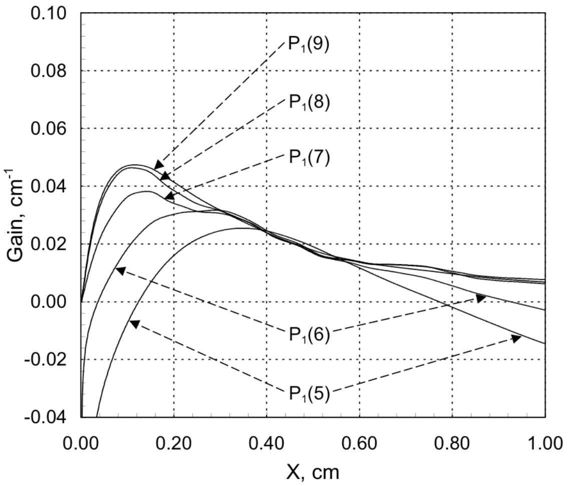

Figure 9. ORNECL-UR Case 8 calculated 1 → 0 individual line gains at iteration 150.

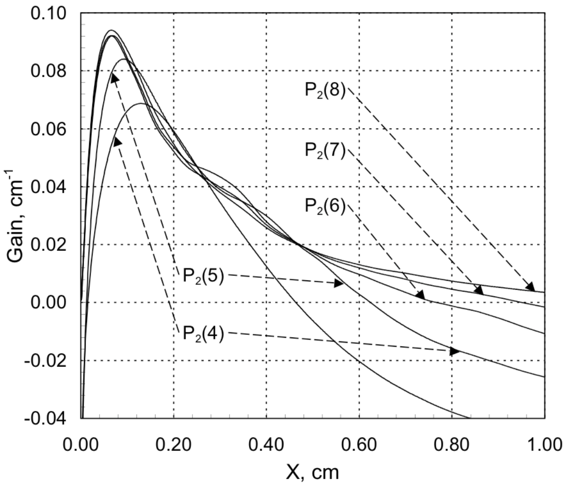

Figure 10. ORNECL-UR Case 8 calculated 2 → 1 individual line gains at iteration 150.

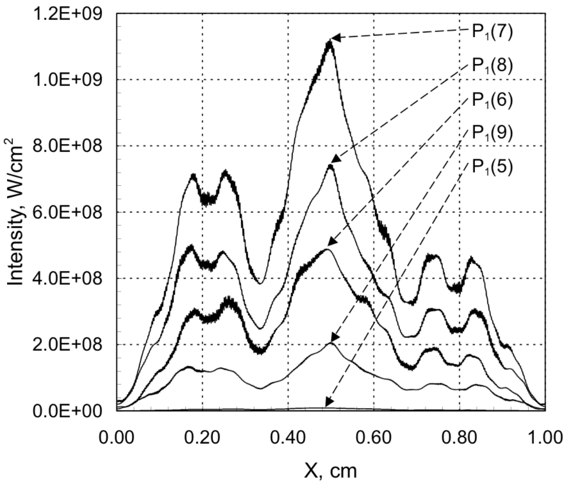

Figure 11. ORNECL-UR Case 8 calculated 1 → 0 individual line intensities at iteration 150.

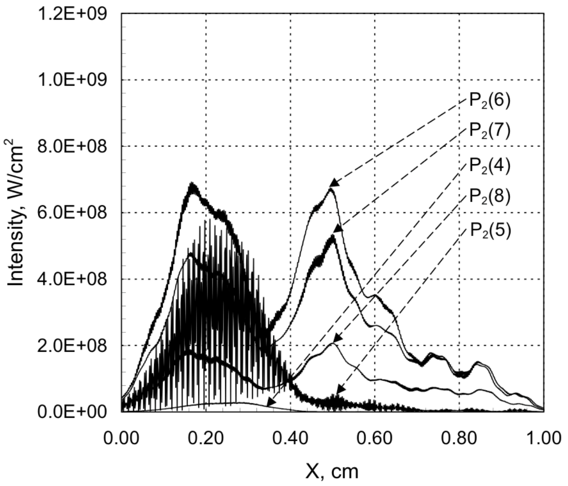

Figure 12. ORNECL-UR Case 8 calculated 2 → 1 individual line intensities at iteration 150.

verify that as n_P is increased by decreasing the resonator magnification to M=1.25 for a fixed N_F, the period of the time-dependent oscillations should increase.

Comparison of Case 1 to 6, Case 7 to 12, and Case 13 to 14, Table 2, shows N_F is fixed while n_p is increased. This is accomplished by changing the resonator magnification from 2 to 1.25. Comparison of Case 2 to 4 and 5 and Case 8 to 10 and 11, Table 2, shows that N_F is varied by changing the mirror separation while n_p remains small. Table 2 summarizes the total outcoupled power time-dependent oscillation results for the fourteen cases. The calculations indicate that reducing the percent SF_6 dissociation in the rebaselining, which led to a less strongly driven medium and lower gain, resulted in about a 10% increase in the amplitude modulation of the total outcoupled power oscillation. The rebaselining process had a small effect on the oscillation periods. For both baseline parameter sets, when an M=2, L=100cm, X_C=4 mm resonator was changed to an M=1.25, L=100 cm, X_C = 4 mm resonator, the oscillations disappeared as predicted by the proposed mechanism. With 6.3% SF_6 dissociation, when the M=2, L=100 cm, X_C=3.125 mm resonator was changed to an M=1.25, L=100 cm, X_C=3.125 mm resonator, the time-dependent oscillation period increased as predicted by the proposed mechanism. While the amplitude modulation in these two cases is so small the oscillations are almost non-existent, there is no question that they are present in the calculations. Among both baseline parameter sets, when N_F increased by changing from an M=2, L=100 cm, X_C=5 mm resonator to an M=2, L=80 cm, X_C=5 mm resonator, the period of the time-dependent oscillations decreased and the amplitude of the oscillations increased as predicted by the proposed mechanism. For both baseline parameter sets, as N_F decreased by changing from an M=2, L=100 cm, X_C=5 mm resonator to an M=2, L=200 cm, X_C=5 mm resonator, the time-dependent oscillations do not occur as predicted by the proposed mechanism. The calculations indicate that to reduce or eliminate time-dependent oscillations in a confocal unstable resonator, the Fresnel number should be less than 3 or the number of passes required for a wave to exit the resonator after leaving the Fresnel core should be greater than 4.

Case	M	L (cm)	X_C (mm)	P_{OUT-T} (watts)	n_P	N_F	τ (ns)	Amp. Mod. (% P_{OUT-T})
1	2.00	100	4.000	24.60	1.24	5.57	33.87, 200.0	0.28, 0.03
2	2.00	100	5.000	20.02	1.56	8.87	45.93, 206.7, 3306	0.37, 0.11
3	2.00	100	6.000	17.56	1.82	12.54	26.43, 185.0	5.34, 3.30
4	2.00	80	5.000	24.45	1.72	10.89	28.81	0.41
5	2.00	200	5.000	24.01	1.06	4.35	---	---
6	1.25	100	4.000	30.57	3.85	5.57	---	---
7	2.00	100	4.000	13.83	1.24	5.57	34.45	0.36
8	2.00	100	5.000	9.16	1.56	8.81	46.40, 208.8	0.55, 0.13
9	2.00	100	6.000	8.59	1.82	12.54	25.79, 155.2	5.92, 3.41
10	2.00	80	5.000	11.12	1.72	10.89	31.56	0.63
11	2.00	200	5.000	13.36	1.06	4.35	---	---
12	1.25	100	4.000	20.60	3.85	5.57	---	---
13	2.00	100	3.125	15.92	1.56	3.40	21.11	0.02
14	1.25	100	3.125	13.27	2.74	3.40	47.14	0.05

Table 2. Summary of ORNECLUR confocal unstable resonator results. M is the resonator magnification, L is the resonator mirror spacing, P_{OUT-T} is the total outcoupled power, n_P is the number of passes required for a wave to exit the resonator after leaving the central Fresnel Zone, N_F is the Fresnel Number, τ is the period of the time-dependent oscillation of the total outcoupled power, and Amp. Mod. is the amplitude modulation of the calculated oscillations for each case. The "---" indicates no lines oscillated.

V. Concluding Remarks

The proposed mechanism for the time-dependent oscillations which may occur in unstable resonators on lines whose saturated gain does not fill the resonator is supported by the calculations presented in Section IV. The functionality of the inoperable HF chemical laser model RDRIVER was restored and verified. The Bell Aerospace Textron wave-optics strip resonator model was coupled to the chemical kinetic, fluid dynamic, rotational non-equilibrium, exact $E_{v,J}$ model ORNECL. The resulting code is denoted ORNECL-UR. The validity of ORNECL-UR was verified by reproducing the MNORO3UR calculations for a subsonic CL-II chemical laser. Initial ORNECL-UR calculations and experimental data[10] were used to rebaseline ORNECL-UR to accurately predict total outcoupled power. ORNECL-UR was used to model resonator geometries suggested by previous studies.

Conditions for the reduction or elimination of time-dependent oscillations in a cw HF chemical laser confocal unstable resonator were derived from the results of the calculations presented in Section IV. The calculations indicate that to reduce or eliminate time-dependent oscillations in a confocal unstable resonator, the Fresnel number should be less than 3 or the number of passes required for a wave to exit the resonator after leaving the Fresnel core should be greater than 4. This suggests that unstable resonators for high-energy HF chemical lasers be designed with $N_F < 3$ or $n_P > 4$ to minimize or eliminate these oscillations. Low gain systems, such as HF overtone, would tend to require $n_P > 4$ and may thereby inherently avoid such oscillations; this hypothesis should be tested experimentally.

To improve the value and accuracy of the numerical model ORNECL-UR, certain steps may be taken. The rebaselined ORNECL-UR accurately predicts trends in total outcoupled power, oscillation period, and oscillation amplitudes as n_p and N_F were varied, but ORNECL-UR did not accurately predict the magnitude of the amplitude modulation. Since ORNECL was originally baselined to the vertically averaged measured zero power gain distributions in the UIUC SSL,[11,12] these vertically averaged gains may result in the calculated gains extending too far downstream. The ORNECL-UR under prediction of the magnitude of the amplitude of the time-dependent oscillations in SSL unstable resonators indicates the baselining to the zero power gain data should be revisited. Further, ORNECL-UR is a 2-D strip resonator model, while the experimental data were obtained with a 3-D resonator with slit scraper mirrors; therefore the experiments would have greater diffractive losses than predicted by the existing model. A 3-D wave-optics model coupled to ORNECL should improve the simulation of the experiments.

Acknowledgements

This work was supported by the Missile Defense Agency (MDA) and the U.S. Army through a subcontract from Northrop Grumman. The authors gratefully thank the MDA, the U.S. Army AMRDEC, and Northrop Grumman Space & Technology for their support of this research. We also wish to thank J. Mulroy, R. Graves, S. Patterson, M. Kwok, J. Betts, J. Solle, and S. J. Mayer.

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