

Final Report

U.S. Department of Energy

Office of Basic Energy Studies

Photoacoustic and Thermal Effects
in
Particulate Suspensions

Gerald J. Diebold

Department Chemistry, Brown University

Providence, RI, USA, 02912

April 2009

Contents

I	Research Synopsis	1
1	Research on the photoacoustic effect	1
	a Chemical effects	1
	b Physical effects	1
	c Transient grating studies	1
2	Devices and diagnostics	2
3	Ludwig-Soret Effect	2
4	Miscellaneous	2
II	Publications	2
1	Selected journal articles	2
2	Complete list of journal articles	3
3	Books	8
4	Review articles	8
5	Book reviews	8
III	Work Statement	8

Abstract

A summary of the research areas investigated by the author during the grant period is given. Experiments and theory have been carried out on the photoacoustic effect arising from a number of physical and chemical processes. A number of studies of the photoacoustic effect as it occurs in transient grating experiments have been completed. The research done with the Ludwig-Soret effect on the generation of shock waves is reported. Other research, such as that carried out on interferometric and beam deflection microphones, the use of microphones in vacuum as momentum flux detectors, and chemical generation of sonoluminescence is listed. A list of published research including selected publications, a complete list of journal articles, books, review articles, and reviews are given. A work statement is included.

I Research Synopsis

1 Research on the photoacoustic effect

The author has conducted research on generation of sound waves by absorption of optical radiation, known as the photoacoustic or optoacoustic effect. Research areas where papers have been published include the following:

a Chemical effects

Chemical generation of the photoacoustic effect by photodissociation and chain reaction that give a chemically amplified photoacoustic effect

Solution to the nonlinear Riccati equation describing sound generation by recombination of radicals

Discovery of a "giant" photoacoustic effect in carbon suspensions

Trace detection using the chemically amplified photoacoustic effect

b Physical effects

Theory and experiment for generation of the photoacoustic effect from isotropic solid and fluid bodies including spheres, layers and cylinders

Formulation of a theory for the photoacoustic effect for volume changes induced by chemical or physical mechanisms including a wave equation for pressure that quantitatively describes the effect

Theorems for generation of the photoacoustic effect from symmetric bodies giving mappings of the spatial distribution of laser radiation into the time profile of the acoustic wave for short and long laser pulses

What might be called a "phonon maser" based on the photoacoustic effect where interference effects are generated in a series of layers irradiated by amplitude modulated optical radiation

Determination of the angular distribution of photofragments using a microphone under vacuum

The determination of the sensitivity of a membrane as a momentum flux detector

Generation of the photoacoustic effect through heat diffusion

Theoretical study of the photoacoustic point source

Photoacoustic theory for a reflecting sphere with sound generation external to the sphere

Discovery of shock waves from laser irradiation of carbon suspensions

c Transient grating studies

Theoretical and experimental investigation of the photoacoustic effect from an assembly of particles irradiated in a transient grating apparatus

Establishment of an experimental method for evaluating photodynamic therapy agents using a transient grating apparatus

Study of heat diffusion from micelles excited in a laser generated transient grating

Determination of thermophysical properties of ionic liquids using a transient grating apparatus

Laser generation of gas bubbles from solutions and colloidal suspensions

2 Devices and diagnostics

A non contact beam deflection membrane microphone for photoacoustic trace detection
Photoacoustic apparatus for study of chemical reactions at low concentrations

3 Ludwig-Soret Effect

Experimental discovery of thermal diffusion (Ludwig-Soret) shock waves
Mathematical solution to the nonlinear partial differential equation that describes the motion of components of a mixture in a thermal field

4 Miscellaneous

Generation of sonoluminescence through chemical reaction
Laser induced chemical synthesis in carbon suspensions
Diffraction of light from phase gratings with a large modulation depth
The use of transient gratings for determination of the quantum yield of $^1\Delta O_2$ from photodynamic therapy agents.
Study of the effects of thermal inertia in laser induced reactions in particulate suspensions

II Publications

1 Selected journal articles

Science and Nature:

"Generation of Ultrasonic Waves from a Layered Source" with T. Sun, Nature 355, 806 (1992)
"Chemical Amplification of Optoacoustic Signals", with M. T. O'Connor, Nature 301, 321 (1983);
(see editorial p 286)
"Photoacoustic 'Signatures' of Particulate Matter: Optical Production of Acoustic Monopole Radiation", with M. I. Khan, and S. M. Park, Science 250, 101 (1990)
G Diebold and H. X. Chen, "Chemical Generation of Acoustic Waves: A 'Giant' Photoacoustic Effect, Science 270, 963 (1995)

Physical Review Letters:

"Thermal Diffusion in a Sinusoidal Temperature Field" with S. Danworaphong, and W. Craig, Phys. Rev. Lett, 92, 125,901 (2004)
"Photoacoustic Point Source" with I. G. Calasso and W. Craig, Phys. Rev. Lett. 86, 3550 (2001)
"Photoacoustic Monopole Radiation in One, Two, and Three Dimensions", with T. Sun and M. I Khan, Phys. Rev. Lett. 67, 3384 (1991)
"Thermal Diffusion Shock Waves" with S. Danworaphong, W. Craig, and V. Gusev, Phys. Rev. Lett. 94, 095901 (2005) see also Virtual Journal of Nanoscale Science and Technology 21 March 2005
"Interference in Atomic Fluorescence Following Photodissociation of Homonuclear Diatomic Molecules", Phys. Rev. Lett. 51, 1344 (1983).

Angewandte Chemie International Edition:

"Laser Induced "Regeneration" of Colloidal Particles: The Effects of Thermal Inertia on the Chemical Reactivity of Laser Heated Particles" with T. E. McGrath and A. C. Beveridge, *Angew. Chemie* 38, 3353 (1999)

"Laser Initiated Chemical Reactions in Carbon Suspensions", with H. X. Chen, and T. E. McGrath *Angew. Chem. Int. Ed. Engl.* 36, 163 (1997)

"Introduction of Bulky Perfluoroalkyl Groups at the Periphery of Zinc Perfluorophthalocyanine: Chemical, Structural, Electronic, and Preliminary Photophysical, and Biological Effects" with Barbara Bench, Andrew Beveridge, Johan E. van Lier, and Sergiu Gorun, *Angew. Chemie Int. Eng. Ed.* 41, 747, (2002)

J. American Chemical Society Letters:

"Chemical Kinetics in Dilute Solution: Photoacoustic Detection of Small Absorbance Changes in Chemical Reactions". with V. E. Anderson, H. Z. Cheng, A. Mahmood, and D. A. Sweigart, *J. Am. Chem. Soc.*, 109, 6191 (1987).

Applied Physics Letters:

"Photoacoustic Shock Generation in Carbon Suspensions" with A. C. Beveridge, T. E. McGrath, and A. A. Karabutov, *Appl. Phys. Lett.* 75, 4204 (1999)

"Potential Distributions from Electroacoustic Polarization Sources" Cuong Nguyen, Vitalyi Gusev, and Gerald Diebold, *Appl. Phys. Lett.* 93, 1841041-3 (2008)

"Frequency Domain Vibration Potential Imaging: Objects with Symmetry in One Dimension", A. Beveridge, S. Li, and G. J. Diebold and C. Nguyen, *Appl. Phys. Lett.* 89, 243902 (2006)

"A Thermal Piston Model for the Optoacoustic Effect: Sound Generation in an Optically Thick Gas", with R. B. Stewart, *Appl. Phys. Lett.*, 50, 13 (1987).

"Sonoluminescence Initiated by Laser Irradiation of Carbon Suspensions", with T. E. McGrath and A. C. Beveridge, *Appl. Phys. Lett.* 73, 1029 (1998)

"Photoacoustic Shock Generation in Carbon Suspensions" with A. C. Beveridge, T. E. McGrath, and A. A. Karabutov, *Appl. Phys. Lett.* 75, 4204 (1999)

"Acoustic Radiation Pressure: a "Phase Contrast" Agent for X-ray Phase Contrast Imaging, with C. Bailat, T. Hamilton, C. Rose-Petruck *Appl. Phys. Lett* 85 4517 (2004)

"Acoustic Radiation Pressure: a "Phase Contrast" Agent for X-ray Phase Contrast Imaging, with C. Bailat, T. Hamilton, C. Rose-Petruck *Appl. Phys. Lett* 85 4517 (2004)

"Total Internal Reflectance Optoacoustic Spectroscopy", with P. R. Muessig, *J. Appl. Phys.*, 54, (8), 4251 (1983).

2 Complete list of journal articles

1. "Acoustic Wave Generation in a Periodically Photodissociated Gas", *J. Phys. Chem.*, 84, 2213 (1980).

2. "A Highly Variable Optoacoustic Phase Angle within the S0-S1 Band of Glyoxal", with M. B. Robin, N. A. Kuebler, and K. Kaya, *Chem. Phys. Lett.* 70, 93 (1980)

3. "Optoacoustic Detection of Chain Reactions", with J. Hayden, *Chem. Phys.*, 49, 429 (1980).

4. "Detection of Several Electronically Metastable Atomic States by Gas Phase EPR", with I. V. Rivas, S. Shafeizad and D. L. McFadden, *Chem. Phys.*, 52, 453 (1980).

5. "The Optoacoustic Effect in a Photodissociated Gas", *Proceedings of the IEEE Ultrasonics Symposium* 1, 502 (1980).

6. "Direct Detection of Momentum Flux in Atomic and Molecular Beams", with J. G. Choi, J. Hayden, and M. T. O'Connor, *J. Appl. Phys.* 52, 6016 (1981).

7. "Multiphoton Ionization Detection of NO Scattered from Solid Surfaces", with J. S. Hayden, *J. Chem. Phys.* 77, 4767 (1982).
8. "Microphone Detection of Pulsed Atomic and Molecular Beams", with J. G. Choi, *Chem. Phys.*, 73, 19 (1982).
9. "Laser Schlieren Microphone for Optoacoustic Spectroscopy", with J. G. Choi, *Appl. Optics*, 21, 4087 (1982).
10. "Chemical Amplification of Optoacoustic Signals", with M. T. O'Connor, *Nature* 301, 321 (1983).
11. "Total Internal Reflectance Optoacoustic Spectroscopy", with P. R. Muessig, *J. Appl. Phys.*, 54, (8), 4251 (1983).
12. "Interference in Atomic Fluorescence Following Photodissociation of Homonuclear Diatomic Molecules", *Phys. Rev. Lett.* 51, 1344 (1983).
13. "Interference in Atomic Fluorescence Excited by Photodissociation of Homonuclear Diatomic Molecules", in "Coherence and Quantum Optics V, L. Mandel and E. Wolf eds (Plenum, New York, 1984).
14. "Radiation Induced Thermal Noise in Photoacoustic Detection Cells", with R. Stewart, *J. Appl. Phys.*, 56, 1992 (1984).
15. "Optoacoustic Detection of Photodissociation and Termolecular Recombination in Cl₂", with M. T. O'Connor, *J. Chem. Phys.*, 81, 812, (1984).
16. "The Chemically Amplified Optoacoustic Effect: Application to Chemical Kinetics and Trace Detection". *Proc. International Conference on Lasers' 84, San Francisco, 1985.*
17. "Quantum Mechanical Interference in Two Photon Absorption: A Nonlinear Analog of the Hanle Effect", *Phys. Rev. A* 32, 2739 (1985).
18. "Interference in Atomic Fluorescence Excited by Molecular Photodissociation", *Phys. Rev. A* 32, 1458 (1985).
19. "Trace Detection Based on Chemical Amplification of the Optoacoustic Effect" with J. G. Choi, *Anal. Chem.* 57, 2989 (1985).
20. "The Inverse Optoacoustic Effect", *Proc. 4th Int. Topical Meeting on Photoacoustic, Thermal and Related Sciences*, Montreal, 1985 with S. Didascalou and R. Stewart.
21. "Quantum Beats in Atomic Fluorescence Excited by Molecular Photodissociation", *J. Chem. Phys.*, 85, 25 (1986).
22. "Relaxation of Optically Pumped Na on Impact with LiF" with P. R. Muessig, *Surface Science* 165, L59 (1986).
23. "Photochemical Generation of the Optoacoustic Effect: An Acoustic Analog of the Method of Intermittent Activation" *J. Phys. Chem.* 90, 711 (1986).
24. "The Inverse Optoacoustic Effect: Sound Generation Through Emission of Blackbody Radiation" with S. Didascalou and R. B. Stewart, *Optics Commun.* 58, 103 (1986).
25. "Photochemical Generation of the Optoacoustic Effect: An Acoustic Analog of the Method of Intermittent Activation" with M. T. O'Connor and R. B. Stewart, *J. Phys. Chem.* 90, 711 (1986).
26. "Quantum Interference in Two-Photon Absorption: Polarization and Magnetic Field Effects in Atomic Sr", *Phys. Rev. A*, 34, 2547 (1986).
27. "A Thermal Piston Model for the Optoacoustic Effect: Sound Generation in an Optically Thick Gas", with R. B. Stewart, *Appl. Phys. Lett.*, 50, 13 (1987).
28. "A Helmholtz Resonator Optoacoustic Detector for Gas Chromatography" with J. G. Choi, *Anal. Chem.*, 59, 519 (1987).

29. "Chemical Kinetics in Dilute Solution: Photoacoustic Detection of Small Absorbance Changes in Chemical Reactions". with V. E. Anderson, H. Z. Cheng, A. Mahmood, and D. A. Sweigart, *J. Am. Chem. Soc.*, 109, 6191 (1987).
30. "An Interferometric Microphone for Optoacoustic Spectroscopy", with S. M. Park, *Rev. Sci. Instrument*, 58, 772 (1987).
31. "Interference in Two-Photon Absorption at High Field Crossings" with R. Stewart in "Atomic and Molecular Processes with Short Intense Laser Pulses", (Plenum, New York, 1988). A. Bandrauk, ed.
32. "Pressure and Velocity Profiles Generated by Laser-Heated Spherical Droplets" with X. Hu in "Photoacoustic and Photothermal Phenomena", (Springer-Verlag, Heidelberg, 1988), P. Hess and J. Pelzl, eds.
33. "Optoacoustic Measurement of Isotope Effects in the H₂-Cl₂ Reactions", with S. Wyers, "Photoacoustic and Photothermal Phenomena", (Springer-Verlag, Heidelberg, 1988). P. Hess and J. Pelzl, eds.
34. "Numerical Calculation of the Photoacoustic Signal Generated by a Droplet" *AIP Conf. Proc.* 172, 747 (1988).
35. "The Photoacoustic Effect Generated by a Spherical Droplet in a Fluid", G. J. Diebold, and P. J. Westervelt, *J. Acoust. Soc. Am.* 84, 2245 (1988)
36. "The Effects of Optical Pumping on Laser Enhanced Electron Impact Ionization" with S. M. Park, *Optics Commun.* 69, 253 (1989).
37. "Photoacoustic Generation of Anisotropic Pressure Waves Through Photodissociation of Cl₂", with S. M. Park, and M. I. Khan, *Opt. Lett.* 15, 771, 1990
38. "Photoacoustic Waveforms from Laser Heated Particulate Matter", with P. Karcher, and S. M. Park, in *Photoacoustic and Photothermal Phenomena II*, (Springer-Verlag, Heidelberg, 1990) J. C. Murphy, J. W. Maclachlan-Spicer, L. C. Aamodt, and B. S. H. Royce, eds.
39. "Selective Ionization of Ba and Sr Isotopes based on a Two-Photon Interference Effect", with S. M. Park, *Phys. Rev. A* 42, 417, (1990)
40. "Production of Anisotropic Photoacoustic Pressure Waves by Photodissociation of Molecular Chlorine", with S. M. Park, and M. I. Khan. (Springer-Verlag, Heidelberg, 1990) J. C. Murphy, J. W. Maclachlan-Spicer, L. C. Aamodt, and B. S. H. Royce, eds.
41. "Photoacoustic 'Signatures' of Particulate Matter: Optical Production of Acoustic Monopole Radiation", with M. I. Khan, and S. M. Park, *Science* 250, 101 (1990)
42. "Photoacoustic Effect in Strongly Absorbing Fluids", with S. M. Park, M. I. Khan, and H. Z. Cheng, *Ultrasonics* 29, 63, (1991)
43. "Photoacoustic Monopole Radiation in One, Two, and Three Dimensions", with T. Sun and M. I. Khan, *Phys. Rev. Lett.* 67, 3384 (1991)
44. "Photoacoustic Waveforms Generated by Fluid Bodies" with T. Sun and M. I. Khan, in "Photoacoustic and Photothermal Phenomena", Springer-Verlag, Heidelberg, 1992, D. Bicanic, ed.)
45. "Generation of Ultrasonic Waves from a Layered Photoacoustic Source" with T. Sun, *Nature* 355, 806 (1992)
46. "Investigation of Viscosity and Heat Conduction Effects on the Evolution of a Transient Picosecond Photoacoustic Grating" with T. Sun, J. Morais, and M. B. Zimmt, *J. Chem. Phys.* 97, 9324 (1992)
47. "Photoacoustic Waves Generated by Absorption of Laser Radiation by Optically Thin Layers" with M. I. Khan and T. Sun, *J. Acoust. Soc. Am.* 93, 1417 (1993)

48. "Photoacoustic Waves Generated by Absorption of Laser Radiation in Optically Thin Cylinders" with M. I. Khan and T. Sun. *J. Acoust. Soc. Am.* 94, 931 (1993).
49. "Properties of Photoacoustic Waves in One, Two, and Three Dimensions" with T. Sun, *Acustica* 80, 339 (1994)
50. "Distributed Source Photoacoustic Generation of Ultrasound" with T. Sun and H. Chen, *Ultrasonics* 32, 265 (1994).
51. "Thermally Launched Photoacoustic Waves", with Y. N. Cao, H. X. Chen, T. Sun, and M. B. Zimmt, *Journal De Physique C7*, 713 (1994).
52. "The Photoacoustic Effect Generated by an Isotropic Solid Sphere" with M. I. Khan, *Ultrasonics* 33, 265 (1995).
53. "Thermally Generated Photoacoustic Gratings", with H. X. Chen *Proc. 15'th Int. Congress on Acoustics, Trondheim, Vol. I*, 337 (1995).
54. "Chemical Generation of Acoustic Waves: A 'Giant' Photoacoustic Effect, with H. X. Chen, *Science* 270, 963 (1995).
55. "The Photoacoustic Effect Generated by Laser Irradiation of an Isotropic Solid Cylinder" With M. I. Khan *Ultrasonics* 34, 19 (1996)
56. "Production of the Photoacoustic Effect and Transient Gratings by Molecular Volume Changes", with H. X. Chen, *J. Chem. Phys.* 104, 6730 (1996).
57. "Effects of Heat Conduction and Viscosity on Photoacoustic Waves from Droplets", with Y. N. Cao, *Opt. Eng.* 36, 417 (1997)
58. "Laser Initiated Chemical Reactions in Carbon Suspensions", with H. X. Chen, and T. E. McGrath *Angew. Chem. Int. Ed. Engl.* 36, 163 (1997)
59. "Generation of the Photoacoustic Effect through Heat Diffusion: Transient Grating Measurements in Reverse Micellar Solutions", with Y. N. Cao, H. X. Chen, T. Sun and M. B. Zimmt, *J. Phys. Chem.*, 101, 3005 (1997)
60. "Transient Grating Studies of Ultrasonic Attenuation in Reverse Micellar Solutions" with Y. N. Cao, and M. B. Zimmt, *Chem. Phys. Lett.* 276, 388 (1997)
61. "Chemical Generation of Sound Waves: Shock Waves and A "Giant" Photoacoustic Effect" with H. X. Chen, T. E. Mc Grath, and A. C. Beveridge, *Proc. IEEE Conference on Ultrasonics, Toronto*, 1, 719, 1997
62. "Theory of Thin Layer Photoacoustic Cells for Determination of Volume Changes in Solution", *J. Phys. Chem.* 102, 5404 (1998)
63. "Sonoluminescence Initiated by Laser Irradiation of Carbon Suspensions", with T. E. McGrath and A. C. Beveridge, *Appl. Phys. Lett.* 73, 1029 (1998)
64. "Sonoluminescence and Voltage Generation in Laser Irradiated Colloidal Suspensions", with T. E. Mc Grath and A. C. Beveridge, *Proc. X Int. Conf. on Photoacoustic and Photothermal Phenomena, Rome*, 1998
65. "Diffraction of Light from Phase Gratings at Large Modulation Depths: Experimental Results in Liquids Using High Power Lasers" with H. X. Chen, *Optics Lett.*, 24 211 (1999)
66. "Laser Induced "Regeneration" of Colloidal Particles: The Effects of Thermal Inertia on the Chemical Reactivity of Laser Heated Particles" with T. E. McGrath and A. C. Beveridge, *Angew. Chemie* 38, 3353 (1999)
67. "Photoacoustic Shock Generation in Carbon Suspensions" with A. C. Beveridge, T. E. McGrath, and A. A. Karabutov, *Appl. Phys. Lett.* 75, 4204 (1999)
68. "The Photoacoustic Effect Generated by Heat Diffusion" with I. Calasso and W. Craig, *Analytical Sciences* 17, 249, (2001)

69. "The Photoacoustic Point Source" with I. G. Calasso and W. Craig, *Phys. Rev. Lett.* 86, 3550 (2001)
70. "Transient Grating Studies of Laser Induced $^1\Delta$ O₂ Production By Photodynamic Therapy Agents" with A. C. Beveridge, B. A. Bench, I. G. Calasso, and S. S. Gorun, *Proc. SPIE* 4265, (Biomedical Optoacoustics II) 167 (2001)
71. "Photoacoustic Evaluation of Photodynamic Therapy Agents" with Andrew C. Beveridge, Barbara A. Bench, Irio G. Calasso, and Sergiu M. Gorun, *Proc ICA* 2001
72. "Introduction of Bulky Perfluoroalkyl Groups at the Periphery of Zinc Perfluorophthalocyanine: Chemical, Structural, Electronic, and Preliminary Photophysical, and Biological Effects" with Barbara Bench, Andrew Beveridge, Wesley M. Sharman, Johan E. van Lier, and Sergiu Gorun, *Angew. Chemie Int. Eng. Ed.* 41, 747, (2002)
73. "Laser Initiated Chemical Reactions in Carbon Suspensions" with T. E. McGrath, D. Bartels, and R. Crowell, *J. Phys. Chem.* 106, 10072 (2002)
74. "The Photoacoustic Effect Generated by an Incompressible Sphere" with A. C. Beveridge and T. Hamilton, *J. Acoust. Soc. Am.* 112, 1780 (2002)
75. "The Photoacoustic Effect at Reflecting Interfaces", with Theron Hamilton *Rev. Sci. Instrum.*, 74, 801 (2003)
76. "Internally Excited Acoustic Resonator for Photoacoustic Trace Detection", with S. Danworaphong, I. G. Calasso, A. Beveridge, C. Gmachl, F. Capasso, D. L. Sivco, and A. Y. Cho, *Appl Opt.* 27, 5561 (2003).
77. "Evaluation of Photodynamic Therapy Agents through Transient Grating Measurements" with A. C. Beveridge, B. A. Bench, and S. M. Gorun, *J. Phys. Chem. A* 107, 5138 (2003)
78. "Thermal Diffusion in a Sinusoidal Temperature Field" with S. Danworaphong, and W. Craig, *Phys. Rev. Lett.* 92, 125901 (2004).
79. "Quantities, Terminology and Symbols in Photothermal and Related Spectroscopies" IUPAC Physical Chemistry Division, Pure and Applied Chemistry with M. Terazima, N. Hirota, S. Braslavsky, A. Mandelis, S. Bialkowski, R. J. D. Miller, D. Fournier, R. Palmer, and A. Tam. *IUPAC* 76, 1083-1118 (2004)
80. "Resonant Microphone based on Laser Beam Deflection", with K. Roark, *J. Appl. Phys.* 96, 864 (2004)
81. "Thermal Diffusion Shock Waves" with S. Danworaphong, W. Craig, and V. Gusev, *Phys. Rev. Lett.* 94, 095901 (2005)
82. "Acoustically Modulated X-Ray Phase Contrast and Vibration Potential Imaging" with a. C. Beveridge, C. J. Bailat, T. J. Hamilton, S. Wang, C. Rose-Petruck, and V. E. Gusev *Proceedings of the SPIE* 5697, 90-98 (2005) Selected as the best conference paper
83. "Thermal Diffusion Shock Waves" with S. Danworaphong, W. Craig, and V. Gusev, *Phys. Rev. Lett.* 94, 095901 (2005) selected for *Virtual Journal of Nanoscale Science and Technology* 21 March 2005
84. "Mathematical Analysis of Thermal Diffusion Shock Waves", with V. Gusev, R. LiVoti, and S. Danworaphong, *Phys. Rev. E* 72, 041205, (2005)
85. "Transient Gratings Generated by Particulate Suspensions: The Uniformly Irradiated Sphere and the Point Source" with C. Frez, I. G. Calasso *J. Chem. Phys.* 124, 034905 (2006)
86. "Determination of Thermophysical Properties of Room Temperature Ionic Liquids by the Transient Grating Technique", with C. Frez, C. D. Tran and S. Yu *J. Chem. Eng. Data.* 51, 1250 (2006)

88. "Laser Generation of Gas Bubbles: Photoacoustic and Photothermal Effects Recorded in Transient Grating Experiments", C. Frez and G. J. Diebold, J. Chem. Phys. 129, 184506 (2008) also Virtual Journal of Ultrafast Science, December 2008.

89. "A Search for Laser Heating of a Sonoluminescing Bubble" G. Cao, S. Danworaphong, and G. J. Diebold, Eur. Phys. J. 153, 215-221 (2008).

90. "Photoacoustic Effect from Particles and Bubbles" C. Frez and G. J. Diebold, Eur. Phys. J. 153, 307-311 (2008).

91. "Potential Distributions from Electroacoustic Polarization Sources" Cuong Nguyen, Vitalyi Gusev, and Gerald Diebold, Appl. Phys. Lett. 93, 1841041-3 (2008)

3 Books

Thermal Diffusion Shock Waves, Sorasak Danworaphong, Walter Craig and Gerald J. Diebold, (VDM Verlag, Beau-Bassin, Germany) 2009

4 Review articles

"The Photoacoustic Effect in One, Two, and Three Dimensions" (in Photoacoustic Imaging and Spectroscopy, L. Wang, ed. In press)

"Application of the Photoacoustic Effect to Studies of Gas Phase Chemical Kinetics" in "Photoacoustic, Photothermal, and Photochemical Processes in Gases" (Springer-Verlag, Heidelberg, 1989) P. Hess, ed.

5 Book reviews

Radiation Acoustics by L. M. Lyamshev in J. Acoust. Soc. Am. 119, 14, (2006)

III Work Statement

All funds have been expended as of April 14, 2009