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Under the present tenure of support by SDIO-IST/AFOSR we were able to develop a very comprehensive research program in the area of photonics. This program covered microscopic theory of optical nonlinearity, design and synthesis of novel structures, materials processing for guided waves, measurements of optical nonlinearities and study of device processes. We made significant accomplishments in each topic as recognized by the number of invitations received to give talks at various international conferences.

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FINAL REPORT

PROJECT: Molecular Engineering, Dynamics of Electron Transport and Nonlinear Optical Interaction in Langmuir-Blodgett Films of Organic Semiconductor Heterostructure

SPONSOR: SDIO-IST/USAFOSR

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1. SUMMARY

Under the present tenure of support by SDIO-IST/AFOSR we were able to develop a very comprehensive research program in the area of photonics. This program covered microscopic theory of optical nonlinearity, design and synthesis of novel structures, materials processing for guided waves, measurements of optical nonlinearities and study of device processes. We made significant accomplishments in each topic as recognized by the number of invitations received to give talks at various international conferences. We have published extensively. In this progress report these accomplishments are listed separately under each topic. This description is followed by a list of publications and patents filed resulting from this support and invited talks presented during the tenure of this support.

Theory

We have used both the classical anharmonic oscillator approach as well as the ab-initio calculations to understand the microscopic nature of optical nonlinearities in organic structures. Our ultimate goal is to understand the structure-property relationship so that one may be able to predict structures with enhanced optical nonlinearities. The focus of our work has been on third-order optical nonlinearity.

We developed a simple model of coupled locally anharmonic oscillators which can be used to describe the optical nonlinearities in conjugated organic monomeric, oligomeric and polymeric structures [1]. This method can very readily be used to explain the dependence of the band gap, the linear polarizability, α, and the second hyperpolarizability (microscopic third-order nonlinear optical coefficient), γ, on the number of repeat units for the oligomers of thiophene and benzene. The results predicted by the coupled anharmonic oscillator model are in good agreement with those of the

experimental studies on thiophene and benzene oligomers recently reported by our group.

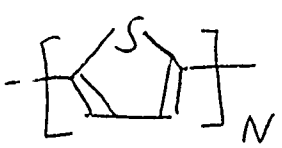
Static polarizability and second hyperpolarizability tensors have also been computed for a series of polyenes, polyynes and cumulenes by ab initio SCF theory [2] using the finite field (FF) calculations in which a polynomial fit of either energy or induced dipole moment as a function of field strength was conducted. Fully coupled (FF) and uncoupled (SOS) ab initio SCF calculations, using identical small basis sets, were found to be in reasonably good agreement for linear polarizabilities but not for the hyperpolarizabilities (nonlinear optical coefficients). Diffuse orbital basis functions are required for qualitatively correct hyperpolarizabilities of small conjugated π systems. We have used a corresponding orbital analysis to separate the σ and π electron contributions to optical nonlinearities. The π-electron contribution dominates the optical nonlinearity. Polarizability and second hyperpolarizability are given by the first and third derivatives, respectively, of charge density with respect to field strength. A contour map of the first derivative density for an acetylenic chain is nearly periodic, corresponding to localized polarization of individual triple bonds. A map of the third derivative density does not exhibit this feature, corresponding to longer range charge shifts induced by the applied electric field.

With a goal to investigate the role of heavy atoms in determining optical nonlinearities, we have conducted [3] ab-initio calculations of polarizability, α, and first and second hyperpolarizabilities, β and γ for the haloform series CHX_3 where X = F, Cl, Br, and I, using the Effective Core Potential (ECP) approach. The microscopic optical nonlinearities α, β and γ were calculated as the derivatives of the energy with respect to the

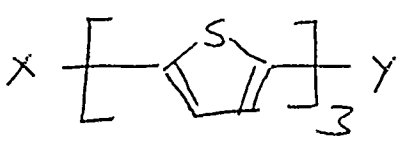
electric field, with the energy determined by means of the Self-Consistent-Field approach (SCF), and nonlinearities calculated in the static field limit by means of the Coupled Perturbed Hartree-Fock (CPHF) formalism. To test the usefulness of the ECP method, nonlinear optical responses for the lighter members of the series, CHF_3 and $CHCl_3$, were computed by using both all electron and ECP calculations. The results are compared, and are found to be in excellent agreement. The effects of various basis sets and inclusion of diffuse and polarization functions are also examined to select a basis set which gives a good description of optical nonlinearities. The ECP technique is, then, used to calculate optical nonlinearities for $CHBr_3$ and CHI_3. Although a very good agreement was found between the calculated and experimental polarizabilities for the haloform series, a rather poor agreement was obtained for the higher order polarizabilities.

Design and Synthesis

Our effort under this topic has been focused on making sequentially built and systematically derivatized structures with an objective that measurements of optical nonlinearities on these compounds will yield an insight into structure-property relationship. To investigate the dependence of the microscopic third-order optical nonlinearity Y on the number of repeat units, we prepared the α-trimer, tetramer, pentamer and hexamer of thiophene (I):

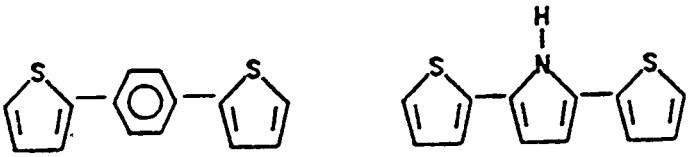


thiophene oligomers
I



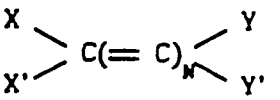
X, Y = NO_2
II

The dependence of both α and Y on the number of repeat units N was measured and compared with theoretical predictions. A satisfactory agreement was found. To examine the effect of systematic derivatization, structures II were prepared and measurements were made. We also prepared the following derivatized structures.



The measurements of α and Y were made [4]. A comparative study was used to determine the effectiveness of the phenyl, thiophene and pyrole rings in determining Y.

Another group of compounds we have made and are currently investigating is based on rigid cumulene structures III.



III

We have made structures with N = 3 and 5, X = X' = Y = Y' =  and studied their nonlinear behavior [5].

Materials Processing, Langmuir-Blodgett Films Work

The research under this category has focussed on the preparation of optical quality films and characterization by using various structural and spectroscopic techniques. Ultrathin films with a monolayer resolution have been prepared using the Langmuir-Blodgett method [6-10]. Thin films of

optical waveguide dimensions were made by using solution casting techniques such as spin-coating and doctor blading [11]. To a very limited extent vacuum deposition has also been used. The objective has been to improve on the optical quality of these films for guided wave or surface-plasmon nonlinear optics.

Molecular assemblies prepared by the Langmuir-Blodgett technique provide useful structures to probe structure-property relationships for nonlinear optical processes. We developed a comprehensive research program in which we studied the Langmuir-Blodgett films of optically nonlinear organic structures. The films were carefully characterized by a variety of surface and spectroscopic techniques. Both second and third order nonlinear optical processes were investigated.

One specific example is that of polythiophene. Monolayer film formation at the air/water interface was investigated for both electrochemically and chemically prepared poly(3-dodecylthiophene) using surface pressure-molecular area isotherms [10]. Only the electrochemically prepared polymer formed a stable monolayer, which was successfully transferred using the horizontal lifting method. The transferred Langmuir-Blodgett films were characterized by u.v.-visible spectroscopy and quartz crystal microbalance measurements. We have also found strong third-order nonlinear optical response from the Langmuir-Blodgett films of poly(3-dodecylthiophene).

Experimental Study of Nonlinearity

For experimental study of third-order optical nonlinearity we extensively use the method of femtosecond degenerate four wave mixing. This method has the advantage that one can obtain information on both the magnitude and response time of optical nonlinearity. With a goal to

understand the structure-property relationship for third-order microscopic optical nonlinearity, we have investigated the nonlinearities of a number of sequentially built and systematically derivatized π-conjugated structures using degenerate four-wave mixing.

We have also investigated the nonlinear response of many conjugated polymers, unoriented as well as stretch oriented. The third-order nonlinear optical susceptibility was investigated at wavelengths of 602 and 580 nm for a 10:1 stretch-oriented uniaxial film of poly (p-phenylene vinylene) using femtosecond degenerate four wave mixing [12]. A relatively large $\chi^{(3)}$ with a subpicosecond response was observed. A large anisotropy in the $\chi^{(3)}$ value was found, the largest component of $\chi^{(3)}$ (= $5X10^{-10}$ esu) being along the draw direction. This is in agreement with theory which predicts the largest component of Y along the polymer chain.

Electronically resonant third-order optical nonlinearity in several photoresponsive polymers were studied by picosecond and femtosecond degenerate four-wave mixing to investigate the role of photoexcited charge carriers [10,13]. Both the magnitude and the response time of the observed optical nonlinearities seem to vary over a wide range.

An interesting example is poly(3-dodecylthiophene). The electronically resonance enhanced third-order optical susceptibility of undoped poly(3-dodecylthiophene) was found to be $\chi^{(3)}\sim10^{-9}$ esu, large enough to allow the first reported observation of a degenerate four-wave mixing signal from ultrathin Langmuir-Blodgett films of this material [10]. Despite the resonant character, this nonlinearity exhibits femtosecond response. In situ iodine-doping studies of UV-Visible absorption, electrical conductivity and third-order nonlinear optical susceptibility were carried out. Upon doping, the conductivity changed by more than eight orders of magnitude but the $\chi^{(3)}$ value decreased to within ten percent of the original value.

We also studied the resonant $\chi^{(3)}$ behavior of Langmuir-Blodgett films of several phthalocyanines [2,6,7]. Again, the nonlinearity was sufficiently large to observe the degenerate four-wave mixing signal even from a monolayer. The value of $\chi^{(3)}$ is $> 10^{-9}$ esu with response being in several picoseconds. Both the magnitude of $\chi^{(3)}$ and the decay of the signal was found to be dependent on the laser intensity. We assign the intensity dependent decay to the presence of bimolecular processes (exciton-exciton annihilation) [7].

Device Processes

Our study under this category focused on the investigation of nonlinear optical processes in waveguides and fibers. We reported the first clear demonstration [14] of intensity-dependent phase shift due to electronic nonlinearity in a nonlinear polymer waveguide in which propagation distances over 5 cm were achieved with total attenuation of ~1.2 cm^{-1}. Intensity-dependent coupling angle, intensity-dependent coupling efficiency, and limiter action behavior (useful for power limiter sensor protection devices) were observed in the polyamic acid waveguide using grating excitation with 400 fs, 80 ps, and 10 ns pulses. A nonlinear grating coupler analysis identifies the subpicosecond and picosecond processes with electronic nonlinearity, but the dominant effect in the nanosecond experiment is due to thermal nonlinearity derived from weak absorptions. The magnitude and sign of n_2 of electronic nonlinearity were determined from this study.

Novel Electroactive and Nonlinear Optical Heterostructures

In this section we discuss some of our very recent accomplishments in producing novel heterostructures for applications in electronics and photonics.

(a) Crystalline complexes for efficient frequency doubling.

For high density optical data storage, there is a need for highly efficient frequency doubling materials. We have developed new heterostructures which are binary crystalline complexes that show second-order nonlinearity ranking among the highest [15]. These crystalline complexes do not possess the structural features that have been used in the past for the design of second-order nonlinear material. This new class of material does not rely on π-conjugation and, therefore, offers challenge for developing theoretical models to explain their nonlinearity. For technological applications we have obtained highly efficient phase-matched frequency doubling in our heterostructures.

(b) Sol-gel silica-polymer composites for integrated optics.

We have prepared to our knowledge the first compatible blend between an inorganic polymer, silica glass, and a π-conjugated optical nonlinear polymer, poly (p-phenylene vinylene), homogeneously mixed over large composition ranges [16,17]. This composite material was prepared by combining sol-gel processing techniques applicable to the silica glass with the preparation of the organic polymer from a water/alcohol soluble sulfonium salt precursor. The organic polymer precursor and the inorganic sol were mixed in a common solvent and converted to the final composite material. The thermal conversion of the organic precursor polymer released HCl which also catalyzed the inorganic sol. The composite material has been characterized by IR, UV-visible spectral analysis and thermogravimetric and differential scanning calorimetric analysis. We have investigated the third-order nonlinearity in this system using femtosecond degenerate four wave mixing and have observed response in less than 100 femtoseconds. The material can be cast into various forms. Thin films cast by the doctor

blading technique exhibit good optical quality. We have achieved optical waveguiding at 1.06 μ in a film of this composite material.

(c) Nonlinear optical processes in a liquid core hollow fiber.

In optical processing, optical amplification and pulse shaping will play important roles. We have observed novel nonlinear optical phenomena in an organic liquid core hollow fiber which can conveniently be used for optical amplification and pulse shaping [18-22]. By using a long interaction length (250 cm) provided by the fiber we have observed novel superbroadening (> 200 cm^{-1}) of stimulated scattering added on the Stokes side of the pump (Rayleigh) line and the stimulated Raman scattering lines of several anisotropic liquids (eg benzene). To explain these effects, we have proposed a photon scattering model of Rayleigh-Kerr optical effect and Raman-induced optical Kerr effect.

For device applications, we have demonstrated the application of this broadening in high gain amplification of a broad band optical signal [20]. For this purpose a hollow core fiber system filled with liquid benzene was used. Using 4 picosecond dye laser pulses as the pump source, stimulated amplification of the accompanying ≈ 550 cm^{-1} broad spontaneous emission was achieved with an amplification factor reaching 2.3×10^4.

(d) Langmuir-Blodgett film heterostructure.

Poly-n-vinyl carbazole is a photoconductive polymer which has been used for xerography. We have been successful in making Langmuir-Blodgett film heterostructures of poly-n-vinyl carbazole: TCNQ-$C_{18}H_{37}$ which exhibit charge transfer interaction in monolayer films [23]. These films have the advantage that they provide monolayer and successively deposited multilayer structures. We have successfully transferred such monolayer and multilayer Langmuir-Blodgett films and characterized them by various techniques.

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(Also serves as references for the Progress Report.)

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2. "Third-Order Nonlinear Optical Effects in Organic Polymeric Films" P. N. Prasad, in Nonlinear Optical Properties of Polymers, Materials Research Society Symposium Proceedings Vol. 109 Eds. A. J. Heeger, J. Orenstein and D. R. Ulrich (1988) p. 271.
3. "Theoretical and Experimental Studies of Optical Nonlinearities of Haloforms CHX_3, X=F, Cl, Br, I" S. P. Karna, M. Dupuis, E. Perrin, and P. N. Prasad, J. Chem. Phys. 92, 7418 (1990).
4. "The Study of Microscopic Third-Order Optical Nonlinearities in Sequentially Built and Systematically Derivatized Structures" M. T. Zhao, B. P. Singh, M. Samoc and P. N. Prasad, J. Phys. Chem. 93, 7916 (1989).
5. "Nonlinear Optical Properties of Various Cumulenes" I. Kminek, J. Klimovic and P. N. Prasad, manuscript under preparation.
6. "Nonlinear Optical Interactions in Langmuir-Blodgett Organic Semiconductor Hetero Structures" P. N. Prasad, M. K. Casstevens, J. Pfleger, and P. Logsdon, Symposium on Multifunctional Materials - SPIE Proceedings Vol. 878 (1988) p. 106-112.
7. "Nonlinear Optics of Langmuir-Blodgett Films" P. N. Prasad, M. Casstevens and M. Samoc in Proceedings of Symposium on "Photochemistry of Thin Films" SPIE 1056, 117 (1989).

8. "Langmuir-Blodgett Films for Nonlinear Optics" in Proceedings of NATO Advanced Study Institute at Spetses Island, Greece, June 12-23, 1989, Ed. R. M. Metzger (in Press).

9. "Spectroscopic and Surface Studies of Langmuir-Blodgett Films of an Axially Substituted Silicon Phthalocyanine [PcSi(OSiMePhOH$_2$)" M. K. Casstevens, W.M.K.P. Wijekoon, and P. N. Prasad, submitted to Langmuir.

10. "Conductive and Optically Nonlinear Polymeric Langmuir-Blodgett Films of Poly(3-dodecyl thiophene)" P. Logsdon, J. Pfleger and P. N. Prasad, Synthetic Metals 26, 369 (1988).

11. "Efficient Grating Coupling to Poly-4-BCMU Optical Waveguides" Q. Gong, G. Assanto, R. J. Zanoni, G. I. Stegeman, R. Burzynski, and P. N. Prasad, Appl. Opt. 29, 3887 (1990).

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13. "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices" P. N. Prasad in Nonlinear Optical Materials, Proceeding of the International Congress on Optical Science and Engineering. Hamburg, Germany, SPIE., proceeding vol. 1017, p. 2 (1989).

14. "Nonlinear Optical Processes in a Polymer Waveguide-Grating Coupler: Measurements of Electronic and Thermal Nonlinearities" R. Burzynski, B. P. Singh, P. N. Prasad, R. Zanoni and G. I. Stegeman, Appl. Phys. Lett. 53, 2011 (1988).

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16. "Nonlinear Optical Processes in Polymers and Sol-gel Silica Composites" P. N. Prasad in Ultrastructure processing of Ceramics, Glasses and Composites eds. D. Uhlman and D. R. Ulrich, John Wiley (in Press).

17. "Poly(p-phenylenevinylene)-silica Composites: A Novel Sol-gel Processed Nonlinear Optical Material for Optical Waveguide" C. J. Wung, Y. Pang, P. N. Prasad and F. E. Karasz, Polymer (in Press).

18. "Stimulated Kerr Scattering and Reorientation Work of Molecules in Liquid CS_2" G. S. He and P. N. Prasad, Phys. Rev. A 41, 2687 (1990).

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21. "Stimulated Rayleigh-Kerr Scattering in a CS_2 Liquid-core Fiber System" G. S. He and P. N. Prasad, Optics Commun. 73, 161 (1989).

22. "Stimulated Rayleigh-Kerr and Raman-Kerr Scattering in a Liquid-core Hollow Fiber System" G. S. He and P. N. Prasad, Fiber and Integrated Optics 9, 11 (1990).

23. M. Casstevens, M. Carpenter and P. N. Prasad, to be published.

24. "Study of Anisotropy of Acoustic Wave propagation in Stretched Poly (vinyledene difluoride) Film Using the Picosecond Transient Grating Technique" R. Burzynski, Y. Pang, D. N. Rao and P. N. Prasad, Polymer 30, 1247 (1989).

25. "Photonics and Nonlinear Optics - Materials and Devices" in Proceedings of NATO Advanced Study Institute at Spetses Island, Greece, June 12-23, 1989, Ed. R. M. Metzger (in Press).

26. "Anisotropy of the Linear and Third-order Nonlinear Optical Properties of a Stretch-Oriented Poly(2,5-dimethoxy paraphenylene vinylene)" J. Swiatkiewicz, P. N. Prasad, F. E. Karasz, M. A. Druy and P. Glatkowski, Appl. Phys. Lett. 56, 892 (1990).

27. "Nonlinear Optical Effects in Organic Materials" P. N. Prasad in "Nonlinear Optics in Solids" Ed. O. Keller, Springer Ser. Wave Phen. (Springer, Berlin, Heidelberg, 1990), p. 304.

3. PATENTS DEVELOPED UNDER THE PRESENT SDIO-IST/AFOSR CONTRACT

1. "Third Order Nonlinear Optically Active Composites, Method of Making Same and Photonic Media/Comprising the Same" P. N. Prasad, F. E. Karasz, Y. Pang and C. J. Wung, Patent filed on February 17, 1989 (application no. 312132).
2. "A New Class of Nonlinear Optical Molecular Materials Using Binary Crystalline Complexes for Efficient Second Harmonic Generation and Electro-Optic Modulation" P. N. Prasad and A. Samoc, Patent application being processed.

4. INVITED TALKS AND WORKSHOPS ON RESEARCH SUPPORTED BY SDIO-IST/AFOSR

1. SPIE - The International Society for Optical Engineering, 31st Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, August 20, 1987.

   Tutorial Lecture on "Molecular Engineering of Ultrathin Organic Polymeric Films with the Langmuir-Blodgett Technique: Molecular Designs and Device Application".

2. NSF Chemistry/Chemical Engineering Planning Workshop on Chemical Processing of Advanced Materials for Information Storage and Handling, Washington, D.C., September 14-15, 1987.

3. Symposium on Electroresponsive Polymers, Brookhaven National Laboratory, October 5, 1987.

   "Nonlinear Optical Effects in Polymeric Films".

4. University of West Virginia, Department of Chemistry, Morgantown, WV, October 21, 1987.

   "Nonlinear Optical Effects in Organic Molecules and Polymers".

5. The Materials Research Society 1987 Fall Meeting, Boston, MA, December 3, 1987.

   "Nonlinear Optical Properties of Polymers".

6. National Materials Advisory Board, Committee on Liquid Crystalline Polymers, National Academy of Sciences, Washington, DC 20418.

   "Nonlinear Optical Effects in Liquid Crystalline Polymers".

7. SPIE - The International Society for Optical Engineering, Meeting, Los Angeles, CA, January 10, 1988.

   Tutorial Lecture on "Nonlinear Optical Materials".

8. SPIE - The International Society for Optical Engineering, Meeting, Los Angeles, CA, January 12, 1988, Symposium on Multifunctional Materials.

   "NLO Interactions in Langmuir-Blodgett Organic Semiconductor Heterostructures".

9. Johns Hopkins University, Department of Materials Science, Baltimore, MD, March 2, 1988.

   "Picosecond and Femtosecond Degenerate Four Wave Mixing Study of Nonlinear Optical Effects and Mechanical Properties of Polymer Films".

10. University of Nevada at Reno, Department of Chemistry, Reno, NV, March 23, 1988.

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11. Iowa State University, Department of Chemistry, Ames, IA, March 25, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers".

12. AFOSR Contractor Review of Nonlinear Optical Polymers. National Academy of Sciences, Washington, DC, April 21, 1988.

13. A Topical Workshop on Organic and Polymeric Nonlinear Optical Materials, Sponsored by Division of Polymer Chemistry, American Chemical Society, May 16, 1988, Virginia Beach, VA.

    "Nonlinear Optical Effects in Polymeric Films".

14. US-UK Optical Glass and Macromolecular Materials Seminars, June 17, 1988, Pitlochry, Scotland.

    "Charge Carrier Dynamics and Nonlinear Optical Processes in Organic Langmuir-Blodgett Films".

15. NATO Advanced Research Workshop on "Polymers for Nonlinear Optics" June 24, 1988, Sophia Antipolis, France.

    "Ultrafast Nonlinear Optical Processes in Organic Polymers".

16. International Conference on "Organic Materials for Nonlinear Optics" June 29, 1988, Oxford, England.

    "Ultrafast Third Order Nonlinear Optical Processes in Organic Polymers".

17. Gordon Conference on Dielectric Phenomena, July 27, 1988, New Hampshire.

    "Recent Advances in the Field of Nonlinear Optics".

18. SPIE - The International Society for Optical Engineering, 32nd Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, CA, August 16, 1988.

    Tutorial Lecture on "Introduction to Nonlinear Optical Materials".

19. SPIE - the International Society for Optical Engineering, 32nd Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, CA, August 17, 1988.

    Tutorial Lecture on "Molecular Engineering of Ultrathin Organic Polymeric Films with the Langmuir-Blodgett Technique: Molecular Designs and Device Applications".

20. Topical meeting on Nonlinear Optical Properties of Materials, Optical Society of America, Troy, NY, August 23, 1988.

    "Optical Nonlinearities of Polymers".

21. Trinity College, Department of Physics, Dublin, Ireland, September 16, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers".

22. The International Congress on Optical Science and Engineering, Hamburg, Germany, September 21, 1988.

    Tutorial Lecture on "Introduction to Nonlinear Optical Materials".

23. The International Congress on Optical Science and Engineering. Hamburg, Germany, September 22, 1988.

    Plenary Lecture on "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices".

24. Technical University of Munich, Department of Physics, Germany, September 27, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers".

25. National School on Nonlinear Optics, Brallo (Milan), Italy, September 30, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers".

26. NTT Opto-Electronics Laboratories, Tokai, Naka-gum, Ibasaki, Japan, November 9, 1988.

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27. Research Institute for Polymers and Textiles, Tsukuba, Japan, November 10, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices".

28. The University of Tokyo, Department of Physics, Tokyo, Japan, November 11, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices".

29. Tokyo University of Agriculture and Technology, Koganei, Tokyo, Japan, November 14, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices".

30. Materials Research Society Fall Meeting, Boston, MA, December 2, 1988.

    "Nonlinear Optical Properties of Rigid Rod Polymers and Model Compounds".

31. Syracuse University, Department of Chemistry, Syracuse, NY, December 13, 1988.

    "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices".

32. SPIE - The International Society for Optical Engineering Meeting, Los Angeles, CA, January 17, 1989. Symposium on Multifunctional Materials.
    "Nonlinear Optics of Langmuir-Blodgett Films".
33. SPIE - The International Society for Optical Engineering Meeting, Los Angeles, CA, January 19, 1989. Tutorial Lecture.
    "Introduction to Nonlinear Optical Materials".
34. Fourth International Conference on Ultrastructure Processing of Ceramics, Glasses and Composites, Tucson, AZ, February 21, 1989.
    "Nonlinear Optical Processes in Polymers and Sol-gel Composites".
35. Electric Power Research Institute Workshop on "Polymers in the Generation, Storage, Transmission and Distribution of Electric Power", Baltimore, Maryland, March 15, 1989.
    "New Developments in the Nonlinear Optical Properties of Polymers and Their Applications: The Technology of Advanced Polymer Photonics".
36. American Physical Society Meeting, Division of High Polymer Physics Symposium, St. Louis, MO, March 24, 1989.
    "Nonlinear Optical Effects in Organic Molecules and Polymers - Theory, Measurements and Devices".
37. ACS Spring Symposium on Nonlinear Optics and Materials, Rochester Section, Rochester, NY, April 19, 1989.
    "Third-Order Nonlinear Optical Processes in Organic Molecules and Polymers."
38. International Congress on Optical Science and Engineering, Paris, France, April 24, 1989. A one day Tutorial on
    "Introduction to Nonlinear Optical Materials".
39. Quantum Electronics and Laser Science Conference '89, Baltimore, MD, April 24, 1989.
    "Dynamics of Third-Order Nonlinear Processes in Organic Molecules and Polymers" M. Samoc, J. Swiatkiewicz and P. N. Prasad.
40. University of Nantes, Institute of Physics and Chemistry of Materials, Nantes, France, April 25, 1989.
    "Nonlinear Optical Effects in Conjugated Polymers".
41. University of Lille, Department of Chemistry, Lille, France, April 26, 1989.
    "Time-Resolved Studies of Nonlinear Optical Processes in Organic Molecules and Polymers".

42. University of Lille, Department of Physics, Lille, France, April 27, 1989.

    "Nonlinear Optical Effects in Organic Crystals and Polymers".

43. Allied-Signal, Morristown, NJ, May 24, 1989.

    "Nonlinear Optical Effects in Polymers".

44. The New York Academy of Sciences, Section of Polymer Science, New York, NY, May 24, 1989.

    "Nonlinear Optical Properties of Polymers and Their Applications: The Technology of Advanced Polymers Photonics".

45. University of Wyoming, Department of Chemistry, Laramie, WY, June 13-16, 1989. Five Lectures under 1989 Summer Lecture Series in Chemistry

    "Nonlinear Optical Effects - Theory, Materials, Measurements and Devices".

46. NATO Advanced Study Institute on "Lower-Dimensional Systems and Molecular Devices" Spetses Island, Greece, June 19, 1989.

    "Photonics and Nonlinear Optics - Materials and Devices".

47. NATO Advanced Study Institute on "Lower-Dimensional Systems and Molecular Devices" Spetses Island, Greece, June 21, 1989.

    "Langmuir-Blodgett Films for Nonlinear Optics".

48. International Summer School on Nonlinear Optics, Aalborg, DENMARK, July 31 - August 4, 1989. Two lectures on

    "Nonlinear Optical Effects in Organic Materials".

49. SPIE - The International Society for Optical Engineers, 33rd Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, CA, August 7, 1989. Tutorial Lecture

    "Introduction to Nonlinear Optical Materials".

50. US-UK Optical Glass and Macromolecular Materials Workshop, Ilkley, U.K., August 29-31, 1989.

    "Novel Electroactive and Nonlinear Optical Heterostructures".

51. Nonlinear Optical Polymers Contractors Conference, Long Beach, CA, September 24-26, 1989.

    "Experimental and Theoretical Studies of Nonlinear Optical Effects in Molecular Materials and Polymers".

52. American Chemical Society, Live Satellite Television course, November 17, 1989.

    "Nonlinear Optical Properties of Polymers".

53. Materials Research Society, Fall Meeting 1989, Boston, MA, November 30, 1989.

"Novel Electroactive and Nonlinear Optical Heterostructures".

54. Pacific Basin Chemical Congress, American Chemical Society, December 17, 1989, Symposium on Polymers for Photonics.

"Studies of Third-Order Nonlinear Optical Effect in Sequentially Built and Systematically Derivatized Organic Structures".

55. Pacific Basin Chemical Congress, American Chemical Society, December 17, 1989, Symposium on Time-Resolved Vibrational and Other Molecular Dynamical Processes.

"Dynamics of Nonlinear Optical Processes in Organic Molecules and Polymers".

56. Joint United State - Israel Workshop on "Light Energy Conversion: Natural Systems and Synthetic Materials", February 5, 1990.

"Nonlinear Optical Effects in Molecular Materials and Polymers".

57. Hoechst-Celanese Corporation, February 21, 1990.

"Nonlinear Optics and Photonics with Molecular Materials and Polymers".

58. Michigan State University, Center for Fundamental Materials Research, February 23, 1990.

"Polymers for Electronics and Photonics".

59. Materials Research Society, Spring Meeting 1990, San Francisco, CA, April 19, 1990, Symposium on Better Ceramics Through Chemistry IV.

"Sol-gel Processed Inorganic and Organically Modified Composities For Nonlinear Optics and Photonics".

60. American Chemical Society, Spring Meeting, 1990, Boston, MA. April 22, 1990. Symposium on "New Materials for Nonlinear Optics". A tutorial lecture on

"Third-order Nonlinear Optical Effects in Molecular and Polymeric Materials".

61. Chemical Research Council, 1st New Industrial Chemistry and Engineering Conference on Future Directions in Polymer Science and Technology, Keystone Resort, CO, May 15, 1990.

"Nonlinear Optical Properties of Polymers".

62. University of Waterloo, Department of Chemistry Seminar, Waterloo, Ontario, CANADA, May 22, 1990.

"Nonlinear Optical Effects in Molecular Materials and Polymers".

63. Air Force Nonlinear Optical Polymers Contractors Meeting, Washington, D.C., June 4, 1990.
"Ultrafast Third-Order Nonlinear Optical Processes".

64. Air Force Nonlinear Optical Polymers Contractors Meeting, Washington, D.C., June 5, 1990.
"Theoretical Computations of Optical Nonlinearities: Ab Initio vs Semiempirical" S. Karna and P. N. Prasad.

65. "Nonlinear Optics - 1990", Summer School, University of Rochester, NY, June 18, 1990. Tutorial Lecture on
"Nonlinear Optical Materials".

66. Nippon Oil and Fats, Tsukuba City, Japan, July 2, 1990.
"Organic Materials for Nonlinear Optics".

67. Japanese Synthetic Rubber Company, Tsukuba City, Japan, July 4, 1990.
"Nonlinear Optics and Photonics with Organic and Polymeric Materials".

68. Teijin Fundamental Research Laboratory, Tokyo, Japan, July 5, 1990.
"New Development in Nonlinear Optics of Organic and Polymeric Materials".

69. Mitsui Totsu Chemicals, Tokyo, Japan, July 6, 1990.
"New Polymeric and Composite Materials for Nonlinear Optics and Photonics".

70. Tokyo University of Agriculture and Technology, Tokyo, Japan, July 7, 1990.
"New Developments in Nonlinear Optics of Organic and Polymeric Materials".

71. Showa Denko, Tokyo, Japan, July 9, 1990.
"Polymeric and Composite Materials for Nonlinear Optics and Photonics".

72. Toshiba R&D Center, Tokyo, Japan, July 10, 1990.
"Photonics with Molecular and Polymeric Materials".

73. The Symposium of Optics and Electronics, Tokyo, Japan, July 11, 1990.
"Molecular and Polymeric Materials for Nonlinear Optics and Photonics".

74. SPIE - The International Society for Optical Engineering Meeting, San Diego, CA, Symposium on Sol-Gel Optics, July 11, 1990.
"Sol-Gel Processed Inorganic and Organically Modified Composites for Nonlinear Optics and Photonics".

75. SPIE - The International Society for Optical Engineering Meeting, San Diego, CA, July 12, 1990. Tutorial Lecture:
"Introduction to Nonlinear Optical Materials".