Computer controlled cw laser spectrometer

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A computer controlled cw UV–visible dye laser source for spectroscopic use has been developed. Computer control facilitates both continuous single-frequency scanning and data acquisition. With 4 W of Ar-ion laser pump power, such a spectrometer can generate in excess of 1 W of cw single-frequency power in the visible and up to 1 mW in the UV by using extracavity nonlinear optical mixing. The laser spectrometer has been tested by performing high-resolution measurements of the fluorescence spectrum of I_2 in the visible and of the absorption spectrum of SO_2 in the UV.

Introduction

The wavelength tunability and the narrow linewidth of the single-frequency output of cw dye lasers are useful in many spectroscopic applications. The spectral range of these lasers can be extended to both the UV and IR regions through use of nonlinear optical mixing techniques. In this paper the development of a versatile computer controlled cw visible–UV dye laser spectrometer will be described. Computer control facilitates a number of interrelated operations that are necessary for multimode and single-frequency scanning of the dye laser and synchronous tracking of the optimum orientation of the nonlinear optical crystal. In addition, the use of on-line computer control permits convenient wavelength and frequency calibration, monitoring and optimization of power, and spectral data acquisition and processing. In fact, several groups have applied computer control to tunable lasers in recent years. Examples include optical parametric oscillators,[1,2] an electrooptically tuned cw dye laser,[3] and pulsed dye lasers.[4,5] This work describes a computerized cw laser spectrometer capable of long-range (>20 Å) single-frequency scans in the visible and UV. The scanning and resolution capabilities of the spectrometer have been tested on the I_2 spectrum in the visible region and on SO_2 in the UV region.

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Experimental Details of Laser Spectrometer

The computer controlled laser spectrometer is shown schematically in Fig. 1. The spectrometer consists of several components: (a) a high power cw pump laser, either an Ar-ion or Kr-ion laser; (b) a cw dye laser in either a linear or ring type cavity configuration; (c) a nonlinear optical crystal; (d) diagnostic instrumentation to monitor wavelength, frequency, and visible–UV power levels; and (e) a minicomputer system.

The central part of the spectrometer is the dye laser. A high-power single-frequency ring dye laser has been developed that is similar to the recently reported Spectra-Physics model 380A dye laser.[6] This laser has a four-mirror figure-eight optical resonator geometry as shown in Fig. 2. One resonator arm has a tight focus and contains the dye jet stream, while the other arm is collimated for insertion of the various wavelength selection elements. Coarse tuning with a linewidth of 40 GHz is accomplished with a three-element quartz birefringent filter. High-power single-frequency scanning requires two additional intracavity optical elements. A coated airspaced etalon [free spectral range (FSR) = 30 GHz, 33% reflectivity] and an uncoated solid etalon (FSR = 170 GHz which limits lasing to a single transmission peak of the airspaced etalon) produced optimum output power and single-frequency scanning with a linewidth of ±20 MHz. The birefringent filter orientation is controlled by a stepping motor (Superior Electric type MO61-FC02) suitably geared to permit a frequency resolution of 6 GHz/step. The thick airspaced etalon is controlled by the voltage output from a digital-to-analog converter (DAC) amplified by a high-voltage ramp generator (Burleigh model RC-42). The thin solid etalon is angle tuned using a galvanometric scanner combination (General Scanning models 208-AX 200), which is controlled by a second DAC output. With such a birefringent filter–etalon combination, single-frequency scans of up to 20 Å with dye laser cavity mode hops at c/L = 200-MHz intervals can

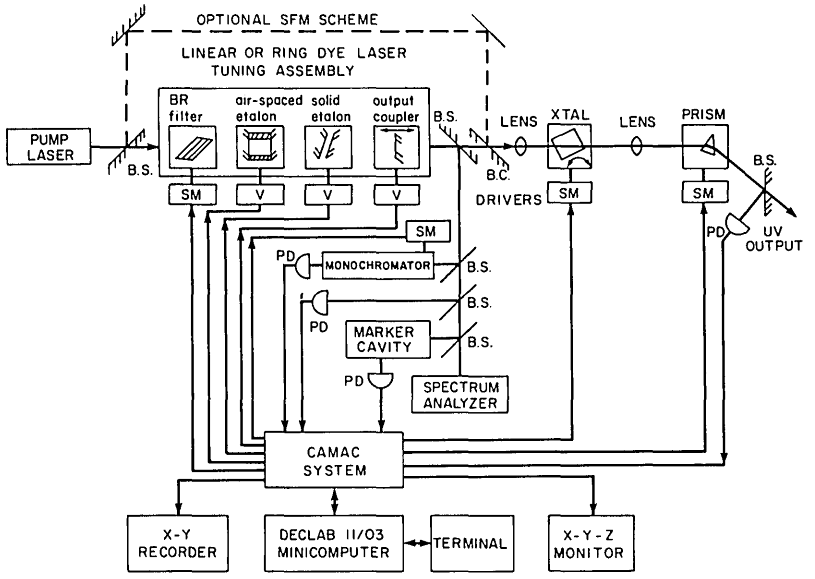

Fig. 1. Schematic of computer controlled visible–UV cw laser spectrometer.

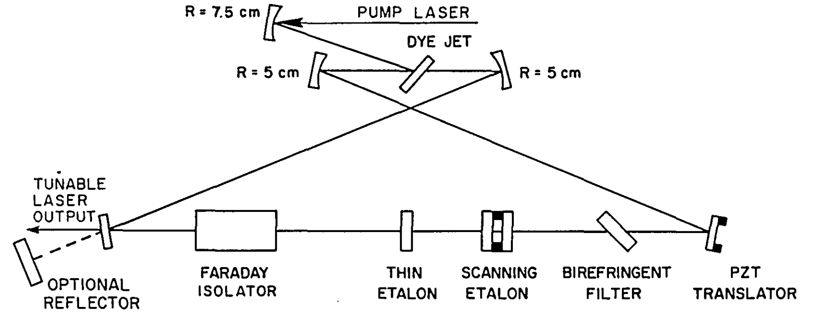

Fig. 2. Ring cavity configuration for a tunable cw dye laser.

be achieved. Continuous frequency scanning requires synchronous tracking of the effective cavity length (using either a PZT translator or a tilted scan plate responding to a third DAC output) with respect to the airspaced etalon spacing. In order to insure unidirectional laser output from such a traveling wave ring type laser either an external reflector[7] or a nonreciprocal Faraday device[8] with low cavity insertion loss is used. The compact optical isolator used in this ring dye laser consisted of an AR coated Faraday rotator glass rod, 1 cm in length, placed in a cylindrical stack of high field permanent magnets (2kOe) and a 0.5-min thick c-axis quartz plate, which acted both as a polarization rotator and as an etalon.

With a 2×10^{-3} molar solution of the dye Rh6G in ethylene glycol, the dye laser spectrometer produces a TEM_{00} multimode output power of 2 W with 7-W input pump power and a single-frequency power of 1.5 W with 6-W pump power at 514.5 nm (~25% conversion efficiency). This represents a considerable improvement in dye laser efficiency as compared with the conventional linear type dye laser.

Generation of tunable cw UV radiation is accomplished conveniently external to the dye laser cavity as shown in Fig. 1 but less efficiently than for intracavity optical mixing. Details of various optimum second harmonic (SHG) and sum frequency (SFM) mixing schemes that generate radiation spanning the UV wavelength region from 410 nm to 211 nm are given in Refs. 9–11. For this system, UV output powers of 1.4 mW (multimode) and 1 mW (single frequency) have been obtained for a fundamental dye laser power of 1.1 W by SHG in a 25-mm long ammonium dihydrogen arsenate (ADA) crystal. The nonlinear optical crystal is placed in a special optical mount[12] containing index matching fluid that minimizes beam displacement as the crystal is rotated to optimize the phase matching conditions. The nonlinear optical crystal is rotated by a stepping motor driven rotation stage with a resolution of 30 arc sec. A separate motor controlled prism serves as both a UV wavelength discriminator and a beam steering device to keep the output direction unchanged.

The dye laser wavelength is monitored by a monochromator. For convenience a ¼-m Jobin Yvon H-20 monochromator with a spectral resolution of 1 nm is controlled by a geared down stepping motor with an accuracy of 0.3 Å/step. A temperature stabilized optical spectrum analyzer with a FSR of 8 GHz served as a reference cavity for calibration of the airspaced etalon and to provide frequency markers during scans. Several visible and UV photodiode-operational amplifier detectors were used to monitor the power levels, as shown in Fig. 1. The signals from these detectors were input to a multiplexed analog-to-digital converter (ADC).

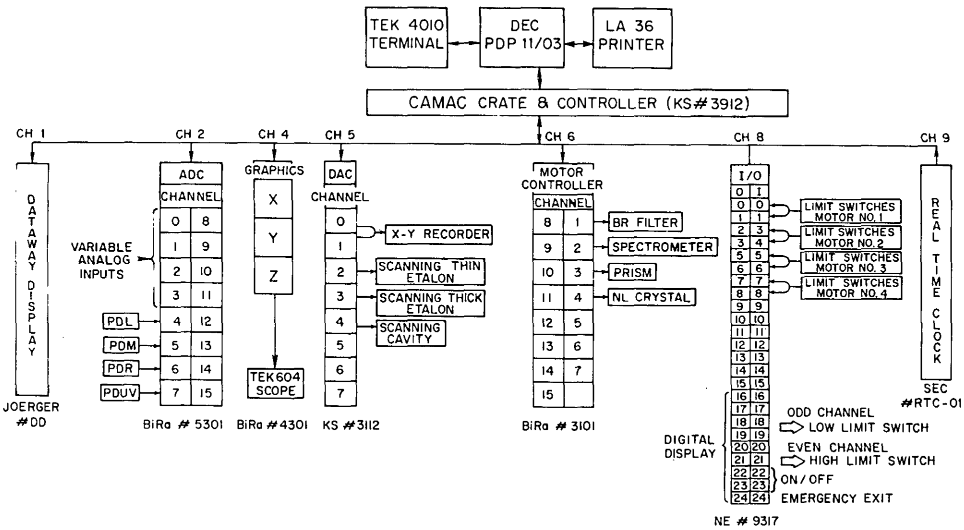

Fig. 3. CAMAC control system for computerized laser spectrometer.

Minicomputer System

The various operations and elements of the laser spectrometer are controlled by a DEC PDP-11 VO3 minicomputer with a 28K word memory interfaced via a CAMAC system shown in Fig. 3. CAMAC interfacing provides a standardized and flexible method for transmitting digital control and data information between computer and various instrumentation modules. This approach allows the use of a wide variety of readily available modular interface hardware, which is compatible with most minicomputer systems.

A crate controller (Kinetic Systems model 3912) is used as the interface between the PDP-11 VO3 and the various CAMAC modules. Stepping motors are operated by a stepping motor controller (BiRa Systems model 3101A) followed by stepping motor driver modules (Superior Electric STM 101). The photodiode detectors are connected to a sixteen-channel 12-bit differential input ADC (BiRa Systems model 5301). The scanning and cavity length elements of the dye laser are controlled by the voltage outputs of an eight-channel 12-bit DAC (Kinetic Systems model 3112). A real-time clock (SEC model RTC-01) permits adjustment of the scan speed of the various stepping motors to eliminate undesirable resonances. A 24-bit input/output module (NEC model 9017) is used to read the position of all the limit switches associated with the various stepping motors. Several data display options are provided. An X–Y–Z graphics display driver (BiRa Systems model 4301) allows convenient real-time monitoring of photodetector data on a Tektronix model 604 oscilloscope. The input/output module is also used to drive two 4-digit alphanumeric displays for readout of current data such as signal magnitude, motor position, wavelength, or power. Two channels of the DAC converter are used to drive an X–Y recorder (Houston Instruments model 2000) for generation of plots of data.

Software Considerations

The software consists of a main program and about forty subroutines, mainly written in Fortran IV, which operate under the DEC RT11 operating system.[13] Some subroutines are written in assembler language to minimize computation time (Fortran versions thereof simply require too much time). Some of the important functions of the software are: (a) coarse wavelength tuning by setting the birefringent filter (BRF); (b) scan rate selection; (c) wavelength and frequency calibration; (d) optimization of UV power by appropriate orientation of the phase matching angle of the nonlinear optical crystal; (e) fine wavelength selection by adjustment of intracavity etalons; (f) tracking of the dye laser cavity length; (g) UV output direction control; (h) data acquisition and processing; and (i) data display, listing, and storage. The laser spectrometer is controlled with up to seven motors consisting of four stepping motors to adjust the BR filter, the SHG crystal angle, the monochromator, and the UV separating prism and three voltage controlled scanners to adjust the two intracavity etalons and the cavity length. The software allows any motor (stepping or scanning) to be moved to a desired location within hardware or software limits. Data can be taken, filtered with a suitable time constant, stored, and displayed as a function of motor position from any of the various photodetectors as any motor is scanned.

The fundamental concept underlying the design of the software is that the positions of the various optical elements are stable and reproducible enough to permit open-loop operation. Tight closed-loop control of the elements is not necessary, and the software is thus significantly simpler. Initialization of the spectrometer requires the generation and storage of various cross-reference tables, which relate the positions of each motor to a corresponding set of wavelengths or frequencies. First, a table of the BRF position vs monochromator position is generated by setting the BRF to a number of positions (typically eleven) over the effective tuning range of a given organic dye and adjusting the monochromator for maximum output signal at the exit slit. The resulting data are fitted with a cubic polynomial. This fitted curve is used to create a cross-reference table between 100 BRF motor positions and 100 monochromator motor positions. Positions between these are readily determined by linear interpolation. Since the monochromator position is linear in wavelength with a known ratio, entry of the monochromator reading at only one point calibrates the BRF position in terms of wavelength throughout the dye laser tuning range. The laser spectrometer can now be operated in convenient wavelength units.

A similar procedure is used to construct the cross-reference tables of BRF position vs nonlinear optical crystal phase matching angle and vs prism angle by monitoring the UV power. The software then allows automatic tracking of both the crystal and the prism with the BR filter. For single-frequency operation of the spectrometer, two intracavity etalons are inserted in the dye laser. The proper control of these elements requires the generation of three additional cross-reference tables: the airspaced etalon position vs frequency, the solid etalon tilt position vs frequency, and the BRF position vs frequency. The airspaced etalon is cross referenced by monitoring the output of the 8-GHz marker cavity. Calibration of the position of the tilted etalon requires monitoring the modulation of the output power due to the intracavity 30-GHz airspaced etalon as the tilted etalon is scanned. Finally, a table

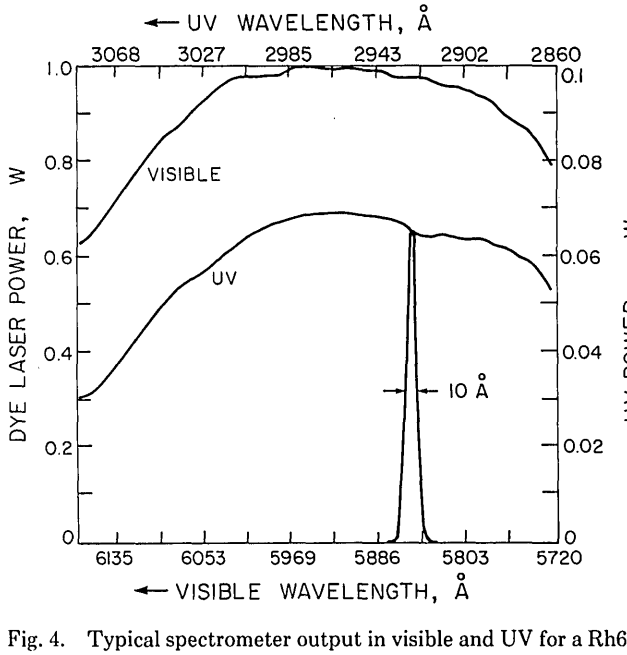

Fig. 4. Typical spectrometer output in visible and UV for a Rh6G dye laser showing effective computer controlled tracking of the dye laser and the orientation of an ADP crystal. Dye laser was operating multimode with 4 W of Ar laser pump power at 5145 Å. Typical scan time of depicted power spectrum is 30 sec.

relating the BRF position to a change in frequency is generated from the wavelength table for a 20-Å range.

Upon completion of these seven tables, which typically takes 30 min, the laser system is ready for high-resolution spectroscopic scanning. Single-mode scan speeds up to 0.2 Å/sec are possible, with adjustable time constants for each of the ADC inputs. Typical single-frequency scans of the order of 90 GHz are obtained by updating each motor position according to the cross-reference tables. The scans can be extended to about 1600 GHz by repetitive computer controlled resetting of the airspaced etalon and tilted etalon. Continuous high-resolution single-mode scans without cavity mode hops can be performed by tracking the dye laser cavity length simultaneously with both etalons. Scanning the dye laser cavity length with a mirror mounted on a PZT translator or a thin intracavity plate set at Brewster's angle allows generation of continuously tunable radiation over a 40-GHz frequency range. During each scan, data from up to four of the various signal sources can be acquired, digitally filtered, and stored in memory. At the end of the scan, these data may be displayed on the graphics terminal, plotted on the X–Y recorder, or stored on a diskette.

Evaluation of Visible–UV Laser Spectrometer

Typical multimode output of the laser spectrometer is shown as a function of wavelength in Fig. 4. The visible power for the Rh6G dye laser is between 0.6 W and 1.0 W for the region from 572 nm to 617.6 nm. Using a 2.5-cm long ammonium dihydrogen phosphate (ADP) crystal for doubling, useful UV output power (although lower than for ADA) is obtained from 286 nm to 308.8 nm. The narrow spike with a full width at half-maximum (FWHM) of 10 Å shows the UV output when the crystal and prism angles are held at fixed angles as the BRF is scanned. The broad UV curve in Fig. 4 shows the output when the crystal and prism angles are continuously tracked according to the cross-reference tables. This output is within a few percent of optimum for the entire wavelength scan. The long-term stability of the spectrometer is excellent, and these cross-reference tables are valid from day to day. In fact, these tables need to be regenerated only if an actual change is made to the spectrometer.

The fluorescence spectrum of I_2 in the visible and the absorption spectrum of SO_2 in the UV served as convenient spectroscopic calibration media for evaluating the laser spectrometer in terms of resolution capability, scan and tuning range, and amplitude and frequency stability. Figure 5 shows the fluorescence spectrum of room temperature I_2 obtained by computer controlled scanning of a multimode Rh6G dye laser. The experimental apparatus consisted of the laser spectrometer, the I_2 cell, and a photomultiplier. A Doppler linewidth limited high-resolution fluorescence spectrum of I_2 obtained from a single-frequency dye laser scan of 80 GHz (~1 Å) is shown in Fig. 6. Rotational structure is clearly resolved for this mode of operation of the laser spectrometer.

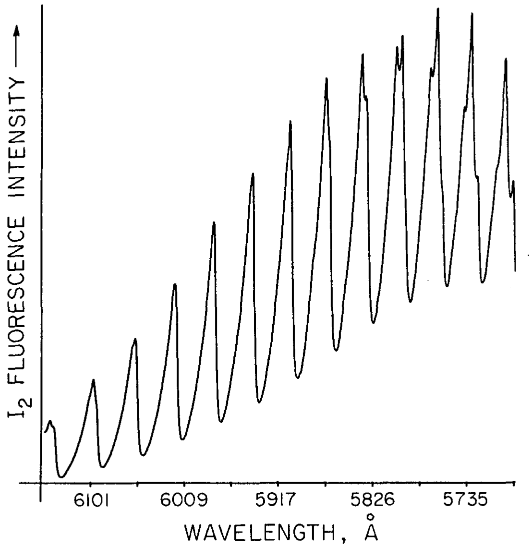

Fig. 5. Low-resolution I_2 fluorescence spectrum from 569 nm to 615 nm; I_2 vapor pressure 0.2 Torr; Rh6G dye laser linewidth = 40 GHz; peak power = 500 mW.

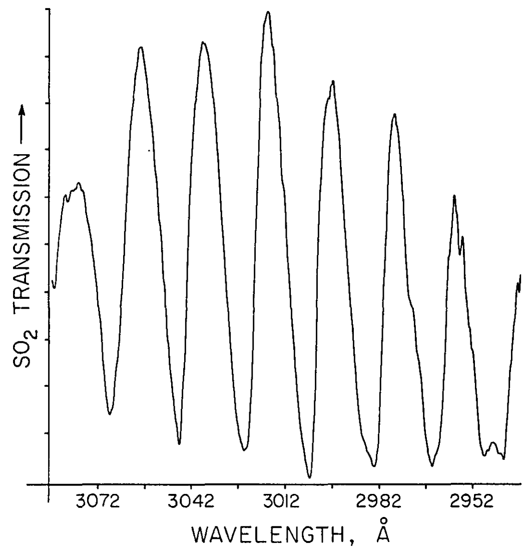

Fig. 7. Low-resolution SO_2 absorption spectrum from 294 nm to 309 nm. SO_2 pressure 2 Torr; cell length 25 cm, peak power 0.05 mW.

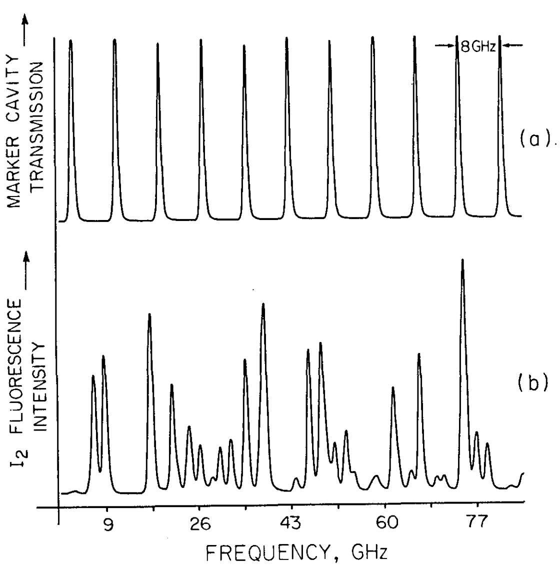

Fig. 6. High-resolution I_2 fluorescence spectrum near 600.2 nm; I_2 vapor pressure 0.2 Torr; Rh6G laser linewidth ±20 MHz; probe power 500 mW; scan interval 85 GHz.

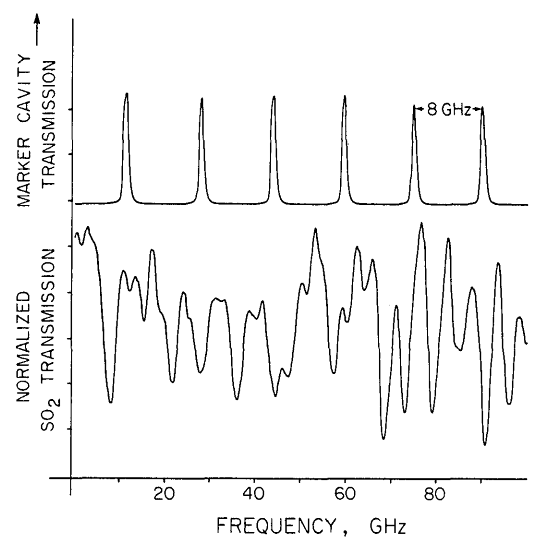

Fig. 8. High-resolution SO_2 absorption spectrum near 305 nm, probe power 0.03 mW, UV scan interval 100 GHz.

The UV absorption spectrum of SO_2 at 2 Torr (25-cm path length) obtained by frequency doubling the multimode dye laser output using an ADP crystal is given in Fig. 7. For the absorption measurement, the above mentioned photomultiplier was replaced by a UV sensitive photodiode. A normalized SO_2 spectrum obtained by a single-frequency scanning over a 100-GHz (~0.3 Å) range in the UV is reproduced in Fig. 8.

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13. The software sources can be obtained by contacting J. Kasper at UCLA.

Books *continued from page 1889*

less than 3×10^{-24} cm. To grasp how small this is, if the neutron were expanded to the size of the earth, this would correspond to an incremental height of 0.01 cm in the Northern Hemisphere! A planned experiment with bottled ultracold neutrons may lower the limit to about 10^{-27} cm or, with further improvements, to 10^{-28} cm. The ratio μ_n/μ_p of the magnetic moment of the neutron to that of the proton was measured to be −0.68497945(17). A new experimental apparatus is planned to detect parity violating small rotations of the neutron spin due to the weak interaction when the neutron passes through matter.

The contribution by **Bergman,** "The Dielectric Constant of a Composite Material—A Problem in Classical Physics," is not related to other contributions in the book, but I have found a very strained and tenuous connection to one of Lamb's old research interests. The author defines functions of the microscopic geometry of the materials which permit him to calculate bounds on dielectric constant and to develop a new approach to discussion of critical properties of composite systems near a percolation threshold. But the percolation problem has many points of contact with the problem of phase change, and the latter was studied by Lamb and Ashkin circa 1940.

The last two papers are **Scully, Shea,** and **McCullen**'s "State Reduction in Quantum Mechanics: A Calculational Example," and **Cantrell** and **Scully**'s "The EPR Paradox Revisited." Lamb was interested in the measurement problem in quantum mechanics, as shown by his 1969 article in *Physics Today.* Both of these papers are related to the aspects of quantum measurement and the notion of the completeness of quantum mechanics that surfaced with the celebrated paper of Einstein, Podolsky, and Rosen in 1935. In briefest outline, they conclude that no paradox exists if the statistical matrix is properly used to describe the effect of the measuring apparatus or, better, the whole system. However, this answer would still not satisfy Einstein. He would say that the use of statistical matrices means that one is using a kind of statistical mechanics; thus one is dealing with an ensemble of equivalent systems, not with a theory in which the one real system of interest has a place. Without at least the legitimacy of talking about the actual real system as something "existing," Einstein felt, one would not have what could be accepted as a "complete" theory. He thought quantum mechanics was correct as far as it went—he just wanted to go further. On this point the two papers are mute, but they have much company! Physicists interested in foundations, philosophers of science, and students will find these papers of interest, and it is good to have a specific example worked out carefully, but the reality issue between Einstein and Bohr *et al.* is yet to be exorcised away.

In conclusion, this is an excellent festschrift, pleasing in form, content, and even literary style. It will be of value to many for a long time to come, and is a fitting tribute to the man it honors.

JEROME ROTHSTEIN

Academician A. A. Lebedev—Selected Works. Edited by P. P. FEOFILOV. Nauka Press, Leningrad, 1974. 286 pp. 2R. 12kop.

This book is a selection of the most important original papers of Academician A. A. Lebedev, one of the leading figures in the creation and development of the optics industry in Russia after the Revolution. His scientific activities were wide-ranging and included the study of the microstructure of glass, the industrial production of optical glass, optical and electron instruments, and semiconductors. Although he was a scientist of great productivity and his active scientific life spanned half a century, his publications are relatively few, the greater part being in this small volume. The reason is that Lebedev chiefly worked in the direction of other less-experienced scientists, suggesting lines of research and helping in case of difficulties. He invariably refused to add his name to the resulting publications even though he had contributed substantially to the project. He is remembered by Soviet science not only for his own scientific creativity but chiefly as a formative influence on a whole generation of Soviet scientists.

The book opens with an account of his life and scientific career, commencing with his early days under D. S. Rozhdestvenskii and his work in the Twenties in the production of optical glass, which eventually freed the Soviet Union from the need to import this strategic commodity. He subsequently established his own laboratory (Laboratory of Applied Physical Optics), whose main aim was to develop those theoretical advances in optics that showed promise of practical application. Some of the early work carried out in his laboratory included an analysis of the structure of glass by x rays and the development of an all-Russian electron microscope. Subsequent projects included work in semiconductors, photoconduction, infrared imaging, and optical range finders. From 1950 he was editor in chief of the physics section of *Izvestiya Akademii Nauk SSSR.* He died in 1969.

The collected works contain thirty articles and begin with Lebedev's first paper, published in 1915, on the Stokes law as applied to liquid spheres. There are four articles on the production and annealing of optical glass, a result of his work in establishing an optical glass industry in Russia; some on instrumental techniques in optics; and a review of new instrumental techniques. There are several papers on the microstructure of glass and how it can be investigated by x-ray techniques and spectral methods—papers representative of one of his most important fields of research. An article on the Russian model of an electron microscope is interesting, since it is a summary of the achievements of his laboratory in providing the Soviet Union with a machine based entirely on its own technology. Also given are a few papers on natural physical phenomena such as the investigation of short optical wavelengths in solar radiation, the green line in night airglow, and the transparency in different parts of the spectrum of natural clouds and fog.

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